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Special Collection:

Past and Future of Marine
Ecosystems

Key Points:

- For marine environments, 25 anthropogenic pressures are projected to worsen in the future under business-as-usual scenarios
- We identify eight pressures without future projections, and we recommend prioritizing assessments of their trajectories
- This study underscores the importance of addressing and mitigating all known pressures to promote future healthy ocean ecosystems

Supporting Information:

Supporting Information may be found in the online version of this article.

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Knowns and Unknowns in Future Human Pressures on the Ocean

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Abstract Growing demands on ocean resources are placing increasing pressures on ocean ecosystems. To assess the current state of knowledge of future human pressures on the ocean, we conducted a literature review of recent and projected trends of 25 anthropogenic pressures, comprising most of the identified human pressures on the global oceans. To better understand gaps in the data, we developed a comprehensive framework of the activities contributing to each pressure. All pressures were allocated to five categories (biological disruption, disturbance and removal, altered ocean chemistry, pollution, and climate pressures). All pressures are expected to worsen in the future under business-as-usual scenarios (or similar) based on past trajectories and/or models of future scenarios. Eight of the pressures assessed have not been projected into the future (diseases and pathogens, introduced coastal wildlife predation, disruption to sediment dynamics, wildlife strikes, organic and inorganic chemical pollution, light and noise pollution), likely due to the limited availability of data describing current pressures, the challenges of modeling future pressures, and high levels of uncertainty. We thus recommend they receive priority attention to assess their likely future trajectories, given their potential magnitude of influence.

Plain Language Summary Ocean ecosystems face increasing challenges owing to growing demands on ocean resources, pollution and climate change. To better predict the future trajectories of human pressures on the ocean, we conducted a review of 25 human-induced pressures on global oceans. All pressures are expected to worsen in the future if current trends continue. Some pressures (i.e., diseases and pathogens, introduced coastal wildlife predation, disruption to sediment dynamics, wildlife strikes, organic and inorganic chemical pollution, light and noise pollution) lack future projections and need urgent attention to assess their potential impacts.

1. Introduction

The ocean covers 71% of the earth's surface and is critical for planetary and human health (Costanza, 1999). Humans rely on the ocean for oxygen production, food, buffering from global temperature increases, natural resources, transportation, emotional wellbeing, and leisure, among many other uses. These activities, both terrestrial and marine, result in pressures that put substantial stress on marine organisms and ecosystems (Halpern et al., 2008, 2015; O'Hara et al., 2021). In the future, these pressures are projected to increase given expanding populations and economies, as well as the development of novel uses of marine regions and methods of resource extraction (Jouffray et al., 2020; Sumaila et al., 2021). The need to address current and future pressures has become one of the most important, complex and urgent challenges facing humanity, reflected in global policies such as the Sustainable Development Goals (United Nations, 2015) and the Ocean Decade (UNESCO-IOC, 2021).

Building on previous work (Butt et al., 2022; Halpern et al., 2008, 2015), we develop a comprehensive framework of human activities and the resulting pressures on marine environments. Similar to Elliott et al. (2020), we define “pressures” as the variables, resulting from human actions, that most directly affect the physiology and life-history of marine taxa, and ultimately ecosystems. These pressures operate at different scales, from organisms (e.g., reduced survival) to populations and ecosystems (e.g., habitat loss), resulting in impacts which are often negative but can be positive to some organisms (Oesterwind et al., 2016). We define “activities” as the human actions that create pressures, such as land-based agriculture, Mari culture, fishing, mining, exploration, shipping, and tourism (e.g., Dailianis et al., 2018). The relationship between activities and pressures can be complex, such that a single activity can generate multiple pressures and a single pressure can result from many different activities

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(Halpern et al., 2008; O'Hara & Halpern, 2022). For example, marine mining and exploration places pressure on the ocean by transforming habitats, and generating chemical pollution and ocean noise, while ocean noise can be emitted by many different human activities, including fishing, oil and gas exploration, and shipping.

The distinction between pressures and activities are often conflated. We focus explicitly on pressures (vs. activities) because this is what organisms respond to (are affected by) and, for that reason, should be the basis of modeling impacts. Pressures have a history of being successfully used to estimate impacts on marine habitats (Halpern et al., 2008, 2015) and species (O'Hara et al., 2021) based on their physiology and life history (Butt et al., 2022). Although pressures provide the most direct way of estimating impacts, understanding the linkages between activities and pressures is critical for several reasons. Activity data are often more readily available because they can be easier to monitor and are also more likely to be the target of management and regulation. In these cases, activity data can serve as a proxy or be used to model pressures, but this requires mapping the relationships between these variables.

Although there is published information on current marine activities (e.g., Crona et al., 2021) and ocean pressures (Crain et al., 2008; Gissi et al., 2021; Halpern et al., 2008), as well as the accelerated rate of change over the last 50 years (Halpern et al., 2015; Jouffray et al., 2020), less has been done to synthesize what we know about future pressures for the mid-to long-term (but see O'Hara & Halpern, 2022). To address this, we review the literature on the current and projected future pressures placed on oceans by human activities, without addressing ultimate impacts or outcomes. Although we focus on pressures, we link them to their corresponding human activities given that in many cases only activity data are available, and both are used, sometimes interchangeably, by researchers and managers. Our aim is to provide an overview of the expected future trajectory of each pressure, synthesizing information on how far into the future the pressure is projected, its predicted trajectory (trend direction, magnitude, and confidence in projections) and to describe the data underlying the future projections (e.g., spatial resolution, analysis type, and scenarios). Based on this synthesis, we highlight the gaps in knowledge, providing recommendations about future research priorities.

2. Methods

A list of anthropogenic pressures ($n = 25$) and corresponding activities was pre-determined and defined, building on similar efforts to catalog pressures (Halpern et al., 2008; O'Hara & Halpern, 2022). The summarized list is presented in Figure 1 and the full description of each pressure in Supporting Information S1. This was followed by a scoping review (Collins et al., 2015) to identify available publications on projected ocean pressures at a global scale that had either quantitative or qualitative trend outputs.

The literature search was completed between February and May 2022, using SCOPUS database. Academic journal articles, books, reports and gray literature published between 2000 and 2022, in English, were included. Word search criteria (of titles) included: (global* OR world OR ocean OR coast*) AND (forecast* OR project* OR trend OR predict* OR estimate* OR ensemble OR review); with additional key words according to each pressure (e.g., "sea level rise"). The results of the database were automatically organized by relevance. A minimum of 60 results was examined by reading the title, abstract, and in some cases full document, to determine its importance. This threshold was chosen arbitrarily.

Additional sources of information were searched, including reports from the Intergovernmental Panel on Climate Change (IPCC), Food and Agriculture Organization (FAO), and United Nations (UN). Cross references (snowball sampling) and other documents suggested by co-authors were assessed if relevant. This approach may introduce potential biases, as it tends to exclude less cited and more recent works with clear relevance. However all co-authors have a good exposure to recent publications and were able to suggest useful sources that mitigate this bias. We then synthesized the literature using a narrative approach (Booth, 2016) which characterizes studies in terms of multiple groupings to explore heterogeneity descriptively, rather than statistically. The synthesis phase consisted of extracting and categorizing the projected pressure data from selected papers based on: spatial resolution; temporal range; type of analysis (e.g., quantitative/mapped, qualitative/unmapped, qualitative, or mixed); if available, the specific scenarios used for future projections (i.e., Representative Concentration Pathway (RCP), Shared Socioeconomic Pathway (SSP)); and description of the general trend of each pressure (e.g., upward, downward or static trajectory). The terminology is described in Table 1.

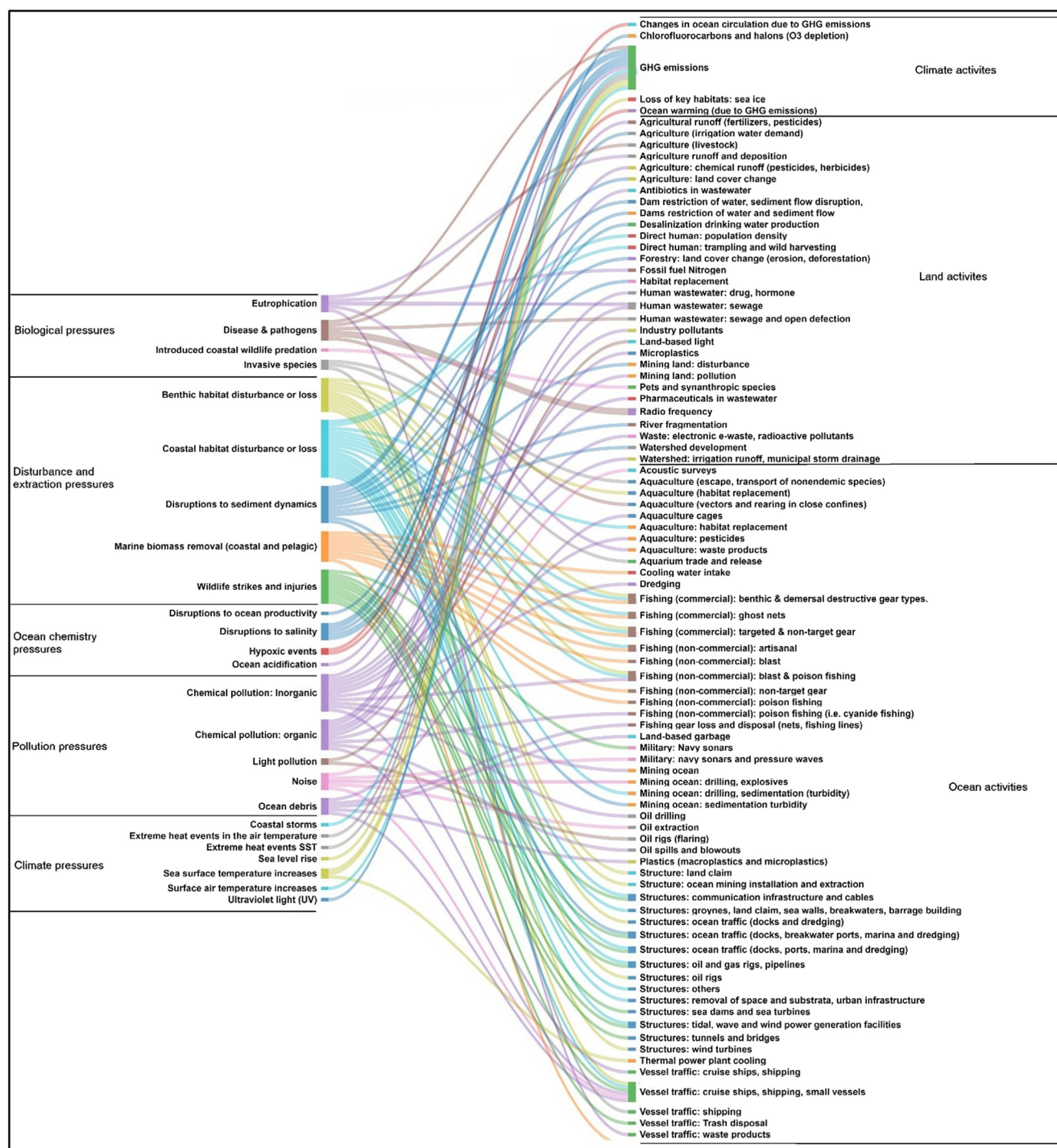


Figure 1. Sankeymatic diagram of marine anthropogenic pressures in the left column and corresponding activities in the right column organized according to categories. The line thickness has no quantitative value (Made with the SankeyMATICS program).

3. Results

A total of 1,681 documents were reviewed, from which 67 met the criteria for selection. The full list of publications selected for each pressure is presented in Table S1 of Supporting Information S1 and an extended summary of the findings in Supporting Information S1. From the 25 pressures assessed, only eight lacked future projections at a global scale. These include diseases and pathogens, introduced coastal wildlife predation,

Table 1
Definitions of Terminology Used

Category	Term	Definition
Scenarios used to estimate future projections	Shared socioeconomic pathway (SSP) and representative concentration pathway (RCP)	SSP and RCP are frameworks used to model future projections of environmental pressures, incorporating socioeconomic trends and greenhouse gas trajectories, respectively. The SSPs describe 5 potential pathways of global socioeconomic development, based on variables such as population, technological advancements, climate policies, and gross domestic product. These narrative storylines are then paired with greenhouse gas emission pathways (RCPs) which result in specified levels of radiative forcing (i.e., difference between the amount of energy entering and leaving the atmosphere) in 2100. An SSP scenario may have multiple potential RCPs. The most common are: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5.
Type of analysis	Quantitative mapped	Data values are described relative to their spatial location.
	Quantitative unmapped	Data are not spatially represented.
	Qualitative	Non-numerical, descriptive, data (e.g., interviews).
	Mixed	Combination of above.

disruption to sediment dynamics, wildlife strikes, organic and inorganic chemical pollution, light and noise pollution. Figure 2 and Table 2 show which of the pressures have been projected, the expected future trend, and the confidence level.

For the 17 projected pressures, Figure 3 shows the different approaches and outputs of future projections for the 86 studies assessed (based on 67 unique articles), including quantitative mapping analyses (81%), quantitative unmapped (18%) and qualitative analyses (1%). The spatial resolution of projections ranged between 15 arc s (450 m) up to regional or country level. The timeframe covered by projections ranged between the years 2050 and 2300 (there is an exception in the upper limit: an ocean acidification article projected up to the year 12,000). Figure 4 describes the number of studies according to the projected trend for each pressure. The scenario frameworks used for the projection models were predominantly (48.5%) the “Representative Concentration Pathway” (RCP), followed by “Shared Socioeconomic Pathways” (SSPs) (13%); SSP-RCP (10%); Special Report on Emissions Scenarios (SRES) (10%); “Business-as-usual scenario” (BAU) (6.5%); Millennium Ecosystem Assessment (MEA) (4%), and “other” (8%).

4. Discussion

Anthropogenic pressures on global oceans have increased in most places during recent history, impacting marine species (O’Hara et al., 2021), habitats and ecosystems (Halpern et al., 2008, 2015). To better understand future pressures on the oceans, we reviewed the current literature describing the future projections of pressures that impact marine systems. Of the 25 pressures we identified, all but eight have future projections, at least to some extent, and all show a tendency to get worse (Figure 2). The eight pressures without projections are also likely to increase or expand in the coming decades, based on their underlying activities and past trajectories. Pressures without future projections were often very complex, with many drivers, and high uncertainty with regard to how these drivers may change. Given the importance of comprehensive assessments, filling gaps in pressure data should be a priority for researchers and managers, but will require a collaborative effort from multiple stakeholders. While individual scientist and research institutions can contribute significantly, Intergovernmental organizations such as the Intergovernmental Panel on Climate Change (IPCC), scientific networks such as the Coupled Model Intercomparison Project (CMIP) or the Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP) are well placed to bridge these gaps in knowledge.

Many of the pressures with future projections had other limitations that hinder our assessment of future impacts. Perhaps most importantly, estimates of future projections for several of the pressures have a great deal of uncertainty and should be integrated into future studies. In many cases, it is more difficult to model human responses to changing global conditions (e.g., change in pollution) than it is to model physical variables, such as SST. Another limitation is that many pressure estimates are incomplete, and include only a portion of the underlying activities, or drivers. For example, data describing current patterns of global land use (a component of habitat

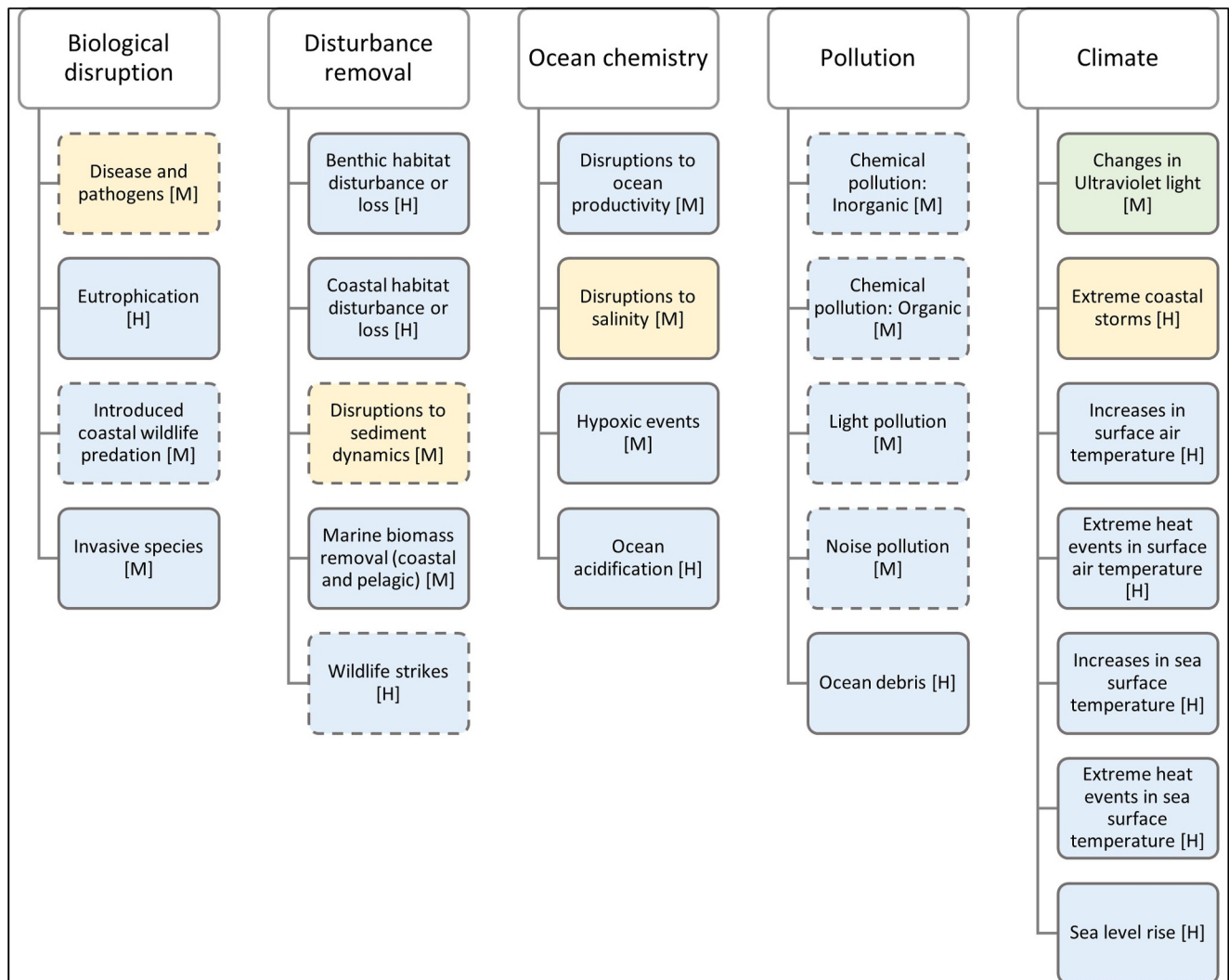


Figure 2. Marine anthropogenic pressures ($n = 25$) classified into five categories. Pressures with future projections at the global scale are outlined with a solid line ($n = 17$) and those without future projections are outlined with a dashed line ($n = 8$). Colors indicate the direction of the projected change (or, the historical direction of change for the eight pressures that are not projected). The confidence level of the projection is indicated in parentheses (High: H, Medium: M and Low: L). Future trends are represented in different colors: green (decrease), yellow (mixed regional variance) and blue (increase). An extended summary of the findings is presented in Supporting Information S1.

disturbance and loss, e.g., aquaculture, marine structures, coastal hardening) are unavailable or limited, and data on future projections are even more scarce. Furthermore, future projections often describe general patterns of change but they do not include high resolution spatial descriptions of future magnitudes or extents. This information is critical to estimating the impact of pressures on marine taxa and ecosystems because it helps quantify the exposure of organisms to the pressures.

Understanding the linkages between activities and pressures will be key to improving the quality of projected pressure data. In many cases, activity data can be a suitable proxy for pressure data or can be used to model pressures. For example, human population is associated with many pressures (e.g., pollution, disturbance and extraction pressures). The world population is projected to grow from the current 8 billion to almost 10 billion inhabitants in 2050 (United Nations, 2022), of which at least 1 billion people will live along the coast (Merkens et al., 2016). By the year 2100, Asia and Africa are expected to reach a population of 9 billion, out of 11 billion people (FAO, 2017). Environmental change can also alter human migratory patterns, and coastal migration can even reverse owing the impacts of climate change in these vulnerable areas (Hugo, 2011). Among other things, this information could be used to model future light pollution.

Table 2

Summary of the Results for Each Pressure, Including Latest Year of Projection, or Not Projected (NP), the Expected Trend, Its Confidence and General Notes

Pressure	Year ^a	Trend ^b	Confidence	Notes
Biological pressures				
Diseases and pathogens	NP	±	Medium	We were unable to find projections of this pressure, however, there are observations of recent increase in marine disease (Ward & Lafferty, 2004) and vector borne diseases have expanded from the tropics/subtropics to temperate regions (i.e., Caminade et al., 2014; Liu-Helmersson et al., 2014; Ogden, 2017)
Eutrophication	2050	+	High	Projected to shift from industrialized countries to developing countries mainly in South East Asia (Liu et al., 2012; Seitzinger et al., 2002, 2010). The frequency, magnitude and duration of harmful algal blooms (HABs; i.e., a rapid proliferation of microscopic algae that produce toxic compounds) has increased in recent times together with expansion into new locations and changes in toxicity (Glibert & Burford, 2017; Gilbert et al., 2014). This pattern is projected to continue into the future.
Introduced coastal wildlife predation	NP	+	Medium	Some localized studies are available (i.e., extinctions due to feral cats on Medina et al., 2011) to describe current pressures. Coastal human population density is probably a good proxy measure that has been projected into the future.
Invasive species	2060	+	Medium	Generally projected to decrease in the tropics and increase in the temperate regions (Seebens et al., 2016).
Disturbance and extraction pressures				
Benthic habitat disturbance or loss	2100	+	High	Benthic biomass under RCP 8.5 was estimated to decrease 5.2% due to climate change by 2100. Polar oceans and some upwelling areas may increase the benthic biomass, but most other regions will decrease (i.e., up to 38% in the northeast Atlantic; Jones & Cheung, 2015).
Coastal habitat disturbance or loss	2100	+	High	Globally, coastal infrastructure in 30 urban centers has replaced more than half (53%) of the coastline and is expected to increase by 50%–76% by 2043 (Floerl et al., 2021). Coastal pressures are further exacerbated by climate change (i.e., ambient shoreline changes and coastal recession driven by SLR, could result in the disappearance of almost half of the world's sandy beaches by 2100, Voudoukas et al., 2020).
Disruptions to sediment dynamics	NP	±	Medium	Future projected sedimentation patterns along coastal zones do not exist, but patterns will be spatially heterogenous based on current and historical changes. Past trends indicate decreased sediment flux in the northern hemisphere and rapid increases in the southern hemisphere due to land use change (Dethier et al., 2022).
Marine biomass removal (coastal and pelagic)	2100	+	Medium	Decline of animal biomass, stock and maximum sustainable yield (MSY) due to climate change and overfishing (Coll et al., 2020; Free et al., 2020; Gaines et al., 2018; Galbraith et al., 2017; Lotze et al., 2019). The MSY defined as the maximum production of food from the sea on a sustained basis year after year (Chapman, 1949 in Finley & Oreskes, 2013). The MSY is projected to decrease for equatorial countries and increase for poleward countries (Free et al., 2020; Jones & Cheung, 2015).
Wildlife strikes	NP	+	High	Wildlife strikes have not been projected, however, they are linked to global maritime traffic, which increased by 258% between 2006 and 2014 and is projected to increase 240%–1,209% by 2050, relative to 2014 (Sardain et al., 2019). Currently, higher resolution data describing the spatial patterns of shipping change are unavailable, but increases in shipping traffic will be highest along connections with large, fast-growing economies, notably Northeast Asia. The accelerated decline in Arctic Sea ice in recent decades suggests the possibility of future trans-Arctic shipping routes linking the Atlantic and Pacific Oceans (Wei et al., 2020).
Ocean chemistry pressures				
Disruptions to ocean productivity	2300	+	Medium	The NPP is defined as the amount of carbon dioxide that phytoplankton convert from carbon dioxide to organic carbon using photosynthesis and is the basis of marine ecosystems. Significant redistribution of marine net primary productivity (NPP) is projected by 2100 (Stock et al., 2014). NPP is projected to decline by –3% under SSP5-8.5 by 2080–2099 (Kwiatkowski et al., 2020). Moore et al. (2018) suggested a steady decline of 24% north of 30°S by the year 2300. In contrast, NPP has been projected to increase in offshore polar regions due to higher mean underwater light levels (Cooley et al., 2022).

Table 2
Continued

Pressure	Year ^a	Trend ^b	Confidence	Notes
Disruptions to salinity	2100	±	Medium	Changes to salinity in the surface waters of the open ocean are expected to generally be less extreme than near-shore regions. In the 21st century, the fresh ocean regions (North and South Pacific, Southern, Indian Ocean and Arctic Ocean and Bay Bengal) will get fresher and salty ocean regions (Atlantic and Equatorial Indian Ocean) will get saltier (Fox-Kemper et al., 2021; IPCC, 2021). Near shore changes to salinity, due to changes in rainfall and land-use, are not currently projected at the global scale.
Hypoxic events	2100	+	Medium	CMIP6 model projections estimate subsurface oxygen will decline by 11.2% for the SSP5-8.5 scenario by 2081–2100 (IPCC, 2022). The changes are not spatially uniform and there is a high degree of disagreement in regard to the spatial distribution of change (Bopp et al., 2013; Kwiatkowski et al., 2020). However, projections suggest the North Pacific, North Atlantic, Southern Ocean, subtropical South Pacific, and South Indian Ocean will all undergo deoxygenation; in contrast, the tropical Atlantic and the tropical Indian Oceans show increasing O ₂ concentrations in response to climate change.
Ocean acidification	12000	+	High	The pH of the ocean is strongly projected to keep decreasing (Kwiatkowski et al., 2020).
Pollution pressures				
Chemical pollution (inorganic)	NP	+	Medium	There are no global projections of this pressure, which has many contributing sources. However, some heavy metals have been researched individually; for example, mercury by Zhang, Song, et al., 2021.
Chemical pollution (organic)	NP	+	Medium	We were unable to find global projections of this pressure, which has many contributing sources. However, Octaviani et al. (2015) found secondary emissions (re-volatilization from land and sea surfaces) will dominate global atmospheric cycling of POPs. A secondary volatilization of DDT caused by global warming will still be continuously transported to the north polar area, and the net export of PCB153 out of the Arctic will increase in the future (Octaviani et al., 2015).
Light pollution	NP	+	Medium	Global light emissions observed through satellites showed an increase of at least 49% from 1992 to 2017 (Sánchez de Miguel et al., 2021). We expect that global light pollution will continue to increase given projected increases in coastal population and GDP, which are both associated with increasing light pollution (and have future projections).
Noise pollution	NP	+	Medium	No global projections were found; however, maritime traffic is the most common source of noise which is increasing quickly and is generally expected to continue increasing. We failed to find current and future projections for other sources, such as, mining for natural resources, construction, blast fishing, military sonar and sub-seabed geological storage of CO ₂ . Climate change will magnify noise pollution, because sound absorption decreases with increasing temperature and decreasing seawater pH (Ilyina et al., 2010). Affatati et al. (2022) identified two “acoustic hotspots” where future sound speed is predicted to increase under BAU by 2100: The Greenland Sea and the north-western Atlantic Ocean (East of Newfoundland), where the average speed of sound is likely to be greater than 1.5% by 2100.
Ocean debris	2100	+	High	Lebreton et al. (2019) predicts that for a BAU scenario, the quantities of buoyant macroplastics at the surface of the ocean and coastline could quadruple by 2050, concentrated in its majority along the shoreline (when compared to the offshore and coastal surface layer) and eventually degrading in to microplastics.
Climate pressures				
Changes in ultraviolet light (UV)	2100	-	Medium	Tendency to decrease in the future, mainly due to: increasing concentrations of greenhouse gases, a possible decline in solar activity, increase in cloud cover, and reduced reflectivity due to melting ice (Bais et al., 2015). Bais et al. (2011) estimated that UV radiation by the end of the century will be on average 12% lower at high latitudes in both hemispheres, 3% lower at mid latitudes, and marginally higher (1%) in the tropics, relative to 1980. These findings are opposite to Watanabe et al. (2011) who suggested that all sky UV radiation in the northern mid-latitudes is projected to increase in the 21st century.
Extreme coastal storms	2100	±	High	Tropical cyclones (TC) remain a challenge to project owing to the short historical record, the spatial resolution of climate models relative to the scale of storm drivers; and low annual frequency and large variability, from days to decades (Roberts et al., 2020). According to IPCC, the global proportion of category 3–5 TCs has likely increased over

Table 2
Continued

Pressure	Year ^a	Trend ^b	Confidence	Notes
				the past 40 years and peak intensities in the North Pacific Ocean are likely moving poleward. Bhatia et al. (2018) found significant decreases in TC days between 30°S and 30°N in the south Indian, north Indian, western Australian, and western Pacific basins. The IPCC projected trends are highly variable among regions. There is medium confidence that the total global frequency of TCs will decrease or remain unchanged. But high confidence that the proportion of intense TCs, as well as their projected intensity, will increase (IPCC, 2021).
Increases in surface air temperature	2300	+	High	Huang et al. (2022) estimated that land surface air temperature under SSP5-8.5 will increase by 5.8°C. Similarly, Tebaldi et al. (2021) estimated that an average of 2°C warming would be reached by 2039, and 5°C warming will be reached in the mid-2090s under SSP5-8.5.
Extreme heat events in surface air temperature	2300	+	High	In recent decades heat waves (HW) have increased and future climate scenarios project increases in frequency and intensity (Meehl et al., 2012; Cesar et al., 2013; Russo et al., 2014; IPCC, 2021; Dosio et al., 2018, estimated that 13.8% of the world population will be exposed to severe HW every 5 years under a 1.5°C scenario (with the greatest threats to Africa, South America, and Southeast Asia) and this triples to 36.9% under a 2°C warming scenario.
Increases in sea surface temperature (SST)	2100	+	High	SST has increased in recent years, and is projected to increase in the future (i.e., Bopp et al., 2013; Cocco et al., 2013; Ruela et al., 2020; Kwiatkowski et al., 2020; IPCC, 2021). According to Kwiatkowski et al. (2020), by the end of the century, SST is projected to increase by 3.5°C under SSP5-8.5. The Northern Hemisphere has a higher annual SST increment than the Southern Hemisphere and the Northern Sub-Tropical shows the highest significant increase (4.3°C on RCP 8.5; Ruela et al., 2020).
Extreme heat events in sea surface temperature (SST)	2100	+	High	Between 1982 and 2016 the number of marine heat waves (MHW) days has doubled, and projected to increase by 26-fold under a 2°C scenario (Frölicher et al., 2018). Future MHWs are also expected to increase in duration and intensity (Plecha & Soares, 2020), with many parts of the ocean reaching a near-permanent MHW state by the late 21st century (Oliver et al., 2019). Qiu et al. (2021) projected the largest changes in the tropics, North Pacific, and North Atlantic with an increase in intensity (up to 4°C) and duration. Under SSP5-8.5, the intensities nearly double with a near-permanent MHW state occurring by the 2070s (Qiu et al., 2021).
Sea level rise	2300	+	High	The CMIP6 project indicates sea level will increase 0.52–1.05 m (SSP5-RCP8.5) by 2100 according to the most pessimistic climate scenario and 0.30–0.64 m for the most optimistic scenario (SSP1-RCP2.6; Hermans et al., 2021).

^aYear: Maximum projected year. ^bTrend: Increase (+); Decrease (−); Mix (±).

Understanding the linkages between activities and pressures would also improve our estimates of the pressures resulting from land-based activities. More than 80% of the pollution of the ocean arises from land-based sources reaching the ocean through rivers, runoff, atmospheric deposition and direct discharges, and pollution crosses national boundaries (Landrigan et al., 2020). This makes effective management of the underlying activities difficult. To mitigate most (if not all) ocean pressures, multinational actions are needed (Tulloch et al., 2020), as well as both regional and global pressure models and maps, to inform both regional and global cumulative impact studies, which in turn can inform local, regional and global management responses.

In addition to improvements to pressure data, studies of future marine impacts will benefit from better understanding how pressures impact marine organisms and habitats. Although there has been work to understand how pressures impact organisms based on their physiology and life history (Butt et al., 2022; O'Hara et al., 2021), these models require further testing and refinement. Furthermore, interactions among multiple pressures and the ecological consequences are largely unknown, and projecting multiple co-occurring pressures can create a vast number of uncertainties derived from modeling assumptions and a lack of data.

Geo-engineering interventions to address climate change can become a pressure and impact the ocean in unknown ways. Even though techniques such as solar radiation management, injecting aerosols into the atmosphere, ocean fertilization or subseabed geological storage of CO₂ (e.g., Carroll et al., 2014) have been researched, there are no

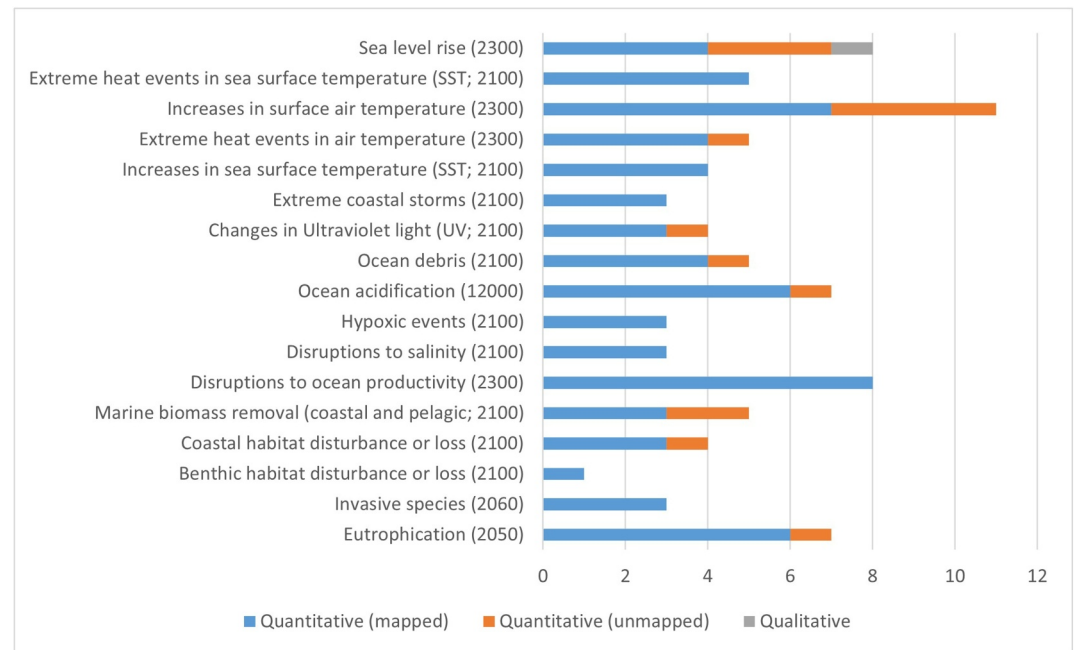


Figure 3. Analytical methods and outputs for 17 projected pressures are detailed, with the latest year of projection in brackets. Bars indicate the number of selected studies that used a quantitative analysis (mapped or unmapped) and qualitative analyses.

data to predict the outcomes of these interventions and there is limited understanding of their consequences, for example, some existing pressures could be mitigated but new ones could be introduced.

Work has been done to assess the current state of the global ocean and to assess the pace of change in cumulative impacts (Halpern et al., 2015). This framework can be used under different future scenarios (i.e., SSP-RCP) to

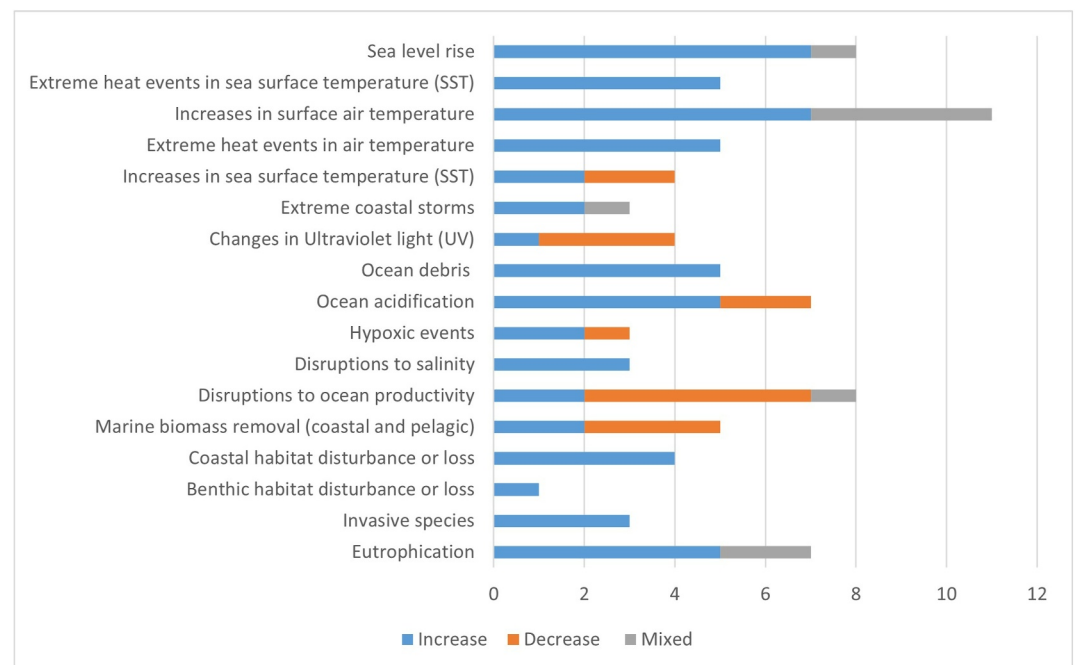


Figure 4. Future trend for the 17 projected pressures, bars indicate the number of selected studies that predicted increases, decreases, or mixed responses for each pressure.

evaluate how the ocean might respond in the future to projected cumulative impacts. For example, some localized studies projected interactions between stressors in the Arctic Ocean and their impacts on populations and ecosystems, up to the year 2040 (Arrigo et al., 2020). This study highlights that climate-related stressors have a larger impact on animal populations than do acute stressors (i.e., shipping and subsistence harvesting). The SSP-RCP frameworks are important standardized scenarios for exploring future trajectories. This approach facilitates collaboration and comparison between transdisciplinary projects. At the same time, it serves as a platform that allows researchers to build on other researchers' data more easily, fostering a unified approach to addressing the complex challenges.

Pressure data provide the basis for cumulative impact studies, which are useful tools for guiding global policy and management. Based on the findings in this review, we provide the following recommendations for research priorities to address future pressures on the ocean:

1. Prioritize research to project the eight pressures that currently lack future projections (e.g., diseases and pathogens, introduced coastal wildlife predation, disruption to sediment dynamics, wildlife strikes, organic and inorganic chemical pollution, light and noise pollution).
2. Fill gaps for pressures that are projected temporally but not spatially. Mapped data is an invaluable tool that can inform and assist decision making.
3. Continue to improve the resolution of projected mapping of ocean pressures.
4. Project a long-term comprehensive cumulative impact assessment. A global ocean projection that estimates the changes in diversity and assess the marine ecosystem response to cumulative pressures can inform management and policy making.
5. Quantify and communicate uncertainties, as a tool to guide research, management and planning actions (i.e., concentrating monitoring efforts in areas of high uncertainty). Projecting multiple co-occurring stressors can create a vast number of uncertainties derived from modeling and lack of data.
6. Improve ocean and coastal sampling, monitoring research and data standardization. This will allow higher resolution and higher quality of projected models.
7. Enable the production of open source data because they are an important resource for making science more accessible, enhancing collaboration and enabling impactful research. This type of research is in turn important for the production of quality research outputs to guide implementation strategies that can mitigate the impacts of pressures.
8. Examine the effectiveness of existing global policies and explore the development and implementation of global frameworks that can address multiple pressures.

Ultimately, to be able to understand and plan for a future ocean, we need to be able to predict impacts, not just pressures. The review and assessment we provide here are key first steps in this direction. Coupled with projections of where species and habitats are likely to be in the future, under climate change scenarios and increased human disturbance, future pressure models can help to predict where and how much natural systems will likely be impacted. These models can then be used to assess different scenarios of management and conservation, hopefully allowing for more effective decisions about the safeguarding of future oceans.

Data Availability Statement

Although this research did not create data or codes, it is drawn from a series of publications available in Vargas-Fonseca et al. (2024).

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