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Roberts, Callum Michael orcid.org/0000-0003-2276-4258 (2020) Rebuilding marine life. Nature. pp. 39-51. ISSN: 0028-0836

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

Rebuilding Marine Life

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The UN Sustainable Development Goal 14 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 society receives from a healthy ocean. In this Review 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, should major pressures, including climate change, be 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 GDP and provides employment to 1.5% of the global workforce[1], with an estimated output of US$1.5 trillion in 2010, expected to double by 2030[1]. And 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]. At the same time, 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 growing human dependence on ocean resources and declining marine life under human pressures (Fig. 1) is focusing unprecedented attention on the connection between ocean conservation and human well-being[15]. The UN Sustainable Development Goal 14 (SDG14 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 SDG14 as the life-support systems (populations, habitats, and ecosystems) that deliver the many benefits 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, prominently mitigating climate change, are deployed at scale.

Slowing the decline of marine life and achieving net gains

By the time the general public admired *life below water* through the "*Undersea World of Jacques Cousteau*" (1968-1976), the abundance of large marine animals was already greatly reduced[5-7,18]. And the abundance of marine animals and habitats that support ecosystems services has shrunk to a fraction of what was in place when the first frameworks to conserve and sustain marine life were introduced in the 1980s (Fig. 1), to a fraction of pre-exploitation levels[5,6,19,20]. 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 remarkable recovery once pressures are reduced or removed (Figs. 2-3). Substantial wilderness areas remain in remote regions[26], and large populations of marine animals are still found, for example, in mesopelagic (200-1000 m depth) ocean waters [27].

Regional examples of impressive resilience include the rebound of fish stocks during World Wars I and II following drastic 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 sudden reduction in fertilizer application after the collapse of the Soviet Union. Although these rapid recoveries were unrelated to conservation actions, they helped inform subsequent interventions 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, Table 1).

Impactful Interventions

Hunting Regulation

Species protections through the Convention on the Trade of Endangered Species (CITES, 1975, cites.org) and the global moratorium on commercial whaling (1982, iwc.int) are prominent examples of international 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].

Fisheries management

Successful rebuilding of depleted fish populations has been achieved in many cases through well-proven management actions, including catch and effort restrictions, closed areas, regulation of fishing capacity and gear, catch shares, and co-management arrangements (Suppl. Material 1) [35-39]. These interventions require detailed consideration of socio-economic circumstances, with solutions being tailored to local context[37]. Persistent challenges include harmful subsidies, poverty and lack of alternative employment, illegal and unregulated 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 USA and EU, leading to major improvements today[40-42]. Many hazardous pollutants have been regulated or phased-out through the Stockholm Convention (www.pops.int) and, specifically in the ocean, by the MARPOL Convention (www.imo.org), often reinforced by national and regional policies. Recent attention has focused on curbing plastic pollution entering the ocean, which remains a growing problem, with inputs currently estimated at between 4.8 to 12.7 million Mton 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[3,44]. In 2000, only 0.13 million km^2 (0.003%) of the ocean was protected, but MPAs now cover 27.4 million km^2 (7.6% of ocean area, or 4.8% if considering fully implemented MPAs (mpatlas.org, accessed May 3, 2019). MPA coverage continues to grow at about 8% per year (Fig. 2., Suppl. Video V1) .

The 21st Century has seen a global surge of active habitat protection and restoration initiatives (Fig. 2, Suppl. Material 1, Suppl.Videos V1 and V2), even in challenging environments adjoining coastal megacities (Suppl. Material 1). These efforts have delivered benefits, such as improved water quality following oyster reef restoration. Additionally, Blue Carbon strategies, submitted within Nationally Determined Contributions of > 50 nations, at the heart of the Paris Agreement[46], are being used to mitigate climate change and improve coastal protection by restoring seagrass, saltmarsh and mangrove habitats[46-47] (Suppl. Material 1).

Recovery to date

Extinction risk reductions

The proportion of marine species assessed by the IUCN Red List as threatened with global extinction (Suppl. Mat. S2) has decreased from 18% in 2000 to 11.4% in 2019 (sd=1.7%, n=1743), with trends being relatively uniform across ocean basins and guilds (Fig. S2.1). In part, this reflects a growing number of species that has 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, Table S2). Some large marine species have exhibited particularly striking rebounds, even from the brink of extinction (Fig. 3c). Humpback whales migrating from Antarctica to eastern Australia have been increasing at 10% to 13% year^{-1}, from a few hundred animals in 1968 to >40,000 currently[49]. Northern elephant seals recovered from about 20 breeding individuals in 1880 to >200,000 today[50], and gray seal populations have increased by 1410% in eastern Canada[51] and 823% in the Baltic[41] since 1977. Southern sea otters have grown from about 50 individuals in 1911 to several thousand today[35]. While still endangered, most sea turtle populations for which trends are available are increasing in size[52], ranging from 4-14% increase year^{-1} for green turtle nesting populations[52].

Fisheries recovery

Using a comprehensive stock assessment database[53] we found that fish populations with available scientific assessments are increasingly managed for sustainability. The proportion of stocks with fishing mortality estimates (F) below the level that would produce maximum sustainable yield ($F < F_{MSY}$) has increased from 60% in 2000 to 68% in 2012. Many fish stocks subjected to such management interventions display positive trends (Fig. 3a), and globally aggregated stock assessments suggest a slowing-down of fish stock depletion[21,36,39], although this trend has not been measured for the majority of stocks that lack scientific assessment[36]. The most recent report of the Food and Agriculture Organisation on global fisheries[21] also suggests that two thirds of large-scale commercial fisheries are exploited at sustainable rates, but again this figure does also not account for smaller stocks or non-target by-catch 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 due to improved management and regulatory status compared to unassessed species[36], which still represent the majority of fisheries, especially in developing countries.

Pollution reduction

Time-series analyses show that legacy persistent organic pollutants have declined even in marine environments that tend to accumulate them (e.g. the Arctic[55]). The transition toward unleaded gasoline since the 1980's reduced Pb to concentrations comparable to baseline levels across the global ocean by 2010-2011[56]. Likewise, the total ban in 2008 of the anti-fouling chemical TBT (tributyltin) led to rapid declines of imposex (females developing 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 tanker vessel oil spills from 24.7 events per year in the 1970's to 1.7 events per year in the present decade[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 USA[61] (Fig. 1), Europe[62], Baltic Sea[41], and Japan[63].

Habitat restoration

Evidence that mangrove restoration can be achieved at scale first came from the Mekong Delta, possibly the largest (1,500 km^2) habitat restoration undertaken to date (Suppl. Material 1). Global loss of mangrove forests has since slowed to 0.11% $year^{-1}$ [64,65], with stable mangrove populations along the Pacific coast of Colombia, Costa Rica, and Panama[66], and increasing populations in the Red Sea[67], Arabian Gulf [68] and China[69]. Large-scale restoration of saltmarshes and oyster reefs has occurred in Europe and the USA (Fig. 2, Suppl. Material 1). Restoration attempts of seagrass, seaweed and coral reef ecosystems are also increasing globally, although they are often very small in scale (Fig. 2, Suppl. Video V2, Suppl. Material 1). Critically, a global inventory of total restored area is critically 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 dramatically and in some cases irreversibly, including the extinction of at least 20 marine species[25]. Yet by increasing abundances of key habitats and keystone species and restoring the three-dimensional complexity of benthic ecosystems, large and long-living marine animals and plants can again fulfill their ecosystem functions, promoting a diverse and vibrant ocean ecosystem. The yardstick of success should be the restoration of marine ecological structure, functions, resilience and ecosystem services, involving a greater capacity 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*, taking swift action to avoid tipping points beyond which collapse may be irreversible[11,18,33,33].

Here we examine 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 (i.e. 10-50% increase), substantial (50-90% increase) or full (> 90% increase)[47].

Marine megafauna

A number of megafauna species, including humpback whales and northern elephant seals, have recovered fully to historical baselines following protection (Fig. 3c), but rates depend on life history: some large whales may require >100 years to recover, while smaller pinnipeds may only need several decades[35] (Fig. 3c,d). Sea turtles have recovery time-scales of up to 100 years, although some populations have partially re-grown much faster (e.g. green turtles in Hawaii increased 6-fold between 1973 and 2016[70]). 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 allows for maximum sustainable yield (B_{MSY}), which fisheries harvest theory predict to be between 37% and 50% of the virgin biomass (B_0), depending on the particular model used (cf. Suppl. Information S2, Fig. S2.2). This range is consistent with an empirical estimate of B_0 for 147 exploited fish stocks, which found contemporary B_{MSY} values to be 40% of B_0, on average, with a range of 26% to 46% across taxa[71]. Reported recovery times to B_{MSY} for exploited finfish and invertebrate stocks range between 3-30 years[35] (Figs. 3 and 4), which is consistent with paleo-reconstructions of pre-historic collapse and recovery of anchovy, sardine and hake stocks[72], data from fisheries closures[54,73], and stock assessments for individual fisheries[74]. However, B_{MSY} should be considered to represent a minimum recovery target[39], since it does not account for ecosystem interactions, and might only provide 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[75,76]. Recovery rates also depend on the fishing pressure imposed on the stock; for example, the time required to rebuild populations depleted to B_{MSY} is estimated to range from about one decade, if fishing mortality (F) is rapidly reduced below the level that produces maximum sustainable yield (F_{MSY}. Longer recovery times unfold if fishing pressure is reduced more slowly[36,77] (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[35,76].

Coastal habitats

Recovery for coastal habitats following removal of stressors or active restoration typically occurs on a similar time scale as fish stock recovery, less than a decade for oyster reefs[78], and other invertebrate populations (Suppl. Information S3) and kelp-dominated habitats[79,80], between one to two decades for saltmarsh[81] and mangrove[82] habitats, and one to several decades for seagrass meadows[83] (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 over a century[84,85]. Recovery timescales of coral reefs impacted by local stressors range from a few years to over 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 causes the interval between bleaching events to shrink[12], with an associated steep reduction in recruitment[86].

In summary, available data suggest that many marine species and habitats require one to three decades to approach undisturbed or reference level ranges after removal of the causes of decline[35,86,87,90-92], with much longer recovery times required for some slow-growing groups[35] (Fig. 3).

Recovery times

The time required to rebuild marine life components depends on the extent of previous declines, which are often substantial. The reduction in species abundance and biomass relative to pre-disturbance baselines averages about 44 and 56%, respectively, across impacted marine ecosystems[87]. Similarly, the Living Blue Planet Report estimated a 49% decline in abundance of marine animal populations between 1970 and 2012[88], although many species and habitats have declined since[89-90]. Moreover, while maximum rates of marine population recovery 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% C.I. 2.42 - 3.41%) across marine ecosystems[20] and a characteristic rebuilding deficit of about 50% of pre-disturbance baselines[87], we provisionally estimate that the average time to reach 90% of undisturbed baselines (i.e. achieve substantial recovery) would be about 21 years (95% C.I. 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). Hence, a longer time scale to achieve substantial (50 to 90%), rather than full (> 90%), recovery may be a more realistic target for rebuilding marine life.

Based on the case studies examined, we provisionally adopt three decades from today (2050) as a target timeline for substantial (i.e. 50 to 90%) recovery of many components of marine life (Fig. 3, Table 1), 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).

Critically, achieving substantial recovery by 2050 requires that major pressures are mitigated soon, including climate change under the Paris Agreement. Climate change impacting the demography, phenology and biogeography of many marine species and compromising productivity of marine ecosystems[9-13,91-93] (Fig. 4). Impacts of realized climate change on many coral reefs today[12] raise concerns about their future prospect (Table 1). Shall we succeed in mitigating against climate change and other pressures, we may witness the beginning of a trend-change from previous steep decline to stabilization and, in many cases, substantial global recovery of marine life in the 21st century (Figs. 1-4).

A roadmap

Steps taken to rebuild marine life to date have involved a process of trial and error that delayed positive outcomes (e.g. in the EU and USA[41,42]), but 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 an unprecedented prominent place in the agendas of governments, corporations, philanthropists, and individuals than ever before[17,95]. 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, Suppl. Information 3). We are at a point when we can choose between 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 imply 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 1970's (Figs. 1 and 2), it is only now that comprehensive benefits (Fig. 3) are becoming evident at a larger scale. Likewise, since most current MPAs are less than 10 years old (Fig. 2), their full benefits, which increase with reserve age, are yet to be realized[94], in the case of MPAs properly managed and enforced[94].

Recovery Wedges

There is no silver bullet for achieving substantial recovery of marine life by 2050. Rather, recovery requires stacking a number of complementary actions, here termed recovery wedges, each helping to raise the recovery rate to reach or exceed the target of 2.4% increase year^{-1} across different ecosystem components (Table 1, Suppl. Information S1, S3 and S4). These wedges include protecting vulnerable habitats and species, adopting cautionary harvesting strategies, restoring habitats, reducing pollution, and mitigating climate change (Table 1, Suppl. Information S1, S3 and S4). The strength of the contribution of each of these wedges to the recovery target varies across species and ecosystems. For instance, mitigating climate change is the basal wedge to set coral reefs on a recovery trajectory, while improved habitat protection and fisheries management are the largest wedges for marine vertebrates and deep-sea habitats (Table 1, Suppl. Information S3).

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 where industry introduces new chemicals faster than their risks can be assessed. Challenges remain for persistent legacy pollutants (e.g. CO_2, organochlorines and plastics) already added to the atmosphere and oceans, whose removal requires novel capture 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). Growth of MPAs (Fig. 2, Suppl. Video V1) is currently on track to meet the target of 10% of ocean area protected by 2020, 30% by 2037 and 50% by 2044[96]. Many fish stocks could recover to B_{MSY} by 2030, assuming global management reforms couple the use of closed and protected areas with measures to reduce overfishing and collateral ecosystem damage, adapted to local context (Fig. 4, Table 1). However, projected climate impacts on ocean productivity and increase in extreme events[93] can delay recovery and, depending on emission pathways, may prevent recovery altogether (e.g. Fig. 4). The current focus on quantitative targets of percent ocean area protected has prompted concerns over the quality and effectiveness of MPAs[97]. Although 71% of assessed MPAs have been successful in enhancing fish populations, the level of protection is often weak (94% allow fishing[98]), and many areas are undermined by insufficient human and financial capacity[99]. Improving the effectiveness of MPAs requires enhanced resourcing, governance, level of protection[98-100] and siting to better match the geography of threats [101], and to ensure desired outcomes.

The current surge in restoration efforts (Fig. 2, Suppl. 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 4197 ha[102], restoring mangroves to their original extent of 225,000 km^2 by 2050 would require initiating 70 projects per year. This is not unrealistic, as realization of the benefits, such as reducing storm damage in low-lying areas[40,103,104], encourages further growth in restoration efforts (Fig. 2, Video V2). Past coastal restoration projects had reported average success rates ranging from 38% (seagrass) to 64% (saltmarshes and corals)[102], but reasons for failure are well understood[78,105-107], 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[102]. Emerging technologies are now being developed to restore coral species in the presence of climate change[108,109], but long-term testing is required before their effectiveness and lack of negative consequences are proven. Kelp restoration at a national scale in Japan provides a successful model, rooted in cultural practices, for linking restoration to sustainable fishing (Suppl. Material S1). More broadly, these practices recognize that sustainable harvest of marine resources ought to be balanced by broader restoration actions embedded in a social-ecological context, including reducing greenhouse gas emissions, restoring habitats, removing marine litter, or managing hydrological flows to avoid hypoxia (Suppl. Material S1). These restoration experiences (Suppl. Material S1) also find involvement of local communities to be essential, because of their economic dependence, commitment to place, and ownership[110].

Removing pollution is a basal 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[41,42,111]. Additional interventions (e.g., restoring hydrological flows or rebuilding oyster reefs), can catalyze additional removal of nutrients while improving biodiversity[111]. Seaweed aquaculture can help to alleviate eutrophication and reduce hypoxia[111,112]. Nutrient reduction has the additional benefit of locally reducing coastal acidification[113] 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 reduce acidification of coastal waters[22,113]. Large-scale experiments in anoxic basins of the Baltic Sea for example, have shown that treatment of sediments with phosphorus-binding agents help break biogeochemical feedback loops keeping ecosystems in an alternative anoxic stable state[114].

Oil spills from tanker vessels should decline further with the incoming International Maritime Organisation (IMO) requirement (13 F of Annex 1 of MARPOL) for double hulls in new large oil tankers, although deep-water drilling, illustrated by the catastrophic Deep-Water Horizon Spill in 2010[115], and increasing risks of oil spills from future oil drilling and tanker routes in the Arctic[116] present new challenges. Noise pollution from shipping and other industrial activities, such as drilling, pile driving and seismic surveys should be reduced[117]. Likewise, worldwide efforts to reduce or ban single-use plastic (initiated in developing nations), taxes on plastic bags, deposit-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 critical components of marine life (Table 1). These include natural variability and intensification of environmental extremes caused by anthropogenic climate change (Fig. 4), “black swans” (i.e. unexpected natural or social events), and failure to meet commitments to reduce existing pressures and mitigate climate change. In addition, growing human population, likely to exceed 9 billion by 2050, will create additional demands for seafood, coastal space and other ocean resources. Accordingly, the aspiration if that recovery targets by 2050, if all necessary recovery wedges are stacked, could be substantial to full recovery (i.e. 50 to 100% increase relative to present) for most rebuilding components (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[13,93] (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 (Suppl. Information S1). Incentives to develop alternative sources of livelihood, relocate landholders, mediate land-tenure conflicts[110], 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[118]. Reduced sediment supply due to dam construction in watersheds[119] is also an important challenge for the recovery of salt marshes and mangroves, exacerbated by sea level rise and climate change (Table 1). However, these habitats may be less vulnerable than previously thought[120], with a recent assessment concluding that global gains of 60% of coastal wetland area are possible under sea level rise[120]. In 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[121].

Overcoming the climate change roadblock

Climate change is the critical backdrop against which all future rebuilding efforts will play out. Current greenhouse gas emission trajectories lead to warming by 2100 of 2.6 to 4.5 °C above pre-industrial levels, far exceeding the long-term goal of the Paris Agreement[122]. Much stronger emission reduction efforts[122,123] are needed to fill the gap between target emissions and projected emissions under the present voluntary Nationally Determined Contributions[124] a challenging but not impossible task[123]. 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[10-13,93], propelled by species displacements and mass mortalities from future heat waves[11-13,93]. Mapping the areas where the likelihood of these transitions is high can help prioritize where and how restoration interventions should be deployed[118]. For instance, conserving and restoring vegetated coastal habitats will help to defend shorelines against increasing risks from sea level rise while helping to mitigate climate change[4,40,103]. Well-managed MPAs may help build resilience to climate change[121]. However, many of them are already affected by ocean warming with further climate change potentially compromising their performance in the future[125].

Rebuilding coral reefs carries the highest risk of failure (Table 1), as cumulative pressures (e.g. overfishing and pollution) driving their historic decline are now increasingly compounded by warming-induced bleaching[11,12]. The IPCC projects that global warming to 1.5°C above pre-industrial levels will result in very high risks and losses of coral reefs[13] unless adaptation occurs faster than currently anticipated. A study published after the 1.5 °C IPCC assessment[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 (~0.5 °C) than before, suggesting that the remaining coral populations now have a higher thermal threshold for bleaching, either due to decline of thermally-vulnerable species and genotypes and/or acclimation[126]. 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[102]. 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 catalyze recovery by reducing multiple pressures while repairing key processes, including herbivory and larval recruitment[11,109]. Mitigating the drivers of coral loss, particularly climate change, and developing innovative approaches within this decade are imperatives to revert coral losses at scale[108-109]. Efforts are underway to find corals resistant to temperatures and acidity levels expected by the end of the 21st century, to understand the mechanisms of their resistance and to use 'assisted evolution' to engineer these characteristics into other corals[108,109]. These efforts are in their infancy and their benefits currently unproven.

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

Investment needed and returns expected

Substantial rebuilding of marine life by 2050 requires sustained effort and financial support (Suppl. Material S4), with an estimated cost of at least $10-20 billion per year to extend protection actions to reach 50% of the ocean space[127] and substantial additional funds for restoration. This is comparable to establishing a global MPA network conserving 20-30% of the ocean ($5 to $19 billion annually[127,128]). Yet the economic return from this commitment will be significant, around $10 per $1 invested and in excess of one million jobs[127,128]. Ecotourism in protected areas provides 4 to 12 times greater economic returns than fishing without reserves[36] (e.g. A$5.5bn annually and 53,800 full time jobs in the Great Barrier Reef[129]). Rebuilt fisheries could increase the annual profits of the global seafood industry by $53 billion[126]. Conserving coastal wetlands could save the insurance industry $52 billion annually through reducing storm flooding[127], while providing additional benefits of carbon sequestration, income and subsistence from harvesting, and from fisheries supported by coastal wetlands [40,127].

A global rebuilding effort of exploited fish stocks could increase fishing yields by ~15% and profits by ~80%[36,77] while reducing by-catch mortality, thereby helping to promote recovery in non-target species as well[130]. Rebuilding fish stocks can be supported by market-based instruments, such as rationalizing global fishing subsidies[77], taxes and catch shares[38], to end perverse incentives[131], and by the growth of truly sustainable aquaculture to reduce pressure on wild stocks[2]. Whereas most regulatory measures focus on commercial fisheries, subsistence[132] and recreational[133] 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[127,134] 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 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[127,135]. Hence, commitments of governments, required to meet the UN SDGs by 2030, need to be supported and reinforced by commitments from society, non-governmental agents, including philanthropic groups, corporations and industry (Suppl. Information S4). The sectors operating 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 net positive conservation impact as part of their social license to operate in the ocean space. Human use of the ocean should be designed for net positive conservation impact, creating add-on benefits[136] that increase prosperity and catalyze 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 growing human population, its alignment with societal values, and its widespread societal benefits. Growing numbers of success stories and positive outlooks 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*'[137] (e.g. #oceanoptimism in social media), conveying solutions and opportunities for actions that help drive positive change[138]. 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, Nationally Determined Contributions (NDCs) toward rebuilding marine life[127]. 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[127].

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[139]. This mandate would require funding of around $30 million annually, which could be financed through long-term bonds in international capital markets or taxes on resource extraction[139]. 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, including those in High Seas[139]. 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 [140].

Rebuilding marine life will also require active oversight, participation and cooperation by local, regional, and national stakeholders. Readiness and capacity to implement recovery wedges differs across nations, and cooperation to rebuild marine life should remain flexible to adapt to variable cultural settings, and locally-designed approaches may be most effective[141] (Suppl. Information S1). Past failures in some nations can inform new governance arrangements to avoid repeating 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[103,105-107]. For instance, many developed nations have already implemented nutrient reduction plans but global fertilizer use is rising globally, supported mainly by demands from developing nations, which 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[142].

Calls for international assistance to support recovery, whether it is for coastal wetlands to reduce risks of damages from natural disasters[103] or marine life generally[127], should include assistance to improve governance and build institutional capacity. However, the capacity of both developed and developing nations to deploy effective recovery actions is already substantial. Mangrove restoration projects are significantly larger and cheaper but similarly successful (about 50% survival reported) in developing nations compared to developed ones[102], and small-island states are showing growing leadership in responding to plastics pollution and the marine impacts of climate change (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[103]. Currently, the UN's Green Climate Fund has mobilized $10.3 billion annually to assist developing countries adapt to climate change, with a goal of $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" (e.g. saltmarshes, oyster and coral reefs, mangroves, and seagrass beds) could increase resilience of coastal communities to climate change and to extreme events while improving their livelihoods[103].

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 substantial 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 nurturing 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.

Acknowledgements

This work was supported by King Abdullah University of Science and Technology through baseline funding to CMD and SA. GLB was supported by the Simons Collaboration on Computational Biogeochemical Modeling of Marine Ecosystems/CBIOMES (Grant ID: 549931); J-PG 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; HKL and BW by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Ocean Frontier Institute (Module G); JCC by the Catedra Arauco in Environmental Ethic-UC and Centro Interdisciplinario de Cambio Global-UC. We thank Tomohiro Kuwae, Robert J. Orth, the Mars Sustainable Solutions - part of Mars, Inc., and Christopher Haight at NYC Parks, and Bryan DeAngelis for supplying details on restoration projects; Letizia Valuzzi, Reny Devassy, Anieka Parry and Fadiyah Baalkhuyur for help with the inventory of restoration projects, Elizabeth McLeod for help locating materials, and Alex Buxton and Seda 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

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Table 1. **Scenarios conducive to achieving the best aspirational outcomes toward rebuilding marine life**. These include rebuilding wedges, assessment of the maximum recovery targets by 2050 shall these wedges be fully activated, key actors, actions, opportunities, benefits, roadblocks and remedial actions to rebuild different components of marine life (priority increases from lowest in blue, to yellow, orange and highest in red). See Suppl. Information 3 for details.

Rebuilding	Saltmarshes	Mangroves	Seagrass	Coral reefs	Kelp	Oyster reefs	Fisheries	Megafauna	Deep-sea
Protect species									
Harvest wisely									
Protect spaces									
Restore habitats									
Reduce pollution									
Mitigate climate change									
Rcovery targets by 2050	Substantial to Complete	Substantial to Complete	Substantial to	Partial to Substantiial	Substantial to	Substantial to Complete	Substantial to	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	Government, fishers organizations and civil	Government, fishers organizations, NGOs and civil society	Government, fishers organizations and civil society	Government, fishers organizations, NGOs, and civil society	International sea bed authority, state and federal governments, mining/exploration companies, civil
Key Actions	Protection of remaining saltmarsh, providing sources of sediment, potentially planting native species, providing space for landward migration, restoring hydrological connections	Protection, Provide alternative livelihoods for dependent communities, providie space for landward migration; restore hydrological connections,	Reduce nutrient inputs, protect, avoid physical impacts, and conduct restoration projects	Ambitious reduction of green-house emissions. Reduce excess sediment and nutrient inputs, improve water quality, protect	Restoration: remove excess herbivores. rebuild their predators, reduce sediment loads on rocky substrate	Protect remaining reefs, prohibiton of natural reef harvests, improve water quality, restore reefs	Reduce overfishing, bycatch and incidental mortality, ban destructive fishing practices, protect spawning/ breeding areas and	Protect, reduce bycatch, reduce incidental mortality (ship strikes, entanglement, ghost gear), reduce pollution (noise, debris, chemical),	Regulate industries operating in the deep-sea. Ban deep sea fishing and impose a moratorium on deep-sea mining until technologies free of impacts are available. Improve environmental safety of oil and
Key Opportunities	Blue Carbon and coastal defense strategies against storms and sea level rise, links to management for enhancing water quality , food provision and biodiversity strategies	Blue Carbon and coastal defense strategies against storms and sea level rise, links to management for enhancing water quality , food provision and	Blue Carbon and coastal defense strategies against storms and sea level rise, links to managem ent for enhancing water	Link to coastal defense, 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 release pressure on wild stocks	Marine wildlife tourism, cultural benefits, ethics	High % of unique, unexplored habitats and new species, potential for novel products important in fighting/preventing disease. Huge carbon sink potential.
Key Benefits	Improved fisheries, protection from sea level rise and storm surges, recreational and cultural benefits,	Improved fisheries, biodiversity and coastal defense, recreation cultural	Protect shoreline from erosion and rebuilding biodiversit	Provision of fish, Protection from sea level rise and storm surges,	Enhanced fisheries	Improved water quality, increased habitat, recreational and cultural benefits, food	Improved quality and quantity of seafood supply	Increased connectivity among ocean basins, enhanced nutrient cycling and	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 (e.g. areas occupied by harbors), 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 equatorial range edge of kelp species, high herbivore pressure and sediment accumulation on rocky substrates	Poor management of fisheries on remaining reefs, degraded habitats, restoration costs, increased prevelance 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 monumentally difficult and expensive. Development multi-governmental cooperation, buy-in, and action toward 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, reduce local stressors	Ambitious efforts to mitigate climate change, effective restoration technologies using thermal resistant genotypes, manage for resilience	Restore with thermal resistant genotypes, 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 programs for critically endangered species	Create MPAs as refuge sites, safeguard migration routes, restore coastal breeding/nursery sites to aid recovery, develop breeding programs for critically endangered species	Protect what has not been damaged or destroyed and prevent further destruction in places that have. Widespread education on fragility of deep sea and benefits of deep sea ecosystems, strengthen regulation, decrease pollution, recycle products that require rare earth metals.

Figure Legends

Figure 1. Global Pressures on Marine Life. Many human pressures commenced well before the industrial revolution, and a number of those peaked in the 1980's and are slowing down at present (with much 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 direct destruction of coastal habitat. Pollution (synthetic fertilizer, 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 toward more sustainable harvest in many regions, while regulatory frameworks are reducing some forms of pollution. Climate change, caused by greenhouse gas emissions accumulated since the onset of the industrial revolution, became sizeable, against background variability, in the 1960's 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 20th Century.

Figure 2. Global growth of restoration interventions. Distribution and growth of Marine Protected Areas (left panels) and ecosystem restoration projects (right panels). Numbers within symbols represent aggregated restoration projects where location was not provided (cf. Suppl. Information 1 for detailed examples, Suppl. Information 2 for data sources and Suppl. Videos V1 and V2 for animation of growth over time).

Figure 3. Recovery trends of marine populations showing (a) Current population trends in scientifically assessed fisheries stocks based on the ratio of the annual biomass B relative to the biomass that produces maximum sustainable yield, BMSY; (b) percent of assessed marine mammal populations showing increasing or decreasing population trends or no change; (c) sample recovery trajectories of recovering species and habitats from different parts of the world; note that units were adjusted to a common scale by multiplying (*) or dividing (/) as indicated in the legend, numbers at the end of the legends indicate initial count at the beginning of time series; and (d) range of recovery times for marine populations and habitats and mean ± 95% confidence limits (cl) recovery times for marine ecosystems. Lines indicate reported range. See Suppl. Information 2 for details on data sources and methods and Table S3 for data sources for panel d.

Figure. 4. Recovery projections for assessed fish stocks. (a) Trajectories of fisheries stock biomass (B) relative to the biomass supporting maximum sustainable yield (BMSY, the ratio denoted B/BMSY), over time based on scientific assessment of 371 globally distributed fish stocks in the RAM Legacy Stock Assessment Database (version 4.44). Open circles give the biomass-weighted global average of stock B/BMSY, asterisks represent years without sufficient data, red and green lines represent four idealized future scenarios (BMSY values were taken from stock assessments where available and estimated as 50% of the maximum historical biomass otherwise; see Suppl. Information S2). (b) Frequency distributions for estimated recovery times to BMSY for 172 stocks that are currently depleted to below BMSY. Projections refer to three scenarios, corresponding to no fishing, fishing at 60% or 90% of fishing pressure associated with maximum sustainable yield (FMSY). Projections show that under various scenarios of reduced fishing pressure (F<FMSY) and different productivity regimes, the majority of fish stocks could recover to BMSY with high probability before 2040. Note that recovery to

virgin biomass (B0) would take much longer. Solid lines give the median and hashed lines the mean estimate of years to recovery. Productivity for each stock in panels b-d was fixed at mean stock-specific historical productivity. See Supplementary Information S2 for details of data sources and methods.

Rebuilding	Saltmarshes	Mangroves	Seagrass	Coral reefs	Kelp	Oyster reefs	Fisheries	Megafauna	Deep-sea
Protect species									
Harvest wisely									
Protect spaces									
Restore habitats									
Reduce pollution									
Mitigate climate change									
Rcovery targets by 2050	Substantial to Complete	Substantial to Complete	Substantial to	Partial to Substantiial	Substantial to	Substantial to Complete	Substantial to	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 sea bed authority, state and federal governments, mining/exploration companies, civil society, fishing industry.
Key Actions	Protection of remaining saltmarsh, providing sources of sediment, potentially planting native species, providing space for landward migration, restoring hydrological connections	Protection, Provide alternative livelihoods for dependent communities, providie space for landward migration; restore hydrological connections, maintain sediment supply, restore damaged forests	Reduce nutrient inputs, protect, avoid physical impacts, and conduct restoration projects	Ambitious reduction of green-house emissions. Reduce excess sediment and nutrient inputs, improve water quality, protect reefs, rebuild food webs, and restore damaged reefs	Restoration: remove excess herbivores. rebuild their predators, reduce sediment loads on rocky substrates and plant kelps	Protect remaining reefs, prohibiton of natural reef harvests, improve water quality, restore reefs	Reduce overfishing, bycatch and incidental mortality, ban destructive fishing practices, protect spawning/ breeding areas and nursery grounds, remove perverse incentives	Protect, reduce bycatch, reduce incidental mortality (ship strikes, entanglement, ghost gear), reduce pollution (noise, debris, chemical), protect breeding/haul out sites, safegard migration routes, reduce competition with fisheries	Regulate industries operating in the deep-sea. Ban deep sea fishing and impose a moratorium on deep-sea mining until technologies free of impacts are available. Improve environmental safety of oil and gas operations. Develop facilities to test technologies prior to real-ocean deployment.
Key Opportunities	Blue Carbon and coastal defense strategies against storms and sea level rise, links to management for enhancing water quality, food provision and biodiversity strategies	Blue Carbon and coastal defense strategies against storms and sea level rise, links to management for enhancing water quality, food provision and	Blue Carbon and coastal defense strategies against storms and sea level rise, links to management for enhancing water	Link to coastal defense, 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 release pressure on wild stocks	Marine wildlife tourism, cultural benefits, ethics	High % of unique, unexplored habitats and new species, potential for novel products important in fighting/preventing disease. Huge carbon sink potential.
Key Benefits	Improved fisheries, protection from sea level rise and storm surges, recreational and cultural benefits,	Improved fisheries, biodiversity and coastal defense, recreation cultural	Protect shoreline from erosion and rebuilding biodiversit	Provision of fish, Protection from sea level rise and storm surges,	Enhanced fisheries	Improved water quality, increased habitat, recreational and cultural benefits, food	Improved quality and quantity of seafood supply	Increased connectivity among ocean basins, enhanced nutrient cycling and	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 (e.g. areas occupied by harbors), 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 equatorial range edge of kelp species, high herbivore pressure and sediment accumulation on rocky substrates	Poor management of fisheries on remaining reefs, degraded habitats, restoration costs, increased prevelance 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 monumentally difficult and expensive. Development multi-governmental cooperation, buy-in, and action toward this goal.
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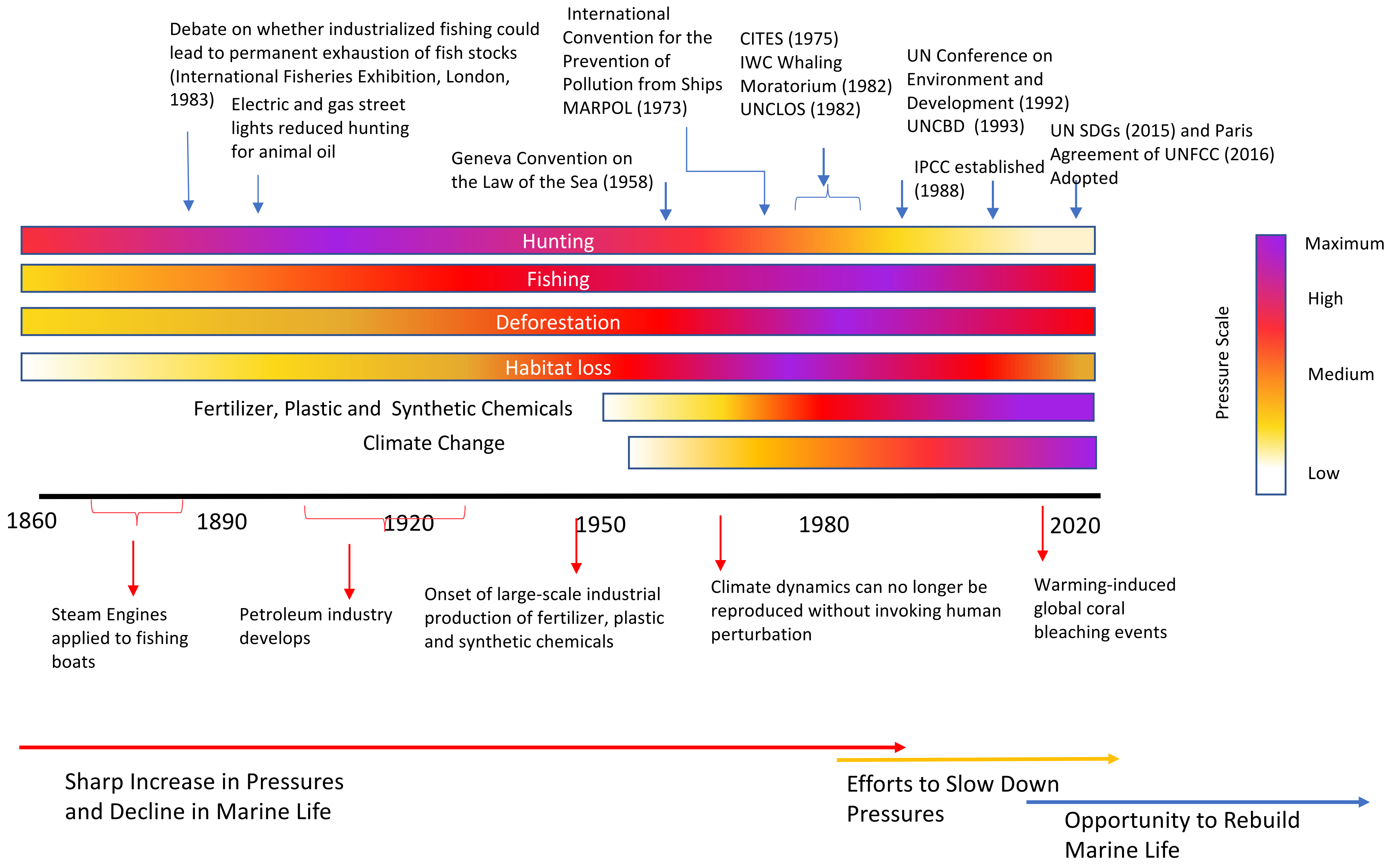
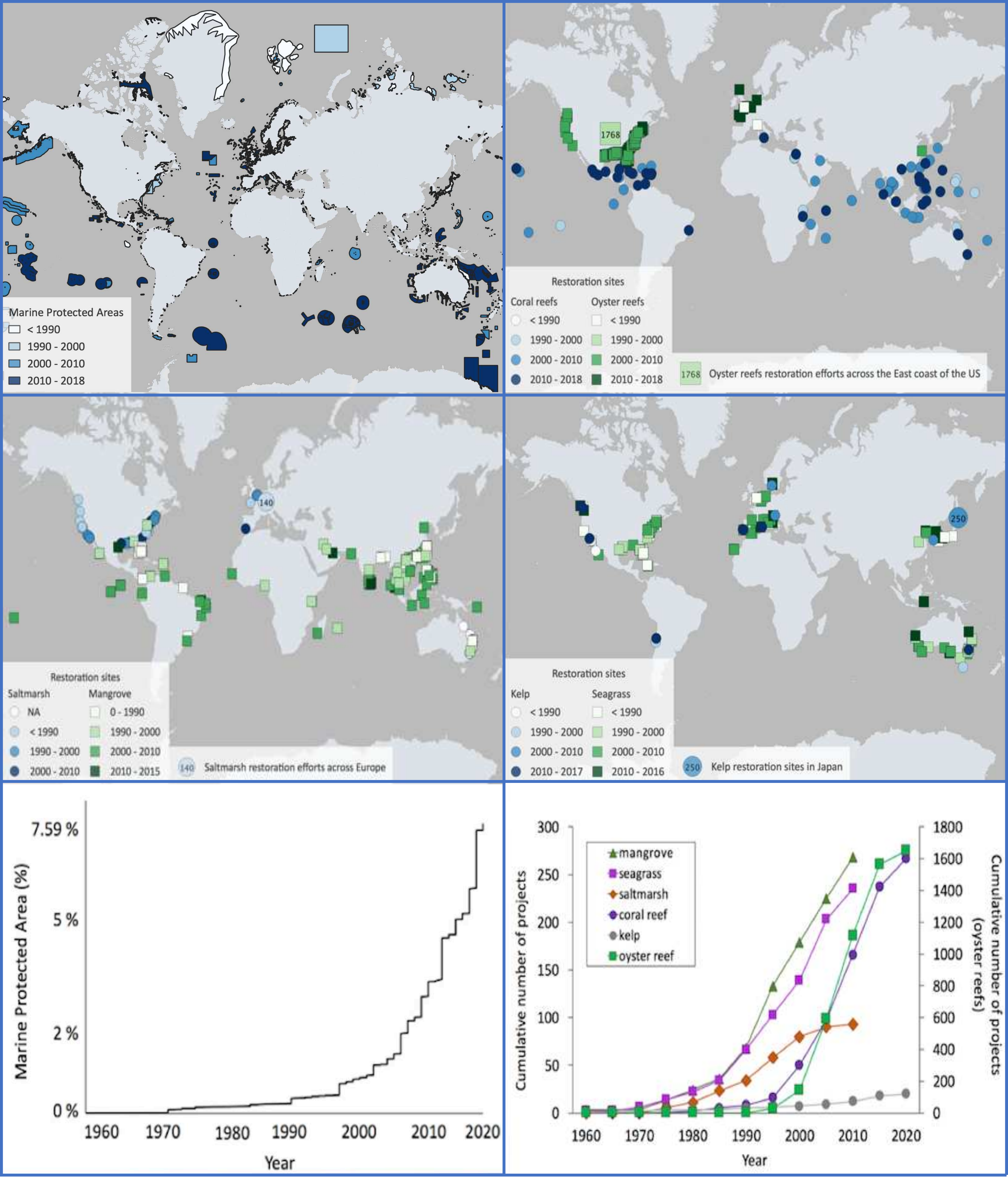
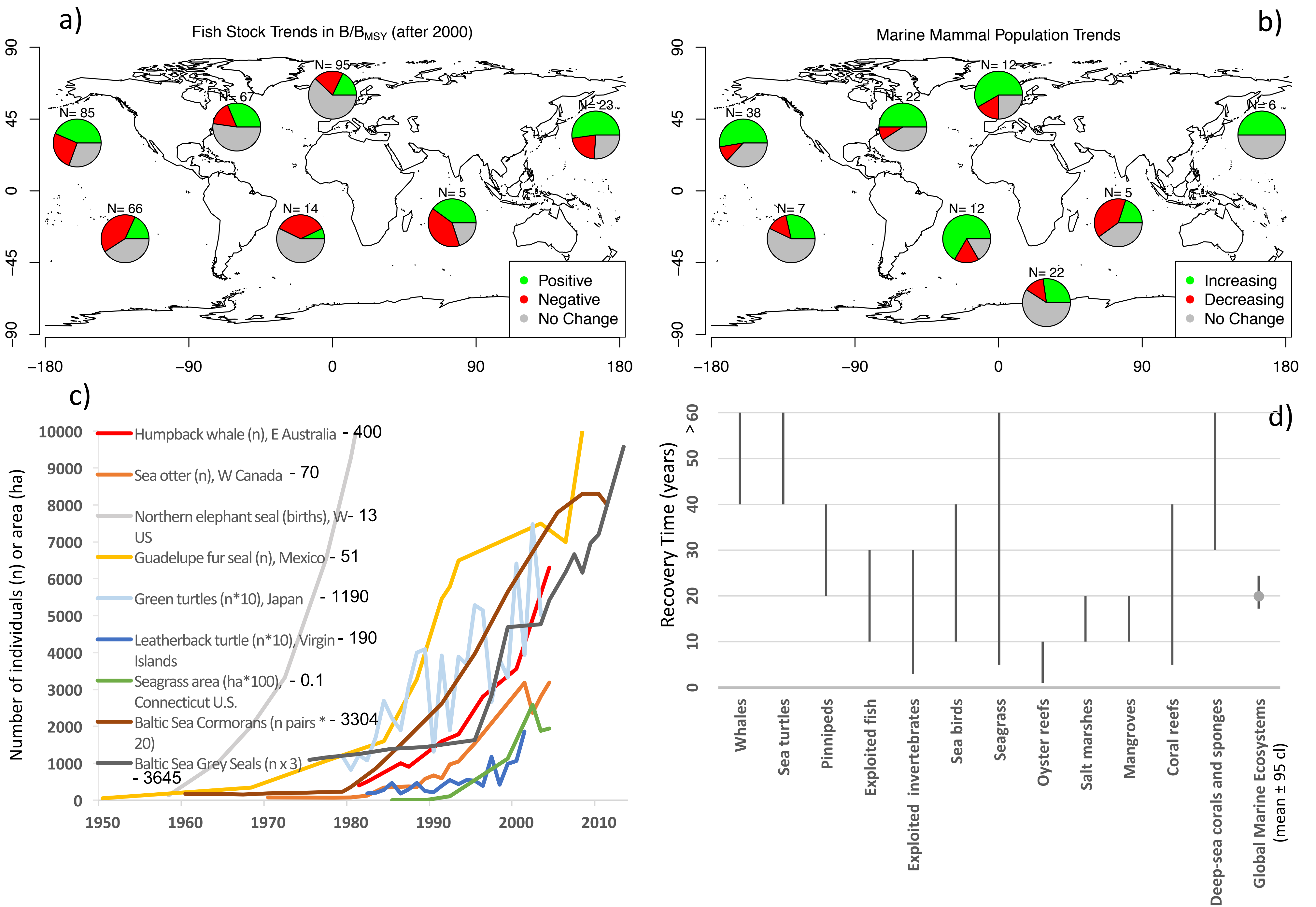
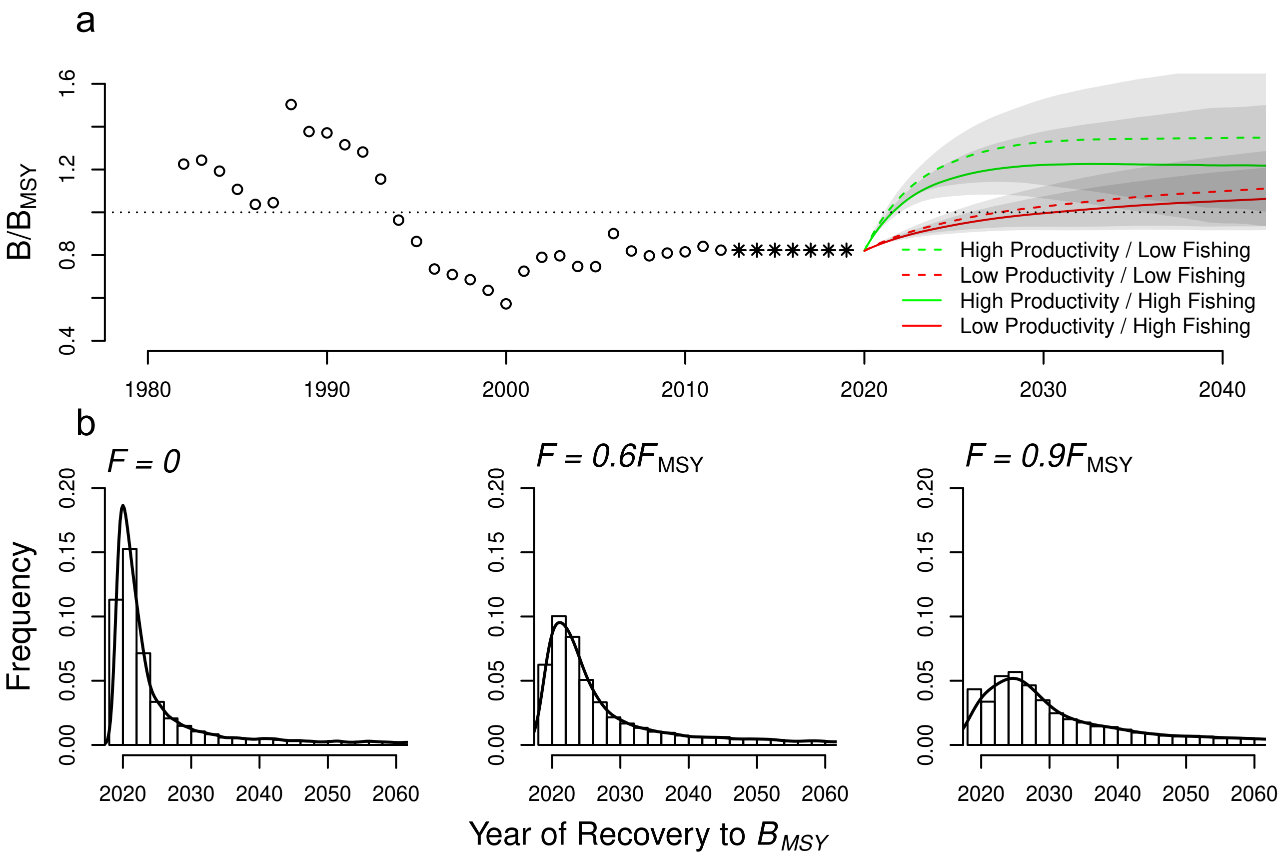

Debate on whether industrialized fishing could lead to permanent exhaustion of fish stocks (International Fisheries Exhibition, London, 1983)
Electric and gas street lights reduced hunting for animal oil
Geneva Convention on the Law of the Sea (1958)
International Convention for the Prevention of Pollution from Ships MARPOL (1973)
CITES (1975)
IWC Whaling Moratorium (1982)
UNCLOS (1982)
UN Conference on Environment and Development (1992)
UNCBD (1993)
IPCC established (1988)
UN SDGs (2015) and Paris Agreement of UNFCC (2016) Adopted
Hunting
Fishing
Deforestation
Habitat loss
Fertilizer, Plastic and Synthetic Chemicals
Climate Change
Pressure Scale
Maximum
High
Medium
Low
1860
1890
1920
1950
1980
2020
Steam Engines applied to fishing boats
Petroleum industry develops
Onset of large-scale industrial production of fertilizer, plastic and synthetic chemicals
Climate dynamics can no longer be reproduced without invoking human perturbation
Warming-induced global coral bleaching events
Sharp Increase in Pressures and Decline in Marine Life
Efforts to Slow Down Pressures
Opportunity to Rebuild Marine Life


Marine Protected Areas
< 1990
1990 - 2000
2000 - 2010
2010 - 2018
1768
Restoration sites
Coral reefs
Oyster reefs
< 1990
1990 - 2000
2000 - 2010
2010 - 2018
Oyster reefs restoration efforts across the East coast of the US
140
Restoration sites
Saltmarsh
Mangrove
NA
0 - 1990
< 1990
1990 - 2000
2000 - 2010
2010 - 2015
Saltmarsh restoration efforts across Europe
250
Restoration sites
Kelp
Seagrass
< 1990
1990 - 2000
2000 - 2010
2010 - 2017
2010 - 2016
Kelp restoration sites in Japan
Marine Protected Area (%)
7.59 %
5 %
2 %
0 %
1960
1970
1980
1990
2000
2010
2020
Year
Cumulative number of projects
Cumulative number of projects (oyster reefs)
300
250
200
150
100
50
0
1800
1600
1400
1200
1000
800
600
400
200
mangrove
seagrass
saltmarsh
coral reef
kelp
oyster reef



a)
Fish Stock Trends in B/B$_{MSY}$ (after 2000)
N= 95
N= 67
N= 85
N= 23
N= 66
N= 14
N= 5
Positive
Negative
No Change
b)
Marine Mammal Population Trends
N= 12
N= 22
N= 38
N= 6
N= 7
N= 12
N= 5
N= 22
Increasing
Decreasing
No Change
c)
Number of individuals (n) or area (ha)
Humpback whale (n), E Australia - 400
Sea otter (n), W Canada - 70
Northern elephant seal (births), W-US - 13
Guadelupe fur seal (n), Mexico - 51
Green turtles (n*10), Japan - 1190
Leatherback turtle (n*10), Virgin Islands - 190
Seagrass area (ha*100), Connecticut U.S. - 0.1
Baltic Sea Cormorans (n pairs * 20) - 3304
Baltic Sea Grey Seals (n x 3) - 3645
d)
Recovery Time (years)
Whales
Sea turtles
Pinnipeds
Exploited fish
Exploited invertebrates
Sea birds
Seagrass
Oyster reefs
Salt marshes
Mangroves
Coral reefs
Deep-sea corals and sponges
Global Marine Ecosystems (mean ± 95 cl)



a
B/B_MSY
1.6
1.2
0.8
0.4
High Productivity / Low Fishing
Low Productivity / Low Fishing
High Productivity / High Fishing
Low Productivity / High Fishing
1980
1990
2000
2010
2020
2030
2040
b
F = 0
F = 0.6F_MSY
F = 0.9F_MSY
Frequency
0.00
0.05
0.10
0.15
0.20
2020
2030
2040
2050
2060
Year of Recovery to B_MSY