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Rebuilding Marine Life

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47 The UN Sustainable Development Goal 14 aims to “conserve and sustainably use the oceans,
48 seas and marine resources for sustainable development”. Achieving this goal will require
49 rebuilding the marine life-support systems that deliver the many benefits society receives
50 from a healthy ocean. In this Review we document the recovery of marine populations,
51 habitats and ecosystems following past conservation interventions. Recovery rates across
52 studies suggest that substantial recovery of the abundance, structure, and function of marine
53 life could be achieved by 2050, should major pressures, including climate change, be
54 mitigated. Rebuilding marine life represents a doable Grand Challenge for humanity, an
55 ethical obligation, and a smart economic objective to achieve a sustainable future.
56

57

58 The ability of the ocean to support human wellbeing is at a crossroads. The ocean currently
59 contributes 2.5% of global GDP and provides employment to 1.5% of the global workforce¹,
60 with an estimated output of US\$1.5 trillion in 2010, expected to double by 2030¹. And there
61 is increased attention on the ocean as a source of food and water², clean energy¹, and as a
62 means to mitigate climate change^{3,4}. At the same time, many marine species, habitats and
63 ecosystems have suffered catastrophic declines⁵⁻⁸ and climate change is further undermining
64 ocean productivity and biodiversity⁹⁻¹⁴ (Fig. 1).

65

66 The conflict between growing human dependence on ocean resources and declining marine
67 life under human pressures (Fig. 1) is focusing unprecedented attention on the connection
68 between ocean conservation and human well-being¹⁵. The UN Sustainable Development Goal
69 14 (SDG14 or “*life below water*”) aims to “*conserve and sustainably use the oceans, seas*
70 *and marine resources for sustainable development*”
71 (<https://sustainabledevelopment.un.org/sdg14>). Achieving this goal will require rebuilding
72 marine life, defined in the context of SDG14 as the life-support systems (populations,
73 habitats, and ecosystems) that deliver the many benefits society receives from a healthy
74 ocean^{16,17}. Here we show that, in addition to being a necessary goal, substantially rebuilding
75 marine life within a human generation is largely achievable, if the required actions,
76 prominently mitigating climate change, are deployed at scale.

77 Slowing the decline of marine life and achieving net gains

78 By the time the general public admired *life below water* through the “*Undersea World of*
79 *Jacques Cousteau*” (1968-1976), the abundance of large marine animals was already greatly
80 reduced^{5-7,18}. And the abundance of marine animals and habitats that support ecosystems
81 services has shrunk to a fraction of what was in place when the first frameworks to conserve
82 and sustain marine life were introduced in the 1980s (Fig. 1), to a fraction of pre-exploitation
83 levels^{5,6,19,20}. Currently, at least one-third of fish stocks are overfished²¹, one-third to half of
84 vulnerable marine habitats have been lost⁸, a substantial fraction of the coastal ocean suffers
85 from pollution, eutrophication, oxygen depletion and is stressed by ocean warming²²⁻²³, and
86 many marine species are threatened with extinction^{7,24-25}. Nevertheless, biodiversity losses in
87 the ocean are less pronounced than on land⁷, and many marine species are capable of
88 remarkable recovery once pressures are reduced or removed (Figs. 2-3). Substantial
89 wilderness areas remain in remote regions²⁶, and large populations of marine animals are still
90 found, for example, in mesopelagic (200-1000 m depth) ocean waters²⁷.

91

92

93

94 Regional examples of impressive resilience include the rebound of fish stocks during World
95 Wars I and II following drastic reduction in fishing pressure²⁸, the recovery since 1958 of
96 coral reefs in the Marshall Islands from 76 megatons of nuclear tests²⁹, and the improved
97 health of the Black Sea³⁰ and Adriatic Sea³¹ following sudden reduction in fertilizer
98 application after the collapse of the Soviet Union. Although these rapid recoveries were
99 unrelated to conservation actions, they helped inform subsequent interventions deployed in
100 response to widespread ocean degradation^{7,32-33}. These interventions include a suite of

101 initiatives to save threatened species, protect and restore vulnerable habitats, constrain
102 fishing, reduce pollution, and mitigate climate change (Fig. 1, Table 1).

103

104 **Impactful Interventions**

105

106 *Hunting Regulation*

107 Species protections through the Convention on the Trade of Endangered Species (CITES,
108 1975, cites.org) and the global moratorium on commercial whaling (1982, iwc.int) are
109 prominent examples of international actions to protect marine life³⁴ (Fig. 1). These actions
110 have been supplemented by national initiatives to reduce hunting pressure on endangered
111 species and protect their breeding habitat^{34,35}.

112

113 *Fisheries management*

114 Successful rebuilding of depleted fish populations has been achieved in many cases through
115 well-proven management actions, including catch and effort restrictions, closed areas,
116 regulation of fishing capacity and gear, catch shares, and co-management arrangements
117 (Suppl. Material 1)³⁵⁻³⁹. These interventions require detailed consideration of socio-
118 economic circumstances, with solutions being tailored to local context³⁷. Persistent
119 challenges include harmful subsidies, poverty and lack of alternative employment, illegal and
120 unregulated fishing, and the disruptive ecological impacts of many fisheries³⁶⁻³⁹.

121

122 *Water quality improvement*

123 Policies to lower inputs of nutrients and sewage to reduce coastal eutrophication and hypoxia
124 were initiated four decades ago in the USA and EU, leading to major improvements today⁴⁰⁻
125 ⁴². Many hazardous pollutants have been regulated or phased-out through the Stockholm
126 Convention (www.pops.int) and, specifically in the ocean, by the MARPOL Convention

127 (www.imo.org), often reinforced by national and regional policies. Recent attention has
128 focused on curbing plastic pollution entering the ocean, which remains a growing problem,
129 with inputs currently estimated at between 4.8 to 12.7 million Mton per year⁴³.

130

131 *Habitat protection and restoration*

132 The need to better protect sensitive habitats, including non-target species, has inspired the use
133 of Marine Protected Areas (MPAs) as a comprehensive management tool^{3,44}. In 2000, only
134 0.13 million km² (0.003%) of the ocean was protected, but MPAs now cover 27.4 million
135 km² (7.6% of ocean area, or 4.8% if considering fully implemented MPAs (mpAtlas.org,
136 accessed May 3, 2019). MPA coverage continues to grow at about 8% per year (Fig. 2.,
137 Suppl. Video V1) .

138

139 The 21st Century has seen a global surge of active habitat protection and restoration
140 initiatives (Fig. 2, Suppl. Material 1, Suppl.Videos V1 and V2), even in challenging
141 environments adjoining coastal megacities (Suppl. Material 1). These efforts have delivered
142 benefits, such as improved water quality following oyster reef restoration. Additionally, Blue
143 Carbon strategies, submitted within Nationally Determined Contributions of > 50 nations, at
144 the heart of the Paris Agreement⁴⁶, are being used to mitigate climate change and improve
145 coastal protection by restoring seagrass, saltmarsh and mangrove habitats⁴⁶⁻⁴⁷ (Suppl.
146 Material 1).

147

148 **Recovery to date**

149

150 *Extinction risk reductions*

151 The proportion of marine species assessed by the IUCN Red List as threatened with global
152 extinction (Suppl. Mat. S2) has decreased from 18% in 2000 to 11.4% in 2019 (sd=1.7%,

153 n=1743), with trends being relatively uniform across ocean basins and guilds (Fig. S2.1). In
154 part, this reflects a growing number of species that has been assessed. However, many
155 assessed species have improved their threat status over the past decade⁴⁸⁻⁵¹. For marine
156 mammals, 47% of 124 well-assessed populations³⁴ showed a significant increase over the
157 past decades, with 40% unchanged and only 13% decreasing (Fig. 3b, Table S2). Some large
158 marine species have exhibited particularly striking rebounds, even from the brink of
159 extinction (Fig. 3c). Humpback whales migrating from Antarctica to eastern Australia have
160 been increasing at 10% to 13% year⁻¹, from a few hundred animals in 1968 to >40,000
161 currently⁴⁹. Northern elephant seals recovered from about 20 breeding individuals in 1880 to
162 >200,000 today⁵⁰, and gray seal populations have increased by 1410% in eastern Canada⁵¹
163 and 823% in the Baltic⁴¹ since 1977. Southern sea otters have grown from about 50
164 individuals in 1911 to several thousand today³⁵. While still endangered, most sea turtle
165 populations for which trends are available are increasing in size⁵², ranging from 4-14%
166 increase year⁻¹ for green turtle nesting populations⁵².

167

168 *Fisheries recovery*

169 Using a comprehensive stock assessment database⁵³ we found that fish populations with
170 available scientific assessments are increasingly managed for sustainability. The proportion
171 of stocks with fishing mortality estimates (F) below the level that would produce maximum
172 sustainable yield ($F < F_{MSY}$) has increased from 60% in 2000 to 68% in 2012. Many fish
173 stocks subjected to such management interventions display positive trends (Fig. 3a), and
174 globally aggregated stock assessments suggest a slowing-down of fish stock depletion^{21,36,39},
175 although this trend has not been measured for the majority of stocks that lack scientific
176 assessment³⁶. The most recent report of the Food and Agriculture Organisation on global
177 fisheries²¹ also suggests that two thirds of large-scale commercial fisheries are exploited at

178 sustainable rates, but again this figure does also not account for smaller stocks or non-target
179 by-catch species, which are often not assessed and in poor condition^{36,54}. Available data
180 suggests that scientifically-assessed stocks generally have a better likelihood of recovery due
181 to improved management and regulatory status compared to unassessed species³⁶, which still
182 represent the majority of fisheries, especially in developing countries.

183
184 *Pollution reduction*

185 Time-series analyses show that legacy persistent organic pollutants have declined even in
186 marine environments that tend to accumulate them (e.g. the Arctic⁵⁵). The transition toward
187 unleaded gasoline since the 1980's reduced Pb to concentrations comparable to baseline
188 levels across the global ocean by 2010-2011⁵⁶. Likewise, the total ban in 2008 of the anti-
189 fouling chemical TBT (tributyltin) led to rapid declines of imposex (females developing male
190 sexual organs), a TBT-specific symptom, in an indicator gastropod⁵⁷. Improved safety
191 regulations have also led to a 14-fold reduction in large tanker vessel oil spills from 24.7
192 events per year in the 1970's to 1.7 events per year in the present decade⁵⁸. Whereas evidence
193 of improved coastal water quality following nutrient reductions was equivocal a decade
194 ago⁵⁹, multiple success stories have now been confirmed^{41,60}, with positive ecosystem effects
195 such as the net recovery of seagrass meadows in the USA⁶¹ (Fig. 1), Europe⁶², Baltic Sea⁴¹,
196 and Japan⁶³.

197
198 *Habitat restoration*

199
200 Evidence that mangrove restoration can be achieved at scale first came from the Mekong
201 Delta, possibly the largest (1,500 km²) habitat restoration undertaken to date (Suppl. Material
202 1). Global loss of mangrove forests has since slowed to 0.11% year⁻¹^{64,65}, with stable
203 mangrove populations along the Pacific coast of Colombia, Costa Rica, and Panama⁶⁶, and
204 increasing populations in the Red Sea⁶⁷, Arabian Gulf⁶⁸ and China⁶⁹. Large-scale restoration

205 of saltmarshes and oyster reefs has occurred in Europe and the USA (Fig. 2, Suppl. Material
206 1). Restoration attempts of seagrass, seaweed and coral reef ecosystems are also increasing
207 globally, although they are often very small in scale (Fig. 2, Suppl. Video V2, Suppl.
208 Material 1). Critically, a global inventory of total restored area is critically missing.
209

210 Potential for rebuilding

211 Efforts to rebuild marine life cannot aim to return the ocean to any particular past reference
212 point. Our records of marine life are too fragmented to compose a robust baseline, and the
213 ocean has changed dramatically and in some cases irreversibly, including the extinction of at
214 least 20 marine species²⁵. Yet by increasing abundances of key habitats and keystone species
215 and restoring the three-dimensional complexity of benthic ecosystems, large and long-living
216 marine animals and plants can again fulfill their ecosystem functions, promoting a diverse
217 and vibrant ocean ecosystem. The yardstick of success should be the restoration of marine
218 ecological structure, functions, resilience and ecosystem services, involving a greater
219 capacity to supply the growing needs of an additional 2 to 3 billion people by 2050. To meet
220 this goal, rebuilding of depleted populations and ecosystems must replace the goal of
221 conserving and sustaining the *status quo*, taking swift action to avoid tipping points beyond
222 which collapse may be irreversible^{11,18,33,33}.

223 Here we examine rates of recovery of marine species and habitats to date, and propose a
224 tentative timeframe in which substantial recovery of marine life may be possible, should
225 major pressures, including climate change, be mitigated. We broadly define recovery as the
226 rebound in populations of marine species and habitats following losses, which can be partial
227 (i.e. 10-50% increase), substantial (50-90% increase) or full (> 90% increase)⁴⁷.

228

229 *Marine megafauna*

230

231 A number of megafauna species, including humpback whales and northern elephant seals,
232 have recovered fully to historical baselines following protection (Fig. 3c), but rates depend on
233 life history: some large whales may require >100 years to recover, while smaller pinnipeds
234 may only need several decades³⁵ (Fig. 3c,d). Sea turtles have recovery time-scales of up to
235 100 years, although some populations have partially re-grown much faster (e.g. green turtles
236 in Hawaii increased 6-fold between 1973 and 2016⁷⁰). Seabird populations typically require a
237 few decades to recover^{35,41} (Fig. 3c,d).

238

239 *Fish stocks*

240

241 Recovery can also refer to achieving resilient populations that support the full extent of
242 ecosystem functions and services that characterize them. For instance, fish stock recovery is
243 often defined in terms of biomass increases to the level that allows for maximum sustainable
244 yield (B_{MSY}), which fisheries harvest theory predict to be between 37% and 50% of the virgin
245 biomass (B_0), depending on the particular model used (cf. Suppl. Information S2, Fig. S2.2).
246 This range is consistent with an empirical estimate of B_0 for 147 exploited fish stocks, which
247 found contemporary B_{MSY} values to be 40% of B_0 , on average, with a range of 26% to 46%
248 across taxa⁷¹. Reported recovery times to B_{MSY} for exploited finfish and invertebrate stocks
249 range between 3-30 years³⁵ (Figs. 3 and 4), which is consistent with paleo-reconstructions of
250 pre-historic collapse and recovery of anchovy, sardine and hake stocks⁷², data from fisheries
251 closures^{54,73}, and stock assessments for individual fisheries⁷⁴. However, B_{MSY} should be
252 considered to represent a minimum recovery target³⁹, since it does not account for ecosystem
253 interactions, and might only provide limited resilience in the face of environmental
254 uncertainty and change.

255

256 Minimum recovery times of populations are set by the maximum intrinsic rate of population
257 increase (r_{\max}), which is typically higher than observed rates, resulting in longer recovery
258 times^{75,76}. Recovery rates also depend on the fishing pressure imposed on the stock; for
259 example, the time required to rebuild populations depleted to B_{MSY} is estimated to range from
260 about one decade, if fishing mortality (F) is rapidly reduced below the level that produces
261 maximum sustainable yield (F_{MSY}). Longer recovery times unfold if fishing pressure is
262 reduced more slowly^{36,77} (Fig. 4). Recovery for longer-lived, slow-growing species such as
263 most elasmobranchs (sharks, rays and skates), depleted coral reef fish and deep-sea species,
264 may take much longer^{35,76}.

265

266 *Coastal habitats*

267

268 Recovery for coastal habitats following removal of stressors or active restoration typically
269 occurs on a similar time scale as fish stock recovery, less than a decade for oyster reefs⁷⁸, and
270 other invertebrate populations (Suppl. Information S3) and kelp-dominated habitats^{79,80},
271 between one to two decades for saltmarsh⁸¹ and mangrove⁸² habitats, and one to several
272 decades for seagrass meadows⁸³ (Fig. 3d). Deep-sea corals and sponges grow more slowly
273 and recovery times from trawling disturbance or oil spills may range from 30 years to over a
274 century^{84,85}. Recovery timescales of coral reefs impacted by local stressors range from a few
275 years to over a decade (Fig. 3d). However, recovery from severe coral bleaching has taken
276 well over a decade and will slow in the future as ocean warming causes the interval between
277 bleaching events to shrink¹², with an associated steep reduction in recruitment⁸⁶.

278

279 In summary, available data suggest that many marine species and habitats require one to three
280 decades to approach undisturbed or reference level ranges after removal of the causes of

281 decline^{35,86,87,90-92}, with much longer recovery times required for some slow-growing groups³⁵
282 (Fig. 3).

283

284 *Recovery times*

285

286 The time required to rebuild marine life components depends on the extent of previous
287 declines, which are often substantial. The reduction in species abundance and biomass
288 relative to pre-disturbance baselines averages about 44 and 56%, respectively, across
289 impacted marine ecosystems⁸⁷. Similarly, the Living Blue Planet Report estimated a 49%
290 decline in abundance of marine animal populations between 1970 and 2012⁸⁸, although many
291 species and habitats have declined since⁸⁹⁻⁹⁰. Moreover, while maximum rates of marine
292 population recovery typically range from 2 to 10% per year²⁰ (Fig. 3c), rates slow down as
293 carrying capacity is approached²⁰. Assuming a reported average annual recovery rate of
294 2.95% (95% C.I. 2.42 - 3.41%) across marine ecosystems²⁰ and a characteristic rebuilding
295 deficit of about 50% of pre-disturbance baselines⁸⁷, we provisionally estimate that the
296 average time to reach 90% of undisturbed baselines (i.e. achieve substantial recovery) would
297 be about 21 years (95% C.I. 18 - 25 years) (Fig. 3d). However, the expectation of an average
298 recovery time of about two decades is compromised by the fact that many species and
299 habitats continue to decline, and some pressures, such as climate change and plastic
300 pollution, are still increasing (Fig. 1). Hence, a longer time scale to achieve substantial (50 to
301 90%), rather than full (> 90%), recovery may be a more realistic target for rebuilding marine
302 life.

303

304 Based on the case studies examined, we provisionally adopt three decades from today (2050)
305 as a target timeline for substantial (i.e. 50 to 90%) recovery of many components of marine
306 life (Fig. 3, Table 1), recognizing that many slow-growing, severely depleted species and

307 threatened habitats may take longer to recover (Fig. 3), and that natural variability may delay
308 recovery further (Fig. 4).

309

310 Critically, achieving substantial recovery by 2050 requires that major pressures are mitigated
311 soon, including climate change under the Paris Agreement. Climate change impacting the
312 demography, phenology and biogeography of many marine species and compromising
313 productivity of marine ecosystems^{9-13,91-93} (Fig. 4). Impacts of realized climate change on
314 many coral reefs today¹² raise concerns about their future prospect (Table 1). Shall we
315 succeed in mitigating against climate change and other pressures, we may witness the
316 beginning of a trend-change from previous steep decline to stabilization and, in many cases,
317 substantial global recovery of marine life in the 21st century (Figs. 1-4).

318

319 [A roadmap](#)

320

321 Steps taken to rebuild marine life to date have involved a process of trial and error that
322 delayed positive outcomes (e.g. in the EU and USA^{41,42}), but generated know-how to cost-
323 effectively propel subsequent efforts at scale. Improved ocean stewardship, as required by
324 UN SDG 14, is a goal shared across many nations, cultures, faiths, and political systems,
325 occupying an unprecedented prominent place in the agendas of governments, corporations,
326 philanthropists, and individuals than ever before^{17,95}. This provides a window of opportunity
327 to mitigate existing pressures over the next decade while supporting global initiatives to
328 achieve substantial recovery of marine life by 2050 (Table 1, Suppl. Information 3). We are
329 at a point when we can choose between a legacy of a resilient and vibrant ocean or an
330 irreversibly disrupted ocean, for the generations to follow.

331

332 Some of the interventions required to rebuild marine life have already been initiated, but
333 decadal time lags imply that the full benefits are yet to be realized^{35,36,39,47,48,59}. Because most
334 policies to reduce local pressures and prompt recovery of marine life were introduced after
335 the 1970's (Figs. 1 and 2), it is only now that comprehensive benefits (Fig. 3) are becoming
336 evident at a larger scale. Likewise, since most current MPAs are less than 10 years old (Fig.
337 2), their full benefits, which increase with reserve age, are yet to be realized⁹⁴, in the case of
338 MPAs properly managed and enforced⁹⁴.

339

340 *Recovery Wedges*

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

352

353 Ongoing efforts to remove pressures on marine life from anthropogenic climate change,
354 hunting, fishing, habitat destruction, pollution and eutrophication (Fig. 1) must be expanded
355 and made more effective (Table 1). A new framework to predict risks of new synthetic

356 chemicals is required to avoid circumstances where industry introduces new chemicals faster
357 than their risks can be assessed. Challenges remain for persistent legacy pollutants (e.g. CO₂,
358 organochlorines and plastics) already added to the atmosphere and oceans, whose removal
359 requires novel capture technologies and protection of long-term sinks, such as marine
360 sediments, to avoid their remobilization.

361

362 MPAs represent a necessary and powerful recovery wedge across multiple components of the
363 ocean ecosystem, spanning from coastal habitats to fish and megafauna populations (Table
364 1). Growth of MPAs (Fig. 2, Suppl. Video V1) is currently on track to meet the target of 10%
365 of ocean area protected by 2020, 30% by 2037 and 50% by 2044⁹⁶. Many fish stocks could
366 recover to B_{MSY} by 2030, assuming global management reforms couple the use of closed and
367 protected areas with measures to reduce overfishing and collateral ecosystem damage,
368 adapted to local context (Fig. 4, Table 1). However, projected climate impacts on ocean
369 productivity and increase in extreme events⁹³ can delay recovery and, depending on emission
370 pathways, may prevent recovery altogether (e.g. Fig. 4). The current focus on quantitative
371 targets of percent ocean area protected has prompted concerns over the quality and
372 effectiveness of MPAs⁹⁷. Although 71% of assessed MPAs have been successful in
373 enhancing fish populations, the level of protection is often weak (94% allow fishing⁹⁸), and
374 many areas are undermined by insufficient human and financial capacity⁹⁹. Improving the
375 effectiveness of MPAs requires enhanced resourcing, governance, level of protection⁹⁸⁻¹⁰⁰
376 and siting to better match the geography of threats¹⁰¹, and to ensure desired outcomes.

377

378 The current surge in restoration efforts (Fig. 2, Suppl. Video 2) can, if sustained, be an
379 instrumental recovery wedge to meet rebuilding targets for marine habitats by 2050 (Table
380 1). For instance, assuming a mean project size of 4197 ha¹⁰², restoring mangroves to their

381 original extent of 225,000 km² by 2050 would require initiating 70 projects per year. This is
382 not unrealistic, as realization of the benefits, such as reducing storm damage in low-lying
383 areas^{40,103,104}, encourages further growth in restoration efforts (Fig. 2, Video V2). Past
384 coastal restoration projects had reported average success rates ranging from 38% (seagrass)
385 to 64% (saltmarshes and corals)¹⁰², but reasons for failure are well understood^{78,105-107}, which
386 should improve future outcomes. Much can be learned from increased reporting of failed
387 attempts, because the published literature may be biased towards successful restoration
388 projects¹⁰². Emerging technologies are now being developed to restore coral species in the
389 presence of climate change^{108,109}, but long-term testing is required before their effectiveness
390 and lack of negative consequences are proven. Kelp restoration at a national scale in Japan
391 provides a successful model, rooted in cultural practices, for linking restoration to sustainable
392 fishing (Suppl. Material S1). More broadly, these practices recognize that sustainable harvest
393 of marine resources ought to be balanced by broader restoration actions embedded in a
394 social-ecological context, including reducing greenhouse gas emissions, restoring habitats,
395 removing marine litter, or managing hydrological flows to avoid hypoxia (Suppl. Material
396 S1). These restoration experiences (Suppl. Material S1) also find involvement of local
397 communities to be essential, because of their economic dependence, commitment to place,
398 and ownership¹¹⁰.

399

400 Removing pollution is a basal recovery wedge for seagrass meadows, coral reefs, and kelp
401 forests (Table 1). Three decades of efforts to abate coastal eutrophication have provided
402 valuable knowledge on how actionable science can guide restoration successes^{41,42,111}.
403 Additional interventions (e.g., restoring hydrological flows or rebuilding oyster reefs), can
404 catalyze additional removal of nutrients while improving biodiversity¹¹¹. Seaweed
405 aquaculture can help to alleviate eutrophication and reduce hypoxia^{111,112}. Nutrient reduction

406 has the additional benefit of locally reducing coastal acidification¹¹³ and hypoxia²³ directly
407 and indirectly through the recovery of seagrass meadows. Reducing sulfur dioxide
408 precipitation, hypoxia, eutrophication, emissions and runoff from acidic fertilizers also helps
409 reduce acidification of coastal waters^{22,113}. Large-scale experiments in anoxic basins of the
410 Baltic Sea for example, have shown that treatment of sediments with phosphorus-binding
411 agents help break biogeochemical feedback loops keeping ecosystems in an alternative
412 anoxic stable state¹¹⁴.

413

414 Oil spills from tanker vessels should decline further with the incoming International Maritime
415 Organisation (IMO) requirement (13 F of Annex 1 of MARPOL) for double hulls in new
416 large oil tankers, although deep-water drilling, illustrated by the catastrophic Deep-Water
417 Horizon Spill in 2010¹¹⁵, and increasing risks of oil spills from future oil drilling and tanker
418 routes in the Arctic¹¹⁶ present new challenges. Noise pollution from shipping and other
419 industrial activities, such as drilling, pile driving and seismic surveys should be reduced¹¹⁷.
420 Likewise, worldwide efforts to reduce or ban single-use plastic (initiated in developing
421 nations), taxes on plastic bags, deposit-refunds on bottles, and other market-based
422 instruments are being deployed to reduce marine litter, while providing incentives to build a
423 circular economy for existing plastics while developing safer materials.

424

425 *Roadblocks*

426

427 A number of roadblocks may delay or prevent recovery of some critical components of
428 marine life (Table 1). These include natural variability and intensification of environmental
429 extremes caused by anthropogenic climate change (Fig. 4), “black swans” (i.e. unexpected
430 natural or social events), and failure to meet commitments to reduce existing pressures and

431 mitigate climate change. In addition, growing human population, likely to exceed 9 billion by
432 2050, will create additional demands for seafood, coastal space and other ocean resources.
433 Accordingly, the aspiration if that recovery targets by 2050, if all necessary recovery wedges
434 are stacked, could be substantial to full recovery (i.e. 50 to 100% increase relative to present)
435 for most rebuilding components (Table 1). Partial to substantial (10 to >50 %) recovery can
436 be targeted for deep-sea habitats, where slow-recovery rates lead to a modest rebuilding
437 scope by 2050, and for coral reefs, where existing and projected climate change severely
438 limits the rebuilding prospects^{13,93} (Table 1).

439

440 A major roadblock to recovery for intertidal habitats, such as mangroves and saltmarshes, is
441 their conversion to urban areas, aquaculture ponds or infrastructure (Table 1). However, even
442 in large cities, such as New York and Shenzhen, some restoration of degraded habitats has
443 been achieved (Suppl. Information S1). Incentives to develop alternative sources of
444 livelihood, relocate landholders, mediate land-tenure conflicts¹¹⁰, and improve land use
445 planning can release more habitat for coastal restoration (Table 1). Tools are emerging to
446 prioritize sites for restoration based on past experience and a broad suite of biophysical and
447 socio-economic predictors of success¹¹⁸. Reduced sediment supply due to dam construction
448 in watersheds¹¹⁹ is also an important challenge for the recovery of salt marshes and
449 mangroves, exacerbated by sea level rise and climate change (Table 1). However, these
450 habitats may be less vulnerable than previously thought¹²⁰, with a recent assessment
451 concluding that global gains of 60% of coastal wetland area are possible under sea level
452 rise¹²⁰. In contrast, enhanced sediment load from land clearing is often responsible for losses
453 of nearshore coral reefs and hinders their capacity to recover from coral bleaching¹²¹.

454

455 *Overcoming the climate change roadblock*

456 Climate change is the critical backdrop against which all future rebuilding efforts will play
457 out. Current greenhouse gas emission trajectories lead to warming by 2100 of 2.6 to 4.5 °C
458 above pre-industrial levels, far exceeding the long-term goal of the Paris Agreement¹²².
459 Much stronger emission reduction efforts^{122,123} are needed to fill the gap between target
460 emissions and projected emissions under the present voluntary Nationally Determined
461 Contributions¹²⁴ a challenging but not impossible task¹²³. Efforts to rebuild marine life need
462 to consider unavoidable impacts brought about by ocean warming, acidification and sea level
463 rise already committed by past emissions, even if the climate mitigation wedge, represented
464 by the Paris Agreement, is fully implemented. These changes include projected shifts in
465 habitats and communities at subtropical-tropical (coral to algal turf and seaweed),
466 subtropical-temperate (kelp to coral and urchin barrens, saltmarsh to mangrove) temperate-
467 Arctic (bare to kelp, ice fauna to pelagic), and intertidal (coastal squeeze) boundaries^{10-13,93},
468 propelled by species displacements and mass mortalities from future heat waves^{11-13,93}.
469 Mapping the areas where the likelihood of these transitions is high can help prioritize where
470 and how restoration interventions should be deployed¹¹⁸. For instance, conserving and
471 restoring vegetated coastal habitats will help to defend shorelines against increasing risks
472 from sea level rise while helping to mitigate climate change^{4,40,103}. Well-managed MPAs may
473 help build resilience to climate change¹²¹. However, many of them are already affected by
474 ocean warming with further climate change potentially compromising their performance in
475 the future¹²⁵.

476

477 Rebuilding coral reefs carries the highest risk of failure (Table 1), as cumulative pressures
478 (e.g. overfishing and pollution) driving their historic decline are now increasingly
479 compounded by warming-induced bleaching^{11,12}. The IPCC projects that global warming to
480 1.5°C above pre-industrial levels will result in very high risks and losses of coral reefs¹³

481 unless adaptation occurs faster than currently anticipated. A study published after the 1.5 °C
482 IPCC assessment¹³, shows that while coral bleaching has increased in frequency and intensity
483 in the last decade, the onset of coral bleaching is now occurring at significantly warmer
484 temperatures (~0.5 °C) than before, suggesting that the remaining coral populations now have
485 a higher thermal threshold for bleaching, either due to decline of thermally-vulnerable species
486 and genotypes and/or acclimation¹²⁶. However, the capacity to restore coral reefs lags behind
487 that of all other marine habitats, because coral-reef restoration efforts typically have a very
488 small footprint, and are expensive and slow¹⁰². Coral restoration often fails because the
489 original causes of mortality remain unchecked, and despite decades of effort (Fig. 2), only
490 tens of hectares have been regrown so far. Our growing knowledge of ecological processes in
491 coral reefs provides opportunities to catalyze recovery by reducing multiple pressures while
492 repairing key processes, including herbivory and larval recruitment^{11,109}. Mitigating the
493 drivers of coral loss, particularly climate change, and developing innovative approaches
494 within this decade are imperatives to revert coral losses at scale¹⁰⁸⁻¹⁰⁹. Efforts are underway to
495 find corals resistant to temperatures and acidity levels expected by the end of the 21st century,
496 to understand the mechanisms of their resistance and to use ‘assisted evolution’ to engineer
497 these characteristics into other corals^{108,109}. These efforts are in their infancy and their
498 benefits currently unproven.

499

500 Overall then, societal benefits that would accrue from substantially rebuilding marine life by
501 2050 will be significantly dependent on the mitigation of greenhouse emissions and on the
502 development of efficient CO₂ capture and removal technologies to meet or, preferably,
503 exceed the targets of the Paris Agreement.

504

505 *Investment needed and returns expected*

506 Substantial rebuilding of marine life by 2050 requires sustained effort and financial support
507 (Suppl. Material S4), with an estimated cost of at least \$10-20 billion per year to extend
508 protection actions to reach 50% of the ocean space¹²⁷ and substantial additional funds for
509 restoration. This is comparable to establishing a global MPA network conserving 20-30% of
510 the ocean (\$5 to \$19 billion annually^{127,128}). Yet the economic return from this commitment
511 will be significant, around \$10 per \$1 invested and in excess of one million jobs^{127,128}.

512 Ecotourism in protected areas provides 4 to 12 times greater economic returns than fishing
513 without reserves³⁶ (e.g. A\$5.5bn annually and 53,800 full time jobs in the Great Barrier
514 Reef¹²⁹). Rebuilt fisheries could increase the annual profits of the global seafood industry by
515 \$53 billion¹²⁶. Conserving coastal wetlands could save the insurance industry \$52 billion
516 annually through reducing storm flooding¹²⁷, while providing additional benefits of carbon
517 sequestration, income and subsistence from harvesting, and from fisheries supported by
518 coastal wetlands^{40,127}.

519

520 A global rebuilding effort of exploited fish stocks could increase fishing yields by ~15% and
521 profits by ~80%^{36,77} while reducing by-catch mortality, thereby helping to promote recovery
522 in non-target species as well¹³⁰. Rebuilding fish stocks can be supported by market-based
523 instruments, such as rationalizing global fishing subsidies⁷⁷, taxes and catch shares³⁸, to end
524 perverse incentives¹³¹, and by the growth of truly sustainable aquaculture to reduce pressure
525 on wild stocks². Whereas most regulatory measures focus on commercial fisheries,
526 subsistence¹³² and recreational¹³³ fishing are also globally relevant and need to be aligned
527 with rebuilding efforts to achieve sustainability.

528

529 *Call to action*

530 Rebuilding marine life requires a global partnership of diverse interests, including
531 governments, businesses, resource users, and civil society^{127,134} aligned around an evidence-
532 based action plan supported by a sound policy framework, a science and educational plan,
533 quantitative targets, metrics for success, and a business plan. It also requires leadership to
534 assemble the scientific and socio-economic knowledge and technologies required to rebuild
535 marine life and the capacity to deploy them. A concerted global effort to restore and protect
536 marine life and ecosystems could create millions of new, and in many cases, well-paying,
537 jobs^{127,135}. Hence, commitments of governments, required to meet the UN SDGs by 2030,
538 need to be supported and reinforced by commitments from society, non-governmental agents,
539 including philanthropic groups, corporations and industry (Suppl. Information S4). The
540 sectors operating in the ocean spaces, which bear considerable responsibility for the losses
541 thus far experienced and, in many cases, are likely to be the main beneficiaries of efforts to
542 rebuild marine life, must change their ethos to commit to net positive conservation impact as
543 part of their social license to operate in the ocean space. Human use of the ocean should be
544 designed for net positive conservation impact, creating add-on benefits¹³⁶ that increase
545 prosperity and catalyze political will to deploy further efforts in a positive feedback spiral of
546 ocean bounty.

547

548 The long-term commitment to rebuilding marine life requires a powerful narrative, supported
549 by scientific evidence that conveys its feasibility in the face of climate change and growing
550 human population, its alignment with societal values, and its widespread societal benefits.
551 Growing numbers of success stories and positive outlooks could shift the balance from a
552 wave of pessimism that dominated past scientific narratives of the future ocean^{5,7,11,32,33} to
553 evidence-based ‘*ocean optimism*’¹³⁷ (e.g. #oceanoptimism in social media), conveying
554 solutions and opportunities for actions that help drive positive change¹³⁸. This optimism must

555 be balanced with transparent and robust communication of the risks posed by relevant
556 pressures that are yet to be mitigated.

557

558 Rebuilding marine life will benefit from nations declaring, analogous to the Paris Agreement
559 on climate change, Nationally Determined Contributions (NDCs) toward rebuilding marine
560 life¹²⁷. NDCs aimed at rebuilding marine life will be essential for accountability, auditing
561 milestones and forecasting success in reaching goals. NDCs can include both commitments
562 for action within national Economic Exclusive Zones, as well as a catalogue of actionable
563 opportunities available to investors, corporations and philanthropists¹²⁷.

564

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

574

575 The UN initiated, in 2018, an Intergovernmental Conference to reach a new legally-binding
576 treaty to protect marine life in the High Seas by 2020. This proposed treaty could enhance
577 cooperation, governance and funds for conservation and restoration of high-seas and deep-sea
578 ecosystems damaged or at risk from commercial interests¹³⁹. This mandate would require
579 funding of around \$30 million annually, which could be financed through long-term bonds in

580 international capital markets or taxes on resource extraction¹³⁹. Internationally Agreed
581 Contributions will also be required, because populations of many species are shared across
582 Exclusive Economic Zones of multiple nations. This approach could follow the model of the
583 Regional Fisheries Management Organizations bringing together nations to manage shared
584 fish stocks, including those in High Seas¹³⁹. For example, in September 2010 the Convention
585 for the Protection of the Marine Environment of the North-East Atlantic (OSPAR)
586 established the world's first MPA network on the high seas covering 286,200 km²¹⁴⁰.
587
588 Rebuilding marine life will also require active oversight, participation and cooperation by
589 local, regional, and national stakeholders. Readiness and capacity to implement recovery
590 wedges differs across nations, and cooperation to rebuild marine life should remain flexible
591 to adapt to variable cultural settings, and locally-designed approaches may be most
592 effective¹⁴¹ (Suppl. Information S1). Past failures in some nations can inform new
593 governance arrangements to avoid repeating mistakes elsewhere. Rebuilding marine life
594 should draw on successful marine policy formulation, management actions, and technologies
595 to nurture a learning curve that will propel future outcomes while reducing cost^{103,105-107}. For
596 instance, many developed nations have already implemented nutrient reduction plans but
597 global fertilizer use is rising globally, supported mainly by demands from developing nations,
598 which also continue to develop their shorelines. Adopting the measures now in place in
599 developed nations to increase nitrogen-use efficiency in South and East Asia could lower
600 global synthetic fertilizer use by 2050, even under the increased crop production required to
601 feed a growing population¹⁴².

602

603 Calls for international assistance to support recovery, whether it is for coastal wetlands to
604 reduce risks of damages from natural disasters¹⁰³ or marine life generally¹²⁷, should include

605 assistance to improve governance and build institutional capacity. However, the capacity of
606 both developed and developing nations to deploy effective recovery actions is already
607 substantial. Mangrove restoration projects are significantly larger and cheaper but similarly
608 successful (about 50% survival reported) in developing nations compared to developed
609 ones¹⁰², and small-island states are showing growing leadership in responding to plastics
610 pollution and the marine impacts of climate change (aosis.org). However, many developing
611 countries need particularly high levels of investment to conserve and restore habitats that
612 protect populations at risk in low-lying coastal areas, which could be financed through
613 international climate-change adaptation funds¹⁰³. Currently, the UN's Green Climate Fund
614 has mobilized \$10.3 billion annually to assist developing countries adapt to climate change,
615 with a goal of \$100 billion per year in 2020 ([https://www.greenclimate.fund/how-we-](https://www.greenclimate.fund/how-we-work/resource-mobilization)
616 [work/resource-mobilization](https://www.greenclimate.fund/how-we-work/resource-mobilization)). Allocating a sizeable fraction of these funds to developing
617 countries for the conservation and restoration of “blue infrastructure” (e.g. saltmarshes,
618 oyster and coral reefs, mangroves, and seagrass beds) could increase resilience of coastal
619 communities to climate change and to extreme events while improving their livelihoods¹⁰³.

620

621 Conclusion

622 Based on the data reviewed here we conclude that substantial rebuilding across many
623 components of marine life by 2050 is an achievable Grand Challenge for science and society.
624 Meeting this challenge requires immediate action to reduce relevant pressures, including
625 climate change, safeguarding places of remaining abundance, and recovering depleted
626 populations, habitats and ecosystems elsewhere. This will require sustained substantial
627 perseverance and substantial commitment of financial resources, but we suggest that the
628 ecological, economic and social gains will be far-reaching. Success requires the

629 establishment of a committed and resilient global partnership of governments and societies
630 aligned with this goal, supported by coordinated policies, adequate financial and market
631 mechanisms, and evolving scientific and technological advances nurturing a fast learning
632 curve of rebuilding interventions. Meeting the challenge of substantially rebuilding marine
633 life would be a historic milestone in humanity's quest to achieve a globally sustainable
634 future.

635

636

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653

654

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657

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659

660 Additional information

661 Supplementary information is available for this paper

662

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664

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666

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1022 Table 1. **Scenarios conducive to achieving the best aspirational outcomes toward**
1023 **rebuilding marine life.** These include rebuilding wedges, assessment of the maximum
1024 recovery targets by 2050 shall these wedges be fully activated, key actors, actions,
1025 opportunities, benefits, roadblocks and remedial actions to rebuild different components of
1026 marine life (priority increases from lowest in blue, to yellow, orange and highest in red). See
1027 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									
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 to Complete	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, NGOs	Government, fishers organizations and civil society	Government, fishers organizations, NGOs and civil society	Government, fishers organizations, NGOs, and civil society	Government, fishers organizations, NGOs, and civil society	International seabed authority, state and federal governments, mining/exploration companies, civil society
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, provide space for landward migration; restore hydrological connections,	Reduce nutrient inputs, protect, avoid physical impacts, and conduct restoration projects	Ambitious reduction of greenhouse emissions. Reduce excess sediment and nutrient inputs, improve water quality, protect	Restoration: remove excess herbivores, rebuild their predator, reduce sediment loads on rocky substrate	Protect remaining reefs, prohibition 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), 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 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 water	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, 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 biodiversity	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.

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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 activity.	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 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 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.

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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 \pm 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

1081 virgin biomass (B_0) would take much longer. Solid lines give the median and hashed lines the
1082 mean estimate of years to recovery. Productivity for each stock in panels b-d was fixed at mean
1083 stock-specific historical productivity. See Supplementary Information S2 for details of data
1084 sources and methods.
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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									
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 to Complete	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 and 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 greenhouse emissions. Reduce excess sediment and nutrient inputs, improve water quality, protect reefs, and rebuild food webs, and restore reefs	Restoration: remove excess herbivores. Rebuild their predator, reduce sediment loads on rocky substrate and plant kelps	Protect remaining reefs, prohibition 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, safeguard 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 biodiversity strategies	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 biodiversity	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 activity.	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 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 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 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.







