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Ocean recoveries for tomorrow's Earth: Hitting a moving target

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## REVIEW SUMMARY

## TOMORROW'S EARTH

## Ocean recoveries for tomorrow's Earth: Hitting a moving target

Kurt E. Ingeman\*, Jameal F. Samhouri, Adrian C. Stier\*

**BACKGROUND:** Ocean defaunation and loss of marine ecosystem services present an urgent need to recover degraded ocean ecosystems. Growing scientific awareness, strong regulations, and effective management have begun to fulfill the promise of recovery. Unfortunately, many efforts remain unsuccessful, in part because marine ecosystems and human societies are changing. Rapid shifts in environmental conditions are undermining previously effective recovery strategies. Moreover, divergent perceptions of recovery exist. Efforts toward reversing marine degradation must address the dynamic social-ecological landscape in which recoveries occur, or forever chase a moving target.

**ADVANCES:** Recovery efforts of tomorrow will require institutional and tactical flexibility to keep pace with a changing ocean, and an inclusive concept of recovery. Further, vital population-level efforts will be most successful when complemented by a broader ecosystem and social-ecological perspective. In this Review, we provide a synthesis of ocean-recovery goals as moving targets and highlight promising steps

forward. (i) Society can envision a more inclusive definition of recovery by recognizing a multiplicity of recovery goals. While acknowledging the priority of basic conservation imperatives, successful recoveries can encompass a range of outcomes in the space between minimum ecological viability and maximum carrying capacity. (ii) Research can help anticipate future recovery dynamics and identify pathways toward resilient ecosystems. Ongoing advances are improving our ability to predict the effects of environmental change on ocean productivity and to calibrate recovery targets to changing conditions. As a complement to predict-and-prescribe methods, research can also point the way toward robust approaches in the face of irreducible uncertainty. (iii) Policy-makers can embrace nimble approaches to keep pace with change and integrate governance to operate seamlessly from local to regional scales. Future recovery frameworks should enable rapid response to changing conditions and allow fluid coordination among institutions. Such policies will mitigate conflicts between recovery objectives at different spatial

scales and better integrate local knowledge and traditional cultural practices around recovery.

**OUTLOOK:** Application of these principles will help to reshape recovery of marine ecosystems, yet important scientific questions and societal barriers remain. For researchers, interactions among multiple components of environmental change will test the limits of prediction in tomorrow's ocean. For managers and policy-makers, operationalizing an inclusive definition of recovery organized around social-ecological

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resilience will prove more challenging than simply recrafting recovery policies with new recovery metrics. Rather, this process will involve designing policies that align incentives for

disparate human actors toward coherent recovery goals. Looking ahead, emerging technologies can enable interventions necessary to match the scale of the challenge. It remains possible to recover lost biodiversity in the ocean and to enhance the delivery of marine ecosystem services. Doing so will require a strategic, nuanced, and flexible conceptualization of ocean recoveries that can keep pace with ever-changing physical, ecological, and social environments. ■

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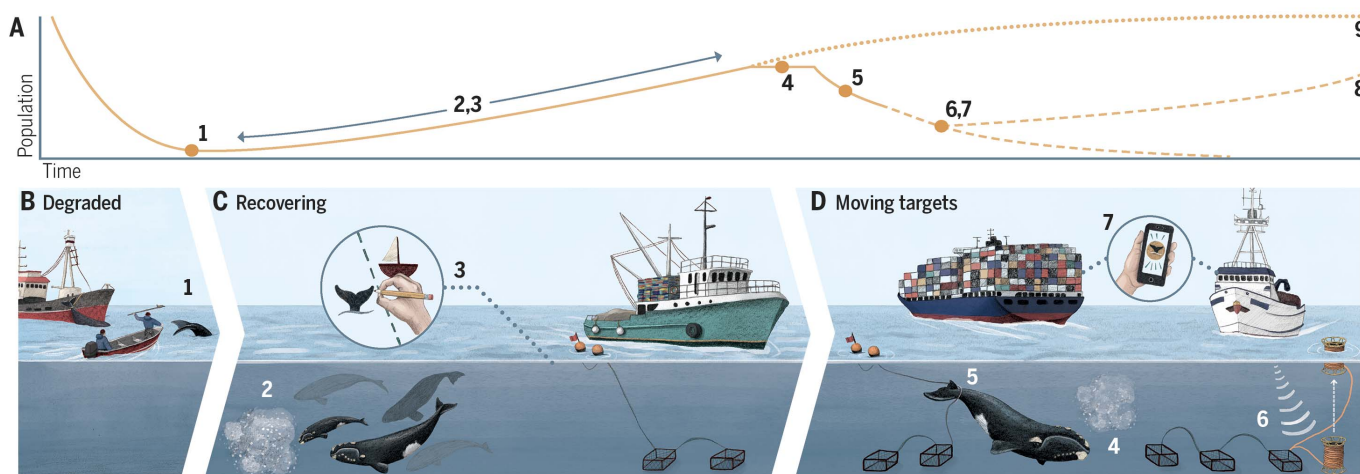
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## TOMORROW'S EARTH

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## Environmental shifts create moving targets for marine recoveries.

(A to D) Since the end of whaling (1), North Atlantic right whales have experienced steady recovery, fueled by abundant copepod prey (2) and aided by vessel speed restrictions and routing human activities away from sensitive habitats (3). Rapid warming has caused reproductive failure by reducing the availability of copepods (4). In 2017, whales followed prey into areas where effective vessel

avoidance measures were not in place, substantially increasing mortality from collisions and entanglement (5). Extending vessel restrictions may be effective in reducing mortality. Looking ahead, "rope-less" fishing gear (6) and real-time data sharing (7) offer hope for resuming recovery. Reduced productivity and increased mortality may necessitate recalibrating recovery timelines (8) compared to original projections (9).

## REVIEW

## TOMORROW'S EARTH

# Ocean recoveries for tomorrow's Earth: Hitting a moving target

Kurt E. Ingeman<sup>1\*</sup>, Jameal F. Samhour<sup>2</sup>, Adrian C. Stier<sup>1\*</sup>

Growing scientific awareness, strong regulations, and effective management have begun to fulfill the promise of recovery in the ocean. However, many efforts toward ocean recovery remain unsuccessful, in part because marine ecosystems and the human societies that depend upon them are constantly changing. Furthermore, recovery efforts are embedded in marine social-ecological systems where large-scale dynamics can inhibit recovery. We argue that the ways forward are to (i) rethink an inclusive definition of recovery that embraces a diversity of stakeholder perspectives about acceptable recovery goals and ecosystem outcomes; (ii) encourage research that enables anticipation of feasible recovery states and identifies pathways toward resilient ecosystems; and (iii) adopt policies that are sufficiently nimble to keep pace with rapid change and governance that works seamlessly from local to regional scales. Application of these principles can facilitate successful recoveries in a world where environmental conditions and social imperatives are constantly shifting.

Billions of people depend upon the ocean for food, livelihoods, energy production, and trade. Although humans have used ocean resources for millennia, the increasing scale and scope of human activity (1) have radically transformed the biological and physical properties of the ocean (2, 3), imperiling ocean ecosystems and the continued delivery of vital marine services (4). Humans living on tomorrow's Earth will demand even more from the ocean. Navigating a pathway toward a prosperous and sustainable future depends on recovering degraded populations and ecosystems and harnessing the intrinsic and instrumental benefits the ocean can provide.

In recent years, growing scientific awareness, strong regulations, and increasingly sophisticated management have begun to fulfill the promise of ocean recoveries; familiar examples include the rebuilding of fisheries, recovery of taxa protected by threatened and endangered species laws (5), and restoration of important marine habitats (6). However, many marine recovery efforts have failed to reach their objectives, even after decades of active intervention (7, 8). In other cases, recovery of depleted populations has surpassed expectations (though often remaining below historical levels), resulting in the colonization of novel habitats (9) and bringing new conservation conflicts to light (10, 11).

The inability to simply turn back the clock should come as no surprise given that recovery

efforts often fail to consider the complex and adaptive nature of the ocean systems (12). Indeed, the oceans and the social systems that depend upon them are inherently dynamic, and increasingly so in an era of rapid climate change and globally connected markets (13). Moreover, marine social-ecological systems vary across space and comprise diverse stakeholder groups who derive value from different aspects of marine systems. These dynamic environmental, ecological, and societal contexts present a shifting landscape for defining and achieving successful ocean recoveries (14).

Yet, current conceptions of recovery can be narrow in scope and out of step with rapidly changing environmental conditions, making them insufficient for tomorrow's ocean with its diversity of intrinsic and anthropocentric values. To effectively reverse marine degradation, we must embrace the dynamic nature of recovery targets—and the flexible solutions required to hit these moving targets (Fig. 1). To be clear, this assertion does not imply a lowering of standards or relaxing of mandates for recovery. Rather, it is a call for a broader definition of recovery that acknowledges that oceans—and the human systems connected to them—are dynamic, and which embraces the manifold nature of recovery success.

Here, we synthesize how recent scientific advances offer pathways to successfully recovering marine populations and ecosystems in tomorrow's ocean. We discuss ways that management and policy can promote recovery by becoming more agile and integrated across scales. Finally, we highlight the promise of emerging technology to enable the ambitious interventions necessary to match the challenge of ocean recoveries in an uncertain future.

## Redefining recovery

We define population and ecosystem recovery as a sustained increase in the attributes of the system that provide lasting ecological and social value. At a minimum, recovery entails the return of population viability and ecological function. A “recovered” system will not necessarily remain in stasis, but an important metric of recovery at the ecosystem-level is improved resilience—the ability to resist shifts toward less-functional states and to rapidly recover function when such shifts occur (15).

Although we see a role for human preferences in defining recovery success, it is not our contention that recovery targets are purely subjective. In many instances, recovery has a specific, legal, and biologically informed definition. For example, for a species listed under the U.S. Endangered Species Act, a recovery plan is designed to achieve the long-term survival of the species such that it is self-sustaining, with the goal of eventual delisting, irrespective of human preferences or economic considerations. Within any given recovery, there are numerous well-established objectives and biologically relevant elements (Box 1).

These biological criteria provide a minimum baseline for single-species recovery targets. However, there is often space for multiple recovery outcomes that fall between the “floor” of a self-sustaining population and a “ceiling” such as maximum carrying capacity. It is in this space where human value judgments may enter into recovery planning.

For instance, consider the following increasingly ambitious recovery goals for an overexploited species: recovery to a point where (i) population growth rates are positive (viability); (ii) population growth rate is maximized; (iii) harvest maximizes economic return; (iv) or the maximum carrying capacity (unfished biomass) is achieved (Fig. 2). Biodiversity preservation and population viability can thus provide minimum, nonnegotiable criteria for recovery; in some cases, recovery planning can be as simple as doubling down on the commitment to these aims. Above this floor, however, additional human value judgments can enter into recovery planning. For example, different stakeholders might prefer to maximize the growth rate of a recovering species for maximum yield (Fig. 2; ii), while others might prefer to maximize the abundance of a species (Fig. 2; iv), creating a trade-off between potential recovery targets.

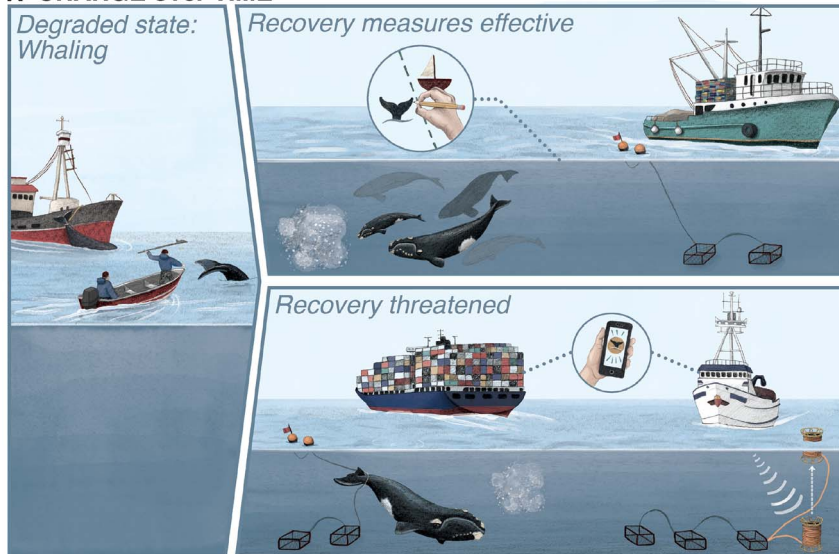
An analogous multitude of recovery targets and similar trade-offs exist when defining recovery at the higher levels of biophysical organization. Coupled human and natural systems are increasingly understood to behave as complex adaptive systems, characterized by large-scale, macroscopic dynamics that both emerge from—and feed back into—lower-order interactions (16). As a result, these systems often exhibit unexpected (“black swan”) events (17) and are subject to crossing tipping points into alternative states (18). Such rapid and unexpected shifts in the state of an ecosystems can shift the relative abundance of certain key species, fundamentally

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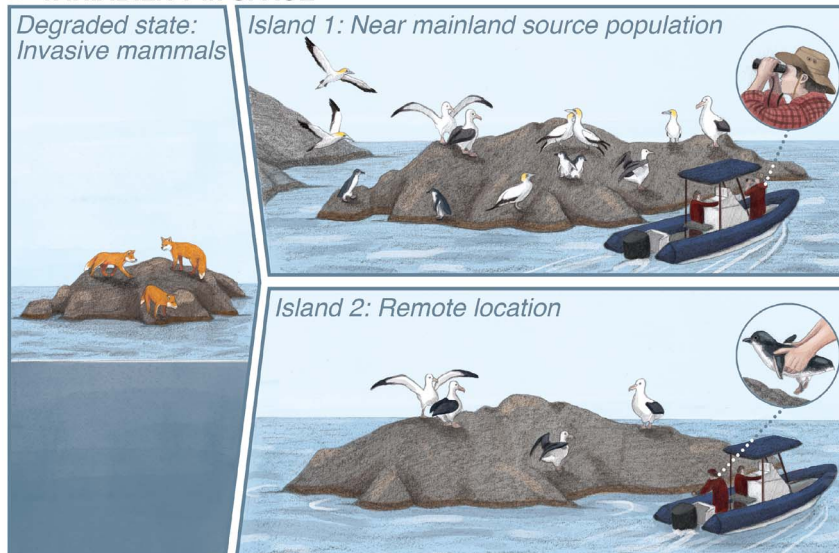
**Fig. 1. Three dimensions of moving targets in marine recoveries.** (A) Temporal shifts in environmental conditions can introduce challenges both for setting achievable recovery targets and for designing effective interventions.

Ending most directed harvest of cetaceans and adopting limited avoidance measures were sufficient to initiate recovery. However, changing ocean conditions affect birth rates and mortality, necessitating the adoption of innovative measures and revised recovery targets (36). (B) Variability in space can demand flexible recovery interventions and limit the utility of measures initiated at a single scale. After invasive mammal eradication, islands in proximity to the mainland may recover diverse and abundant seabird communities through natural dispersal (96). This local success may not translate into broader metapopulation recovery, and remote islands will likely require active relocation of poorly dispersing species to recover preinvasion seabird diversity. (C) Differences in human perceptions of recovery success can limit the support of stakeholders that are not represented in the recovery planning and implementation process. Sea otter recovery can increase a range of ecosystem services associated with kelp dominance, while otter-free habitats are perceived to offer alternative cultural, economic, and conservation value (25). Recovery efforts grounded in stakeholder participation can inform trade-offs among alternative recovery goals.

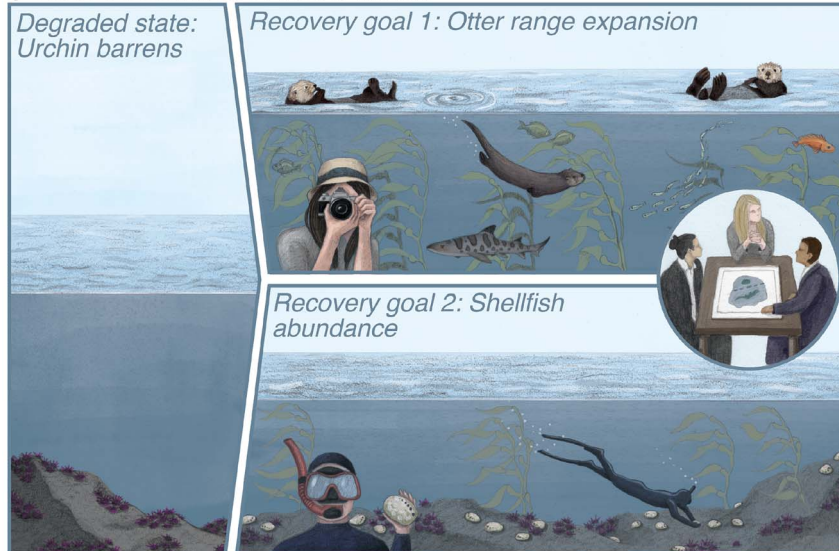
**A CHANGE over TIME**



**B VARIABILITY in SPACE**



**C DIFFERENCES in PERCEPTIONS**



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FIGURE 1. BOERSMA

**Box 1. A typology of recovery concepts.**

A minimum definition of recovery (for species) is movement in the opposite direction of extinction, often with the end goal being a viable and self-sustaining population (100). It has been argued that basic viability represents a low bar for recovery and that positive conservation should look beyond this criterion to include the restoration of other attributes as recovery goals (e.g., population redundancy) (100). Similarly, at the ecosystem-level, return of ecosystem function represents a reasonable minimum recovery target, yet other attributes beyond basic function can represent alternative and more ambitious recovery goals. The question remains: What do we mean by recovery? Here, we suggest a typology of recovery concepts based on a series of key distinctions.

**Historical/novel**

The reference to which progress toward recovery is compared may be historical, or represent a novel state (that nevertheless contains an attribute absent in the degraded system). At one extreme is the return to a prehuman condition. In many cases, such complete ecological recovery may be difficult to attain because (i) the ecological record is ambiguous or incomplete and (ii) shifts in environmental, ecological, or social contexts may preclude such a return (14). At the other extreme, reclamation denotes the recovery of ecological function without reference to historical precedent (101). Between these extremes lie recoveries of managed systems, such as fisheries, for which rebuilding denotes progress toward a quasi-natural, managed reference state—often an intermediate population size that seeks to maximize productivity.

**Static/dynamic**

A related distinction is the extent to which recovery benchmarks are perceived as static states versus dynamic references. Drawn from terrestrial restoration literature, the dynamic reference concept acknowledges that historical reference systems displayed a range of spatial and temporal variation and that contemporary conditions no longer equate to the past (58). Accordingly, success is measured by comparing recovery to contemporary references. A key component of this concept is the inclusion of a range of acceptable recovery scenarios, rather than a single optimum state.

**Human/nature**

This distinction describes the extent to which human benefit versus ecological metrics are the goals of recovery. Complete anthropocentric recovery restores populations or processes only to the extent that they increase services for human beings (102). Beyond human utility, measures taken to prevent extinction or restore self-sustaining populations may be termed biodiversity recovery. Other objectives include restored ecosystem processes: Rewilding focuses on restoring animal populations—not as an end in itself—but rather to restore a modern analog of a functioning ecosystem, often through trophic interactions (83). Alternatively, recovery measures may seek to increase resilience to future disturbances, exemplified by the introduction of heat-tolerant coral species to stave off algal dominance.

**Active/passive**

Another axis is the extent to which managers must actively intervene to speed recovery versus allowing recovery to occur unassisted. Where degradation is ongoing, an intermediate strategy would be to remove the source of decline, which we term passive recovery following the restoration literature (103). For example, in an estuarine system degraded by eutrophication, recovery strategies could range from business-as-usual (unassisted), to reduction of nutrient inputs (passive), to modifying estuary hydrodynamics (active). Where on this continuum of intervention the ideal approach lies depends on a suite of factors, including the magnitude of degradation, intended recovery timeline, the costs of active measures, the desires of stakeholders, and legal mandates. Clearly, an important assumption is that more costly, active interventions will purchase improved outcomes, but general evidence for this relationship remains elusive (7).

**Population/ecosystem**

A final distinction is between efforts toward the recovery of individual populations—typically the focus of species legislation and traditional fisheries management—versus broader ecosystem and social-ecological recovery. The latter approach, though less common, has been operationalized to an advanced degree in a few cases (Puget Sound and Chesapeake Bay systems (14, 89)). A key challenge is in identifying appropriate metrics for measuring progress toward recovery of ecosystems and coupled social systems.

In this manuscript, we suggest an inclusive definition of recovery aimed at bridging multiple ecological and anthropocentric values, at maintaining relevance in a dynamic future, and at addressing the complexities of recoveries in social-ecological systems.

altering the nature of the ecosystem itself and the economic and cultural benefits it provides. Because such systems are constantly evolving, recovery of these systems is often synonymous with regeneration or reorganization in response to disturbance (15).

With the dynamic nature of marine social-ecological systems in mind, we define the floor of ecosystem recovery as the return of fundamental ecosystem processes and functions. Above this floor, a similar plurality of alternative ecosystem recovery targets exists, including prioritizing maintenance of biodiversity or delivery of ecosystem services, some combination of the two, or stability of the entire system. Our definition is an attempt to account for such multiple values from the ocean (including the intrinsic value of nature), for changing conditions, and to provide a framework that applies broadly to recovery in levels of organization above populations (i.e., ecosystems and social-ecological systems).

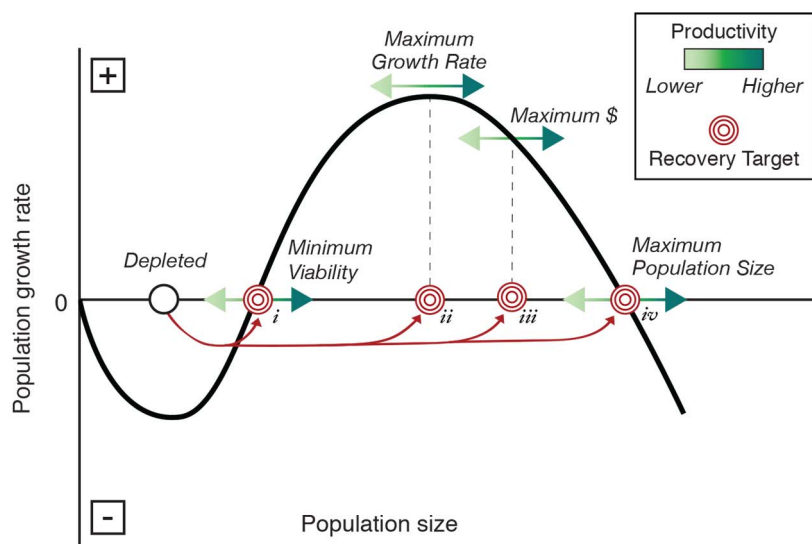
**Challenges associated with recovery as a moving target**

The definition of recovery that we offer above provides some flexibility for including disparate perspectives of alternative stakeholder groups and changes in system capacity over time and across space. However, developing practical advice to define targets for ocean recoveries requires that we dissect these complexities in finer detail.

**Perspectives on recovery targets can reasonably differ**

Human perceptions of what defines successful population or ecosystem recovery can vary substantially based on how an individual interacts with—and values—a species or ecosystem. These differences can generate conflict among actors within the system connected through common-pool resources (19) and complicate clear definitions of recovery targets.

These challenges are exemplified in the ongoing conflict surrounding whether or not there has been recovery of the previously collapsed Pacific herring fishery in British Columbia. There, the highly mobile commercial fleet derives value from high biomass of herring at the regional scale. The cultural and economic value to First Nations is rooted in herring occupancy of traditional spawning habitats (for a site-based egg harvest) as well as region-wide herring biomass as a key resource for harvested species (e.g., salmon and halibut) and for species of conservation concern (e.g., mammal and seabird predators). Recently, the estimated herring biomass at large spatial scales has increased, triggering a potential opening for the commercial fishery. However, conflict exists between these different participant groups as to whether this is herring “recovery” for at least two reasons. First, herring has not recovered in numerous locations historically harvested by First Nations (20). Second, traditional ecological knowledge suggests that a much higher herring biomass is possible than assumed in the current herring stock assessment, supporting the argument that the current



**Fig 2. Variation in recovery targets of a single species.** Population growth rate as a function of population size for a harvested species. Assuming an Allee effect, population growth rate can be negative (below the x axis) when populations are small owing to mechanisms such as inbreeding depression and mate limitation. Numerals (i to iv) represent potential population recovery targets (red) relative to the depleted state (open circle). Four possible recovery targets are shown: (i) population growth rates become positive (minimum viability); (ii) population growth rate is maximized (biomass at maximum sustainable yield,  $B_{MSY}$ ); (iii) harvest maximizes economic return (biomass at maximum sustainable profit,  $B_{MSP}$ ; (iv) and the maximum carrying capacity (unfished biomass,  $B_0$ ) is achieved. Each of the four depicted recovery targets may change as a function of productivity, represented by green arrows, where a shift to higher productivity is shown in darker green. In addition to changing the location of the targets, human impacts can also change the strength of the feedbacks that produce positive growth rate when populations are large and negative growth rate when they are small (not shown). Red lines connect depleted state to potential recovery targets, and vertical dashed lines connect recovery targets to population growth rate for (ii) and (iii).

moratorium should persist until herring biomass increases further (21). Thus, diverse value sets, sources of knowledge, and ways of interacting with the ocean and its resources can lead to differing participant perspectives on single-species recovery targets.

Setting and achieving recovery targets for ecosystems containing multiple interconnected species can also be complicated by variation in how stakeholders value individual components of an ecosystem. Ecosystem recovery often entails a shift in the relative abundance of biological resources, redistributing resources compared to the unrecovered state (22). Thus, when stakeholders perceive greater or lesser value from different attributes of an ecosystem, support for recovery measures will vary strongly among groups, making one stakeholder's recovery success another one's failure. This is exemplified in the recovery of marine mammals that also consume fishes on the U.S. West Coast. For example, southern resident killer whales consume endangered chinook salmon (23), sperm whales prey upon commercially harvested sablefish (24), sea otters prey upon endangered abalone (25), and seals and sea lions prey upon endangered salmon and sturgeon (26). Although the tourism industry has grown with the recovery of marine mammals, and some marine mammals

can positively influence certain fished species (27), mammal recoveries have also often been associated with higher mortality of fished species and with threatening the recovery of other depleted species. Evidence for whether and how marine mammal recoveries actually deter catch or lower recovery success of endangered prey remains mixed (28–30). However, the perception that marine mammal recoveries have increased competition with fisheries or placed the recovery of endangered prey at risk demands renewed attention to identifying targets that encompass multiple interconnected species.

#### **The parameters that shape recovery are changing rapidly over time and differ across space**

Temporal shifts can fundamentally alter how we define the floor and ceiling of recovery described above. For a single harvested population, a reduction in ocean productivity might change the minimum viable population, the population size at which yield is maximized, or the maximum unfished biomass in a system (Fig. 2; green arrows). Physical conditions underlie fundamental biological processes, so directional shifts and increasing variability in ocean conditions will necessarily alter future recovery targets and trajectories. For example, warming and acidification

affect the demographic rates and productivity of recovering species through numerous physiological and behavioral pathways (31), by altering disease dynamics (32), and by inducing rapid evolution (33).

Likewise, changing conditions can also lead to geographic range shifts among species with different thermal tolerances, introducing novel (or decoupling existing) trophic interactions (34), and potentially suppressing or enhancing the rate of recovery compared to expectations (35). Temporal shifts in the environment can complicate recovery planning by affecting multiple components of the recovery process. For example, in coral ecosystems, changing ocean conditions have lengthened coral recovery timelines while narrowing the window of opportunity for recovery between increasingly frequent disturbance events (Box 2 and Fig. 3).

The challenges associated with the recovery of the North Atlantic right whale are a clear example of how changes in ocean conditions can thwart attempts to set achievable recovery targets and design effective interventions. This species has experienced steady recovery from industrial whaling until recent, rapid warming in the Gulf of Maine caused unprecedented reproductive failure by reducing copepod prey productivity (36). At the same time, successful measures to reduce ship-strike mortality (relocation of shipping lanes) are needed in new locations as right whales have followed prey poleward into the Gulf of St. Lawrence (37) (Fig. 1A). Notably, the temporal changes described here did not occur uniformly across the seascape, making recovery challenging to address not only in time, but also across space.

Just as changes in environmental conditions over time alter expectations for recovery, spatial heterogeneity and connectivity in marine systems mean that (i) recovery potential is not spatially uniform and (ii) recovery goals specified at different spatial scales may not align. Many local populations of marine species are connected to other local populations through dispersal (i.e., metapopulations) (38). As a result, local recovery efforts can increase the abundance of individual populations without improving metapopulation recovery. Conversely, measures aimed at promoting regional, metapopulation recovery can inadvertently cause local depletion (39). For example, Pacific herring spawn in discrete, nearshore habitats, creating populations with different levels of productivity that fluctuate out of sync with one another (40). Conserving this population diversity to retain such asynchronous dynamics can accomplish regional objectives, such as reducing variability in abundance at the metapopulation scale (41). Yet, management practices that increase the spatial variation among populations—regional-scale harvest limits in the herring example—can also enhance the risk that local populations fail to recover. Indeed, some traditionally occupied spawning sites have been lost over time (42), thereby reducing the spatial diversity necessary to buffer against changing conditions.

## Box 2. Temporal shifts create moving targets for coral-reef recovery.

With repeated cycles of recovery from disturbance, interacting drivers of decline, and sensitivity to global change, reef-forming corals are a rich system with which to understand ecosystem recoveries in the Anthropocene. Changing conditions have altered numerous aspects of the recovery process, limiting the utility of historic communities and previously observed recovery timelines as useful benchmarks for recovery.

### Not all recoveries are alike

Coral recoveries can follow diverse trajectories mediated by the source(s) of disturbance, interactions among stressors, and historical contingencies. First, recovery from disturbances such as cyclones, predatory starfish outbreaks, and bleaching each proceed at different rates, depending in part on the extent to which physical structure is damaged. Second, multistressor interactions can interact synergistically (104), so efforts to measure recovery from any one stressor offer little insight into realistic recovery dynamics in a multistressor environment. Third, after a disturbance has reset the clock for a coral community, priority effects can determine the trajectory of recovery (105). These factors challenge our ability to predict coral recovery timelines.

### A moving target

Layered onto these naturally complex recovery dynamics are the effects of global change. The chronic effects of increased temperature can delay recovery from acute stressors and increase variability compared to prewarming recovery events (Fig. 3A) (97). Observations of coral recovery showed an 84% decrease in recovery rates between 1992 and 2010 (106), attributed to the combined effects of acute and chronic stressors. As a result, historical responses to disturbance no longer provide informative benchmarks for future recoveries.

Additionally, global change has altered both the frequency and magnitude of acute disturbances themselves with the average number of years between severe bleaching events declining from 25 to 6 (Fig. 3B) (98). This shorter interval does not allow a sufficient window for recovery, even for the fastest-growing coral species.

Finally, corals are highly variable in their susceptibility to mortality from heat stress (107), so thermal anomalies can alter species composition (Fig. 3C) (99). Thus, despite the return of previously observed levels of coral percent cover (a common aggregate metric of community recovery), persistent changes in coral community composition can alter reef-scale properties, resulting in altered recovery from future disturbances (108). Taken together, these findings indicate that reefs are unlikely to achieve or remain in any static or historically informed “recovered” state. Rather, coral ecosystems in the modern era are likely to continue to reorganize into novel, heat-tolerant assemblages (109), requiring managers to redefine recovery targets for an era of global change.

## How feedbacks can inhibit recovery

Human-induced changes in the floor or ceiling for recovery described above can be further complicated by the existence of feedbacks, which can reinforce the decline of a species or ecosystem. For example, many marine populations exhibit negative population growth rate at low densities because individuals are unable to find a mate or experience inbreeding depression due to low genetic diversity (43). Low densities, in turn, exacerbate negative growth rates in a reinforcing feedback loop. The challenge for incremental recovery efforts is that a self-sustaining (viable) population (Fig. 2; *i*) is only achieved when the population is pushed beyond this threshold, a target that can shift with human actions (Fig. 2; arrows). Similarly, at the ecosystem level, many marine systems can be “tipped” into a less preferred state by large disturbances. Once such a shift occurs, reinforcing feedbacks can prevent ecosystem recovery back to the predisturbance state (a phenomenon known as hysteresis) (44).

Human activity can alter recovery potential, as well as the management actions needed to achieve a stated recovery target. By altering envi-

ronmental conditions, human actions can change the location of the recovery floor—the minimum viable population required for positive growth. For instance, in the Dutch Wadden Sea, disease and gradual eutrophication in the 1930s caused a sudden transformation of eelgrass habitat to bare sediment (45). Ecosystem recovery has been impeded by self-reinforcing feedbacks that have led to decades-long persistence of bare sediment: Loss of eelgrass has decreased sediment stabilization while simultaneously increasing sulfide concentrations, thereby inhibiting eelgrass recruitment and survival (45). Overcoming the feedbacks that inhibit ecosystem recovery goes beyond simply turning back the clock on eelgrass abundance or the original drivers of degradation. Rather, the biological floor for system recovery has effectively been pushed higher, and recovery will require a more substantive intervention.

Beyond shifting the location of recovery targets, human actions can also modify the intensity of reinforcing feedback loops that maintain a social-ecological system in a given state. For example, in the North Sea, anthropogenic changes to ocean conditions have decreased the produc-

tivity of some overfished stocks, intensifying fleet overcapacity and reducing the reliability of stock assessments (46). As fishing becomes less economically viable, fishers increasingly lose incentives to comply with regulations and may turn to illegal practices that further inhibit recovery (46). Thus, changes to the environment can intensify feedbacks that maintain the social-ecological system in a degraded state.

Feedbacks in coupled human and natural systems can further limit the ability for society to derive value from successful recoveries when they do occur. For recoveries to translate into realized gains in goods or services, societies must be sufficiently pliable to harness the benefits of changing resource availability. Yet, rapid adaptation can be hindered by cultural norms, policies, gear investment, and market forces that can lock resource users into “gilded traps,” characterized by ever-increasing dependence on narrow yet lucrative monocultures (e.g., Maine lobster) (47). These self-reinforcing dynamics cause inertia in response to recovery opportunities and increase the social cost of reorganization when recoveries disrupt the status quo (Box 3).

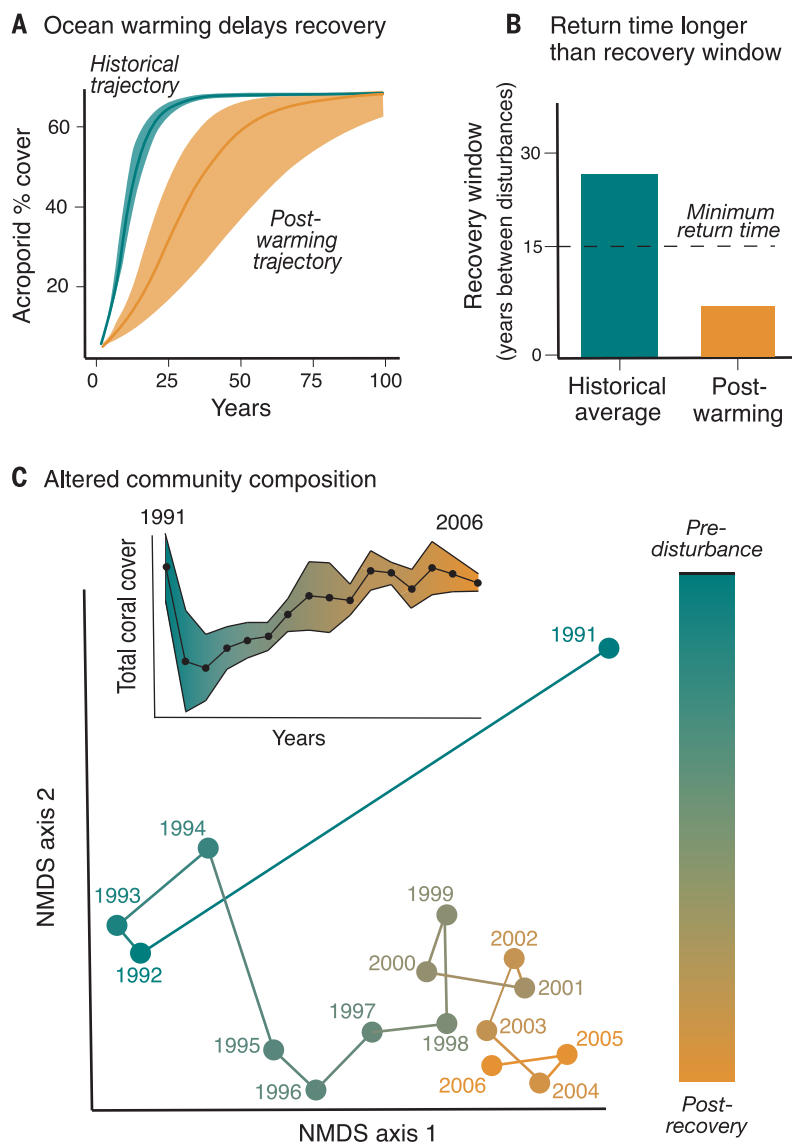
Although we focus above on the challenges that feedbacks present for recovery, the power of feedbacks to maintain healthy ecosystems in the face of disturbance offers key opportunities in an era of global change. For example, at the population level, adaptive evolution has the potential to lower the minimum viable population size for species through evolutionary rescue (48). Similarly, at the ecosystem level, recent evidence in coral reefs suggest that more stress-tolerant corals may heighten the capacity of coral reefs to more readily resist and rapidly recover from environmental shocks (49). As a first step, identifying where system feedbacks enhance—or inhibit—recovery can illuminate management and societal interventions that shift incentives for actors in the system and unlock the potential for self-reinforcing positive change (50).

## Hitting the moving target Toward an inclusive conception of recovery for nature and people

We have argued above that conventional conceptions of recovery limit the ability to respond to variability in space and time. In addition, they constrain approaches for balancing multiple values from the ocean. We further argued that a reductionist approach to ocean recoveries often ignores the emergent dynamics of complex systems that can undermine narrower efforts. Here we offer pragmatic suggestions to build a new recovery concept for tomorrow's ocean.

### Engage stakeholders iteratively to redefine recovery success

Under our above definition, achieving “lasting ecological and social value” can be accomplished in multiple ways, and trade-offs will necessarily arise with the inclusion of diverse recovery goals. Divergent perceptions are a fundamental challenge for managers seeking to facilitate ocean recoveries (51). However, there are several practical



**Fig. 3. Temporal shifts alter coral ecosystem recoveries in the Anthropocene.** (A) Delayed timelines and greater variability in the recovery of acroporid corals after acute disturbance comparing postwarming (orange) to historical recoveries (green) because of the chronic effects of increased temperature. As a result of this temporal shift, recovery targets based on historical trajectories may be unrealistic. [Data redrawn from (97) with permission] (B) Decrease in the number of years between severe bleaching events has substantially narrowed the window for recovery, comparing historical and postwarming averages (green and orange bars, respectively). The average return time for even the fastest recovering, “weedy” coral species (dashed line) is now substantially longer than the available window of recovery opportunity. [Adapted from (98) with permission] (C) Changes in coral community composition over a 15-year recovery following acute disturbance. Despite return to predisturbance levels of total coral cover (inset), differential responses of individual coral species to changing conditions result in a persistent shift in community composition. Recovery to predisturbance community composition may therefore represent an unachievable recovery target. [Redrawn from (99) with permission]

and well-tested approaches to address this challenge. With the caveat that human perceptions of success only play a role after fundamental conservation imperatives have been met, we argue that a critical approach is engaging stakeholders to help in defining recovery success. To do so in a way that both garners support for recovery measures and achieves equitable out-

comes, recovery efforts can (i) initiate early, interactive, and iterative stakeholder participation in framing recovery success and (ii) make explicit the trade-offs among alternative recovery scenarios (52)—and how these trade-offs may shift as marine social ecological systems reorganize in response to continued degradation or recovery (15).

A tangible example of how progress is being made in developing conservation targets based on stakeholder-defined preferences comes from the U.S. Pacific Northwest. Using social science techniques and visual simulations of management scenarios regarding eelgrass recovery in Puget Sound, participants from a variety of stakeholder groups were asked to assess their preferred state (and minimally acceptable condition) of the coupled human and natural system. Using this framework, the authors identified that a 10 to 25% recovery in eelgrass cover corresponded to the overall median stakeholder preference and that little support was to be found for either unconstrained growth or for complete absence of human activity (52). A major challenge comes from ensuring that this dialogue among stakeholders, scientists, and managers is maintained, but this challenge is not insurmountable. Although stakeholder participation can increase the time and costs associated with recovery planning, the long-term benefits of incorporating stakeholder values into the recovery process—increased regulatory compliance, improved trust, and cooperation among groups—can ultimately outweigh short-term considerations (53).

#### Dynamic perceptions, dynamic trade-offs

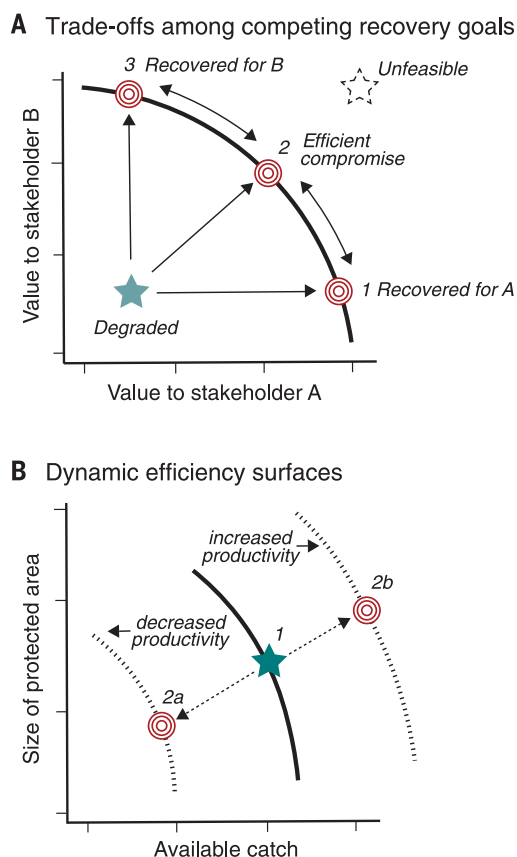
Engaging stakeholders and identifying trade-offs are strategies already embedded in ecosystem-based management (54). However, most management does not yet explicitly acknowledge that perceptions of recovery success can themselves change, or that trade-offs among recovery scenarios can strengthen or weaken with shifting environmental or societal conditions (55) (Fig. 4). For instance, changing ocean productivity as a result of warming could relax or exacerbate the trade-off between fishery yields and recovery efforts, changing the maximum possible catch for a given level of protection (Fig. 4B). This altered trade-off may in turn cause stakeholders' perceptions of success to converge or diverge. A crucial path forward for balancing multiple ocean services in a dynamic and uncertain future will be the continued development of methods to quantify uncertainty and predict change in recovery trade-offs. Scenario analysis (56) is a promising approach for identifying and comparing possible futures under uncertainty and is beginning to be integrated into recovery planning—though more commonly at the ecosystem-level.

We acknowledge that envisioning recovery as a dynamic target that is iteratively defined by stakeholders poses risks for meeting less anthropocentric recovery targets. It remains crucial to avoid allowing the shifting baselines phenomenon to obscure the nature of predegradation marine systems (57). Indeed, a poor understanding of historical states can limit our frame of reference for possible recovery futures. Further, quantifying the breadth of ecosystem variation from the past (through a paleoecological perspective) will allow us to move away from the idea of a single, static recovered state and toward a multiplicity of acceptable recovered states (58).



#### Fig. 4. Shifting trade-offs among multiple ocean recovery objectives.

(A) Conflict among parties with a stake in recoveries can occur when two recovery objectives provide value to different stakeholders. Prior to recovery, the degraded system provides low benefit for both groups (filled star). Recovery benefits cannot be simultaneously maximized for both groups (dashed star). Rather, when benefits to stakeholder A are maximized (1), any increase in value to stakeholder B entails a reduction in value for A (2 and 3). The heavy black line indicates the efficiency frontier, where points along this curve optimize trade-offs. (B) Dynamic efficiency surfaces: Recovery trade-offs may shift with changing environmental or economic circumstances. As an example, changing ocean conditions can increase or decrease local productivity of an exploited species, thereby shifting the location of the efficiency frontier that defines the optimized balance between catch and size of an MPA. Under future conditions, reduced productivity could exacerbate existing trade-offs (arrow left), reducing the amount of catch for a given level of area protection (2a). By contrast, increasing productivity could relax this same trade-off (arrow right), allowing higher level of each recovery objective (2b).



#### The role of science in anticipating change and identifying pathways to resilience

Research can help anticipate future recovery dynamics, evaluate robust interventions, and identify pathways toward resilient ecosystems. Ongoing advances in modeling and empirical approaches are improving the ability to predict the effects of rapid environmental change on ocean productivity and to calibrate recovery trajectories to changing conditions. At the same time, scientists must advance tools to evaluate adaptive and robust recovery interventions in the face of irreducible uncertainty—strategies that may prove more useful than predict-and-prescribe methods in tomorrow's dynamic and connected ocean.

#### Calibrating future recovery targets

Two complementary research avenues are (i) using models and empirical approaches to anticipate the effects of changing conditions and (ii) developing adaptive recovery frameworks that embrace uncertainty and are robust to changing conditions.

Several advances show promise for sensibly calibrating recovery targets. One major innovation links individual physiology to population-level recovery by addressing the ability of organisms to meet metabolic demands through oxygen uptake (59). Falling within this broader class of models, energy allocation models integrate oxygen uptake into adaptive models of foraging behavior and life-history trade-offs to

predict fitness under altered conditions (60). The ability of such models to scale individual physiological constraints to population-level changes in abundance and distribution is particularly valuable for adjusting recovery timelines and considering which species and habitats will persist given social-ecological demands and under changing ocean conditions. Although predictions differ among taxa, one general conclusion is that metabolic trade-offs will represent a primary constraint shaping recoveries in an altered ocean.

A second major advance comes from size-based approaches that offer an alternative way to describe flows of energy and productivity at different size-classes without reference to species identity (61). Related, dynamic bioclimate envelope models project changes in marine species distribution, abundance, and body size at the ocean-basin scale using species-specific tolerances to environmental conditions (62). By projecting latitude-specific changes in fish productivity, these methods have important implications for defining realistic community-level indicators of recovery (e.g., reduced total biomass). The general result that future ocean conditions will drive reductions in mean size of marine fish communities—and thereby rates of productivity (61)—indicates the importance of integrating realistic size distributions into plans for rebuilding fisheries and recovering populations of threatened species. Far from embracing a truncated size structure as the norm (falling victim to shifting baselines), this insight both

enables researchers to realistically project recovery dynamics and emphasizes the need to enact measures to protect large individuals, such as “no-take” reserves.

#### Empirical approaches for anticipating recovery dynamics

At the ecosystem level, life-history traits can be used to predict shifts in species composition that result from climate stressors (63) and to identify the primary trait axes that shape response to perturbation (64). Thus, trait-based strategies offer hope for predicting community recovery timelines in assemblages with diverse individual species' responses, such as coral communities. Observational studies can also provide indirect inference about future recovery dynamics. One strategy borrows from the observation that moderate fishing can shorten recovery times by inducing the evolution of faster growth and earlier maturity (65)—life-history changes that are similar to those predicted under climate change (60).

Another strategy draws on space-for-time substitution studies, which collect information from existing extreme environments that reflect expected future conditions. For example, Kroeker *et al.* (66) used proximity to local CO<sub>2</sub> seeps to infer that future pH levels can result in ecosystem simplification, loss of functional diversity, and missing ecosystem processes (e.g., grazing) in temperate kelp systems. One limitation of employing geographically localized ecosystems as analogs for future conditions is that individual organisms may have dispersed as larvae from distant locations, precluding evolutionary adaptation to local conditions (67). Thus, these studies may underestimate the potential for rapid evolutionary processes to rescue declining populations under future conditions (68). Nevertheless, such an ecosystem approach can uncover recovery-relevant changes in ecosystem processes and species interactions that may be masked in single-species projections.

#### Robust recovery interventions

Improved prediction is not always possible and will always be accompanied by uncertainty. Robust recovery policies describe those that perform despite uncertainty and across a range of possible futures (69). An important class of tactical research tools—collectively known as management strategy evaluation—addresses this uncertainty by testing the effects of modifying any part of a management cycle, from changes in the underlying population dynamics, to data collection and observation error, to implementation of management measures (70). Management strategy evaluation can further distinguish between effective and ineffective recovery strategies in response to environmental change.

For example, in the coastal seas off South Africa, environmentally mediated shifts in the productivity and distribution of pelagic fishes in the early 2000s were linked to an increase in mortality and reduction of breeding success of African penguins (71). Simulations evaluating the effects of the purse-seine fishery on penguin population dynamics indicated that large-scale

**Box 3. Newfoundland cod and shrimp: Recoveries create new challenges for fishing communities.**

Ongoing shifts in the benthic community off the Newfoundland coast in Canada are illustrative of the challenges of defining and attaining recovery success when temporal changes, spatial complexity, and stakeholder preferences interact in complex marine social-ecological systems.

**Cod collapse and recovery**

In 1992, a complete moratorium on commercial harvest for the collapsed Northern stock of Atlantic cod triggered a massive restructuring of the coastal societies dependent on this fishery. In subsequent decades, a lucrative northern shrimp fishery has thrived in Newfoundland in the absence of cod predators and under favorable environmental conditions (110). More recently, managers have substantially reduced the allowable catch of northern shrimp in response to declining abundance—due in part to the incipient recovery of cod as well as warming conditions that favor cod productivity. Species interactions have been similarly dynamic: In the relative absence of forage species (capelin), cod predation on shrimp appears higher than historical estimates (111). From a stakeholder perspective, cod recovery has the potential to reallocate benefits among fisheries (shrimp versus cod) and among different segments within a single fishery (inshore versus offshore shrimp fleets). Thus, the long-awaited recovery of an iconic species is creating new trade-offs for Newfoundland coastal communities.

**Challenges and opportunities**

What paths forward offer hope for addressing moving targets for recovery in Newfoundland waters? First, given spatiotemporal shifts in this system, altered species interactions are shaping recoveries (34) and thereby affecting harvest reference points. If cod continue to rebound (and shrimp decline) under warmer conditions, increased predation may make previously precautionary shrimp harvest levels unsustainable, suggesting a need for updated harvest control rules. Indeed, industry groups have recently called for a reevaluation of shrimp population benchmarks, as these were established in the absence of cod predation and may represent unrealistic targets given the return of the predator.

At this time, managers employ single-species stock assessments. Grounding shrimp management targets in the context of dynamic cod and forage species' abundances using models of intermediate complexity (112) could provide a path toward more precautionary management. Indeed, the integrated management of cod, sprat, and herring in the Baltic Sea offers an example of integrating trophic interactions to provide tactical recommendations for sustainable multi-species harvest levels (113). To address stakeholder preferences, a marine planning process that is guided by spatial trade-off analysis offers the opportunity to explicitly address equitability and efficiency in allocating recovery benefits. Finally, to ensure social resilience and reduce economic pressure to propagate boom-and-bust harvest cycles, policy-makers may consider incentivizing diversification in livelihoods at the individual, community, and regional levels.

reductions in catch would likely be less beneficial than area closures in the face of shifting environmental conditions.

Ultimately, the inability for researchers to pre-determine a single, optimal recovery underscores the need for precautionary target setting (69) and the use of recovery policies-as-experiments that guide future attempts to address moving recovery targets (72).

**Enhancing resilience through diverse and connected recoveries**

An alternative response to uncertainty is rooted in network and portfolio theories and emphasizes the role of maintaining resilient systems with the capacity to adapt to changing conditions (73).

Portfolio theory—borrowed from economics—suggests that the dynamics of an aggregate system are less volatile than the dynamics of component parts, provided that the component parts fluctuate asynchronously. Spatially heterogeneous meta-populations can represent a diversified portfolio of populations that differ in key attributes such

as life-history traits, age structure, habitat association, prey preference, or response to the environment (74). Recovery measures that maintain diverse portfolios therefore (i) increase the likelihood that at least some populations will experience recovery under variable conditions and (ii) preserve the ability for a thriving local population to rescue a declining one (75). Protecting spatial heterogeneity of recovering populations thus fosters resilience to dynamic and unpredictable conditions.

The portfolio concept can also be applied to fostering resilience in broader marine ecosystem recoveries and to promoting resilience in human social systems tied to the ocean. First, preserving species diversity can ensure redundancy in important ecosystem functions. For example, coral reefs that retain an intact guild of parrotfish grazers carry insurance against the loss of invertebrate grazers to disease (76). At the social-ecological level, recent research into Alaskan fishing communities has demonstrated that ports with more diverse catch portfolios showed increased economic stability in the face of shifting environmental and

market forces (77). Exploring management tools that incentivize catch diversity may therefore offer promise for addressing boom-and-bust cycles for resource users, especially given the strongly synchronizing force of globalized markets for marine products.

A corollary to portfolio theory for recovery is the idea that maintaining diverse adaptation networks can allow nature to select the winners in recoveries in an uncertain future. As a contrast to “predict and proscribe” management, maintaining diversity and connectivity can maximize the capacity for biological systems to adapt to dynamic conditions (73). In the context of recovery, this approach could entail designing spatial networks of marine protected areas (MPAs) with connectivity among locations and to environments that could provide future refuges from climate change—even if some of those locations are not currently high-value habitats.

The above perspectives align well with complex adaptive systems theory, with resilience as a central organizing principle. Theory suggests that four conditions are needed to achieve resilience in complex adaptive systems: modular structure (or tightly connected local units that are more loosely connected to the whole), heterogeneity, redundancy, and tight feedback loops (12). To extend the MPA network example, using species dispersal distance as a guide, locations could be clustered to balance the modularity that insulates the network from system-wide catastrophe (78) with the connectivity that allows depleted populations to be rescued by distant, thriving ones. Many scientific advances remain before this approach could be operationalized, yet meta-ecosystem theory and genetic techniques to evaluate connectivity are advancing rapidly. Rather than seeking ecosystem recovery by building up from individual populations, a productive path for future research will be in understanding how to foster the conditions that produce broader ecosystem resilience in complex adaptive systems.

**Nimble policies, integrated governance, and technological solutions****Keeping pace with change**

How can policy support more agile management of recoveries in tomorrow's changing oceans? First, existing legislative tools focused on recoveries can be updated to acknowledge the dynamic nature of recovery targets, but policies to streamline a more frequent and fluid review process will be critical. For example, one quarter of U.S. federally listed species lack a recovery plan altogether. Moreover, half of existing plans are more than 20 years old, and few address climate change (79). The backlog of absent or outdated recovery plans for federally listed species represents an opportunity to update recovery plans with the best available science.

Second, adaptive management approaches to recovery can keep pace with changing marine systems by tightening the adaptive management loop that cycles through monitoring, planning, and implementation of recovery measures. In the ocean of tomorrow, the ability for managers to

react effectively may be overwhelmed by both the pace and magnitude of change, especially for systems prone to abrupt tipping points (18). This suggests that adaptive approaches that are slow to respond may not be sufficiently nimble for tomorrow's recoveries. To be an effective solution for temporal change, future adaptive management will require a wider range of scenario planning, more frequent monitoring, and decision-making structures that are streamlined for rapid response. To revisit the right whale example, altering shipping lanes to avoid sensitive habitats can take years to plan and overcome bureaucratic hurdles. Given the potential for continued shifts in whale distributions and migration routes, recovery measures (e.g., technological innovations like rope-less fishing gear) that can be implemented regardless of range shifts offer an agile complementary approach.

Third, and to that end, modifying existing legislation to require the use of technological advances in real-time forecasting and data distribution can reduce mortality in species recoveries via bycatch and collisions with ships (80). For example, improved forecasting of cetacean habitat use could guide policies to limit the use of mid-frequency sonar or seismic exploration during sensitive periods, actions that will likely reduce the rate of reproductive failure and adult mortality (81).

Finally, learning from the social, political, and economic responses in regions that are experiencing early impacts of rapid ocean change (e.g., oyster larvae die-offs in the Pacific northwest, sea-level rise in the Marshall Islands, coral bleaching on the Great Barrier Reef) can help inform more proactive policy and management structures that address impacts of change before catastrophic disruption occurs.

#### *Emerging technologies to overcome obstacles to recovery success*

Nimble governance that keeps pace with change will be supported by ongoing technological advances. Breakthroughs in data acquisition and processing have opened the door to enforcement of large-scale area protection and real-time interventions to avoid threatened species. For instance, remote-sensing data and innovative modeling of species distributions allow near-real-time predictions about regions of the seascape where swordfish can be targeted while also avoiding bycatch of recovering marine turtles or pinnipeds (80). This dynamic approach to ocean management (82) has the potential to facilitate continued recoveries of protected species with reduced disruption to fisheries compared to seasonal closures. Other opportunities to enhance recoveries through active intervention—while posing very real ethical questions—are on the horizon as well. These include assisted colonization of new habitats for climate refugees, ecological replacement, and rewilding (83), as well as advances in genetic modifications (84). For corals facing increased frequency and intensity of thermal anomalies, technological advances are currently unlocking a wide range of interventions: Emerging avenues range from physiological tools (e.g., acclimation to heat stress, microbiome

manipulation), to genetic manipulation (e.g., managed selection, CRISPR-Cas9 gene manipulation) to population and community interventions (e.g., assisted relocation, promoting growth of seagrass meadows to mitigate acidification) (85). Debate between advocates of such interventionist approaches and proponents of less prescriptive management continues (73), yet the predicted magnitude of environmental change suggests that a range of strategies may be required to achieve meaningful recovery in the coming decades.

#### *Governance that operates fluidly across scales*

Instituting policies to improve the fluidity of governance and integration of institutions across spatial scales will increase efficiency and reduce response time to changing recovery circumstances. For example, in the United States, there are highly valuable fisheries managed by individual states, with federal oversight and the potential for federal intervention if needed with changing ecological and social conditions (e.g., Dungeness crab on the U.S. West Coast).

Matching scales of governance to those of ecological processes that shape species and ecosystem dynamics can tighten the feedbacks between conservation efforts and recovery responses, increasing the likelihood of meeting objectives (86). Large-scale institutions (e.g., federal agencies or regional fisheries management councils)—which are limited in their ability to flexibly adapt to local environmental and social conditions—may inadvertently provide incentives that are not aligned with recovery (87). Conversely, locally optimized efforts can be inefficient for achieving regional conservation goals (88), and local efforts can be futile unless large-scale drivers, such as climate change, are addressed. Such spatial-scale mismatches can lead to suboptimal resource management when collaboration and coordination among institutions at different scales is weak or non-existent (89). Thus, coordinating the activities of local organizations (states, municipalities, or local nongovernmental organizations) that are scaled to address local drivers (pollution control, habitat restoration) with regional or federal institutions that can address regional or larger-scale concerns (climate change, fisheries management) offers promise for better aligning incentives with recovery objectives in spatially structured marine social-ecological systems (50).

For example, coordinated recovery efforts can link national, regional, and local actors to implement a network of MPAs. Here, the proportion of habitat under protection and key locations for protection may be determined by large-scale considerations, such as overall species viability and sufficient genetic diversity. However, local actors, such as local and state planning councils that are responsive to rapid and local variability, could maintain autonomy in setting local recovery benchmarks, monitoring, and enforcement. Such polycentric governance—characterized by distributed decision-making structures—has been previously advocated for managing spatially com-

plex systems (90). We argue that recovery frameworks that are similarly scale-integrated and distributed are suited to enhancing resilience in marine social-ecological systems because of their inherent modularity and heterogeneity.

#### *Coordinating at large scales and across boundaries*

Especially for mobile and migratory organisms, effective recovery measures will necessarily involve coordination among multiple entities and across jurisdictions (91). Large-scale ocean zoning, integrated single-species and ecosystem management plans, and multinational marine networks provide comprehensive tools that offer advantages compared to localized efforts. For example, the effectiveness of small, uncoordinated protected areas can be undermined by wider ecosystem degradation and, in some cases, may merely displace damaging activities. By contrast, broader marine spatial planning can avoid these pitfalls by strategically and comprehensively coordinating ocean activities, protecting key recovery priorities, and weighing broader social-ecological trade-offs (92). Range shifts will likely require new bilateral and multilateral governance frameworks (93). To avoid conflict over who is responsible for—and reaps the benefits of—shifts in ongoing marine recoveries, responsible governments should be proactive in collaborating to share data, standardize monitoring efforts, and coordinate recovery measures (93).

#### *Leveraging local knowledge and values*

Finally, local communities can share responsibility for setting recovery targets and enforcing marine resource management rules with institutions like national governments. Such local efforts may be more suited to leveraging traditional cultural practices around recovery. In Easter Island, recovery of open ocean fisheries is hampered by the fact that centralized fisheries management does not align with traditional practices and beliefs of the Rapanui (94). By contrast, traditional taboos on certain fishing practices show promise for engaging effective participatory recovery planning, as these practices better align with cultural norms. Incorporating traditional taboos on certain fishing practices into local recovery planning can be an effective tool for integrating governance and participatory management.

#### **Conclusions**

Living marine systems are critical to human well-being, and restoring them is a pressing societal concern. To achieve success, efforts toward marine recovery will need to confront the challenges of a dynamic and heterogeneous recovery seascape and acknowledge that marine recoveries can affect social groups in divergent ways. The prospect of degraded marine ecosystems, cycles of conflict over dwindling ocean resources, and increasing inequity offers one (grim) vision of our future. But this future is not inevitable (95): Strategic action and forward-looking management offer hope for hitting moving targets in marine recoveries. Successful recoveries can, in turn, enhance the delivery of marine services, consistent with diverse

sociocultural values, while maintaining the ecological integrity of our ocean.

Achieving the promise of recovery in tomorrow's ocean will require a strategic, nuanced, and flexible conceptualization of recoveries that can keep pace with rapidly changing physical, ecological, and social systems. In some cases, an altered world means there is no possibility of turning back the clock to simply reverse degradation. In these cases, we must be realistic about navigating the remaining pathways to an altered yet diverse, productive, and functional ecosystem. This is not the same as giving up on nature. Rather, embracing an inclusive and forward-looking perspective of recoveries offers the best chance for navigating toward a resilient future for nature and people.

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## Ocean recoveries for tomorrow's Earth: Hitting a moving target

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### Ocean recoveries are moving targets

As the human population has grown, our demands on the ocean have increased rapidly. These demands have similarly increased the pressure we place on these systems, and we now cause considerable damage globally. If we want to maintain healthy ocean ecosystems into the future, we must learn to use ocean resources in a sustainable way and facilitate recovery in regions that have declined. Determining how to make these goals a reality, however, is no small challenge. Ingeman *et al.* review the challenge presented by attempting both to recover and to use ecosystems simultaneously and discuss several approaches for facilitating this essential dual goal.

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