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Review

Climate mediates the predictability of threats to marine biodiversity

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Anthropogenic climate change is driving rapid changes in marine ecosystems across the global ocean. The spatiotemporal footprints of other anthropogenic threats, such as infrastructure development, shipping, and fisheries, will also inevitably shift under climate change, but we find that these shifts are not yet accounted for in most projections of climate futures in marine systems. We summarise what is known about threat-shifting in response to climate change, and identify sources of predictability that have implications for ecological forecasting. We recommend that, where possible, the dynamics of anthropogenic threats are accounted for in nowcasts, forecasts, and projections designed for spatial management and conservation planning, and highlight key themes for future research into threat dynamics in a changing ocean.

Highlights

Anthropogenic climate change and the biodiversity crisis are interacting to drive rapid changes to the structuring of ecosystems and human socioecological systems globally.

As we adapt to climate change, the array of human threats to biodiversity will inevitably shift in form, distribution, and intensity. Climate change will exacerbate some threats, redistribute or ameliorate others, and introduce new issues with uncertain consequences, such as geoengineering.

A major contributor to uncertainty is how and when society will respond to climate change. Consideration of a broader swath of plausible futures will help to better understand the bounds of predictability.

We already have the tools to quantify many elements of uncertainty in assessing future risk to marine biodiversity. Climate adaptation in marine socioecological systems will require a broader uptake and refinement of these tools.

Climate change and the marine biodiversity crisis

The twin crises of global climate change and biodiversity loss are transforming natural systems across all of the major biomes on Earth [1]. Human socioeconomic systems are also changing, as resource distributions and availability shift with intensifying climate impacts, and societies move towards decarbonisation, albeit at variable rates. One consequence is that climate change is now a global amplifier of human–wildlife conflict across marine and terrestrial systems [2].

The global ocean is the front line for the intertwined effects of climate change and biodiversity loss. Direct impacts of climate change on marine biodiversity include the effects of physical and biochemical changes such as ocean warming, deoxygenation, acidification, sea-level rise, and the increasing frequency and severity of extreme events such as marine heatwaves [3]. In response, marine ecosystems are undergoing rapid and widespread change, with limited signs of reversal to pristine states. To avoid extinction, marine species must either shift their ranges to maintain tolerable conditions [3–5], or adapt to changing environments through physiological or behavioural plasticity [6–8].

Marine biodiversity provides ecosystem services critical to human existence, such as food security, oxygen production, and carbon cycling [9]. However, all climate-change scenarios entail a global spatial and structural reorganisation of marine biodiversity, and unrestrained-emissions scenarios entail a global mass extinction comparable to those documented in the paleorecord [10]. Given that the increase in surface ocean heat content by the end of the century will by far exceed that observed over the past century [11], even under optimistic scenarios, rapid changes in the structure of ocean ecosystems already observed are likely to accelerate, with abrupt consequences for biodiversity [12]. Coral bleaching has affected all oceans of the world [13]. Sea-level rise will entail significant and largely unavoidable impacts on coastal systems from mid-century onwards [14]. Population crashes of commercially important species are occurring in multiple systems [15].

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Other human stressors on marine ecosystems including fishing, aquaculture, shipping, marine infrastructure development, and pollution, are expanding throughout the global ocean, and can act synergistically with climate impacts to exacerbate pressure on biodiversity. As human society responds to the climate crisis, the footprints of anthropogenic stressors will shift, with important consequences for conservation. Climate change will intensify some threatening processes, redistribute others, and introduce new risks to marine biodiversity [16,17].

To conserve marine biodiversity into the future, and hence retain the ecosystem services on which human society depends, we must anticipate climate-driven shifts in the seascape of anthropogenic threats to marine biodiversity. Only approaches that incorporate both shifting ecosystems and shifting human uses of the ocean can support climate-ready conservation and management [18]. However, marine **conservation planning** (see Glossary) seldom considers the impacts of climate change [19]. Furthermore, more attention has focused on ecosystem impacts of climate change, while the interaction between climate change and threatening processes is relatively sparsely explored. Here, we summarize what is known about threat-shifting in response to climate change, and make recommendations regarding the inclusion of threat

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Box 1. Nowcasting, forecasting, and projecting threats to marine biodiversity for conservation and management

Nowcasting

'Nowcasting' can provide information on ecosystem state or species distributions in near-real time. To date, nowcasts have most often been developed using species distribution models (SDMs) that relate numerically the probability of occurrence of a particular species to environmental conditions [82]. However, SDMs are subject to the issues of extrapolation error [83] and nonstationarity – correlative models assume that species–environment relationships will persist unchanged into the future. There is also no standard on how uncertainty is conveyed in operational nowcasting tools [84]. Assimilation of new data into nowcast tools can enhance predictive skill, but while ocean data are routinely assimilated into physical models, ecological data assimilation remains an aspirational frontier.

Near-term forecasting

Ecological forecasts generate predictions over near-term (days–seasons–years) timescales. Recent advances in physical and biogeochemical modelling have enabled skilful forecasting of ocean conditions up to 12 months in advance [80]. Seasonal forecasts have been used to generate ecological forecasts for marine resource management, such as fish catchability [85,86], although skill is variable. Seasonal-to-decadal forecasts can provide valuable information to allow for proactive decision-making under climate change, but are challenging to build [85]. We are not aware of existing nowcasts or forecasts that explicitly incorporate threat dynamics in marine management applications.

Climate projections

Earth System Models can be used to force projections of future ecosystem state, species distributions or abundance, or the changing footprints of human uses, over decadal to end-of-century timescales [73]. However, it is near-impossible to assess the skill of projections, as few observational time series of sufficient length exist for validation, particularly for marine ecosystems. Moreover, projections entail multiple sources of uncertainty [87], with scenario uncertainty dominating in the mid- to long-term.

Implications of predictability

Nowcasting, forecasting, and projecting climate risks to marine biodiversity requires assessment of the temporal and spatial scales over which physical, ecological, and socioeconomic processes, and linkages among these processes, occur (Figure 1). A better understanding of the relative predictability of threats (Figure 2), and the multidimensional impacts of climate on threat-shifting, are important considerations for management of threats to marine biodiversity (Figure 3). Predictability is important because it can provide capacity to prevent unintended social consequences. Such consequences can be one-off, such as billion-dollar economic losses from fishery collapse [15], or cumulative, such as fisheries collapses accelerating the transition from fishing to aquaculture.

dynamics in building **nowcasts**, **forecasts**, and climate **projections** (Box 1) for the management of marine ecosystems.

Shifting dynamics of anthropogenic threat under climate change

The dynamics of anthropogenic threats to marine biodiversity are a function of the interplay among processes that span physical, ecological, and human dimensions, and which themselves vary in scale and predictability (Box 2, Figure 1). Accordingly, each category of threat will vary in predictability (Figure 2), with predictability inversely related to the level of dynamism inherent in the threat. Here we examine a variety of threat processes in the oceans and examine how their predictability may be modified by climate change.

Fisheries

Globally, fisheries **adaptation** to climate change will require the implementation of strategies that account for the changing distribution, and abundance of target populations. Physical variability and change are likely to translate to shifts in fishing effort [20] and targeting strategies, and will require responsive management to set appropriate quotas for changing fish populations [21–23].

Box 2. Where does predictability come from?

The predictability of anthropogenic threats to marine biodiversity stems from a complex interplay among socioeconomic drivers, ecological phenomena, and physical variability and change (Figure I). The sources of predictability in physical and ecological dimensions of marine systems are important factors underlying the distribution and intensity of anthropogenic threats, and potential threat-shifting.

Physical

Predictability of the physical and chemical state of marine ecosystems is largely driven by topographic and bathymetric features, and ocean–atmosphere coupling through climate drivers such as the El Niño Southern Oscillation [81]. Predictability of phenomena, and its influence on the skill of forecasts or projections, is commonly considered explicitly in the physical sciences (e.g., [77]). However, predictability is breaking down in some elements of the global ocean system. For example, the Pacific Decadal Oscillation (PDO) is becoming less predictable as the global warming signal expands [88]. Although inter-model uncertainty abounds, the collapse of the Atlantic Meridional Overturning Circulation (AMOC) following a doubling of CO_2 from 1990 levels has been predicted [89]. Extreme or compound events such as marine heatwaves are abrupt and often unpredictable deviations around more predictable secular trends [80].

Ecological

Ecological systems are inherently chaotic, and therefore, unpredictable. However, predictability in the ecological components of marine ecosystems can arise from a complex interplay among factors including phenology [90], physiological tolerances, and animal cognition [91].

Physical variability and change leads to increasing variability in the timing of biological phenomena. For example, changes in phytoplankton bloom phenology have extensive implications for marine food webs across the global ocean [92]. This can create a ripple effect of declining predictability up the food chain, as consumers respond to producers, potentially leading to mismatches in predator–prey dynamics [93]. The predictability of responses of corals to climate stressors has been the subject of decades of research effort, leading to sophisticated multi-model ensemble approaches that can generate probabilistic projections for coral reef futures that incorporate uncertainty [94]. Giant kelp has been identified as a climate sentinel species owing to predictable responses to ocean warming that can act as 'early warning' indicators of ecosystem-wide effects, although its classification as a climate sentinel has recently been challenged by observations in extreme warming events [95].

Responses of mobile marine species are extremely challenging to predict [96], although environmental predictability is known to be both a driver and a consequence of animal movement [97], and some sentinel species can provide information relevant to understanding or anticipating broader ecosystem change. For example, breeding colony abandonment by Cassin's auklet *(Ptychoramphus aleuticus) preceded anomalously delayed upwelling in the California Current system in 2005* [98].

Glossary

Adaptation: the process of preparing for the risks introduced by climate change, and adapting to its impacts.

Carbon dioxide removal (CDR): the process of capturing and storing carbon dioxide from the atmosphere.

Climate velocity: a measure of the speed and direction of climate change, calculated as the length of a climate trajectory divided by the time between the reference and future time periods.

Conservation planning: the process of developing strategies to manage species and habitats, over time, that incorporates planning for the distribution of anthropogenic activities across a geographical area. Used to develop plans for networks of spatial conservation measures such as area-based management techniques (ABMTs).

Forecast: to predict the future state of a system using analysis of available pertinent data, particularly over near-term timescales (hours–days–weeks–months–seasons–years).

Mitigation: the act of reducing or preventing anthropogenic greenhouse gas emissions to lessen the impacts of climate change.

Nowcast: to estimate the current state of unobserved properties of a system based on observed properties, for example, estimating species distributions based on current physical conditions.

Overshoot: a term describing scenarios or pathways in which prespecified global warming targets (e.g., 1.5°C) are exceeded, before returning to the specified threshold in the future.

Projection: model-derived estimates of the future state of a system based on scenarios of change, such as the Intergovernmental Panel on Climate Change (IPCC) Shared Socioeconomic Pathway (SSP) scenarios. Usually over longer timescales than forecasts (years–decades–centuries).

Solar radiation management (SRM): a set of large-scale strategies designed to reduce global warming by reflecting sunlight back into space.

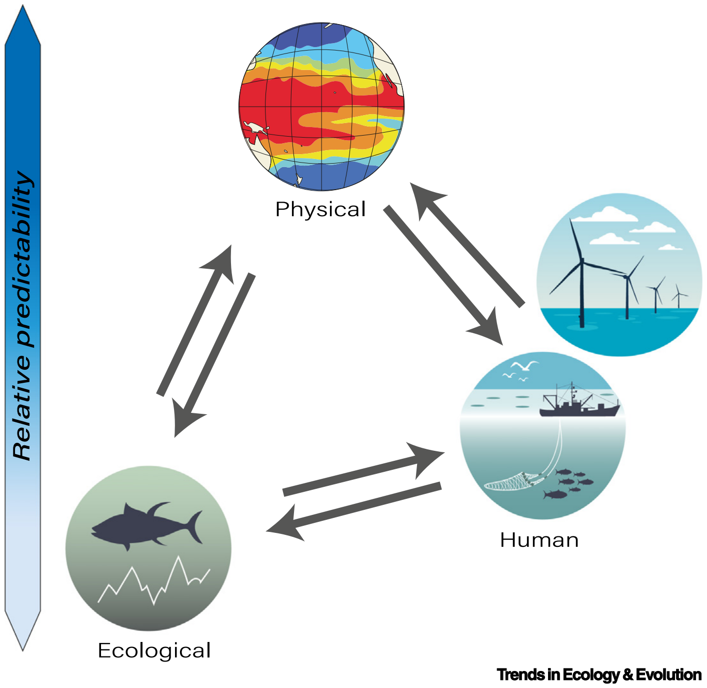
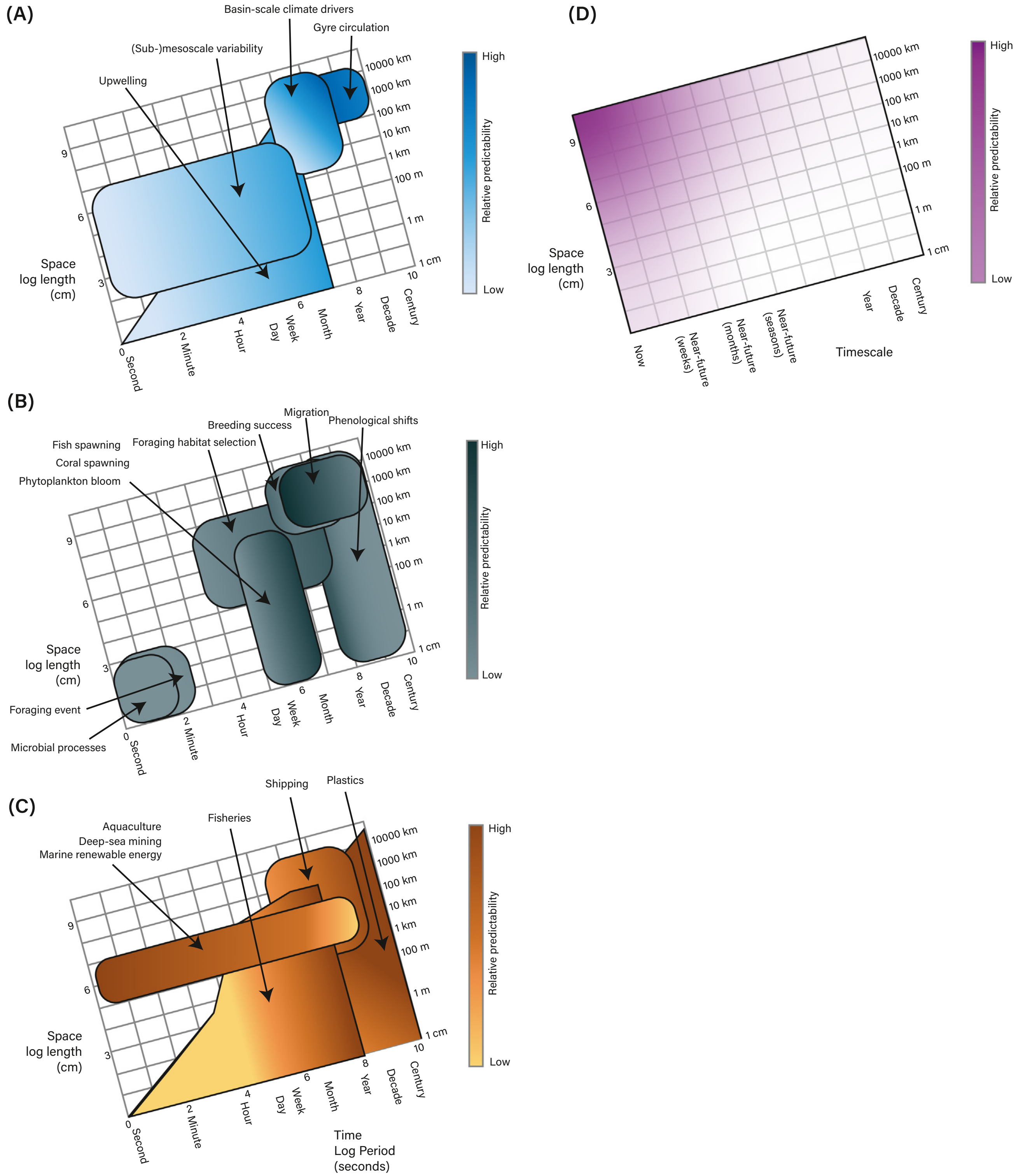


Figure I. Interactions among processes occurring in and across physical, ecological, and human dimensions determine the predictability of anthropogenic threats to marine biodiversity. Arrows imply the directionality of deterministic linkages among processes occurring in each dimension. In general, physical processes are better predicted than socioecological. Assessment of relative predictability of processes is qualitative.

Uncertainty in stock assessment models has led to overoptimistic assessments of stock status in the past [24], necessitating better articulation of uncertainty in changing systems.

Changes in fishing effort resulting from climate change are likely to entail conservation consequences. Moving fisheries is likely to cause ecosystem changes that will impact threatened species. For instance, in the Bering Sea, ground fisheries moving north as water temperatures warm are impacting bottom habitats that provide food for walrus *Odobenus rosmarus* and spectacled eider *Somateria fischeri*, species already in decline due to disappearing sea ice haul-out and resting areas [25]. Moving fisheries is likely to change encounter rates with species of conservation concern, as these populations also move in response to climate change [26]. Notably, because hotspots of incidental interactions with non-target species ('bycatch') are often associated with seascape features such as ocean fronts, climate change can alter the spatiotemporal expression of bycatch risk. For example, seabird bycatch in North Atlantic pelagic longline fisheries is known to be strongly associated with Gulf Stream meanders, which are changing in location with climate-driven variations in intensity and position of the Gulf Stream [27,28].

Moreover, movements in both fisheries and species of conservation concern may happen on short timeframes. Extreme events such as marine heatwaves can result in disruptions to patterns of space use by threatened, endangered or protected species in weeks or months. For example, the Northeast Pacific marine heatwave of 2014–2016 resulted in record numbers of whale entanglements in the central California Current Dungeness crab, *Metacarcinus magister*, fishery, owing to compression of coastal upwelling, reductions in prey availability, and shoreward movement of



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migrating whales [29], leading to significant revenue loss [30]. The acute impacts of the Northeast Pacific marine heatwave, the most extensive yet on record, drove 240 species outside their typical geographic ranges, mass seabird die-offs, kelp forest declines, reduced productivity, and closures of multiple fisheries [31].

Industrialised fisheries. Ocean basin-scale climate drivers such as the North Atlantic Oscillation (NAO) [32], El Niño Southern Oscillation (ENSO) [33], and Pacific Decadal Oscillation (PDO) [34] fundamentally regulate the availability of living marine resources that support fisheries. Changing catch composition in wild-capture fisheries will require agile management as fishing tracks species moving into the domain of existing fisheries (e.g., Bluefin Tuna *Thunnus orientalis*, North Atlantic [35]), and traditional target species disappear (e.g., sardine, anchovy, South Africa [36]). Moreover, climate risk to fisheries is likely to entail socioeconomic ramifications for nations and communities reliant on fisheries for food, livelihoods, and economic security. For example, large-scale redistribution of tuna in response to changing conditions across the Pacific could entail significant consequences for Small Island Developing States (SIDS) that may lose stocks [23].

In addition to species redistributions flowing from changing mean conditions, marine temperature extremes can result in decreases of up to 77% in biomass of exploited species within an exclusive economic zone [37]. Population declines resulting from increasingly suboptimal conditions may be most pronounced for fish and fisheries that have greater dependence on static habitat features, with flow-on socioeconomic and conservation effects [38]. The combined effects of extremes on fisheries and threatened species may be profound.

Artisanal and subsistence fisheries. Technical efficiency, defined as the ratio of actual catch to potential catch using available means, has declined at –3% year^{-1} in the artisanal fleets of 44 nations (1950–2014), posing a serious risk to food security and livelihoods in climate-exposed coastal nations [39]. Climate impacts are projected to be most acute in those settings, and may interact with existing poverty and inequality [40]. Moreover, financial and jurisdictional constraints are likely to have an outsized impact on artisanal, subsistence, or indigenous fishers' inability to move with shifting resources as they might once have done, in contrast to distant-water fishing fleets that can buy access rights to a different jurisdiction. This may result in deteriorating conservation outcomes, even where conditions in nearby jurisdictions are improving.

Aquaculture

Aquaculture is the fastest-growing food-production sector globally, and is also a rapidly growing source of ocean ecosystem transformation. But aquaculture is climate-exposed owing to sensitivity to warming, sea-level rise, diseases, and harmful algal blooms, changes in rainfall and salinity, and vulnerability to marine heatwaves [41]. Even small changes in suitability or susceptibility to disease due to climate change may result in displacement of aquaculture operations, with major implications for biodiversity.

Climate change impacts on the reliability of wild harvest have the potential to accelerate aquaculture development. Massive and rapid population declines due to climate change have occurred in

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Figure 1. Space/time scales of processes occurring in (A) physical, (B) ecological, and (C) human dimensions that mediate anthropogenic pressure on marine biodiversity in the contemporary ocean. Colour gradients show a qualitative scale of relative predictability of processes in the contemporaneous ocean, which often varies with spatiotemporal scale. Predictability of processes in the contemporaneous ocean is important to consider when building nowcasts or short-term forecasts of processes acting at these scales, or of their interactions (e.g., changes in upwelling intensity, linked to changes in primary productivity and foraging-habitat selection by mobile species, then linked to fisheries effort). The 'multiplier' in (D) can be used to adjust values in each panel in the left-hand column to account for the relative decay in predictability into the future over various scales of space and time: that is, predictability decays as timescale lengthens, so what is predictable in the present-day ocean will become less so in the future, particularly at finer spatial scales.

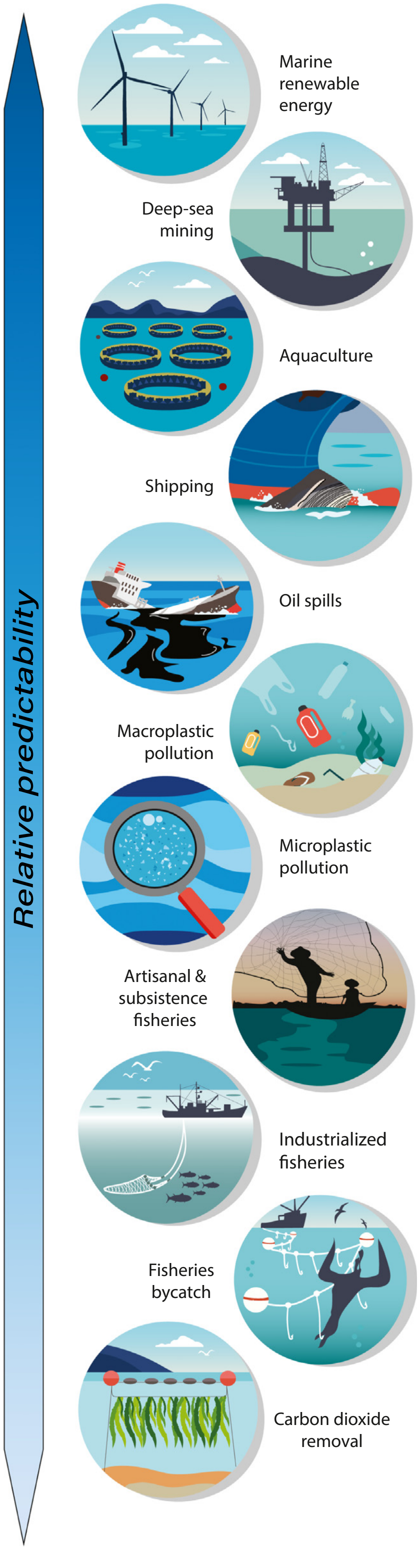
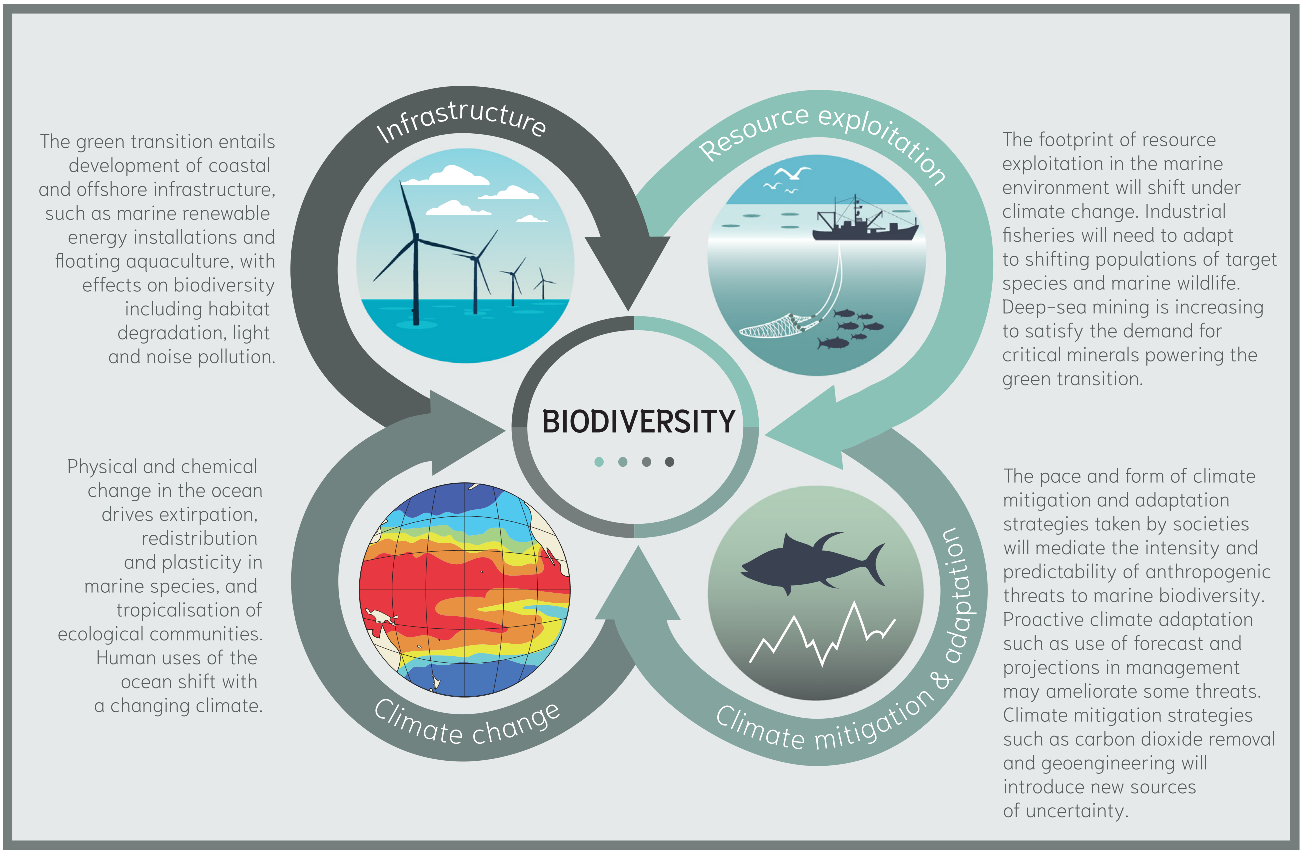


Figure 2. Continuum of relative predictability of anthropogenic threats. The impacts of static threats such as marine renewable energy installations, deep-sea mining, and fixed aquaculture installations on marine biodiversity are likely to be more predictable than dynamic threats such as pollution and fisheries, particularly where complex ecological interactions and responses to physical variability and change determine the predictability of the threat (e.g., fisheries bycatch). The relative predictability of anthropogenic threats to marine biodiversity, and how these threats might evolve in a changing ocean, are important considerations for climate-smart conservation planning.



The green transition entails development of coastal and offshore infrastructure, such as marine renewable energy installations and floating aquaculture, with effects on biodiversity including habitat degradation, light and noise pollution.

The footprint of resource exploitation in the marine environment will shift under climate change. Industrial fisheries will need to adapt to shifting populations of target species and marine wildlife. Deep-sea mining is increasing to satisfy the demand for critical minerals powering the green transition.

Physical and chemical change in the ocean drives extirpation, redistribution and plasticity in marine species, and tropicalisation of ecological communities. Human uses of the ocean shift with a changing climate.

The pace and form of climate mitigation and adaptation strategies taken by societies will mediate the intensity and predictability of anthropogenic threats to marine biodiversity. Proactive climate adaptation such as use of forecast and projections in management may ameliorate some threats. Climate mitigation strategies such as carbon dioxide removal and geoengineering will introduce new sources of uncertainty.

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Figure 3. Anthropogenic threats to marine biodiversity are mediated by climate change, and our response to it through climate mitigation and adaptation. The spatiotemporal footprints of threats will inevitably shift with climate change, both for static threats such as marine infrastructure development and dynamic threats such as fisheries.

commercially important species such as snow crab (*Chionoecetes opilio*) [15]. Further fisheries collapses or unpredictable variations in fisheries subject to natural cycles, such as those for the anchoveta-sardine system, could cause effort presently invested in wild-catch fisheries to be redirected to aquaculture, both to replace lost food sources and to provide alternative livelihoods for displaced fisheries workers.

Recent evidence suggests that some fisheries displaced by marine protected areas (MPAs) do not redirect effort to other areas; instead, restrictions to gear and vessels mean that the fisheries simply cease to be profitable and eventually cease to function [42]. Similar responses have occurred in response to climate change, as was the case for the snow crab fishery, and can also be expected in response to future fisheries collapses precipitated by climate change. This provides impetus to further accelerate the substitution of capture fisheries by aquaculture, with its attendant ecosystem impacts. Those impacts may be spatially very different (coastal) than those of the fisheries they replace (offshore). We can speculate that there is potential for positive feedback as coastal aquaculture may destroy mangrove nurseries essential for fisheries, increasing pressure for aquaculture and coastal transformation.

Shipping

The imprint of shipping is currently one of the most predictable threatening processes to marine biodiversity (Figures 1 and 2) since shipping lanes have remained relatively constant in recent decades. Shipping entails conservation risks such as introduced species, pollution incidents, and ship strike of large pelagic species, all of which are potentially modified by climate change. For example, whale sharks are projected to move in response to changing ocean conditions due to climate change, bringing them more into conflict with shipping lanes, where ship strikes are a major cause of mortality in the species [43].

Ship-strike risk to mobile marine species is quite predictable in comparison to more dynamic processes such as fisheries bycatch risk, where sufficient data exist [43,44]. However, the shipping industry will also need to adapt to changing physical conditions at sea, particularly changes in sea ice, prevailing winds and currents. For example, ice melt in the Arctic Ocean has allowed for rapid increases in shipping traffic, with projections indicating that the Northwest Passage will be fully navigable for part of each year above 2°C of global warming [45], with potentially highly detrimental impacts on biodiversity. Innovation in shipping is moving towards emissions reduction by shifting fuel sources, speeds, and using passive means of propulsion, and the use of ocean models to make real-time adjustments to routes. The transition to more sustainable, carbon-neutral means of freight transport will inevitably change the footprint of threats to marine biodiversity resulting from shipping.

Unexpected consequences of other global phenomena or geopolitical situations also affect the predictability of maritime threats to marine biodiversity. For example, the 'anthropause' that occurred as a result of the COVID-19 pandemic reduced global shipping traffic [46], while attacks on ships in the Red Sea in 2023–2024 resulted in mass disruption as traffic shifted to alternative routes. We can speculate that as climate impacts continue to compound, impacting global order and increasing the rates of zoonotic disease outbreaks, human migration and conflict, the predictability of global transportation patterns, and attendant impacts on marine biodiversity will decline.

Pollution

Extreme weather events increase the release of pollutants into the oceans, the degradation of plastics into microplastics [47], and the likelihood of physical damage to oil and gas or shipping infrastructure, leading to a higher likelihood of catastrophic events [48]. Floating pollutants such as plastics are transported passively in ocean circulation, and aggregate predictably in coastal zones, ocean gyres [49], and ocean fronts and eddies [50]. Prediction of the distribution of plastic pollution will therefore rely predominantly on understanding present accumulation zones [49], and using ocean models [51] in combination with scenarios of resource utilisation and waste management. Policy and consumer decisions will therefore play a major role in mediating the predictability of pollution events.

Deep-sea mining and bioprospecting

Climate change is intensifying other more static threats to marine biodiversity, such as deep-sea mining and bioprospecting. Deep-sea mining for critical minerals is increasing, almost exclusively in Areas Beyond National Jurisdiction (ABNJ), where governance is lacking [52]. Bioprospecting for marine genetic resources is also increasing, predominantly around deep-sea hydrothermal vents and biodiverse seamounts [53]. The predictability of these threats is relatively high spatially (Figures 1 and 2), but their temporal expression and intensity is dependent upon broader socio-economic drivers that are relatively unpredictable.

Potential impacts of climate mitigation: renewable energy, carbon dioxide removal, and geoengineering

Marine conservation issues associated with climate change are not limited to species on the move and the effects of adaptation in fisheries and other sectors – the marine environment may also be heavily impacted by climate change **mitigation** efforts. To restrict global temperature rise below the Paris Agreement 'safe' limit of 1.5°C, or 2°C this century, society will need to rapidly develop renewable energy sources and remove hundreds of gigatons of carbon from the atmosphere, or engage in geoengineering to cool the climate system.

The rapid development of marine infrastructure and renewable energy installations entails consequences for biodiversity [54], including habitat degradation, and underwater light and noise pollution [55,56]. Mitigation solutions such as **carbon dioxide removal** (**CDR**) and other forms of geoengineering will entail consequences that are likely to change the footprint of anthropogenic stressors in the oceans, in potentially unpredictable ways. In marine systems, potential CDR options include ocean alkalinity enhancement [57], ocean fertilisation [58], and macroalgal mariculture [59]. While many approaches have proponents [60], the real-world deployment of marine CDR techniques at scale remains problematic [61]. Foremost among the challenges is that understanding of carbon transport and cycling in the ocean remains incomplete [62], introducing uncertainty in efficacy of marine CDR [63], let alone downstream effects. This lack of predictability would demand careful and detailed monitoring, reporting and verification mechanisms, which are presently in an early stage of development [64].

Geoengineering through **solar radiation management** (**SRM**) comprises numerous techniques (e.g., stratospheric aerosol injection) designed to reflect incoming solar radiation. Modelled scenarios involving SRM focus on when intervention is initiated and what happens if it is stopped. Results suggest that any substantial delay in implementation would likely mean an **overshoot** of at least the 1.5°C target, and an associated rapid cooling back to the target. Such rapid cooling could result in **climate velocities** exceeding those under modest warming scenarios [65], and any sudden termination of SRM would result in yet-more-rapid changes [66]. Both of these scenarios suggest increased uncertainty surrounding the resilience of marine biodiversity in terms of the speed at which species can shift ranges or adapt [66–68]. Importantly, SRM not only fails to deal with aspects of climate change unrelated to warming, especially ocean acidification, but also imposes many other associated risks, many of which have high uncertainty, such as the potential for unforeseen ecological consequences [69].

Land–sea interactions

Interactions among terrestrial and marine environments are also changing as a result of climate change, with consequences for marine biodiversity, particularly in the coastal ocean [14,70]. For example, climate impacts on agriculture and industry are likely to become less predictable and more severe, with extreme weather leading to pollution events in coastal areas through river discharge. Demographic pressure, including tourism, coupled with locked-in sea level rise, entails intensifying impacts for coastal biodiversity. Scenario uncertainty – that is, the uncertainty surrounding how human societies will respond to climate change – fundamentally mediates the predictability of these impacts across the array of anthropogenic threats to marine biodiversity, but perhaps most prominently in impacts to coastal biodiversity at the land–sea interface [14].

Future research directions

Studies of anthropogenic impacts on marine biodiversity often include climate change as just another layer of threat, alongside other stressors such as fishing, shipping, and pollution. Or, in some cases, synergistic effects have been considered [71]. Climate projections of species distributions have been combined with contemporaneous threat surfaces to estimate future risk (e.g., [43]). More rarely considered are the sweeping effects of climate change in continually elevating the risk of extreme events to which marine life and socioeconomic systems must respond, altering the footprint of other stressors, and hence the predictability of their impacts. We are now moving into an era of non-analogue futures, necessitating a step-change in how we incorporate climate change in marine management and conservation planning [19].

We recommend that, where possible, uncertainties in threat dynamics are explicitly considered when developing modelling tools to support nowcasts, forecasts or projections of risk to marine biodiversity (Box 1), particularly for the most dynamic threats, such as fisheries. For example, the Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP) is a global effort to develop model ensembles for projecting climate impacts on marine biodiversity and fisheries. FishMIP 2.0 now includes standardised global fishing forcing to test fishing effects systematically across an ensemble of ecosystem models [72].

We also recommend that projections based on Earth System Models are developed using more than one model, more than one scenario (Shared Socioeconomic Pathway in the CMIP-6 ensemble; Resource Concentration Pathway in CMIP-5; see [73]), and multiple realisations or model 'runs'. Ecological models should be fitted to each ensemble member rather than the aggregate average to better quantify and report uncertainty and inter-model spread [73,74]. Adding further uncertainty is the tendency to consider only one or two scenarios of change, often leading to an over-emphasis on the worst-case scenario. More, and more-realistic, scenarios of change, including overshoot [67,68], should be included when building projections of changing species distributions, abundances, or threats, alongside explicit consideration of uncertainty [75].

Most studies consider ocean surface warming in isolation, neglecting the effects of deoxygenation and acidification, and depth (but see [76]). Temperature is a fundamental determinant of species distributions in the ocean, and surface temperature is represented with better skill in Earth System Models than oxygen concentration or pH. However, consideration of deoxygenation and acidification is critical in projecting ecological and human responses to change [77]. Marine organisms cannot sustain aerobic metabolism in low-oxygen zones, leading to mortality, and the expansion of Oxygen Minimum Zones (OMZs) affects the distribution of commercially valuable pelagic fish [75]. Acidification has extensive implications for marine biodiversity, particularly for calcifying organisms such as corals and echinoderms [77].

Climate adaptation in fisheries will require information regarding the projected effects of change on populations of both commercially important taxa and species of conservation concern. However, the complexity inherent in marine ecosystems renders these dynamics difficult to predict in advance, particularly over timescales greater than the shortest forecast horizons, except where clear and persistent linkages exist with physical variables that can be forecast with reasonable skill. For example, sea surface temperature anomalies have been used to build ecological forecasts of whale entanglement and sea turtle bycatch risk in the California Current system [78]. More research is needed on the scale-dependent responses of marine taxa to physical variability and change, across levels of biological organisation. Comparable to physical ensembles, ecological ensembles can incorporate multiple statistical and mechanistic models of species-response to understand the range of future scenarios [79].

Accurate forecasts of the dynamics of threat intensity, or of changing distributions of marine species, are likely to be most realisable where we have better skill in physical forecasts (e.g., Eastern Tropical Pacific [80]). Maintaining progress in physical modelling, particularly in the multi-year to decadal forecast horizons, will therefore be essential. Dynamical downscaling of Earth System Model (ESM) outputs through regional ocean modelling systems, or equivalents, can provide physical data fields at finer spatial and temporal resolutions [81]. In some cases, better granularity can enhance the utility of climate data for management, although global forecast products can yield more skilful ecological forecasts where they have more ensemble members [74].

Much of the existing literature on ecological forecasting is dominated by applications in North America and Europe. More research is urgently needed in other systems, where adaptation capacity is generally lower. Including an explicit consideration of the predictability of threat dynamics could be useful in expanding ecological forecasting for conservation and management, particularly in data-poor regions. Moreover, better collaboration among physical oceanographers, climate scientists, ecologists, biologists, fisheries scientists, industry, government, and traditional owners will facilitate this ultimate goal.

Concluding remarks

Uncertainty regarding how climate change will impact ecosystems and socioecological systems complicates the design of conservation and management strategies. Most impacts remain highly unpredictable in the contemporaneous ocean (see Outstanding questions; Figure 1), and predictability is likely to decay further with climate change, particularly for the most dynamic threats such as fisheries. There will also be ecological surprises that surpass our conceptual or numerical biological models because of complex ecosystem interactions.

However, robust tools do exist to aid in predicting climate risks to ecosystems. Fisheries stock assessment, species distribution models, and ecosystem models are available to address ecosystem change. Stock assessment, economic and market models are available to assess fisheries change and economic responses. Modelling approaches that incorporate human dimensions, such as the inclusion of fishing in FishMIP 2.0 [72], hold promise for better simulation of climate futures, although uncertainty remains high. Model-based tools such as nowcasting, forecasting, and projections can be extended to incorporate threat dynamics in addition to physical–ecological linkages. There is an urgent need to apply these tools to predicting climate change-related threat shifts. Where uncertainty is clearly communicated [74], accelerated application will help anticipate climate risks such as fisheries collapses.

For conservation planning to become climate-smart [76], we must consider the changing nature of anthropogenic threats. We recommend that, where possible, the predictability of processes occurring across physical, ecological, and human dimensions are explicitly considered in modelling scenarios of future change for management applications and conservation planning.

Outstanding questions

How could nonlinear change, including regime shifts, influence the predictability of anthropogenic threats to marine biodiversity in different systems? Nonlinear changes result in abrupt, potentially irreversible consequences for biodiversity. The identification of tipping elements and tipping points in physical and ecological systems allows for advance identification of nonlinear elements.

How might the predictability of ecological phenomena relevant to the conservation of threatened, endangered and protected species, such as migration, change with climate change? As species decline, move, or adapt to change, the likelihood of interactions with anthropogenic threats at sea, such as fisheries and shipping, will shift.

How might the climate ‘overshoot’ scenario influence adaptation pathways, and hence the predictability of threats to marine biodiversity? Overshoot describes the increasingly likely scenario in which the ‘safe’ limit of 2°C warming this century is exceeded before temperatures stabilise.

How can we explicitly and accurately incorporate the predictability of threats under climate change into risk assessments for vulnerable ecosystems and populations of marine species?

When do we have sufficient skill in an ecological model to extend to nowcasting, forecasting, and projections for management applications?

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Declaration of interests

No interests are declared.

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