Rebuilding marine life

https://doi.org/10.1038/s41586-020-2146-7

Received: 24 May 2019

Accepted: 18 February 2020

Published online: 1 April 2020

Check for updates

Carlos M. Duarte[1,2,3]✉, Susana Agusti[1], Edward Barbier[4], Gregory L. Britten[5], Juan Carlos Castilla[6], Jean-Pierre Gattuso[7,8,9], Robinson W. Fulweiler[10,11], Terry P. Hughes[12], Nancy Knowlton[13], Catherine E. Lovelock[14], Heike K. Lotze[15], Milica Predragovic[1], Elvira Poloczanska[16], Callum Roberts[17] & Boris Worm[15]

Sustainable Development Goal 14 of the United Nations aims to "conserve and sustainably use the oceans, seas and marine resources for sustainable development". Achieving this goal will require rebuilding the marine life-support systems that deliver the many benefits that society receives from a healthy ocean. Here we document the recovery of marine populations, habitats and ecosystems following past conservation interventions. Recovery rates across studies suggest that substantial recovery of the abundance, structure and function of marine life could be achieved by 2050, if major pressures—including climate change—are mitigated. Rebuilding marine life represents a doable Grand Challenge for humanity, an ethical obligation and a smart economic objective to achieve a sustainable future.

The ability of the ocean to support human wellbeing is at a crossroads. The ocean currently contributes 2.5% of global gross domestic product (GDP) and provides employment to 1.5% of the global workforce[1], with an estimated output of US$1.5 trillion in 2010, which is expected to double by 2030[1]. Furthermore, there is increased attention on the ocean as a source of food and water[2], clean energy[1] and as a means to mitigate climate change[3,4]. However, many marine species, habitats and ecosystems have suffered catastrophic declines[5–8], and climate change is further undermining ocean productivity and biodiversity[9–14] (Fig. 1).

The conflict between the growing dependence of humans on ocean resources and the decline in marine life under human pressures (Fig. 1) is focusing the attention on the connection between ocean conservation and human wellbeing[15]. The United Nations Sustainable Development Goal 14 (UN SDG 14 or 'life below water') aims to "conserve and sustainably use the oceans, seas and marine resources for sustainable development" (https://sustainabledevelopment.un.org/sdg14). Achieving this goal will require rebuilding marine life, defined in the context of SDG 14 as the life-support systems (populations, habitats and ecosystems) that deliver the many benefits that society receives from a healthy ocean[16,17]. Here we show that, in addition to being a necessary goal, substantially rebuilding marine life within a human generation is largely achievable, if the required actions—including, notably, the mitigation of climate change—are deployed at scale.

Reversing the decline of marine life

By the time the general public admired life below water through the television series 'The Undersea World of Jacques Cousteau' (1968–1976), the abundance of large marine animals was already greatly reduced[5–7,18]. Since the first frameworks to conserve and sustain marine life were introduced in the 1980s, the abundance of marine animals and habitats that provide essential ecosystems services has shrunk even further[5,6,19,20] (Fig. 1). Currently, at least one-third of fish stocks are overfished[21], one-third to half of vulnerable marine habitats have been lost[8], a substantial fraction of the coastal ocean suffers from pollution, eutrophication, oxygen depletion and is stressed by ocean warming[22,23], and many marine species are threatened with extinction[7,24,25]. Nevertheless, biodiversity losses in the ocean are less pronounced than on land[7] and many marine species are capable of recovery once pressures are reduced or removed (Figs. 2, 3). Substantial areas of wilderness remain in remote regions[26] and large populations of marine animals are still found, for example, in mesopelagic (200–1,000 m depth) ocean waters[27].

Regional examples of impressive resilience include the rebound of fish stocks during World War I and World War II following a marked reduction in fishing pressure[28], the recovery since 1958 of coral reefs in the Marshall Islands from 76 megatons of nuclear tests[29] and the improved health of the Black Sea[30] and Adriatic Sea[31] following a sudden reduction in the application of fertilizers after the collapse of the Soviet Union. Although these rapid recoveries were unrelated to conservation actions, they helped to inform subsequent interventions that have been deployed in response to widespread ocean degradation[7,32,33]. These interventions include a suite of initiatives to save threatened species, protect and restore vulnerable habitats, constrain fishing, reduce pollution and mitigate climate change (Fig. 1 and Table 1).

Impactful interventions

The regulation of hunting. The protection of species through the Convention on International Trade of Endangered Species (CITES, 1975, https://cites.org/) and the global Moratorium on Commercial Whaling (1982, https://iwc.int/home) are prominent examples of inter-

[1]Red Sea Research Center (RSRC), King Abdullah University of Science and Technology, Thuwal, Saudi Arabia. [2]Arctic Research Centre, Department of Biology, Aarhus University, Aarhus, Denmark. [3]Computational Bioscience Research Center (CBRC), King Abdullah University of Science and Technology, Thuwal, Saudi Arabia. [4]Department of Economics, Colorado State University, Fort Collins, CO, USA. [5]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA. [6]Departamento de Ecología, Facultad de Ciencias Biológicas and Centro Interdisciplinario de Cambio Global, Pontificia Universidad Católica de Chile, Santiago, Chile. [7]Laboratoire d'Océanographie de Villefranche, Sorbonne Université, CNRS, Villefranche-sur-Mer, France. [8]Institute for Sustainable Development and International Relations, Sciences Po, Paris, France. [9]Monegasque Association on Ocean Acidification, Prince Albert II of Monaco Foundation, Monaco, Monaco. [10]Department of Earth & Environment, Boston University, Boston, MA, USA. [11]Department of Biology, Boston University, Boston, MA, USA. [12]Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland, Australia. [13]National Museum of Natural History, Smithsonian Institution, Washington, DC, USA. [14]School of Biological Sciences, The University of Queensland, St Lucia, Queensland, Australia. [15]Department of Biology, Dalhousie University, Halifax, Nova Scotia, Canada. [16]Alfred Wegener Institute, Integrative Ecophysiology, Bremerhaven, Germany. [17]Department of Environment and Geography, University of York, York, UK.
✉e-mail: carlos.duarte@kaust.edu.sa

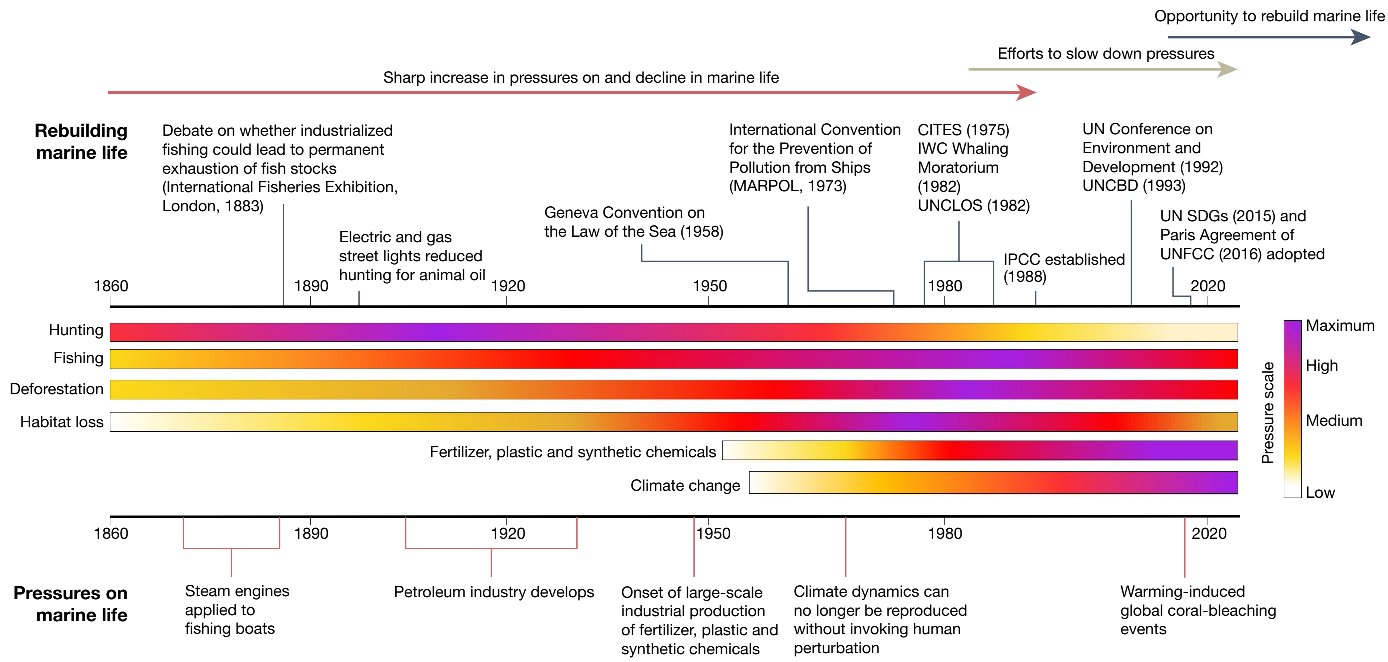

Fig. 1 | Global pressures on marine life. Many human pressures commenced well before the industrial revolution; a number of those pressures peaked in the 1980s and are slowing down at present (with great regional variation), with the notable exceptions of pollution and climate change. Initially, hunting and fishing were followed by deforestation, leading to excess sediment export and the direct destruction of coastal habitats. Pollution (synthetic fertilizers, plastic and industrial chemicals) and climate change represent more-recent threats. Hunting of megafauna has been heavily regulated or banned and fishing is now progressing towards more-sustainable harvests in many regions, and regulatory frameworks are reducing some forms of pollution. Climate change—caused by greenhouse gas emissions that have accumulated since the onset of the industrial revolution—became considerable compared with background variability in the 1960s, and is escalating as greenhouse gases continue to accumulate. As a net result of these cumulative human pressures, marine biodiversity experienced a major decline by the end of the twentieth century.

national actions to protect marine life[34] (Fig. 1). These actions have been supplemented by national initiatives to reduce hunting pressure on endangered species and protect their breeding habitat[34,35].

Management of fisheries. Successful rebuilding of depleted fish populations has been achieved at local and regional scales through well-proven management actions, including catch and effort restrictions, closed areas, regulation of fishing capacity and gear, catch shares and co-management arrangements[35–39] (Supplementary Information 1). These interventions require detailed consideration of socio-economic circumstances, with solutions being tailored to the local context[37]. Persistent challenges include harmful subsidies, poverty and lack of alternative employment, illegal, unregulated and unreported fishing, and the disruptive ecological impacts of many fisheries[36–39].

Water-quality improvement. Policies to lower inputs of nutrients and sewage to reduce coastal eutrophication and hypoxia were initiated four decades ago in the United States and European Union (EU), leading to major improvements today[40–42]. Many hazardous pollutants have been regulated or phased out through the Stockholm Convention (http://www.pops.int/) and, specifically in the ocean, by the MARPOL Convention (http://www.imo.org/), often reinforced by national and regional policies. Recent attention has focused on reducing and preventing plastic pollution from entering the ocean, which remains a growing problem; inputs of plastic are currently estimated at between 4.8 to 12.7 million metric tons per year[43].

Habitat protection and restoration. The need to better protect sensitive habitats, including non-target species, has inspired the use of Marine Protected Areas (MPAs) as a comprehensive management tool[3,15,19,44]. In 2000, only 3.2 million km^2 (0.9%) of the ocean was protected, but MPAs now cover 26.9 million km^2 (7.4% of ocean area, or 5.3% if only considering fully implemented MPAs (http://mpatlas.org/, accessed 6 March 2020). MPA coverage continues to grow at about 8% per year[19] (Fig. 2 and Supplementary Video 1).

The twenty-first century has also seen a global surge of active habitat protection and restoration initiatives (Fig. 2, Supplementary Information 1 and Supplementary Videos 1, 2), even in challenging environments adjoining coastal megacities (Supplementary Information 1). These efforts have delivered benefits, such as improved water quality following oyster reef restoration. Additionally, Blue Carbon strategies, submitted within the nationally determined contributions (NDCs) of more than 50 nations—at the heart of the Paris Agreement—are being used to mitigate climate change and improve coastal protection by restoring seagrass, saltmarsh and mangrove habitats[45–47] (Supplementary Information 1).

Recovery to date

Reductions to the risk of extinction. The proportion of marine species assessed by the IUCN (International Union for Conservation of Nature) Red List as threatened with global extinction (Supplementary Information 2) has decreased from 18.0% in 2000 to 11.4% in 2019 (s.d. = 1.7%, n = 1,743), with trends being relatively uniform across ocean basins and guilds (Supplementary Fig. 2.1). In part, this reflects the growing number of species that have been assessed. However, many assessed species have improved their threat status over the past decade[48–51]. For marine mammals, 47% of 124 well-assessed populations[34] showed a significant increase over the past decades, with 40% unchanged and only 13% decreasing (Fig. 3b and Supplementary Table 2). Some large marine species have exhibited particularly notable rebounds, even from the brink of extinction (Fig. 3c). Humpback whales migrating from Antarctica to eastern Australia have been increasing at 10% to 13% per year, from a few hundred animals in 1968 to more than 40,000 currently[49]. Northern elephant seals recovered from about 20 breeding individuals

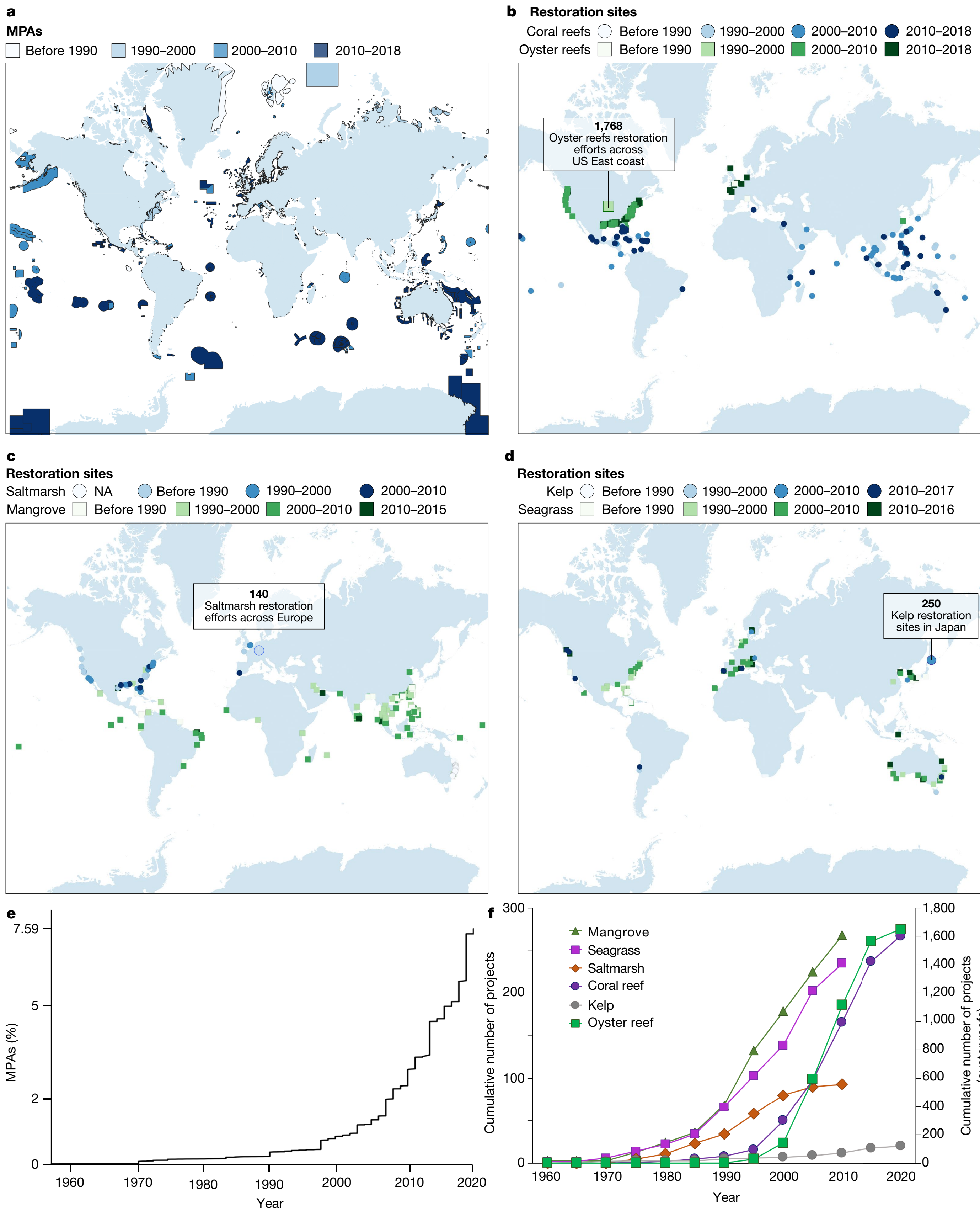

Fig. 2 | Global growth of restoration interventions. Distribution and growth of MPAs (**a**) and ecosystem restoration projects for coral and oyster reefs (**b**), saltmarshes and mangroves (**c**), and kelps and seagrasses (**d**); and the growth of MPAs as per cent of the total ocean area (**e**) and reported restoration projects (**f**) over time. NA, date not available. Numbers within symbols represent aggregated restoration projects for which the location was not provided (see Supplementary Information 1 for detailed examples, Supplementary Information 2 for data sources and Supplementary Videos 1, 2 for the animation of growth over time).

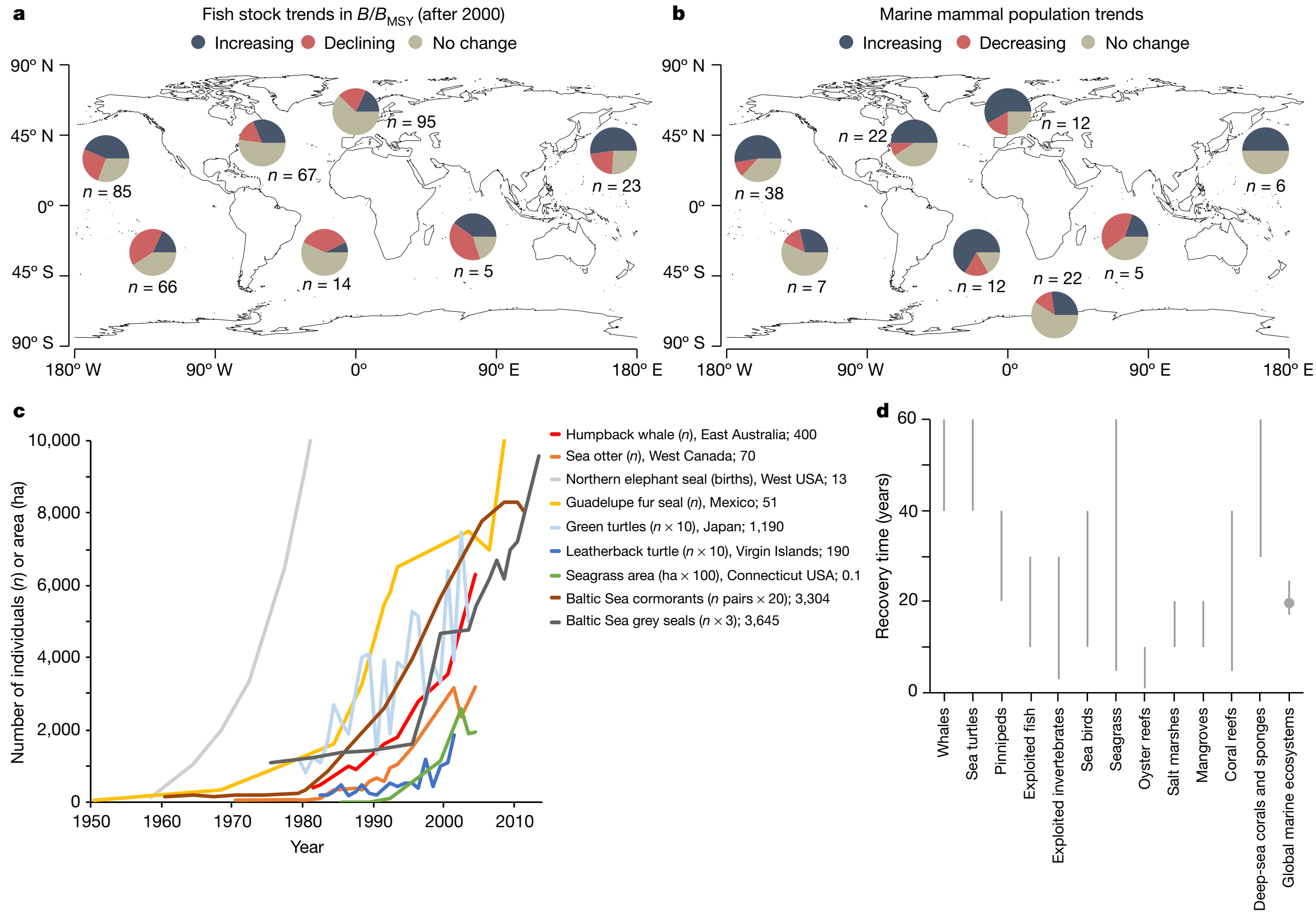

Fig. 3 | Recovery trends of marine populations. a, Current population trends in scientifically assessed fish stocks based on the ratio of the annual biomass *B* relative to the biomass that produces the maximum sustainable yield (B_{MSY}). **b**, Percentage of assessed marine mammal populations that showed increasing or decreasing population trends or showed no change. **c**, Sample trajectories of recovering species and habitats from different parts of the world. Units were adjusted to a common scale by multiplying or dividing as indicated in the legend (*n*×), numbers at the end of the legends indicate the initial count at the beginning of time series. **d**, Range of recovery times for marine populations and habitats, and mean ± 95% confidence limits recovery times for marine ecosystems. Lines indicate the reported range; where extending to 60 years, the maximum recovery time is 60 years or longer. See Supplementary Information 2 for details on data sources and methods, and Supplementary Table 3 for data sources for data shown in **d**.

in 1880 to more than 200,000 today[50], and grey seal populations have increased by 1,410% in eastern Canada[51] and 823% in the Baltic Sea[41] since 1977. Southern sea otters have grown from about 50 individuals in 1911 to several thousand at present[35]. While still endangered, most sea turtle populations for which trends are available are increasing in size[52], with increases in green turtle nesting populations ranging from 4 to 14% per year[52].

Recovery of fish stocks. Using a comprehensive stock-assessment database[53], we find that fish stocks with available scientific assessments are increasingly managed for sustainability. The proportion of stocks with fishing mortality estimates (*F*) below the level that would produce a maximum sustainable yield ($F < F_{MSY}$) has increased from 60% in 2000 to 68% in 2012. Many fish stocks that are subject to such management interventions display positive trends (Fig. 3a), and globally aggregated stock assessments suggest a slowing down of the depletion of fish stocks[21,36,39], although this trend cannot be verified for the majority of stocks, which lack scientific assessments[36]. The most recent report of the Food and Agriculture Organization on global fisheries[21] also suggests that two thirds of large-scale commercial fish stocks are exploited at sustainable rates—although, again, this figure does also not account for smaller stocks or non-target bycatch species, which are often not assessed and in poor condition[36,54]. Available data suggests that scientifically assessed stocks generally have a better likelihood of recovery owing to improved management and regulatory status compared with unassessed stocks[36], which still represent the majority of exploited fish stocks, especially in developing countries.

Reduction in pollution. Time-series analyses show that legacy persistent organic pollutants have declined even in marine environments that tend to accumulate them (for example, the Arctic[55]). The transition towards unleaded gasoline since the 1980s has reduced lead concentrations to concentrations comparable to baseline levels across the global ocean by 2010–2011[56]. Similarly, the total ban in 2008 of the anti-fouling chemical tributyltin (TBT) has led to rapid declines of imposex (females that develop male sexual organs)—a TBT-specific symptom—in an indicator gastropod[57]. Improved safety regulations have also led to a 14-fold reduction in large oil spills from oil tankers from 24.7 events per year in the 1970s to 1.7 events per year in 2010–2019[58]. Whereas evidence of improved coastal water quality following nutrient reductions was equivocal a decade ago[59], multiple success stories have now been confirmed[41,60], with positive ecosystem effects such as the net recovery of seagrass meadows in the United States[61] (Fig. 1), Europe[62], the Baltic Sea[41] and Japan[63].

Habitat restoration. Evidence that mangrove restoration can be achieved at scale first came from the Mekong Delta mangrove forest, possibly the largest (1,500 km^2) habitat restoration undertaken to date[64,65]. Global loss of mangrove forests has since slowed to 0.11% per year[66,67], with stable mangrove populations along the Pacific coast of Colombia, Costa Rica and Panama[68], and increasing populations in the Red Sea[69], Arabian Gulf[70] and China[71]. Large-scale restoration of saltmarshes and oyster reefs has occurred in Europe and the United States (Fig. 2 and Supplementary Information 1). Restoration attempts of seagrass, seaweed and coral reef ecosystems are also increasing globally, although they are often small in scale (Fig. 2, Supplementary Video 2 and Supplementary Information 1). Notably, a global inventory of total restored area is missing.

Potential for rebuilding

Efforts to rebuild marine life cannot aim to return the ocean to any particular past reference point. Our records of marine life are too fragmented to compose a robust baseline, and the ocean has changed considerably and—in some cases—irreversibly, including the extinction of at least 20 marine species[25]. We argue instead that the focus should be on increasing the abundance of key habitats and keystone species, and restoring the three-dimensional complexity of benthic ecosystems. The yardstick of success should be the restoration of marine ecological structure, functions, resilience and ecosystem services, increasing the capacity of marine biota to supply the growing needs of an additional 2 to 3 billion people by 2050. To meet this goal, rebuilding of depleted populations and ecosystems must replace the goal of conserving and sustaining the status quo, and swift action should be taken to avoid potential tipping points beyond which collapse may be irreversible[11,18,33].

Here we examine the rates of recovery of marine species and habitats to date, and propose a tentative timeframe in which substantial recovery of marine life may be possible, should major pressures, including climate change, be mitigated. We broadly define recovery as the rebound in populations of marine species and habitats following losses, which can be partial (that is, 10–50% increase), substantial (50–90% increase) or complete (>90% increase)[47] (Table 1).

Marine megafauna

A number of megafauna species, including humpback whales and northern elephant seals, have recovered to historical baselines following protection (Fig. 3c); however, rates of recovery depend on the life history of the species: some large whales may require more than 100 years to recover, whereas smaller pinnipeds may only need several decades[35] (Fig. 3c, d). Sea turtles have recovery timescales of up to 100 years, although some populations have partially recovered much faster (for example, green turtles in Hawaii increased sixfold between 1973 and 2016)[72]. Seabird populations typically require a few decades to recover[35,41] (Fig. 3c, d).

Fish stocks

Recovery can also refer to achieving resilient populations that support the full extent of ecosystem functions and services that characterize them. For instance, fish stock recovery is often defined in terms of biomass increases to the level that enables the maximum sustainable yield (B_{MSY}), which fisheries harvest theory predicts to be between 37% and 50% of the virgin biomass (B_0), depending on the particular model used (Supplementary Information 2 and Supplementary Fig. 2.2). This range is consistent with an empirical estimate of B_0 for 147 exploited fish stocks, which found that contemporary B_{MSY} values were 40% of B_0, on average, with a range of 26% to 46% across taxa[73]. Reported recovery times to B_{MSY} for overexploited finfish and invertebrate stocks range between 3 and 30 years[35] (Figs. 3, 4), which is consistent with palaeoecological reconstructions of prehistoric collapse and recovery of anchovy, sardine and hake stocks[74], data from fisheries closures[54,75] and fish stock assessments[76]. However, B_{MSY} should be considered to represent a minimum recovery target[39], as it does not account for ecosystem interactions, and might provide only limited resilience in the face of environmental uncertainty and change.

Minimum recovery times of populations are set by the maximum intrinsic rate of population increase (r_{max}), which is typically higher than observed rates, resulting in longer recovery times[77,78]. Recovery rates also depend on the fishing pressure imposed on the stock; for example, rebuilding depleted populations to B_{MSY} may take less than a decade, if fishing mortality is rapidly reduced below F_{MSY}. Longer recovery times are expected if fishing pressure is reduced more slowly[36,79] (Fig. 4). Recovery for longer-lived, slow-growing species such as most elasmobranchs (sharks, rays and skates), depleted coral reef fish and deep-sea species may take much longer[35,78].

Coastal habitats

The recovery of coastal habitats after the removal of stressors or following active restoration of the habitat typically occurs on a similar timescale as fish stock recovery, less than a decade for oyster reefs[80] and other invertebrate populations (Supplementary Information 3), and kelp-dominated habitats[81,82], between one to two decades for saltmarsh[83] and mangrove[84] habitats, and one to several decades for seagrass meadows[85] (Fig. 3d). Deep-sea corals and sponges grow more slowly and recovery times from trawling disturbance or oil spills may range from 30 years to more than a century[86,87]. Recovery timescales of coral reefs that are affected by local stressors range from a few years to more than a decade (Fig. 3d). However, recovery from severe coral bleaching has taken well over a decade and will slow in the future as ocean warming shortens the interval between bleaching events[12], with an associated steep reduction in coral-reef recruitment[88].

In summary, available data suggest that many marine species and habitats require one to three decades to approach undisturbed or reference abundance ranges and fish stock biomass that supports maximum sustainable fish catches after removal of the causes of decline[35,88–92], with longer recovery times required for some slow-growing groups[35] (Fig. 3).

Recovery times

The time that is required to rebuild components of marine life depends on the extent of previous declines, which are often substantial. The reduction in species abundance and biomass relative to predisturbance baselines averages about 44 and 56%, respectively, across affected marine ecosystems[89]. Similarly, the Living Blue Planet Report estimated a 49% decline in the abundance of marine animal populations between 1970 and 2012[93], although many species and habitats have declined further since[90,94]. Moreover, although the maximum rates of recovery of marine populations typically range from 2 to 10% per year[20] (Fig. 3c), rates slow down as carrying capacity is approached[20]. Assuming a reported average annual recovery rate of 2.95% (95% confidence interval, 2.42–3.41%) across marine ecosystems[20] and a characteristic rebuilding deficit of about 50% of predisturbance baselines[89], we provisionally estimate that the average time to reach 90% of undisturbed baselines (that is, achieve substantial recovery) would be about 21 years (95% confidence interval, 18–25 years) (Fig. 3d). However, the expectation of an average recovery time of about two decades is compromised by the fact that many species and habitats continue to decline and some pressures, such as climate change and plastic pollution, are still increasing (Fig. 1). Thus, substantial (50–90%), rather than complete (>90%), recovery may be a more realistic target for rebuilding marine life in the short term.

Based on the case studies examined, we provisionally propose three decades from today (2050) as a target timeline for substantial (that is, 50–90%) recovery of many components of marine life (Table 1),

Table 1 | Scenarios conducive to achieving the best aspirational outcomes towards rebuilding marine life

Rebuilding wedges	Saltmarshes	Mangroves	Seagrass	Coral reefs	Kelp	Oyster reefs	Fisheries	Megafauna	Deep-sea habitats
Protect species	Low	Low	Low	Low	Low	High	Critical	Critical	Critical
Harvest wisely	Low	Critical	Low	High	High	Critical	Critical	Critical	Critical
Protect spaces	Critical	Critical	Medium	High	Medium	Critical	High	High	Critical
Restore habitats	Critical	Critical	High	Medium	Medium	Critical	Medium	Medium	Medium
Reduce pollution	Medium	Medium	Critical	Critical	Critical	High	Medium	Medium	High
Mitigate climate change	High	High	High	Critical	High	High	High	High	High
Recovery targets by 2050	Substantial to complete	Substantial to complete	Substantial to complete	Partial to substantial	Substantial to complete	Substantial to complete	Substantial to complete	Substantial	Partial to substantial
Key Actors	Government, civil society and NGOs.	Government, civil society and NGOs.	Government, civil society and NGOs.	Government, tourism operators, fishers organizations, civil society and NGOs.	Government, fishers organizations and civil society.	Government, fishers organizations, NGOs and civil society.	Government, fishers organizations and civil society.	Government, fishers organizations, NGOs and civil society.	International seabed authority, state and federal governments, mining/exploration companies, civil society and fishing industry.
Key Actions	Protection of remaining saltmarshes, providing sources of sediment, potentially planting native species, providing space for landward migration and restoring hydrological connections.	Protection, provide alternative livelihoods for dependent communities, provide space for landward migration, restore hydrological connections, maintain sediment supply and restore damaged forests.	Reduce nutrient inputs, protect, avoid physical impacts, and conduct restoration projects.	Ambitious reduction in greenhouse gas emissions. Reduce excess sediment and nutrient inputs, improve water quality, protect reefs, rebuild food webs and restore damaged reefs.	Restoration requires removal of excess herbivores, by rebuilding their predators, and a reduction in sediment loads on rocky substrates and kelps.	Protect remaining reefs, prohibition of natural reef harvests, improve water quality and restore reefs.	Reduce overfishing, bycatch and incidental mortality, ban destructive fishing practices, protect spawning/breeding areas and nursery grounds, and remove perverse incentives.	Protect, reduce bycatch, reduce incidental mortality (ship strikes, entanglement, ghost gear), reduce pollution (noise, debris, chemical), protect breeding/haul-out sites, safeguard migration routes and reduce competition with fisheries.	Regulate industries that operate in the deep sea. Ban deep-sea fishing and impose a moratorium on deep-sea mining until technologies free of impact are available. Improve environmental safety of oil and gas operations. Develop facilities to test technologies before real-ocean deployment.
Key Opportunities	Blue Carbon and coastal defence strategies against storms and sea-level rise, links to management for enhancing water quality, food provision and biodiversity strategies.	Blue Carbon and coastal defence strategies against storms and sea-level rise, links to management for enhancing water quality, food provision and biodiversity strategies.	Blue Carbon and coastal defence strategies against storms and sea-level rise, links to management for enhancing water quality, food provision and biodiversity strategies.	Link to coastal defence, food provision and biodiversity strategies.	Emerging role in Blue Carbon, water quality and biodiversity strategies.	Link to water quality improvement, biodiversity and coastal protection strategies.	Sustainable seafood, MSC-certified fisheries, develop sustainable aquaculture to reduce pressure on wild stocks.	Marine wildlife tourism, cultural benefits and ethics.	High percentage of unique, unexplored habitats and new species, potential for novel products important in fighting/preventing disease. Huge carbon-sink potential.

Continued

Rebuilding wedges	Saltmarshes	Mangroves	Seagrass	Coral reefs	Kelp	Oyster reefs	Fisheries	Megafauna	Deep-sea habitats
Key Benefits	Improved fisheries, protection from sea-level rise and storm surges, recreational and cultural benefits, hunting.	Improved fisheries, biodiversity and coastal defence, recreation and cultural benefits.	Protect shoreline from erosion and rebuilding biodiversity and fisheries.	Provision of fish, protection from sea-level rise and storm surges, recreational and cultural benefits.	Enhanced fisheries.	Improved water quality, increased habitat, recreational and cultural benefits, food sources.	Improved quality and quantity of seafood supply.	Increased connectivity among ocean basins, enhanced nutrient cycling and ocean productivity.	Huge potential for discoveries and new resources. Avoidance of irreversible damage.
Roadblocks	Many saltmarshes are filled, landward migration impeded because of infrastructure, not enough sediment supply, sea-level rise, increased decomposition rates with rising temperatures and/or excess nutrient loading, reverting land use.	Alternative land uses and infrastructure, lack of alternative livelihoods and incentives for communities, uncertainties around climate change impacts.	Infrastructure (for example, areas occupied by harbours), severe and frequent heat waves with climate change.	Dependence on climate change trajectories, mortality with ocean warming, ocean acidification and increased cyclone activitiy.	Climate change at the edge of the equatorial range of kelp species, high herbivore pressure and sediment accumulation on rocky substrates.	Poor management of fisheries on remaining reefs, degraded habitats, restoration costs, increased prevalence of disease with rising water temperatures.	Cumulative impacts from fishing, pollution, habitat alterations, changing distribution ranges, habitats and food due to climate change.	Losses due to extinction, continued impacts from ship strikes, pollution, habitat alterations, changing habitats and food due to climate change.	Slow and uncertain recovery and success of, hugely costly restoration, which will be extremely difficult and expensive. Development multi-governmental cooperation, buy-in, and action towards this goal.
Remedial Actions	Restore hydrological flows and sediment delivery, restore native plants, restore transitional upland boundaries where possible, increase incentives to relocate users.	Increase incentives to improve management and develop alternative livelihoods, restoration, landscape planning for landward migration.	Compensatory restoration, improve water quality and reduce local stressors.	Ambitious efforts to mitigate climate change and manage to improve resilience.	Restore with thermal-resistant genotypes and reduce sediment delivery to rocky habitats.	Protect remaining reefs, large-scale restoration efforts, defining success with not just increased harvest in mind but the many other benefits oyster reefs provide.	Create MPAs as refuge sites, restore coastal breeding/nursery sites to aid recovery, develop breeding programmes for critically endangered species	Create MPAs as refuge sites, safeguard migration routes, restore coastal breeding/nursery sites to aid recovery and develop breeding programmes for critically endangered species.	Protect what has not been damaged or destroyed and prevent further destruction in places that have already been affected. Widespread education on the fragility of the deep sea and benefits of deep-sea ecosystems, strengthen regulation, decrease pollution and recycle products that require rare earth metals.

Actions include rebuilding wedges, assessment of the maximum recovery targets by 2050 if these wedges are fully activated, as well as key actors, opportunities, benefits, roadblocks and remedial actions to rebuild different components of marine life (priority increases from low to critical). See Supplementary Information 3 for details.

recognizing that many slow-growing, severely depleted species and threatened habitats may take longer to recover (Fig. 3), and that natural variability may delay recovery further (Fig. 4).

Importantly, achieving substantial recovery by 2050 requires that major pressures are mitigated soon, including climate change under the Paris Agreement. Climate change affects the demography, phenology and biogeography of many marine species and compromises the productivity of marine ecosystems[9–13,91,92,95] (Fig. 4). Current impacts of realized climate change on many coral reefs[12] raise concerns about the future prospects of these ecosystems (Table 1). If we succeed in mitigating climate change and other pressures, we may witness a trend change from a previous steep decline to stabilization and, in many cases, substantial global recovery of marine life in the twenty-first century (Figs. 1–4).

A roadmap to recovery

Steps taken to rebuild marine life to date have involved a process of trial and error that delayed positive outcomes (for example, reduction of excessive nutrient inputs in the EU and United States[41,42]), but that generated know-how to cost-effectively propel subsequent efforts at scale. Improved ocean stewardship, as required by UN SDG 14, is a goal shared across many nations, cultures, faiths and political systems, occupying a more-prominent place in the agendas of governments, corporations, philanthropists and individuals than ever before[17,96]. This provides a window of opportunity to mitigate existing pressures over the next decade while supporting global initiatives to achieve substantial recovery of marine life by 2050 (Table 1 and Supplementary Information 3). We are at a point at which we can choose between

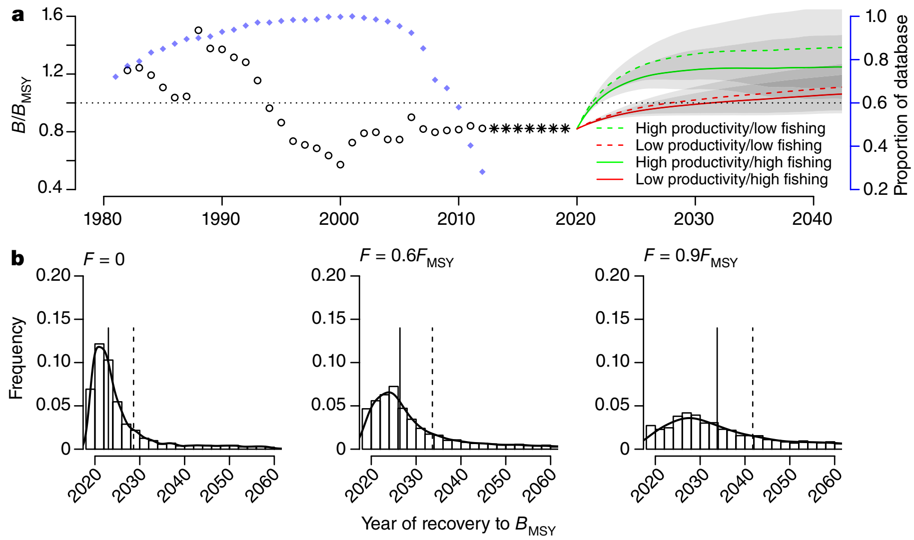

Fig. 4 | Recovery projections for assessed fish stocks. a, Trajectories of exploited fish stock biomass (*B*) relative to the biomass supporting the maximum sustainable yield (B_{MSY}; the ratio of which is denoted B/B_{MSY}) over time based on the scientific assessment of 371 globally distributed fish stocks in the RAM Legacy Stock Assessment Database (version 4.44). Open circles indicate the biomass-weighted global average of stock B/B_{MSY}, asterisks represent years without sufficient data, red and green lines represent four idealized future scenarios (B_{MSY} values were taken from stock assessments where available and estimated as 50% of the maximum historical biomass otherwise; see Supplementary Information 2). Grey shading represents the one s.d. range of the simulations. Purple diamonds give the proportion of the database used in the calculation of B/B_{MSY} for each year. **b**, Frequency distributions for estimated recovery times to B_{MSY} for 172 stocks that are currently depleted to below B_{MSY}. Projections refer to three scenarios, corresponding to no fishing, fishing at 60% or 90% of fishing pressure associated with the maximum sustainable yield (F_{MSY}). Projections show that under various scenarios of reduced fishing pressure ($F < F_{MSY}$) and different productivity regimes, the majority of fish stocks could recover to B_{MSY} with high probability before 2040. Recovery to virgin biomass (B_0) would take much longer. Solid lines indicate the median and hashed lines the mean estimate of years to recovery. Productivity for each stock in **b** was fixed to the mean stock-specific historical productivity. See Supplementary Information 2 for details of data sources and methods.

a legacy of a resilient and vibrant ocean or an irreversibly disrupted ocean, for the generations to follow.

Some of the interventions required to rebuild marine life have already been initiated, but decadal time lags suggest that the full benefits are yet to be realized[35,36,39,47,48,59]. Because most policies to reduce local pressures and prompt recovery of marine life were introduced after the 1970s (Figs. 1, 2), it is only now that comprehensive benefits (Fig. 3) are becoming evident at a larger scale. Similarly, as most current MPAs are less than 10 years old (Fig. 2), their full benefits, which increase with the age of the reserve, are yet to be realized[97], particularly for MPAs that are properly managed and enforced[97].

Recovery wedges

There is no single solution for achieving substantial recovery of marine life by 2050. Rather, recovery requires the strategic stacking of a number of complementary actions, here termed recovery wedges, each of which will help to increase the recovery rate to reach or exceed the target of 2.4% increase per year across different ecosystem components (Table 1 and Supplementary Information 1, 3, 4). These wedges include protecting vulnerable habitats and species, adopting cautionary harvesting strategies, restoring habitats, reducing pollution and mitigating climate change (Table 1 and Supplementary Information 1, 3, 4). The strength of the contribution of each of these wedges to the recovery target can be expected to vary across species and ecosystems. For instance, mitigating climate change is the critical wedge to set coral reefs on a recovery trajectory, whereas improved habitat protection and fisheries management are the critical wedges for the recovery of marine vertebrates and deep-sea habitats (Table 1 and Supplementary Information 3).

Ongoing efforts to remove pressures on marine life from anthropogenic climate change, hunting, fishing, habitat destruction, pollution and eutrophication (Fig. 1) must be expanded and made more effective (Table 1). A new framework to predict risks of new synthetic chemicals is required to avoid circumstances in which industry introduces new chemicals faster than their risks can be assessed. Challenges remain for persistent legacy pollutants (for example, CO_2, organochlorines and plastics) that are already added to the atmosphere and oceans, the removal of which requires novel removal technologies and protection of long-term sinks, such as marine sediments, to avoid their remobilization.

MPAs represent a necessary and powerful recovery wedge across multiple components of the ocean ecosystem, spanning from coastal habitats to fish and megafauna populations (Table 1). The current growth of MPAs (Fig. 2, Supplementary Video 1) is currently on track to meet ambitious targets[98], 10% of ocean area protected by 2020, 30% by 2037 and 50% by 2044. Many fish stocks could recover to B_{MSY} by 2030, assuming global management reforms couple the use of closed and protected areas to measures that reduce overall fishing pressure and collateral ecosystem damage that are adapted to the local context (Fig. 4 and Table 1). However, projected climate impacts on ocean productivity and an increase in extreme events[95] can delay recovery and, depending on emission pathways, may prevent recovery of some components altogether (Fig. 4). The current focus on quantitative targets of the percentage of the ocean area that is protected has prompted concerns over the quality and effectiveness of MPAs[99]. Although 71% of assessed MPAs have been successful in enhancing fish populations, the level of protection is often weak (94% allow fishing[100]), and many areas are undermined by insufficient human and financial capacity[101]. Improving the effectiveness of MPAs requires enhanced resourcing, governance, level of protection[100–102] and siting to better match the geography of threats[103] and to ensure desired outcomes.

The current surge in restoration efforts (Fig. 2 and Supplementary Video 2) can, if sustained, be an instrumental recovery wedge to meet rebuilding targets for marine habitats by 2050 (Table 1). For instance, assuming a mean project size of 4,197 ha (ref. [104]), restoring mangroves to their original extent of 225,000 km^2 by 2050 would require the initiation of 70 projects per year. This is not unrealistic, as realization of the benefits, such as reducing storm damage in low-lying areas[40,105,106], encourages further growth in restoration efforts (Fig. 2 and Supplementary Video 2). Past coastal restoration projects have reported average success rates ranging from 38% (seagrass) to 64% (saltmarshes and corals)[104]; however, reasons for failure are well understood[80,107–109], which should improve future outcomes. Much can be learned from increased reporting of failed attempts, because the published literature may be biased towards successful restoration projects[104]. Emerging technologies are now being developed to restore coral species in the presence of climate change[110,111], although long-term testing is required before their effectiveness and lack of negative consequences are demonstrated. Kelp restoration at a national scale in Japan provides a successful model, rooted in cultural practices, for linking restoration to sustainable fishing (Supplementary Information 1). More broadly, these practices recognize that sustainable harvest of marine resources ought to be balanced by broader restoration actions embedded in a socio-ecological context, including reducing greenhouse gas emissions, restoring habitats, removing marine litter or managing hydrological flows to avoid hypoxia (Supplementary Information 1). These restoration experiences (Supplementary Information 1) also show that involvement of local communities is essential, because of their economic dependence, commitment to place and ownership[112].

Removing pollution is a critical recovery wedge for seagrass meadows, coral reefs and kelp forests (Table 1). Three decades of efforts to abate coastal eutrophication have provided valuable knowledge on how actionable science can guide restoration successes[41,42,113]. Additional interventions (for example, restoring hydrological flows or rebuilding oyster reefs) can catalyse the additional removal of nutrients while improving biodiversity[113]. Seaweed aquaculture can help to alleviate eutrophication and reduce hypoxia[113,114]. Nutrient reduction has the additional benefit of locally reducing coastal acidification[115] and hypoxia[23] directly and indirectly through the recovery of seagrass meadows. Reducing sulfur dioxide precipitation, hypoxia, eutrophication, emissions and runoff from acidic fertilizers also helps to reduce acidification of coastal waters[22,115]. Large-scale experiments in anoxic basins of the Baltic Sea, for example, have shown that treatment of sediments with phosphorus-binding agents helps to break biogeochemical feedback loops that keep ecosystems in an alternative anoxic stable state[116].

Oil spills from oil tankers should decline further with the incoming International Maritime Organisation (IMO) requirement (13F of Annex 1 of MARPOL) for double hulls in new large oil tankers, although deep-water drilling, illustrated by the catastrophic Deepwater Horizon spill in 2010[117], and increasing risks of oil spills from future oil drilling and oil tanker routes in the Arctic[118] present new challenges.· Noise pollution from shipping and other industrial activities, such as drilling, pile driving and seismic surveys, should be reduced[119]. Similarly, worldwide efforts to reduce or ban single-use plastic (initiated in developing nations), taxes on plastic bags, deposits and refunds on bottles, and other market-based instruments are being deployed to reduce marine litter, while providing incentives to build a circular economy for existing plastics while developing safer materials.

Roadblocks

A number of roadblocks may delay or prevent recovery of some of the critical components of marine life (Table 1). These include natural variability and intensification of environmental extremes caused by anthropogenic climate change (Fig. 4), unexpected natural or social events, and a failure to meet commitments to reduce existing pressures and mitigate climate change. In addition, the growing human population, which will probably exceed 9 billion individuals by 2050, will create additional demands for seafood, coastal space and other ocean resources. Accordingly, if all necessary recovery wedges are stacked, a 2050 target of substantial to complete recovery (that is, 50–100% increase relative to the present) for most rebuilding components appears realistic and achievable (Table 1). Partial to substantial (10 to >50%) recovery can be targeted for deep-sea habitats, where slow recovery rates lead to a modest rebuilding scope by 2050, and for coral reefs, where existing and projected climate change severely limits the rebuilding prospects[13,95] (Table 1).

A major roadblock to recovery for intertidal habitats, such as mangroves and saltmarshes, is their conversion to urban areas, aquaculture ponds or infrastructure (Table 1). However, even in large cities, such as New York and Shenzen, some restoration of degraded habitats has been achieved (Supplementary Information 1). Incentives to develop alternative sources of livelihood, relocate landholders, mediate land-tenure conflicts[112] and improve land-use planning can release more habitat for coastal restoration (Table 1). Tools are emerging to prioritize sites for restoration based on past experience and a broad suite of biophysical and socio-economic predictors of success[120]. Reduced sediment supply due to dam construction in watersheds[121] is also an important challenge for the recovery of salt marshes and mangroves, and these challenges are exacerbated by sea-level rise and climate change (Table 1). However, these habitats may be less vulnerable than previously thought[122], with a recent assessment concluding that global gains of 60% of coastal wetland area are possible under sea-level rise[122]. By contrast, enhanced sediment load from land clearing is often responsible for losses of nearshore coral reefs and hinders their capacity to recover from coral bleaching[123].

Overcoming the climate change roadblock

Climate change is the critical backdrop against which all future rebuilding efforts will play out. Current trajectories of greenhouse gas emissions lead to warming by 2100 of 2.6 to 4.5 °C above preindustrial levels, far exceeding the long-term goal of the Paris Agreement (holding the increase in global average temperature to well below 2 °C above preindustrial levels)[124]. Much stronger efforts to reduce emissions[124,125] are needed to reduce the gap between target emissions and projected emissions under the present voluntary NDCs[126] a challenging but not impossible task[125]. Efforts to rebuild marine life need to consider unavoidable impacts brought about by ocean warming, acidification and sea-level rise already committed by past emissions, even if the climate mitigation wedge, represented by the Paris Agreement, is fully implemented. These changes include projected shifts in habitats and communities at subtropical–tropical (coral to algal turf and seaweed), subtropical–temperate (kelp to coral and urchin barrens, saltmarsh to mangrove) temperate–Arctic (bare to kelp, ice fauna to pelagic) and intertidal (coastal squeeze) boundaries[10–13,95], propelled by species displacements and mass mortalities from future heat waves[11–13,95]. Mapping the areas where the likelihood of these transitions is high can help to prioritize where and how restoration interventions should be deployed[120]. For instance, conserving and restoring vegetated coastal habitats will help to defend shorelines against increased risks from sea-level rise while helping to mitigate climate change[4,40,105]. Well-managed MPAs may help to build resilience to climate change[3]. However, many of them are already affected by ocean warming and further climate change may potentially compromise their performance in the future[127].

Rebuilding coral reefs carries the highest risk of failure (Table 1), as cumulative pressures (for example, overfishing and pollution) that drove their historical decline are now increasingly compounded by warming-induced bleaching[11,12]. The IPCC (Intergovernmental Panel on Climate Change) projects that global warming to 1.5 °C above preindustrial levels will result in very high risks and losses of coral reefs[13] unless adaptation occurs faster than currently anticipated. A recent study[13] shows that while coral bleaching has increased in frequency and intensity in the last decade, the onset of coral bleaching is now occurring at significantly warmer temperatures (around 0.5 °C) than previously, suggesting that the remaining coral populations now have a higher thermal threshold for bleaching, due to a decline in thermally vulnerable species and genotypes and/or acclimatization[128]. However, the capacity to restore coral reefs lags behind that of all other marine habitats, because coral-reef restoration efforts typically have a very small footprint, and are expensive and slow[104]. Coral restoration often fails because the original causes of mortality remain unchecked, and despite decades of effort (Fig. 2), only tens of hectares have been regrown so far. Our growing knowledge of ecological processes in coral reefs provides opportunities to catalyse recovery by reducing multiple pressures while repairing key processes, including herbivory and larval recruitment[11,111]. Mitigating the drivers of coral loss, particularly climate change, and developing innovative approaches to restoration within this decade are imperative to revert coral losses at scale[110,111]. Efforts are underway to find corals that are resistant to the temperatures and acidity levels expected by the end of the twenty-first century, to understand the mechanisms of their resistance and to use 'assisted evolution' to engineer these characteristics into other corals[110,111]. However, these efforts are in their infancy and their benefits currently unproven.

Overall, the societal benefits that would accrue from substantially rebuilding marine life by 2050 will depend on the mitigation of greenhouse gas emissions and on the development of efficient CO_2 capture and removal technologies to meet or, preferably, exceed the targets of the Paris Agreement.

Necessary investments and expected returns

Substantial rebuilding of marine life by 2050 requires sustained effort and financial support (Supplementary Information 4), with an estimated cost of at least US$10–20 billion per year to extend protection actions to reach 50% of the ocean space[129] and substantial additional funds for restoration. This is comparable to establishing a global MPA network that conserves 20–30% of the ocean (US$5–19 billion annually[129,130]). Yet the economic return from this commitment will be considerable, around US$10 per US$1 invested and in excess of one million new jobs[129,130]. Ecotourism in protected areas provides 4–12 times greater economic returns than fishing without reserves[36] (for example, AUS$5.5 billion annually and 53,800 full time jobs in the Great Barrier Reef[131]). Rebuilt fisheries alone could increase the annual profits of the global seafood industry by US$53 billion[128]. Conserving coastal wetlands could save the insurance industry US$52 billion annually by reducing storm flooding[129], while providing additional benefits of carbon sequestration, income and subsistence from harvesting, and from fisheries supported by coastal wetlands[40,129].

A global rebuilding effort of exploited fish stocks could increase fishing yields by around 15% and profits by about 80%[36,79] while reducing bycatch mortality, thereby also helping to promote recovery in non-target species[132]. Rebuilding fish stocks can be supported by market-based instruments, such as rationalizing global fishing subsidies[79], taxes and catch shares[38], to end perverse incentives[133] and by the growth of truly sustainable aquaculture to reduce pressure on wild stocks[2]. Whereas most regulatory measures focus on commercial fisheries, subsistence[134] and recreational[135] fishing are also globally relevant and need to be aligned with rebuilding efforts to achieve sustainability.

Call to action

Rebuilding marine life requires a global partnership of diverse interests, including governments, businesses, resource users and civil society[129,136], aligned around an evidence-based action plan supported by a sound policy framework, a science and educational plan, quantitative targets, metrics for success and a business plan. It also requires leadership to assemble the scientific and socio-economic knowledge and the technologies required to rebuild marine life and the capacity to deploy them. A concerted global effort to restore and protect marine life and ecosystems could create millions of new—and in many cases—well-paying jobs[129,137]. Thus, commitments of governments, which are required to meet the UN SDGs by 2030, need to be supported and reinforced by commitments from society, non-government organizations (NGOs) and other agents, such as philanthropic groups, corporations and industry (Supplementary Information 4). The sectors that operate in the ocean spaces, which bear considerable responsibility for the losses thus far experienced and, in many cases, are likely to be the main beneficiaries of efforts to rebuild marine life, must change their ethos to commit to a net positive conservation impact as part of their social license to operate in the ocean space. The use of the ocean by humans should be designed for net positive conservation impact, creating additional benefits[138] that increase prosperity and catalyse political will to deploy further efforts in a positive feedback spiral of ocean bounty.

The long-term commitment to rebuilding marine life requires a powerful narrative, supported by scientific evidence that conveys its feasibility in the face of climate change and a growing human population, its alignment with societal values, and its widespread societal benefits. Growing numbers of success stories could shift the balance from a wave of pessimism that dominated past scientific narratives of the future ocean[5,7,11,32,33] to evidence-based 'ocean optimism'[139] (for example, #oceanoptimism in social media), conveying solutions and opportunities for actions that help to drive positive change[140]. This optimism must be balanced with transparent and robust communication of the risks posed by relevant pressures that are yet to be mitigated.

Rebuilding marine life will benefit from nations declaring, analogous to the Paris Agreement on climate change, NDCs towards rebuilding marine life[129]. NDCs aimed at rebuilding marine life will be essential for accountability, auditing milestones and forecasting success in reaching goals. NDCs can include both commitments for action within national Economic Exclusive Zones, as well as a catalogue of actionable opportunities available to investors, corporations and philanthropists[129].

The global policy framework required to rebuild marine life is largely in place through existing UN mechanisms (targets to be adopted in 2020 under the Global Biodiversity Framework of the CBD, SDGs and Paris Agreement of the UNFCC), if their most ambitious goals are implemented, along with additional international conventions such as the Bonn Convention on the Conservation of Migratory Species of Wild Animals, the Moratorium on Commercial Whaling of the International Whaling Commission (1982), Ramsar Convention on Wetlands of International Importance and CITES, among others. High-level coordination among all UN instruments and international policies addressing the oceans, including the high seas, is needed.

The UN initiated, in 2018, an Intergovernmental Conference to reach a new legally binding treaty to protect marine life in the high seas by 2020. This proposed treaty could enhance cooperation, governance and funds for conservation and restoration of high-seas and deep-sea ecosystems damaged or at risk from commercial interests[141]. This mandate would require funding of around US$30 million annually, which could be financed through long-term bonds in international capital markets or taxes on resource extraction[141]. Internationally agreed contributions will also be required, because populations of many species are shared across Exclusive Economic Zones of multiple nations. This approach could follow the model of the Regional Fisheries Management Organizations, bringing together nations to manage shared fish stocks that straddle national waters and the high seas[141]. For example, in September 2010 the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) established the world's first MPA network on the high seas covering 286,200 km^2 (ref. [142]).

Rebuilding marine life will also require active oversight, participation and cooperation by local, regional and national stakeholders. A readiness and the capacity to implement recovery wedges differs across nations, and cooperation to rebuild marine life should remain flexible to adapt to variable cultural settings; locally designed approaches may be most effective[143] (Supplementary Information 1). Past failures in some nations can inform new governance arrangements to avoid repeating the same mistakes elsewhere. Rebuilding marine life should draw on successful marine policy formulation, management actions and technologies to nurture a learning curve that will propel future outcomes while reducing cost[105,107–109]. For instance, many developed nations have already implemented nutrient reduction plans; however, fertilizer use is rising globally, supported mainly by demands from developing nations that also continue to develop their shorelines. Adopting the measures now in place in developed nations to increase nitrogen-use efficiency in South and East Asia could lower global synthetic fertilizer use by 2050, even under the increased crop production required to feed a growing population[144].

Calls for international assistance to support recovery, whether it is for coastal wetlands to reduce risks of damages from natural disasters[105] or marine life generally[129], should include assistance to improve governance and build institutional capacities. However, the capacity of both developed and developing nations to deploy effective recovery actions is already substantial. Mangrove restoration projects are considerably larger and cheaper but similarly successful (about 50% survival reported) in developing nations compared with developed countries[104], and small-island states are showing growing leadership in response to plastic pollution and the marine impacts of climate change (https://www.aosis.org/). However, many developing countries need particularly high levels of investment to conserve and restore habitats that protect populations at risk in low-lying coastal areas, which could be financed through international climate change adaptation funds[105]. Currently, the UN's Green Climate Fund has mobilized US$10.3 billion annually to assist developing countries to adapt to climate change, with a goal of US$100 billion per year in 2020 (https://www.greenclimate.fund/how-we-work/resource-mobilization). Allocating a sizeable fraction of these funds to developing countries for the conservation and restoration of 'blue infrastructure' (for example, saltmarshes, oyster and coral reefs, mangroves and seagrass beds) could increase the resilience of coastal communities to climate change and to extreme events while improving their livelihoods[105].

Conclusion

Based on the data reviewed here, we conclude that substantial rebuilding across many components of marine life by 2050 is an achievable Grand Challenge for science and society. Meeting this challenge requires immediate action to reduce relevant pressures, including climate change, safeguarding places of remaining abundance, and recovering depleted populations, habitats and ecosystems elsewhere. This will require sustained perseverance and substantial commitment of financial resources, but we suggest that the ecological, economic and social gains will be far-reaching. Success requires the establishment of a committed and resilient global partnership of governments and societies aligned with this goal, supported by coordinated policies, adequate financial and market mechanisms, and evolving scientific and technological advances that nurture a fast learning curve of rebuilding interventions. Meeting the challenge of substantially rebuilding marine life would be a historic milestone in humanity's quest to achieve a globally sustainable future.

1. OECD. *The Ocean Economy in 2030* (OECD Publishing, 2016).
2. Duarte, C. M. et al. Will the oceans help feed humanity? *Bioscience* **59**, 967–976 (2009).
3. Roberts, C. M. et al. Marine reserves can mitigate and promote adaptation to climate change. *Proc. Natl Acad. Sci. USA* **114**, 6167–6175 (2017).
4. Gattuso, J.-P. et al. Ocean solutions to address climate change and its effects on marine ecosystems. *Front. Mar. Sci*. **5**, 337 (2018).
5. Jackson, J. B. et al. Historical overfishing and the recent collapse of coastal ecosystems. *Science* **293**, 629–637 (2001).
6. Lotze, H. K. & Worm, B. Historical baselines for large marine animals. *Trends Ecol. Evol*. **24**, 254–262 (2009).
7. McCauley, D. J. et al. Marine defaunation: animal loss in the global ocean. *Science* **347**, 1255641 (2015).
This paper reviews the historical hunting and associated loss of animals in the ocean and examines current threats that may result in future losses.
8. IPBES. IPBES Global Assessment Summary for Policymakers. https://www.ipbes.net/news/ipbes-global-assessment-summary-policymakers-pdf (2019).
9. Wassmann, P. et al. Footprints of climate change in the Arctic marine ecosystem. *Glob. Change Biol*. **17**, 1235–1249 (2011).
10. Gattuso, J.-P. et al. Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science* **349**, aac4722 (2015).
11. Hughes, T. P. et al. Coral reefs in the Anthropocene. *Nature* **546**, 82–90 (2017).
12. Hughes, T. P. et al. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science* **359**, 80–83 (2018).
This study provides a global assessment of the extent of coral bleaching, with emphasis on the 2015–2016 global coral-reef bleaching events.
13. Hoegh-Guldberg, O. et al. in *Special Report on Global Warming of 1.5 °C* (eds Masson-Delmotte, V. et al.) 175–311 (WMO, 2018).
This IPCC report suggests that, in light of recent coral losses, the research community may have underestimated the risks of climate change for coral reefs, and concludes that even achieving the ambitious goal of 1.5 °C of global warming under the Paris Agreement could result in the loss of 70–90% of reef-building corals compared to that at the time the assessment was made.
14. Lotze, H. K. et al. Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proc. Natl Acad. Sci. USA* **116**, 12907–12912 (2019).
15. Lubchenco, J. & Grorud-Colvert, K. Making waves: the science and politics of ocean protection. *Science* **350**, 382–383 (2015).
16. Costanza, R. et al. The value of the world's ecosystem services and natural capital. *Nature* **387**, 253–260 (1997).
17. Silver, J. J. et al. Blue economy and competing discourses in international oceans governance. J. Environ. *Dev*. **24**, 135–160 (2015).
18. Roberts, C. M. *The Unnatural History of the Sea* (Island Press, 2007).
This book reviews how human pressures drove changes in marine ecosystems and to marine life, providing evidence that the observed impacts on marine ecosystems are not a recent phenomenon.
19. Worm, B. Marine conservation: how to heal an ocean. *Nature* **543**, 630–631 (2017).
20. Jones, H. P. et al. Restoration and repair of Earth's damaged ecosystems. *Proc. R. Soc. Lond. B* **285**, 20172577 (2018).
21. FAO. *The State of World Fisheries and Aquaculture: Meeting the Sustainable Development Goals* (Food and Agriculture Organization of the United Nations, 2018).
22. Doney, S. C. The growing human footprint on coastal and open-ocean biogeochemistry. *Science* **328**, 1512–1516 (2010).
23. Breitburg, D. et al. Declining oxygen in the global ocean and coastal waters. *Science* **359**, eaam7240 (2018).
24. IUCN. The IUCN Red List of Threatened Species. https://www.iucnredlist.org/ (accessed 1 April 2019).
25. Dulvy, N. K., Pinnegar, J. K. & Reynolds, J. D. in *Holocene Extinctions* (ed. Turvey, S. T.) 129–150 (Oxford Univ. Press, 2009).
26. Jones, K. R. et al. The location and protection status of Earth's diminishing marine wilderness. *Curr. Biol*. **28**, 2506–2512 (2018).
27. Irigoien, X. et al. Large mesopelagic fishes biomass and trophic efficiency in the open ocean. *Nat. Commun*. **5**, 3271 (2014).
This study reports an estimate of mesopelagic fish abundance, which exceeds the biomass of all other fish stocks by about 30 times and remains unexploited by fisheries.
28. Beare, D., Hölker, F., Engelhard, G. H., McKenzie, E. & Reid, D. G. An unintended experiment in fisheries science: a marine area protected by war results in Mexican waves in fish numbers-at-age. *Naturwissenschaften* **97**, 797–808 (2010).
29. Richards, Z. T., Beger, M., Pinca, S. & Wallace, C. C. Bikini Atoll coral biodiversity resilience five decades after nuclear testing. *Mar. Pollut. Bull*. **56**, 503–515 (2008).
30. Oguz, T. & Velikova, V. Abrupt transition of the northwestern Black Sea shelf ecosystem from a eutrophic to an alternative pristine state. *Mar. Ecol. Prog. Ser*. **405**, 231–242 (2010).
31. Mozetič, P. et al. Recent trends towards oligotrophication of the northern Adriatic: evidence from chlorophyll a time series. *Estuaries Coast*. **33**, 362–375 (2010).
32. Jackson, J. B. C. Colloquium paper: ecological extinction and evolution in the brave new ocean. *Proc. Natl Acad. Sci. USA* **105**, 11458–11465 (2008).
33. Duarte, C. M. Global change and the future ocean: a grand challenge for marine sciences. *Front. Mar. Sci*. **1**, 63 (2014).
34. Magera, A. M., Mills Flemming, J. E., Kaschner, K., Christensen, L. B. & Lotze, H. K. Recovery trends in marine mammal populations. *PLoS ONE* **8**, e77908 (2013).
35. Lotze, H. K., Coll, M., Magera, A. M., Ward-Paige, C. & Airoldi, L. Recovery of marine animal populations and ecosystems. *Trends Ecol. Evol*. **26**, 595–605 (2011).
This paper provides a discussion of the recovery potential and timescales for marine animal populations and ecosystems.
36. Costello, C. et al. Global fishery prospects under contrasting management regimes. *Proc. Natl Acad. Sci. USA* **113**, 5125–5129 (2016).
37. Castilla, J. C. & Defeo, O. Latin American benthic shell fisheries: emphasis on co-management and experimental practices. *Rev. Fish Biol. Fish*. **11**, 1–30 (2001).
38. Birkenbach, A. M., Kaczan, D. J. & Smith, M. D. Catch shares slow the race to fish. *Nature* **544**, 223–226 (2017).
39. Worm, B. et al. Rebuilding global fisheries. *Science* **325**, 578–585 (2009).
40. Duarte, C. M. et al. The role of coastal plant communities for climate change mitigation and adaption. *Nat. Clim. Change* **3**, 961–968 (2013).
This review summarizes how Blue Carbon strategies, based on the conservation and restoration of vegetated coastal habitats, can help to mitigate climate change and can provide coastal protection, thereby helping coastal communities to adapt to climate change.
41. Reusch, T.B. et al. The Baltic Sea as a time machine for the future coastal ocean. *Sci. Adv*. **4**, eaar8195 (2018).
This review provides a narrative of the difficulties and successes in achieving environmental improvements and recovery of the Baltic Sea, with an emphasis on lessons learned to guide future efforts elsewhere.

42. Boesch, D. F. Barriers and bridges in abating coastal eutrophication. *Front. Mar. Sci*. **6**, 123 (2019).
43. Jambeck, J. R. et al. Plastic waste inputs from land into the ocean. *Science* **347**, 768–771 (2015).
44. Roberts, C. M., Hawkins, J. P. & Gell, F. R. The role of marine reserves in achieving sustainable fisheries. *Phil. Trans. R. Soc. B* **360**, 123–132 (2005).
45. Das, S. & Vincent, J. R. Mangroves protected villages and reduced death toll during Indian super cyclone. *Proc. Natl Acad. Sci. USA* **106**, 7357–7360 (2009).
46. Taillardat, P., Friess, D. A. & Lupascu, M. Mangrove blue carbon strategies for climate change mitigation are most effective at the national scale. *Biol. Lett*. **14**, 20180251 (2018).
47. Lotze, H. K. et al. Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science* **312**, 1806–1809 (2006).
48. Roman, J., Dunphy-Daly, M. M., Johnston, D. W. & Read, A. J. Lifting baselines to address the consequences of conservation success. *Trends Ecol. Evol*. **30**, 299–302 (2015).
49. Bejder, M. et al. Embracing conservation success of recovering humpback whale populations: evaluating the case for downlisting their conservation status in Australia. *Mar. Policy* **66**, 137–141 (2016).
50. Lowry, M. S. et al. Abundance, distribution, and population growth of the northern elephant seal (*Mirounga angustirostris*) in the United States from 1991 to 2010. *Aquat. Mamm*. **40**, 20–31 (2014).
This paper provides a compelling overview of how hunting regulation and protection allowed the remarkable comeback of the northern elephant seal in the Pacific coast of the United States.
51. Fisheries and Oceans Canada. Stock Assessment of Canadian Grey Seals (*Halichoerus grypus*). *Canadian Science Advisory Secretariat Research Document 2014/010* (Fisheries and Oceans Canada, 2014).
52. Mazaris, A. D., Schofield, G., Gkazinou, C., Almpanidou, V. & Hays, G. C. Global sea turtle conservation successes. *Sci. Adv*. **3**, e1600730 (2017).
53. Ricard, D. et al. Examining the knowledge base and status of commercially exploited marine species with the RAM Legacy Stock Assessment Database. *Fish Fish*. **13**, 380–398 (2012).
54. Hutchings, J. A. & Reynolds, J. D. Marine fish population collapses: consequences for recovery and extinction risk. *Bioscience* **54**, 297–309 (2004).
55. Rigét, F. et al. Temporal trends of persistent organic pollutants in Arctic marine and freshwater biota. *Sci. Total Environ*. **649**, 99–110 (2019).
56. Pinedo-González, A. J. et al. Concentration and isotopic composition of dissolved Pb in surface waters of the modern global ocean. *Geochim. Cosmochim. Acta* **235**, 41–54 (2018).
57. Schøyen, M. et al. Levels and trends of tributyltin (TBT) and imposex in dogwhelk (*Nucella lapillus*) along the Norwegian coastline from 1991 to 2017. *Mar. Environ. Res*. **144**, 1–8 (2019).
58. IOTOPF. Oil Tanker Spill Statistics 2016 http://www.itopf.org/ (2016).
59. Duarte, C. M. et al. Return to Neverland: shifting baselines affect eutrophication restoration targets. *Estuaries Coast*. **32**, 29–36 (2009).
60. Lefcheck, J. S. et al. Long-term nutrient reductions lead to the unprecedented recovery of a temperate coastal region. *Proc. Natl Acad. Sci. USA* **115**, 3658–3662 (2018).
61. Tomasko, D. et al. Widespread recovery of seagrass coverage in Southwest Florida (USA): temporal and spatial trends and management actions responsible for success. *Mar. Pollut. Bull*. **135**, 1128–1137 (2018).
62. de los Santos, C.B. et al. Recent trend reversal for declining European seagrass meadows. *Nat. Commun*. **10**, 3356 (2019).
This study reports how decades of efforts to reduce nutrient inputs, improve coastal water quality and conserve and restore seagrass meadows has led to a remarkable trend reversal from sustained losses of seagrass across Europe throughout the twentieth century to a substantial increase between 2000 and 2010.
63. Yoshida, G. et al. in *Blue Carbon in Shallow Coastal Ecosystems* (eds Kuwae, T. & Hori, M.) (Springer Nature, 2019).
64. Arnaud-Haond, S. et al. Genetic recolonization of mangrove: genetic diversity still increasing in the Mekong Delta 30 years after Agent Orange. *Mar. Ecol. Prog. Ser*. **390**, 129–135 (2009).
65. Nam, V. N., Sasmito, S. D., Murdiyarso, D., Purbopuspito, J. & MacKenzie, R. A. Carbon stocks in artificially and naturally regenerated mangrove ecosystems in the Mekong Delta. *Wetl. Ecol. Manag*. **24**, 231–244 (2016).
66. Bunting, P. et al. The global mangrove watch—a new 2010 global baseline of mangrove extent. *Remote Sens*. **10**, 1669 (2018).
67. Hamilton, S. E. & Casey, D. Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21). *Glob. Ecol. Biogeogr*. **25**, 729–738 (2016).
68. López-Angarita, J. et al. Land use patterns and influences of protected areas on mangroves of the eastern tropical Pacific. *Biol. Conserv*. **227**, 82–91 (2018).
69. Almahasheer, H. et al. Decadal stability of Red Sea mangroves. *Estuar. Coast. Shelf Sci*. **169**, 164–172 (2016).
70. Almahasheer, H. Spatial coverage of mangrove communities in the Arabian Gulf. *Environ. Monit. Assess*. **190**, 85 (2018).
71. Chen, L. Z. et al. Recent progresses in mangrove conservation, restoration and research in China. *J. Plant Ecol*. **2**, 45–54 (2009).
72. Piacenza, S. E. et al. Trends and variability in demographic indicators of a recovering population of green sea turtles *Chelonia mydas*. *Endanger. Species Res*. **31**, 103–117 (2016).
73. Thorson, J. T., Cope, J. M., Branch, T. A. & Jensen, O. P. Spawning biomass reference points for exploited marine fishes, incorporating taxonomic and body size information. *Can. J. Fish. Aquat. Sci*. **69**, 1556–1568 (2012).
74. McClatchie, S. et al. Collapse and recovery of forage fish populations prior to commercial exploitation. *Geophys. Res. Lett*. **44**, 1877–1885 (2017).
75. Rosenberg, A. A., Swasey, J. H. & Bowman, M. Rebuilding US fisheries: progress and problems. *Front. Ecol. Environ*. **4**, 303–308 (2006).
76. Neubauer, P., Jensen, O. P., Hutchings, J. A. & Baum, J. K. Resilience and recovery of overexploited marine populations. *Science* **340**, 347–349 (2013).
77. Safina, C., Rosenberg, A. A., Myers, R. A., Quinn, T. J. II & Collie, J. S. U.S. ocean fish recovery: staying the course. *Science* **309**, 707–708 (2005).
78. MacNeil, M. A. et al. Recovery potential of the world's coral reef fishes. *Nature* **520**, 341–344 (2015).
79. Sumaila, U. R. et al. Benefits of rebuilding global marine fisheries outweigh costs. *PLoS ONE* **7**, e40542 (2012).
80. Bersoza Hernández, A. et al. Restoring the eastern oyster: how much progress has been made in 53 years? *Front. Ecol. Environ*. **16**, 463–471 (2018).
81. Graham, M. H. et al. Population dynamics of giant kelp *Macrocystis pyrifera* along a wave exposure gradient. *Mar. Ecol. Prog. Ser*. **148**, 269–279 (1997).
82. Dayton, P. K., Tegner, M. J., Parnell, P. E. & Edwards, P. B. Temporal and spatial patterns of disturbance and recovery in a kelp forest community. *Ecol. Monogr*. **62**, 421–445 (1992).
83. Williams, P. B. & Orr, M. K. Physical evolution of restored breached levee salt marshes in the San Francisco Bay estuary. *Restor. Ecol*. **10**, 527–542 (2002).
84. Alongi, D. M. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. *Estuar. Coast. Shelf Sci*. **76**, 1–13 (2008).
85. Duarte, C. M. Submerged aquatic vegetation in relation to different nutrient regimes. *Ophelia* **41**, 87–112 (1995).
86. Rooper, C. N. et al. Modeling the impacts of bottom trawling and the subsequent recovery rates of sponges and corals in the Aleutian Islands, Alaska. *Cont. Shelf Res*. **31**, 1827–1834 (2011).
87. Girard, F., Shea, K. & Fisher, C. R. Projecting the recovery of a long-lived deep-sea coral species after the Deepwater Horizon oil spill using state-structured models. *J. Appl. Ecol*. **55**, 1812–1822 (2018).
88. Hughes, T. P. et al. Global warming impairs stock–recruitment dynamics of corals. *Nature* **568**, 387–390 (2019).
89. Moreno-Mateos, D. et al. Anthropogenic ecosystem disturbance and the recovery debt. *Nat. Commun*. **8**, 14163 (2017).
90. Thurstan, R. H. & Roberts, C. M. Ecological meltdown in the Firth of Clyde, Scotland: two centuries of change in a coastal marine ecosystem. *PLoS ONE* **5**, e11767 (2010).
91. Britten, G. L. et al. Extended fisheries recovery timelines in a changing environment. *Nat. Commun*. **8**, 15325 (2017).
92. Moore, J. K. et al. Sustained climate warming drives declining marine biological productivity. *Science* **359**, 1139–1143 (2018).
93. WWF. *Living Blue Planet Report* (WWF, 2015).
94. Thurstan, R. H., Brockington, S. & Roberts, C. M. The effects of 118 years of industrial fishing on UK bottom trawl fisheries. *Nat. Commun*. **1**, 15 (2010).
95. IPCC. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. (eds. Pörtner, H.-O. et al.) (IPCC, 2019).
This IPCC Special Report contains an updated assessment of the impacts—both realized and projected—of climate change on the oceans as well as projections on sea-level rise and its associated impacts.
96. Jepson, P. Recoverable Earth: a twenty-first century environmental narrative. *Ambio* **48**, 123–130 (2019).
97. Molloy, P. P., McLean, I. B. & Côté, I. M. Effects of marine reserve age on fish populations: a global meta-analysis. *J. Appl. Ecol*. **46**, 743–751 (2009).
98. Dinerstein, E. et al. A global deal for nature: guiding principles, milestones, and targets. *Sci. Adv*. **5**, eaaw2869 (2019).
99. Sala, E. et al. Assessing real progress towards effective ocean protection. *Mar. Policy* **91**, 11–13 (2018).
100. Costello, M. J. & Ballantine, B. Biodiversity conservation should focus on no-take marine reserves: 94% of marine protected areas allow fishing. *Trends Ecol. Evol*. **30**, 507–509 (2015).
101. Gill, D. A. et al. Capacity shortfalls hinder the performance of marine protected areas globally. *Nature* **543**, 665–669 (2017).
102. O'Leary, B. C. et al. Addressing criticisms of large-scale marine protected areas. *Bioscience* **68**, 359–370 (2018).
103. O'Hara, C. C., Villaseñor-Derbez, J. C., Ralph, G. M. & Halpern, B. S. Mapping status and conservation of global at-risk marine biodiversity. *Conserv. Lett*. **12**, e12651 (2019).
104. Bayraktarov, E. et al. The cost and feasibility of marine coastal restoration. *Ecol. Appl*. **26**, 1055–1074 (2016).
105. Barbier, E. B. Policy: Hurricane Katrina's lessons for the world. *Nature* **524**, 285–287 (2015).
106. Temmerman, S. et al. Ecosystem-based coastal defence in the face of global change. *Nature* **504**, 79–83 (2013).
107. van Katwijk, M. M. et al. Global review of seagrass restoration: the importance of large-scale planting. *J. Appl. Ecol*. **53**, 567–578 (2016).
108. Suggett, D. J. et al. Optimizing return-on-effort for coral nursery and outplanting practices to aid restoration of the Great Barrier Reef. *Restor. Ecol*. **27**, 683–693 (2019).
109. Lewis, R. R. III. Ecological engineering for successful management and restoration of mangrove forests. *Ecol. Eng*. **24**, 403–418 (2005).
110. van Oppen, M. J., Oliver, J. K., Putnam, H. M. & Gates, R. D. Building coral reef resilience through assisted evolution. *Proc. Natl Acad. Sci. USA* **112**, 2307–2313 (2015).
111. National Academies of Sciences, Engineering, and Medicine. *A Research Review of Interventions to Increase the Persistence and Resilience of Coral Reefs* https://doi.org/10.17226/25279 (National Academies Press, 2019).
112. Lovelock, C. E. & Brown, B. M. Land tenure considerations are key to successful mangrove restoration. *Nat. Ecol. Evol*. **3**, 1135 (2019).
113. Duarte, C. M. & Krause-Jensen, D. Intervention options to accelerate ecosystem recovery from coastal eutrophication. *Front. Mar. Sci*. **5**, 470 (2018).
114. Xiao, X. et al. Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. *Sci. Rep*. **7**, 46613 (2017).
115. Carstensen, J. & Duarte, C. M. Drivers of pH variability in coastal ecosystems. *Environ. Sci. Technol*. **53**, 4020–4029 (2019).
116. Rydin, E., Kumblad, L., Wulff, F. & Larsson, P. Remediation of a eutrophic bay in the Baltic Sea. *Environ. Sci. Technol*. **51**, 4559–4566 (2017).

117. Boesch, D. Deep-water drilling remains a risky business. *Nature* **484**, 289 (2012).
118. Johannsdottir, L. & Cook, D. Systemic risk of maritime-related oil spills viewed from an Arctic and insurance perspective. *Ocean Coast. Manage*. **179**, 104853 (2019).
119. Kunc, H. P., McLaughlin, K. E. & Schmidt, R. Aquatic noise pollution: implications for individuals, populations, and ecosystems. *Proc. R. Soc. Lond. B* **283**, 20160839 (2016).
120. Worthington, T. & Spalding, M. *Mangrove Restoration Potential: A global map highlighting a critical opportunity*. https://doi.org/10.17863/CAM.39153 (2018).
121. Kondolf, G. M., Rubin, Z. K. & Minear, J. T. Dams on the Mekong: cumulative sediment starvation. *Water Resour. Res*. **50**, 5158–5169 (2014).
122. Schuerch, M. et al. Future response of global coastal wetlands to sea-level rise. *Nature* **561**, 231–234 (2018).
123. Fabricius, K. E. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Mar. Pollut. Bull*. **50**, 125–146 (2005).
124. Rogelj, J. et al. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* **534**, 631–639 (2016).
125. Tokarska, K. B. & Gillett, N. P. Cumulative carbon emissions budgets consistent with 1.5 °C global warming. *Nat. Clim. Change* **8**, 296–299 (2018).
126. UNEP. *Emissions Gap Report 2019*. https://www.unenvironment.org/resources/emissions-gap-report-2019 (UNEP, 2019).
127. Bruno, J. F. et al. Climate change threatens the world's marine protected areas. *Nat. Clim. Change* **8**, 499–503 (2018).
128. Sully, S., Burkepile, D. E., Donovan, M. K., Hodgson, G. & van Woesik, R. A global analysis of coral bleaching over the past two decades. *Nat. Commun*. **10**, 1264 (2019).
129. Barbier, E. B., Burgess, J. C. & Dean, T. J. How to pay for saving biodiversity. *Science* **360**, 486–488 (2018).
This study provides estimates and funding mechanisms to pay for biodiversity conservation globally, including estimates of investment and benefits for conserving marine biodiversity.
130. Balmford, A., Gravestock, P., Hockley, N., McClean, C. J. & Roberts, C. M. The worldwide costs of marine protected areas. *Proc. Natl Acad. Sci. USA* **101**, 9694–9697 (2004).
131. McCook, L. J. et al. Adaptive management of the Great Barrier Reef: a globally significant demonstration of the benefits of networks of marine reserves. *Proc. Natl Acad. Sci. USA* **107**, 18278–18285 (2010).
132. Burgess, M. G. et al. Protecting marine mammals, turtles, and birds by rebuilding global fisheries. *Science* **359**, 1255–1258 (2018).
133. Lubchenco, J. et al. The right incentives enable ocean sustainability successes and provide hope for the future. *Proc. Natl Acad. Sci. USA* **113**, 14507–14514 (2016).
134. Cisneros-Montemayor, A. M., Pauly, D., Weatherdon, L. V. & Ota, Y. A global estimate of seafood consumption by coastal indigenous peoples. *PLoS ONE* **11**, e0166681 (2016).
135. Arlinghaus, R. et al. Opinion: governing the recreational dimension of global fisheries. *Proc. Natl Acad. Sci. USA* **116**, 5209–5213 (2019).
136. Bäckstrand, K. et al. Non-state actors in global climate governance: from Copenhagen to Paris and beyond. *Env. Polit*. **26**, 561–579 (2017).
137. Hudson, A. Restoring and protecting the world's large marine ecosystems: an engine for job creation and sustainable economic development. Environ. *Dev*. **22**, 150–155 (2017).
138. Gelcich, S., Godoy, N., Prado, L. & Castilla, J. C. Add-on conservation benefits of marine territorial user rights fishery policies in central Chile. *Ecol. Appl*. **18**, 273–281 (2008).
139. Johns, L. N. & Jacquet, J. Doom and gloom versus optimism: an assessment of ocean-related US science journalism (2001–2015). *Glob. Environ. Change* **50**, 142–148 (2018).
140. Balmford, A. & Knowlton, N. Why Earth optimism? *Science* **356**, 225 (2017).
141. Barbier, E. B. et al. Protect the deep sea. *Nature* **505**, 475–477 (2014).
142. O'Leary, B. C. et al. The first network of marine protected areas (MPAs) in the high seas: the process, the challenges and where next. *Mar. Policy* **36**, 598–605 (2012).
143. Rodríguez, J. P. et al. Environment: globalization of conservation: a view from the south. *Science* **317**, 755–756 (2007).
144. Mogollón, J. M. et al. Assessing future reactive nitrogen inputs into global croplands based on the shared socioeconomic pathways. *Environ. Res. Lett*. **13**, 044008 (2018).

Acknowledgements This work was supported by King Abdullah University of Science and Technology through baseline funding to C.M.D. and S.A. G.L.B. was supported by the Simons Collaboration on Computational Biogeochemical Modeling of Marine Ecosystems/CBIOMES (grant number 549931); J.-P.G. was supported by the Prince Albert II of Monaco Foundation, the Ocean Acidification International Coordination Centre of the International Atomic Energy Agency, the Veolia Foundation and the French Facility for Global Environment; H.K.L. and B.W. were supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Ocean Frontier Institute (Module G); J.C.C. was supported by the Catedra Arauco in Environmental Ethic-UC and Centro Interdisciplinario de Cambio Global-UC. We thank T. Kuwae, R. J. Orth, the Mars Sustainable Solutions (part of Mars Inc), and C. Haight and B. DeAngelis for supplying details on restoration projects; L. Valuzzi, R. Devassy, A. Parry and F. Baalkhuyur for help with the inventory of restoration projects, E. McLeod for help locating materials, and A. Buxton and S. Gasparian for help with displays.

Author contributions C.M.D developed the concept and all authors contributed to the design, data compilation, analysis and writing of the Review.

Competing interests The authors declare no competing interests.

Additional information
Supplementary information is available for this paper at https://doi.org/10.1038/s41586-020-2146-7.
Correspondence and requests for materials should be addressed to C.M.D.
Peer review information *Nature* thanks Jonathan S. Lefcheck, Brian MacKenzie and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.
Reprints and permissions information is available at http://www.nature.com/reprints.
Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.