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Anticipating the Future of the World's Ocean

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Abstract

Oceans play critical roles in the lives, economies, cultures, and nutrition of people globally, yet face increasing pressures from human activities that put those benefits at risk. To anticipate the future of the world's ocean, we review the many human activities that impose pressures on marine species and ecosystems, evaluating their impacts on marine life, the degree of scientific uncertainty in those assessments, and the expected trajectory over the next few decades. We highlight that fundamental research should prioritize areas of high potential impact and greater uncertainty about ecosystem vulnerability, such as emerging fisheries, organic chemical pollution, seabed mining, and the interactions of cumulative pressures, and deprioritize research on areas that demonstrate little impact or are well understood, such as plastic pollution and ship strikes to marine fauna. There remains hope for a productive and sustainable future ocean, but the window of opportunity for action is closing.

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1. INTRODUCTION

Widespread scientific research and many synthetic reports are raising increasing concern about the fate of the oceans. Once thought to be too big to be susceptible to human impacts, oceans are showing many signs of significant change resulting from climate change, overfishing, offshore energy, invasive species, coastal development, and more (1). The most recent Intergovernmental Panel on Climate Change report declared a code red for humanity given the scope and impact of climate change on our planet (2). The analogous report for biodiversity and ecosystem services highlighted the negative trends for ocean biodiversity and related services to people (3, 4). The recently released *Second World Ocean Assessment* cataloged the many ways that human activities are benefiting humanity but are also putting significant pressure on ocean ecosystems (1, 5). The overarching theme to these reports is that human impacts on the ocean have led to biodiversity loss and shifts in ecosystem functioning, in turn reducing the ocean's contributions to people (4).

Pressure: a factor that can cause environmental change; anthropogenic pressures are generated by human activity on land or sea

Impact: mortality or reduction of fitness of an individual, population, or community due to vulnerability and exposure to an anthropogenic pressure

Amid these sobering reports, research is also showing the potential for a healthy and resilient future for the oceans if smart action is taken. Fisheries management reform and sustainable aquaculture development can lead to more food produced with less environmental impact (6, 7). Well-designed networks of marine protected areas can boost fisheries, support biodiversity, and protect stored carbon (8). Modest reductions in ship speeds can reduce harm and mortality to whales, greenhouse gas emissions, and noise pollution (9).

Taken together, what do all of these assessments and recent scientific findings tell us about the future of the oceans? What are and will be the major issues that the oceans, and thus humanity, face, and what can and should we be doing to address these issues now in order to ensure a better future? Similarly, which issues are sufficiently well understood that we can act upon them now and shift research attention elsewhere?

In this review we focus on highlighting what we understand well with respect to human pressures on marine species and ecosystems, expected trends in these human pressures in the coming decades, where lurking issues remain that merit more attention, and what these insights tell us about anticipating the near-term future of the world's ocean. In doing so we aim to move beyond cataloging the state of the oceans and toward a synthetic understanding of where things are headed and what we can and should be doing to tip that trajectory toward the most sustainable possible future.

To guide our discussion, we use a simple conceptual model of human impact on marine ecosystems, in which human activities result in pressures that adversely affect vulnerable marine species or ecosystems:

$$I_j(t) = \sum_{i=1}^{I} [A_i(t) \times p_{ij}(t)] \times \sum_{k=1}^{K} v_{kj}, \qquad 1.$$

in which $A_i(t)$ represents current intensity of activity i; p_{ij} represents the marginal contribution of activity i to pressure j, generally in the form of an unintended (indirect) rather than intended (direct) effect; v_{kj} is the vulnerability of some ecological entity k (e.g., a species, taxon, or functional group) to pressure j based on its physiological and life history traits (10); and $I_j(t)$ is the overall impact of pressure j on a given set of ecological entities. In some cases, one activity (e.g., bottom trawl fishing) may drive multiple pressures (e.g., intentional biomass removal, unintentional bycatch, habitat destruction, noise pollution), whereas in other cases, one pressure (e.g., nutrient pollution) may be driven by multiple activities (e.g., agricultural runoff, municipal wastewater, atmospheric deposition of combustion byproducts). The trajectory of future impacts is driven by changes over time in the intensity of an activity $[A_i(t + \Delta t)]$ and/or in the pressures associated with an activity $[p_{ij}(t + \Delta t)]$, often due to regulation, technological innovation, or economic demand. Although this simple model elides complexities such as nonlinearities and interactions among pressures, it incorporates several key issues that are necessary to anticipate the future of the ocean: (*a*) Activities and pressures currently impacting marine ecosystems will remain consequential for the future ocean unless immediate action is taken to reduce the intensity of the activity or mitigate its contribution to pressures; (*b*) increasing intensity of human activities and expansion into more vulnerable ecosystems will exacerbate current impacts and introduce emerging impacts; (*c*) uncertainty in our estimate of the state of the marine system (state uncertainty), driven by environmental stochasticity and the challenge of obtaining precise measures, can confound effective policy and decision making; and (*d*) uncertainty in our understanding of the processes by which activities generate stressors, or more commonly how pressures generate impacts (process uncertainty), especially related to ecological vulnerability to emerging and/or rapidly increasing pressures, will be critical to managing for resilience to future impacts and thus should be a priority for future research.

To evaluate the future state of the ocean, we assess the main activities and pressures that are affecting the oceans now and likely to do so in the future. We draw in particular on recent work by the *Second World Ocean Assessment* (1, 5) and our own work cataloging pressures to oceans (11–14) to structure the list of activities and pressures. The focus on activities in some cases and pressures in others is motivated by how data are typically collected and reported and how pressures connect to the oceans (e.g., fishing directly kills organisms, whereas land-based pollution is integrated via watersheds before pouring into coastal oceans). Activity-based assessments are thus focused on fishing, aquaculture, and offshore ocean activities (e.g., shipping, mining), whereas pressure-based assessments are focused on those derived from land-based activities, climate change, and other types of pollution (e.g., noise, light).

For each pressure or activity, we discuss and assess three axes of information that are critical for anticipating how human activities will affect the future of the ocean: (*a*) impact of the activity or

Vulnerability: the magnitude of potential impact from a pressure—conditional upon exposure—on an individual, population, or community

State uncertainty: uncertainty about the state of the ecological system due to environmental stochasticity and the challenge of obtaining precise measures

Process uncertainty: uncertainty about the mechanism or degree of vulnerability of an individual, population, or community to a pressure

pressure on natural systems (I_j in Equation 1), (*b*) expected trajectory of pressures in the coming 20 years under business as usual assumptions (changes in A or p in the future), and (*c*) current areas where uncertainty remains, particularly process uncertainty in terms of ecological vulnerability (v). Because many recent reports have comprehensively addressed the impact of human activities and pressures on the ocean, in particular the *Second World Ocean Assessment* (1, 5), we limit our treatment of the impact axis to brief summaries. Where appropriate, we evaluate coastal versus offshore areas separately given the large differences in their exposure to activities and pressures. To address expected change in pressure intensities in the future, we assess the likely trajectories of activities that lead to changes in pressures over the coming decades. To address scientific uncertainty, we identify gaps in basic understanding of processes that govern system dynamics (process uncertainty, which is best addressed through investment in fundamental research) rather than gaps in knowledge that arise from data limitations (state uncertainty, which can be addressed through investment in data collection infrastructure). For each axis—impact, trajectory, and uncertainty—we use categorical evaluations (low, medium, high) based on a review of the literature and our own expert judgement.

2. WILD-CAPTURE FISHERIES

Marine capture fisheries are a critical resource to meet nutritional, social, and economic well-being of billions of people globally. The great majority of global marine fisheries production, estimated at 84 million tonnes [1 million tonnes =1 teragram (Tg)] in 2018 (15), goes to human consumption, with the remainder to nonfood or indirect food uses such as feed inputs for aquaculture or livestock (16). Fisheries provide nearly one-fifth of animal-based protein for global diets and are especially critical for food security (15) and micronutrients for coastal developing nations (17). Additionally, fisheries employ 39 million people globally (15), with another 80 million people employed in secondary seafood sectors, approximately 90% of these in small-scale fisheries in developing countries (18).

The undeniable benefits derived from fisheries do not come without cost, and—unique among human activities that affect the marine system—the negative impacts of fishing on marine biomass are direct, intentional, and unavoidable. In addition to direct removal of targeted biomass and nontargeted biomass (bycatch), fishing activity results in habitat destruction (14), loss of trophic supports for other fished and nonfished species (19, 20), introduction of marine debris and plastics from lost and discarded fishing gear (21), noise pollution (22), light pollution (23), and disruption of other critical ecosystem functions such as carbon sequestration in seabed sediments (8). Aside from the pervasive effects of climate change, fisheries impose the greatest impact on marine ecosystems (14) and at-risk marine biodiversity (24).

The scientific and economic foundation of sustainable fisheries management is well established (25). Strong fishery management measures implemented at both stock and national levels have been shown to slow negative trends in stock health and facilitate recovery of depleted stocks (26, 27). Scientifically assessed stocks have on average improved since 2005 (15, 26). However, even in these well-managed fisheries, management decision methods may be particularly sensitive to state uncertainty inherent in assessing status of stocks, introducing substantial uncertainty in expectations of stock recovery (28, 29).

Sustainable management of fisheries varies tremendously with a large divide between industrial fisheries in developed economies versus small-scale fisheries in developing economies (15, 30). Even as scientifically assessed fisheries are improving, stocks in unassessed or poorly managed fisheries are generally thought to be in poor health and/or declining (31). Important levers to reduce uncertainty in the ecological and economic sustainability of global fisheries lie in developing technical and institutional capacity to implement effective management of currently poorly managed and unassessed fisheries.

Small-scale fisheries important to the developing world are often characterized by lack of data to inform stock assessment (32) and less strict management, driving ever-increasing fishing effort on overexploited stocks (33). These complex social-ecological systems display broad diversity across inputs, assets, markets, institutions, and specialization (34), making one-size-fits-all solutions impossible. However, several avenues of action show promise: implementation of rights-based fisheries management such as territorial user rights fisheries (30), improvements in data-limited stock assessment techniques (32), and development of technical and institutional capacity (33, 35). Such investments may seem costly but are likely to pay off relative to the long-term costs of a depleted fishery (30, 32).

Over the next several decades, large changes in total harvest from wild-capture fisheries are not likely, even under significant fisheries reform. Although reforms may result in production gains due to increased biomass of rebuilt stocks and harvest from currently underfished stocks, a recent study estimated that ecological limits impose an upper limit on such gains at 16% when maximizing food production, and only 4% when accounting for economic rationality (6). However, fisheries reforms aimed at recovering stocks and maximizing yield will result in reduced fishing intensity, which in turn reduces unintended impacts of fishing including bycatch (36).

Several other trends are likely to become increasingly important. Climate change will shift stock distributions (see Section 7.1), changing beneficiaries of fishery value and resulting in winners and losers as species ranges shift across political boundaries (37). Technological advances such as real-time satellite-based tracking of fishing vessels will enable transparent and effective governance of transboundary and high seas fisheries (38–40) and greatly enhance global capacity for enforcement against illegal, unreported, and unregulated fishing (41) and forced labor (42). Finally, there is growing interest in the vast potential of mesopelagic fisheries to enhance global seafood production, although primarily for fish meal and oil rather than direct consumption (43). Exploitation of mesopelagic stocks bears risks due to state uncertainty around biomass estimates, as well as process uncertainty around the contribution of these stocks to carbon sequestration and trophic support of other commercially and ecologically important species (43, 44).

3. AQUACULTURE

Farmed seafood, or aquaculture, plays a significant role in the global food system, contributing more than half of all directly consumed seafood globally and nearly half of all aquatic production (6, 7). In 2017, total aquaculture production was 112 Tg, valued at US$250 billion, with roughly two-thirds of this production as food fishes and one-third as aquatic plants. Roughly 45 Tg of this total production is freshwater fishes, and ~18 Tg each of molluscs and other marine species (7, 15).

The potential impacts to ocean ecosystems from aquaculture vary substantially depending on the type of species being grown and the resulting methods and infrastructure used to grow them. Finfish and crustaceans (fed species) often create nutrient pollution, increase risk of pathogen spread and genetic escapes, produce greenhouse gas emissions, and destroy key habitats such as mangroves, especially for shrimp ponds [although this pressure has abated recently (7)]. They also require feed, and this feed is fast becoming the dominant source of environmental pressure from fed aquaculture through impacts from land-based agriculture and harvest of forage fish (45, 46).

Shellfish and algae have many fewer potential pressures associated with their production, in particular because they are not fed, and indeed can create positive outcomes from carbon sequestration, nutrient uptake in eutrophic waters, and habitat creation (47). The main concerns for negative effects are introduction of non-native species and modest habitat loss from farm infrastructure, as well as overharvest of wild seed for stocking shellfish farms. When unfed aquaculture is produced in extremely high densities, for example in some places in China, the uptake of nutrients by seaweed and primary productivity by shellfish can be substantial (48), which could reduce trophic resources necessary to support other endemic wildlife.

Despite the critical role that aquaculture plays in our global and local food systems, it receives a fraction of the attention that fisheries do in the scientific literature or from research funding (49). As such, although research and development work on specific cultivation practices for key species is well known, a wide range of questions about how aquaculture will interact with other ocean uses, especially fisheries, and its potential impact on or benefit to marine systems remain understudied.

In particular, key unknowns about potential innovations in aquaculture limit our ability to anticipate future impacts from production. Very few species have had their life cycle "closed," in which all life stages are reared in captivity. Doing so removes the need to harvest wild seed to restock farmed populations. Innovations in pen design are allowing farms to move further offshore, which significantly reduces many of the environmental impacts from raising high concentrations of animals (50). And perhaps most importantly, rapid advances in alternative feeds suggest a potential future where the need for forage species and agricultural products is significantly reduced, helping mitigate the pressures from the capture and production of those feed components (51).

There is no doubt that historic growth in aquaculture over the past 30 years will continue into the future. With demand for seafood increasing and the human population growing, and with wild fisheries effectively at their maximum production, aquaculture is the only way to meet this demand. Indeed, demand for and production of aquaculture is expected to nearly double current levels by 2050, with a majority of this increase in fed species (6).

4. OCEAN-BASED ACTIVITIES

The past few decades have seen increasing use of the oceans for a wide range of uses beyond fishing (Section 2) and aquaculture (Section 3), including transport, energy, resource extraction, bioprospecting, tourism, and more. Technological advances, societal needs, and the push toward blue economies are increasing the intensity of such activities and driving their impacts deeper and farther into the oceans.

4.1. Shipping

Commercial shipping is one of the dominant uses of the ocean, with nearly 2.0 billion deadweight tons of capacity for goods shipped around the world in 2019 by more than 96,000 ships (1). Additionally, passenger and cruise ships constitute another roughly 5,000 ships and primarily occur in coastal areas, with extensive traffic where they do occur. As one of the few uses of the oceans that traverses nearly every patch of space, the impacts from shipping have the potential to reach every species and ecosystem, with most of this impact in the northern hemisphere and along coastal shipping routes (14, 52).

Commercial ships are a dominant contributor to noise pollution (see also Section 6), introduced and invasive species from ballast water, and air pollution and emissions. In coastal areas in particular, shipping also contributes to animal strikes, mainly of large cetaceans; for endangered populations like the North Atlantic right whale, fin whale, and the blue whale, these strikes can increase mortality by two to eight times as much (53). Shipping also puts modest amounts of pollution into the ocean from engines (oil and petroleum), antifouling materials, and waste dumped from the ships.

With automated ship tracking systems, satellite monitoring, and open data platforms like Global Fishing Watch, high temporal and spatial information on the location and speed of commercial ships is becoming increasingly available (54). With this information it becomes possible to predict where and how much each pollution type is occurring, where invasive species are most likely to emerge, where overlap with species movements are likely to lead to ship strikes, and how much reduced ship speed can reduce impacts (9, 55, 56), although many of these models are still under development.

The distribution and intensity of commercial shipping is expected to increase 2.5- to 12-fold by 2050 as the global economy increasingly depends on trade in goods (56). This growth will lead to new and larger ports and new shipping routes. In particular, the likely ice-free condition in the Arctic within the next decade will dramatically shift shipping into this previously low-traffic global region, altering patterns of shipping in other regions in response.

4.2. Offshore Energy and Resource Extraction

For more than a century we have turned to the sea for oil and gas extraction, pushing further and deeper offshore as technology improved. Many of the largest and most productive oil fields are offshore, with 27% of global oil production and 30% of natural gas production occurring offshore in 2016 (1). This extraction has literally helped fuel the growth of national and global economies.

Pressure to shift energy production to sustainable sources has led to a dramatic increase in offshore renewable energy production and speculation. Although offshore wind energy currently contributes only 0.5% of global installed electricity production capacity, the International Renewable Energy Agency has proposed a roadmap to increase capacity 7-fold by 2030 and an additional 8.5-fold between 2030 and 2050 (57). Much smaller efforts have focused on wave (surface and internal) energy and tidal energy.

The ocean seafloor offers many other valuable resources for human uses. Offshore sand and gravel are extensively mined for beach replenishment and restoration efforts, as well as concrete production. More than 30,000 Tg of sand and gravel are extracted each year (58), with more than half now coming from the seabed. The rate of extraction far exceeds replenishment, such that it now functions as a nonrenewable resource. More recently, with the depletion of precious and essential minerals from terrestrial mines, offshore mining has begun, primarily through leasing potential areas and exploratory extraction. The demand for rare earth minerals and other metals needed for electronic components is creating huge demand for these resources.

All these offshore activities involve building infrastructure or removing the benthic layer to extract resources, and in doing so they destroy the habitat where they occur. For energy infrastructure, there are also pipelines or cables that connect that infrastructure to the shore, further extending their benthic footprint and risking spills and fishing gear entanglement. Oil spills in particular present low-frequency, high-impact consequences; they have become much less frequent over the past few decades (59), but very large spills like Deepwater Horizon in the Gulf of Mexico remind us of the potential for catastrophic impacts. While under construction, and less so while under operation, offshore infrastructure also produces significant amounts of noise pollution (see Section 6). After construction, and because there are typically regulations against other uses accessing the space where the infrastructure sits, the artificial habitat and de facto protection can lead to some benefits to biodiversity (60).

The relatively extensive process for permitting offshore infrastructure and the environmental impact assessments that must be done as part of that process means we know a fair bit about the environmental impacts of these activities, although many details likely remain proprietary. In contrast, we know very little about deep-sea mining impacts because of the limited scope of this mining to date and the difficulties in monitoring and observing at extreme depths. Some reports have found that although deep-sea mining has impacts, these impacts may be less than equivalent mining on land (61).

Nearly all offshore uses are expected to increase in the near future, with offshore oil and gas extraction continuing to show sustained growth and substantial expansion of offshore wind energy generation expected due to strong, sustained oceanic wind resources and fewer conflicting uses compared to on-land wind farms (1). Growth in nearly all types of mining is expected due to increasing demand and fewer on-land resources remaining. Growth in some types of mining, especially deep-sea mining, is less certain due to existing regulatory hurdles.

5. LAND-BASED ACTIVITIES

Coastal marine ecosystems are heavily impacted by pollutants and other stressors originating from land-based activities, including agriculture, mining, industrial manufacturing, fossil fuel combustion that contributes to atmospheric pollution, and urbanization. Chemicals and waste products from these activities generally aggregate in soils and surface water and are carried to the ocean via runoff and rivers, whereas airborne waste products are carried to the ocean via atmospheric transport and deposition. Because these pollutants are quickly diluted with depth and distance from the shore, the greatest impacts of these land-based stressors typically occur in coastal zones.

5.1. Nutrient Pollution

Increases in the input of biologically reactive nitrogen (N) and phosphorus (P) to coastal marine waters since the mid-twentieth century have resulted in coastal eutrophication, harmful algal blooms, and loss of biogenic habitats such as coral reefs and coastal wetlands (62). Human-driven shifts in the natural balance of N to P can disrupt the structure, diversity, and functioning of ecosystems (63). Major sources of anthropogenic N in the oceans come from agricultural runoff, fossil fuel combustion (via atmospheric deposition), livestock waste, and municipal wastewater (62). Fertilizers, livestock waste, and wastewater are also major sources of anthropogenic P pollution, along with industrial discharges and construction (64).

Anthropogenic N inputs doubled in the last half of the twentieth century, approaching parity with natural sources of biologically reactive N, and are expected to increase to 120% of natural sources by 2050 (65). In the twenty-first century, fertilizer use increased by 42% globally between 2002 and 2012 (1); even accounting for increasingly efficient fertilizer use, N losses to the environment may increase by an additional 15% by 2050 under business as usual (66).

Policies and actions to curtail both N and P loading from point sources have proven quite successful in wealthier countries, although curtailing inputs from nonpoint sources (N and P from agricultural sources and N from fossil fuel combustion) has proven to be far more challenging (64, 67). In general, practices to mitigate N inputs also tend to reduce P, although the converse is not generally true (68). Although impacts of nutrient overenrichment on marine systems are generally well understood, climate-driven variation in patterns of precipitation, flooding, and drought will result in variation and state uncertainty around patterns of runoff and freshwater transport of nutrients to the ocean (69).

5.2. Organic Chemical Pollution

Synthetic organic chemicals including persistent organic pollutants (POPs) such as pesticides [e.g., dichlorodiphenyltrichloroethane (DDT)], industrial chemicals [e.g., polychlorinated biphenyls (PCBs)], and industrial byproducts (e.g., dioxins); endocrine disrupting chemicals, many of which are POPs; and pharmaceutical and personal care products intended for health care, cosmetics, and medical use are of increasing concern to marine ecosystems due to their persistence in the environment, bioaccumulation, long-range transport, toxicity, and disruption of biological and ecological processes (70–72). Organic pollutants enter the marine environment via agricultural runoff, industrial discharge, municipal wastewater, and atmospheric deposition, with high concentrations found in coastal areas near urban centers and areas of high industrialization and low concentrations persisting in remote marine ecosystems and organisms (1).

The Stockholm Convention targets a small but increasing number of POPs for elimination or reduction of production (73), and has proven successful in reducing loads of DDT and PCBs in the environment (1, 74). However, the rate of increase and diversification of synthetic chemicals is outstripping other major drivers of environmental change (75). Furthermore, management is hampered by substantial process uncertainty around the complex interactions among emissions, exposure, and toxicity, particularly when considering cumulative effects of exposure to multiple chemical pollutants (71, 75). Despite the rapid increase of potentially harmful pollutants, ecological research on effects of synthetic chemical contamination on biodiversity and ecosystems lags well behind research devoted to other drivers of global change (75).

5.3. Toxic Metals

Elevated concentrations of heavy metals in the marine environment, even biologically essential metals (e.g., iron, manganese), can alter metabolism, reproduction, and behavior of marine species and can be toxic at high enough concentrations (76). In particular, nonessential metals including cadmium, lead, and mercury are a major concern to marine ecosystems due to their toxicity and effects on neurology and development of marine organisms as well as humans (1, 76). Primary sources of heavy metals in the ocean include agricultural runoff, industrial discharge, wastewater discharge, dredging, mining, and atmospheric deposition from fossil fuel combustion and metal refining (76–78).

As measured in the marine system, concentrations of cadmium and lead have generally leveled off but are still detectable above background levels; however, monitoring is concentrated around North America, Europe, and Arctic coasts (1), so regional variation is not adequately captured. Global production of cadmium and lead have remained consistent in recent years (1).

Human activity has elevated atmospheric mercury concentrations 450% above preindustrial levels (78). Global anthropogenic emissions increased by 20% from 2010 to 2015; efforts to reduce emissions in Europe and North America were more than offset by increased emissions associated with increased economic activity elsewhere, particularly East Asia (78). As of 2015, only 30% of total annual atmospheric mercury emissions were attributed to current activity, with another 60% attributed to volatilization of legacy mercury deposited to soils and water from past human activity (78). Even as the Minamata Convention drives reductions in anthropogenic mercury emissions from current activities, legacy mercury will remain a significant source of mercury inputs into aquatic ecosystems (78).

Although the individual toxicity of these metals has been well studied, complex mixtures of metals and other chemical pollutants introduce process uncertainty, confounding predictions of cumulative toxic risk and subtoxic impacts, and bear further investigation (77).

5.4. Plastics: Micro and Macro

The rate of plastic production has increased dramatically over the past 50 years, with a cumulative total of more than 8,300 Tg produced globally by 2015, with roughly half of that production thrown away rather than recycled or incinerated (79). Of that waste, an estimated 5–12 Tg enters the oceans each year (80). Lost and discarded fishing gear is another significant source of marine plastic debris, making up nearly half of the plastic waste found in the Great Pacific Garbage Patch (21). Of particular concern are microplastics, as they are already ubiquitous and macroplastic waste degrades into microplastics, and plastics are persistent in ecosystems for an extremely long time (81). In response to this growing pressure, both research on plastic pollution (82) and funding for plastic pollution mitigation in the ocean (49, 83) has increased dramatically in the past decade.

This high profile of plastic pollution gives the impression that it is having a huge impact on the oceans, yet evidence remains limited that marine organisms are negatively affected by them (84). Entanglement and ingestion of macroplastic by sea turtles, seabirds, and other marine fauna can harm and often kill those individuals, and ingestion of microplastics can cause injuries and disrupt feeding and nutrient uptake (85). Microplastics can adsorb organic chemical pollutants and toxic metals (see Sections 5.2 and 5.3), although these toxins can be transported by natural sediment and organic matter as well, and microplastics will generally be a small fraction of natural suspended particulate matter (86). Despite the near omnipresence of plastics in the marine environment (85), it remains unclear whether these impacts are scaling up to population-level consequences. The marginal impact of an additional unit of plastic pollution [i.e., vulnerability (v_{kj} in Equation 1)] appears to be very small, and further research is not likely to upend our understanding of the magnitude of vulnerability. However, the vast global production of plastics (A_i) and the contribution of that production to marine plastic pollution (p_{ij}) mean that the risk of impact cannot be ignored. This is especially relevant as plastic production continues to increase exponentially, and thus the amount of plastic waste entering the ocean is similarly expected to increase manyfold in the coming decades (80).

5.5. Changes to Sediment Dynamics

Anthropogenic changes in coastal sediment dynamics and sediment inputs threaten river deltas (87), sandy beaches (88, 89), and high-biodiversity coastal ecosystems (90, 91). Habitat loss and degradation can be driven by sediment input decreases (e.g., coastal erosion, beach retreat) or increases (e.g., smothering of coral reefs) (90), resulting in loss of nursery habitats for many species and reductions in productivity of coastal ecosystems (92), coastal protection ecosystem services (93), and resilience to climate change (87).

Changes in sediment supply driven by dams, urbanization, mining, and land-use change have reduced sediment flux for most of the world's major river deltas since 1970 (87), with additional drastic reductions for most major rivers projected by the end of the century (94). These changes in sediment flux, combined with coastal activities including development, sand mining, and sand nourishment, have driven erosion and accretion of sandy shorelines (88) and river deltas (87) globally. Coastal erosion in combination with unchecked sea-level rise (SLR) could drive half of the world's sandy beaches to disappear by 2100 (89). SLR and climate-driven changes in precipitation patterns and coastal dynamics will likely elevate state uncertainty around sediment supply and transport (95, 96).

5.6. Direct Human Impact

Coastal zones are far more densely populated than the global average (97). Due to this substantial human presence, global coastlines and very nearshore coastal ecosystems often experience heavy impact and modification from coastal development, trampling from beach and coastal access and shoreline hardening to protect coastal infrastructure. For example, 14% of the shoreline of the United States has been hardened against erosion and flooding (98), many of the world's major coastal cities have hardened more than half their shoreline (99), and China has modified more than 60% of its coastline (100).

Some methods of shoreline engineering and infrastructure (e.g., seawalls) impose greater impacts on marine biodiversity than others (e.g., riprap revetments and breakwaters), although the effects are highly variable and may depend on such factors as taxonomy, structure design and placement, and sediment dynamics (99). Human presence from coastal tourism and recreation can lead to degradation of coastal ecosystems from trampling or species' behavioral shifts, but the nature and extent of these impacts is not well known. Process uncertainty in the impacts of species behavioral responses to human presence can result in failure to recognize and manage critical interactions, and conversely, wasting resources on managing interactions of little consequence (101).

Increasingly dense coastal populations and urbanization, along with the impacts of SLR and increasingly frequent and intense storms, are likely to motivate increased construction of engineered shorelines and infrastructure (102). Growing global commercial shipping and the need to build and expand ports that service those ships, especially along the emerging Arctic shipping routes, will increase shoreline hardening in many areas (56).

6. NOISE AND LIGHT POLLUTION

Sound can propagate very long distances in water, and for this reason animals from cnidarians to mammals have evolved to use sound as a primary sensory system for navigation, foraging, avoiding predators, mating, and finding settlement habitat, among other uses, especially over longer distances or where light visibility is low (22). The ocean is naturally noisy, cueing animals to the locations of, for example, coasts (via waves), storms, ice edges, and the many organisms making noise, intentionally or otherwise.

The past century in particular has seen the rapid increase in anthropogenic noise, or noise pollution, stemming from commercial shipping and transport (see also Section 4.1), fishing (see also Section 2), offshore energy construction and operation (see also Section 4.2), ocean exploration (seismic surveys), military activities (especially sonar), and airplane and coastal traffic (sound propagating into the water), among others (22). This cacophony of noise pollution now overwhelms natural noise in many parts of the ocean (1), drowning out the ability for animals to use sound as a cue.

Recent syntheses indicate that we understand with high certainty how noise impacts species (22). We know less about how and where noise propagates in the ocean because for many parts of the global ocean we do not have high spatial and temporal resolution data on water properties (temperature, salinity) that affect noise transmission, although the navy probably has this information.

Light pollution interacts with species in ways different from noise pollution. Many species—from larger animals like seabirds and sea turtles to microscopic organisms such as copepods—use light to navigate, hunt, avoid predators, and vertically migrate. The role of light as a cue is particularly important at night and at depth, where low levels of light allow organisms to hide while using light they produce or from the moon and stars above to navigate and hunt (103).

The footprint of light pollution is already substantial, affecting an estimated 22% of the world's coastal areas (23). The dominant source of this light pollution is urban and other human infrastructure along the coast, and light from these developments can reach tens of kilometers out to sea (14). Offshore light pollution comes primarily from oil and gas rigs and commercial fishing vessels, in particular squid boats that use light to attract squid (12). Light from these sources can be equivalent to major metropolitan areas and is easily visible from space.

Because we can measure the source and intensity of anthropogenic light from satellites, we know with very high precision where and how much light pollution reaches the ocean, and likely how much it penetrates into the water. In contrast, we know much less about the consequences of this light pollution. Although an increasing number of publications exist (103) across a wide range of taxa on the impacts of anthropogenic light (104), most attention has focused on terrestrial species. Much less is known about how marine species respond, where the properties of light transmission and the ecology and evolution of species in response to those differences diverge from terrestrial systems.

Both noise and light pollution are expected to increase. Already a majority of the world's population lives near the coast (102), such that both types of pollution are expected to increase substantially in the coming decades. Furthermore, with substantial increases expected in commercial shipping (see Section 4.1) and offshore energy (Section 4.2), there will be commensurate increases in noise pollution. Technology may help reduce these overall increases in noise, through innovations such as noise-reducing rotors for commercial ships, but these innovations are unlikely to be sufficient and widespread enough to compensate for the increase in overall volume.

7. CLIMATE

Since the advent of the industrial revolution in the late 1700s, fossil fuel combustion, deforestation, and other human activities have driven an unprecedented rise in atmospheric carbon dioxide from 280 parts per million (ppm) to more than 410 ppm, still rising at 2.3 ppm per year. Excess carbon dioxide, along with methane and other greenhouse gases, are driving increasingly higher atmospheric temperatures globally. Even under scenarios of ambitious carbon mitigation, trends in atmospheric and oceanic temperature and chemistry will continue for the near future (2). Continued warming is exacerbated by positive feedback loops, including melting of reflective glaciers and Arctic sea ice. Even at modest levels of overall temperature rise, we may be approaching climate tipping points due to release of methane from thawing Arctic permafrost and undersea clathrates, global forest diebacks, and collapse of Greenland and Antarctic ice sheets (105). Process uncertainty around the existence of critical climate thresholds and the magnitude of consequences of exceeding such thresholds amplify the urgency of addressing climate impacts immediately and aggressively.

7.1. Changing Ocean Temperature and Chemistry

Anthropogenic carbon emissions are driving three major threats to global marine ecosystems: increasing ocean temperatures; deoxygenation due to temperature-driven changes in solubility, stratification, and upwelling; and ocean acidification due to absorption of carbon dioxide into marine waters (106, 107). Changes in ocean temperature and chemistry will create novel marine climates with no analog in recent history, shifting the locations of habitable space for many species and eliminating some existing climates that support marine biodiversity (108). Long-term trends will be accompanied by increasing frequency and intensity of short-term extreme heat, acidification, and hypoxic events (107).

Since 1900, average sea surface temperatures increased by 0.74°C and are currently increasing 0.28°C per decade (109). These rising temperatures are driving shifts in species distributions generally poleward, on order of 50–100 km per decade, as organisms move or disperse into suitable areas (110), resulting in biodiversity losses near the equator and increases in higher latitudes (111). Future distributions will most likely be driven by changes in both temperature and oxygen supply as species strive to meet critical thermal tolerance and metabolic demands (110). Species ranges will shift differentially based on physiology, adaptive capacity, mobility, dispersal capacity (110), and biogeographical constraints (112, 113), disrupting food webs as historic species interactions disappear and novel species interactions are introduced (110). Ecosystems and food webs are expected to be more resilient than individual species, even as some species are lost and others introduced (110).

Even as long-term temperature trends are driving species range shifts, marine heat waves on the timescale of days to months have increased in frequency and intensity over the past century (114), a trend that is expected to accelerate under continued global warming (115). Marine heat waves have resulted in physiological stress, mortality, and disruption of ecosystems, particularly coral reefs, kelp beds, and seagrass meadows (116, 117), impacting both biodiversity and provisioning of ecosystem services (116, 118). The drivers and ecological impacts of marine heat waves have been well studied, but better forecasting capacity would be valuable to inform conservation management and adaptation in the face of continued warming and heat waves (117).

As with marine heat waves, short-term marine hypoxic events are expected to increase in frequency and intensity under the current climate trajectory. Extreme hypoxic events negatively impact development, growth, metabolism, and survival of marine species across many taxa and regions. The severity of these impacts may eclipse those of acidification and warming; despite this, deoxygenation and hypoxia have received relatively scant attention in the scientific literature (107).

Ocean surface pH has declined by 0.1 (representing a 26% increase in acidity) since 1800 and is expected to decline by an additional 0.1–0.4 (representing an additional 26% to 151% increase in acidity) by 2100 (109). Ocean acidification is a major concern to calcifying marine species, particularly shelled molluscs, as it impedes their ability to secrete calcium carbonate (119, 120). Changes in the marine carbonate system can impact noncalcifying species through behavior change, disruption of sensory capabilities, and reduction of fertilization success (120, 121) in animals and enhancement of photosynthesis in many seaweeds and phytoplankton species (120). Recent work highlights interactions among multiple mechanisms through which marine life will respond to changes in the seawater carbonate system (120).

To date, research on climate-driven marine species range shifts has focused on case studies and models based on projections of environmental parameters, but there remains substantial process uncertainty in demographic mechanisms—e.g., changes in reproductive success, larval dispersal, adult mobility, and trophic interactions—that underlie these range shifts. Trait-based approaches to understanding community dynamics under climate change may better inform predictions of the function and resilience of novel ecosystems (110). The effects of warming, acidification, and deoxygenation on marine species and ecosystems are likely to compound due to physical and physiological interdependence of these three stressors, but cumulative impacts have received little attention in the scientific literature (107).

7.2. Sea-Level Rise

SLR driven by glacial melt and thermal expansion of warming ocean waters threatens low-lying coastal ecosystems by exacerbating coastal erosion, salinization of surface and ground water, increased flooding and storm surge, and degradation of coastal habitats including mangroves, salt marshes, and coral reefs (122, 123). These ecological impacts can in turn result in major impacts on coastal communities, cities, infrastructure, and low-lying island states (1). Sea levels have on average risen 90 mm since 1993, averaging 4.7 mm per year since 2010 and accelerating (1). Healthy coastal ecosystems are often resilient to modest SLR, but cumulative impacts of other pressures create uncertainty in the capacity of these ecosystems to keep pace with accelerating SLR (124, 125). Mangroves and salt marshes have the capacity to build upward to keep pace with historic SLR, but subsidence and changes in sediment supply from human activities can overcome this process, resulting in wetland degradation (123, 124). Studies have shown that coral reefs can benefit from SLR through increased accommodation space for vertical and lateral expansion (126) and improved resilience to increasing temperatures (127). However, the rate of SLR in the next century is likely to outpace the vertical growth potential of many or most coral reefs, particularly in light of increasing bleaching and acidification (125).

7.3. Ultraviolet Radiation

Widespread use of chlorofluorocarbon (CFC) chemicals throughout the twentieth century reduced the ability of the stratospheric ozone layer to shield Earth's surface from harmful ultraviolet (UV) radiation. Increased UV exposure is harmful to marine organisms, particularly plankton and bacteria, affecting photosynthesis, mobility, growth rates, and metabolic function (128), reducing primary productivity at the ocean surface, and altering the composition and biodiversity of marine communities (129). Ozone depletion and increased UV exposure vary greatly with latitude; effects are most pronounced in the southern hemisphere, particularly above the South Pole (129).

Since the adoption of the Montreal Protocol in 1987, use and production of CFCs and other ozone-depleting substances (many of which are also powerful greenhouse gases) have been dramatically curtailed. Stratospheric ozone concentrations are generally healing at 1–3% per year, and regional concentrations are expected to return to 1980 levels by the 2030s (mid-latitude Northern Hemisphere), 2050s (mid-latitude Southern Hemisphere), and 2060s (Antarctica) (130).

8. ANTICIPATING THE FUTURE OCEAN

The future of the world's ocean will be written by human choices as much as by nature's ability to respond and rebound from those choices. How much will we use (and use up) ocean resources, and can nature absorb those pressures? For many anthropogenic stressors, there is strong scientific understanding linking activities to associated pressures to impacts on species and ecosystems (low process uncertainty, high impact) and a reasonable estimate of future impacts (known trajectory). Impacts from industrial-scale commercial fishing, aquaculture, nutrient pollution, altered sediment dynamics, commercial shipping, offshore energy, and plastic pollution are relatively well understood and thus potentially lower priorities for further research (**Table 1**), although their management remains a priority. In these many cases, the ability to anticipate the future of the oceans is not limited by scientific uncertainty about how the pressures affect biodiversity but rather by the political and economic challenges of implementing effective policy.

In contrast, several pressures and activities stand out where high scientific uncertainty intersects with high ecological impact and potential for future change (**Table 1**). For these issues, investment in further research to reduce process uncertainty should take a high priority, as overly precautionary management is likely to be costly and inefficient, and undermanagement may result in catastrophic consequences. The future impacts of small-scale fishing are uncertain, given many data limitations, but are probably substantial and greater than today, given increasing numbers of human communities dependent on coastal fisheries. Emerging fisheries on mesopelagic species have potentially huge impact on species and systems about which we currently know little. Land-based pollution from inorganic and organic pollutants already heavily impact coastal systems in many parts of the world, and the rapid development of new compounds with unknown consequences for species creates a high-risk scenario. Ocean acidification is a known threat to calcifying organisms in particular, but the capacity of species to adapt to changing conditions remains less well known, and the potential consequences of major ecosystem impacts would be

Table 1 Estimates of ecological impact, the expected trajectory in the coming 20 years, and scientific uncertainty in how each activity or pressure affects species and ecosystems

Category	Activity/pressure	Process uncertainty	Change (~20 years)	Ecological impact	
				Coastal	Offshore
Fishing	Industrial fishing	Low	Low	High	High
	Transboundary species	Low	Medium	High	High
	Emerging fisheries	High	Medium	Low	High
	Small-scale fishing	Medium	Medium	High	Medium
Aquaculture	Finfish/fed shellfish	Low	High	Medium	Medium
	Bivalves/nonfed	Low	High	Low	Low
	Seaweed	Low	High	Low	Low
Ocean-based	Shipping (strikes)	Low	Medium	Low	Low
	Shipping (invasive species)	Medium	Medium	Medium	Low
	Seabed mining	High	Medium	Medium	Medium
	Offshore renewable energy	Low	Medium	Low	Low
	Offshore nonrenewable energy	Low	Medium	Low[a]	Low
Land-based	Nutrient pollution	Low	High	High	Low
	Organic chemical pollution	High	High	High	Low
	Toxic metals	High	Medium	Medium	Low
	Plastic pollution	Low–medium	High	Low	Low
	Sediments	Low	High	High	Low
	Direct human impact	Low	High	High	Not applicable (NA)
Noise and light pollution	Noise pollution	Medium	Medium	Low	Low
	Light pollution	Medium	Medium	Low	Low
Climate	Temperature	Low	High	High	High
	Ocean acidification	Medium	High	High	High
	Sea-level rise	Low	High	Medium	NA
	Ultraviolet radiation	Low	Low	Low–medium	Low–medium

[a]For offshore nonrenewable energy, if there is an oil spill then coastal impact is high.

profound. Seabed mining (particularly of sand and gravel) currently has a large footprint, and there is substantial risk from growing commercial interest to expand into deep-sea areas where we know almost nothing about potential ecological consequences.

Many human impacts on the ocean can be directly managed, when impact can be attributed to specific human activity, and curtailing the activity results in direct curtailing of the impact. Where impact is known to be large and likely increasing, management can work to reduce the extent or intensity of the activity, implement policies or technologies that reduce the pressures associated with a given unit of activity, or both. Climate stressors, however, stand apart from most other activities and pressures listed above, in that the drivers (greenhouse gas emissions) are global and diffuse, and the persistence of elevated carbon dioxide in the atmosphere ensures that stressors will continue to impact the oceans for decades even under the most ambitious management plan. Although climate stressors may be effectively beyond management, reducing impacts attributable to manageable activities will be important to avoid compounding the effects of warming, acidifying, and rising seas as well as to improve resilience of marine ecosystems to climate change.

Perhaps one of the greatest process uncertainties is how multiple stressors interact to create cumulative effects. There is some evidence about the frequency of additive, synergistic, and antagonist pressures, but we know very little about how multiple stressors interact with more than two stressors present (131), and most parts of the ocean experience far more than two stressors at a time (12). The potential for cumulative effects to lead to nonlinear responses in ecosystems, most notably tipping points that push ecosystems past an irreversible point, seems likely (105), but we know little about whether tipping points are common or rare (132), or whether changes are actually irreversible. All of these uncertainties make anticipating the future of the ocean particularly difficult.

Beyond the uncertainties connected to specific stressors, there are key areas of uncertainty at the intersection of stressors and social science disciplines. Interactions between human and ecological systems are fundamental to anticipating the future of the ocean, and the complexity of these interactions leads to additional layers of uncertainty around outcomes of any given management action for species, ecosystems, people, and communities. This uncertainty is compounded by mismatches in the spatial and temporal scale of individual experience, which is determined by how people perceive change in their surroundings; the scale of management action, which is determined by jurisdictional boundaries; and the scale of ecological impact, which is determined by natural processes and human interactions with those processes. Attention to procedural, distributional, and recognitional equity in the (re)allocation of resource rights of people and communities can alleviate social harms, including conflict, disempowerment, human rights abuses, and widening of economic inequality, while improving conservation outcomes by increasing local support for and participation in conservation (133). Even so, unalloyed synergies in conservation are not common; the balance between synergies and trade-offs in social and ecological well-being depends on historical context, resource dependence, and asymmetries of power in governance (134). Considerations of equity and human well-being in conservation action become even more critical in the face of accelerating climate change (135). Better understanding issues of inequity and their interactions with resource management will allow for better forecasts and, in turn, effective management decisions and resource policy.

New and emerging uses of marine resources that we know little about, such as potential widespread fishing of mesopelagic fish stocks or deep-sea mining, play an important role in our imprecision in predicting ocean health in the next few decades. Equally important are the many things we do not even know are on the horizon, in particular new technologies or resource needs not yet imagined. For example, interest in deep-sea mining is being driven in part by the need for the rare metals used in solar panels, electric cars and wind turbines, among other uses. Future technologies, whether ocean related or not, may require materials and resources that are more abundant in the ocean and thus push human activities and associated pressures offshore. Accounting and planning for these unknowable parts of the future can only be done effectively with adaptive management.

The best strategies to improve the health of the future ocean depend on the intersection of potential impact, uncertainty, and trajectory (**Table 1**). For the most part, we know how different activities (A_i in Equation 1) produce different amounts of stressors (p_{ij}), such that relatively little uncertainty remains at the global scale, although local-scale contributions to each will likely vary substantially and thus need to be measured. In contrast, in many cases we do not know how the full diversity of species responds to a given stressor (v_{kj}). More importantly, for many pressures we know the consequence for individual organisms or sometimes whole populations but rarely whether these impacts translate into larger population- or ecosystem-scale changes (101).

Determining whether it is strategic to invest in reducing uncertainty, and how, depends on which type of uncertainty exists. In general, we suggest that the priority for future scientific research should focus on issues where substantial process uncertainty remains. However, we also recognize that reducing uncertainty about the state of the marine system is critical to informing effective and efficient management and conservation, and so investment in improved data collection and monitoring technology should be a priority for policymakers (136). In particular, local data can help tailor strategies for a specific place, and local priorities might differ from the big-picture priorities.

These are questions of how to make research and data investment as strategic as possible. In contrast, altering the impact or trajectory of activities and stressors relies on policy action and technological innovation rather than scientific research. Where potential impact is high and/or trajectory is high, action needs to focus much less on additional research and primarily on reducing the growth and intensity of activities. Ultimately, even with perfect knowledge about how pressures from activities impact species and the likely trends in those activities and pressures, our efforts to change the trajectory of the future ocean depend on how well we can design, implement, and enforce different management strategies.

In addition to support from governmental agencies (the National Science Foundation and the National Oceanic and Atmospheric Administration in particular), a substantial amount of funding (US$1.2 billion in 2020) for ocean-related research and conservation in the United States comes from philanthropic organizations (49), whose priorities may be driven as much by public perception and donor preference as by scientific urgency. In addition to funding of basic science (28% of funding in 2020), philanthropy has been heavily focused on a few specific topics over the past decade, namely marine protected areas and habitat protection (14% of funding), fisheries (10%), and industrial pollution/stressors (14%, dominated by an annual grant from an association of energy companies toward oil spill response capacity). Since 2010 philanthropic funding has increased 5-fold for aquaculture initiatives, 10-fold for climate initiatives, and 20-fold for small-scale fisheries (49). Overall, philanthropic funding for ocean issues has doubled since 2010. Still, current funding is woefully insufficient to achieve conservation goals and avoid costly future impacts. Emerging blue ocean mechanisms can remove barriers to public and private investment in sustainable ocean-based economic activity to help fill this funding gap (137). Such finance projects are likely to prioritize data collection and monitoring toward feasibility analysis and risk reduction (138) rather than primary research to reduce process uncertainty.

In some cases there seems to be a mismatch between scientific understanding and public perception of the magnitude of impact/concern. For example, plastic pollution receives widespread public and scientific attention (139, 140), and foundation funding has increased sevenfold since 2010 to nearly half the funding allocated to fisheries and parity with funding for ocean climate concerns (49)—this despite little evidence of substantial impact on marine ecosystems (84), particularly compared to impacts from fishing or climate change (11, 141). Ultimately, we suggest that current funding and research priorities may need to be realigned to help achieve a healthy ocean. A high priority should be placed on primary research in areas where both process uncertainty and potential for impacts are high, such as mesopelagic fisheries, organic chemical pollutants, and cumulative impacts across multiple stressors. As process uncertainty is reduced, funding for high-impact pressures should shift toward implementation, such as monitoring and enforcement for fisheries and marine protected areas.

The ocean has maintained its potential for resilience in the face of the many pressures humans place on it—to date very few marine species have gone extinct (142), and that humans do not live in the ocean seems to have helped maintain sufficient refuge. But our footprint in the ocean is expanding and the individual and cumulative pressures from our activities are intensifying (14). The ocean cannot maintain its function and vitality much longer in the face of these pressures. The window of time for action is rapidly closing to sustain healthy oceans.

SUMMARY POINTS

1. Anticipating the future of the ocean requires understanding whether and how anthropogenic pressures impact ecosystems, the degree of uncertainty in those assessments, and the expected trajectory of human uses of the ocean.
2. Most research on pressures to oceans has focused on how individuals or populations respond to the presence and intensity of pressures, without further exploring whether these changes translate into wider ecosystem consequences; this uncertainty is critical for resolving both scientific understanding and more strategic management and conservation.
3. Several pressures, including those from shipping, certain types of aquaculture, and overfishing in wild-capture fisheries, are well understood and are known to have large and likely increasing impacts; these pressures can be effectively managed.
4. Several other pressures, including ocean plastic pollution and offshore renewable energy, are known to have relatively little impact despite their high profile in public attention.
5. Climate pressures, particularly rising ocean temperatures, marine heat waves, and ocean acidification, are effectively unavoidable in the next few decades even under aggressive carbon reduction scenarios; therefore, other pressures must be managed to improve ecosystem resilience to these inevitable impacts.
6. Research and funding priorities may need to be realigned to account for the magnitude of process uncertainty and potential for impacts: Resources for primary research should focus on pressures where both process uncertainty and potential for impacts are high, and resources for effective management should be focused on well-understood and high-impact pressures.

FUTURE ISSUES

1. The complexity of interactions among multiple pressures, even among pressures whose individual impacts on marine ecosystems are well understood, remains a critical source of uncertainty in the cumulative impact of human activity on marine ecosystems and should be a high priority for future research.
2. Emerging human activities, including mesopelagic fisheries, seabed mining, and an ever-increasing array of organic chemical pollutants, carry substantial uncertainty around risk of impacts; research to understand potential impacts of these activities, coupled with a precautionary approach to management, will be critical to minimizing risk to vulnerable marine species and ecosystems.
3. Systematic trait-based methods of estimating vulnerability of marine species to anthropogenic pressures would greatly enhance our ability to anticipate and manage the impacts of human activity, including novel and emerging stressors.
4. Managing human activities to support healthy ocean ecosystems will require robust understanding of the complex ways in which ecological condition, resource use policy, and economic incentives interact within and across scales, from local to national to regional to global.

5. Policy and action to better manage human impacts on our oceans will inevitably result in changes in allocation of resource use rights within and among coastal communities; careful attention to the equity implications of conservation policy and marine resource management must be a high priority for an equitable, just, and sustainable future ocean.

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