COMMENTARY

Throwing back the big ones saves a fishery from hot water

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In Lewis Carroll's *Alice in Wonderland*, the Mock Turtle and the Gryphon teach Alice a dance in which everyone partners with a lobster and then throws it "as far out to sea as you can" (1). While the "porpoise" (as the Mock Turtle pronounces "purpose") of throwing lobsters never becomes entirely clear in the story, Le Bris et al. (2) show in PNAS that the century-old practice of returning large and female lobsters back to the waters of Maine has primed the fishery to thrive in the face of climate change (Fig. 1). Their contribution provides key insight that can guide more widespread climate adaptation in fisheries.

Climate change has already reshuffled ecosystems globally, and past and ongoing emissions will continue to drive substantial warming and other environmental changes over the next few decades. One of the challenging questions is therefore whether and how to adapt human activities across a wide range of sectors, from agriculture to water supply, air travel, and coastal development. Fish are the most highly traded food commodity and the largest human food source based on wild species, so fisheries provide a particularly interesting and challenging sector in which to consider climate change adaptation. Fisheries are also one of the most tightly coupled social-ecological systems, with ecological dynamics that strongly affect human behavior, and vice versa.

In the literature on climate change impacts, one of the striking findings has been how quickly marine ecosystems are responding to even relatively small environmental changes in temperature, oxygen, and carbonate chemistry. While the oceans are warming relatively more slowly than are terrestrial ecosystems, marine species are adapted to thermal environments that are substantially more stable as well. This relative historical stability means that even a small amount of warming is large compared with the experience of an organism or the history of an evolutionary lineage. The ecological consequences of current ocean warming have been dramatic; as one example, marine species are moving into new regions a full 10-fold faster than are species on land (3).

Research to date has largely highlighted negative impacts of climate change on fisheries, including (as a

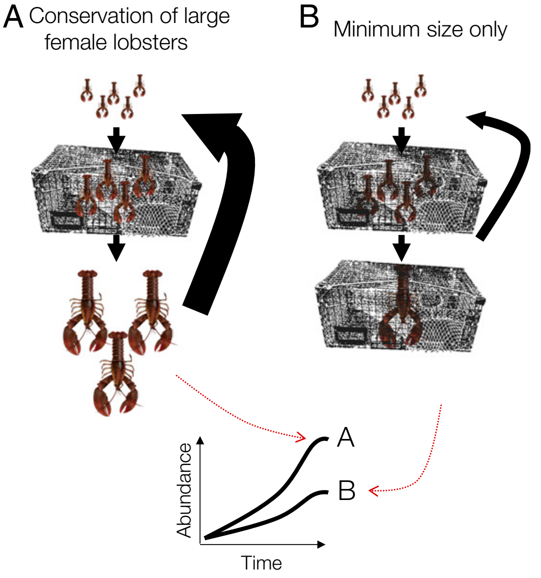

Fig. 1. Illustration of how conservation of large female lobsters may have prepared the Gulf of Maine fishery to flourish as environmental conditions changed. Large females contribute disproportionately to the production of young lobsters and allowed the population to grow more rapidly in favorable conditions (A) than it would have if large females were also harvested in lobster traps (B). Most fisheries only use a minimum size limit, as did the southern New England lobster fishery for many years. However, other mechanisms, including differences in thermal conditions, predators, and disease burden, also contribute to explain the contrasting trajectories of Maine and southern New England lobster populations.

small sampling) an ongoing trade war between Iceland and the European Union over a potentially ocean warming-driven shift in mackerel distribution (4), projected future global declines in fisheries catch (5), and intensified patterns of overfishing (6). In contrast, Le Bris et al. (2) show that the American lobster fishery, in addition to being one of the most valuable fisheries in the United States and Canada, is a welcome example of ocean optimism. Despite over a century of

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predictions of imminent fishery collapse, lobster abundance and fishery catches in Maine have been high and increasing for decades. Tight social networks, strong social norms for conservation behavior, clear mechanisms for collaboration between fishers and managers (co-management), and the biology of the species contribute to this success. Concerning signs have emerged in a nearby lobster fishery, however. After a series of particularly warm summers, the Long Island lobster fishery collapsed in 2000 and has not recovered. Warm temperatures elsewhere in southern New England have also been blamed for recruitment failures.

Le Bris et al. (2) examine the reasons for these contrasting dynamics with a sophisticated population dynamics simulation model for lobster. Their results suggest that recent and contrasting population trends in the Gulf of Maine (increasing abundance) and southern New England (declining abundance) can be explained largely by the warming each region has experienced. The Gulf of Maine has historically been a bit colder than lobster-preferred temperatures, so recent warming has helped to increase the proportion of lobster eggs that survive to become juveniles. In contrast, southern New England was already warm, and further warming has made the waters too hot for lobster. The eastern coast of North America has the steepest coastal latitudinal temperature gradient in the world (7), which helps explain why these adjacent lobster populations have such contrasting dynamics.

Importantly, the results from Le Bris et al. (2) go far beyond such direct temperature impacts. While harder to validate, the use of a simulation model allows them to play "what if" games and to show, for example, that the outbreak of a disease in southern New England appears to have contributed to the lobster decline there. In addition, the removal of predators in the Gulf of Maine has likely contributed to the recent boom in the population further north. Both the appearance of shell disease and the presence of a diverse, less fishing-sensitive assemblage of predators in southern New England are themselves linked to thermal habitat conditions (2, 8), and so represent indirect impacts of the environment that are sensitive to climate change. Recognition of the importance of such indirect climate change impacts has been growing in the scientific community (9).

While the effect on lobsters has been positive, it is also worth noting that historical overfishing of predators like Atlantic cod in the Gulf of Maine has also greatly reduced the diversity of the ecosystem and the diversity of economic options available to coastal fishing communities. The Gulf of Maine has become a lobster monoculture in some ways. Other researchers have warned that such monocultures are prone to collapse (10), including through infection by disease or by the invasion of new predators. The simulations by Le Bris et al. (2) suggest that neither shell disease nor southern predators would cause great declines in future Gulf of Maine lobster populations, although the potential for unexpected dynamics far beyond those envisioned in a simulation must be taken seriously.

Beyond disease and predators, Le Bris et al. (2) also suggest that the strongest species interactions are with humans, and it is here that a bright spot for the future of lobster is to be found. As anyone who has been to the coast of Maine can attest, lobster traps are abundant (around 3 million, in fact). Buoys densely pack the surface of bays, and boats gingerly weave past. For lobsters of the right size, therefore, being caught is highly likely. However, the "right size" for a lobster in Maine not only depends on being large enough (as is common in many fisheries) but also on being small enough (Fig. 1). Such regulations are called slot limits. In addition, female lobsters are marked and returned to the ocean. The slot limits and female conservation efforts are unique features of the Maine fishery and are representative of a natural resource management story with a fascinating social, cultural, and legislative history (11, 12).

Once protected, the large female lobsters serve as a long-lived, stable source of offspring to continue replenishing the population. Lobsters, similar to nearly all marine animals, have indeterminate growth, which means that they continue growing their entire lives. While the typical lobster that appears on a dinner plate weighs only 0.5–1 kg, the largest caught [19 kg (13)] weighed perhaps as much as four Cheshire cats. With egg production proportional to volume, large lobsters produce orders of magnitude more eggs than small lobsters. Le Bris et al. (2) suggest that about half of the Gulf of Maine increase in lobster abundance can be attributed to the conservation of large females, while about a quarter of the decline in southern New England, which until recently had no upper size limit, could have been prevented by protection of large lobsters.

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Conserving what are sometimes called "big, old, fat, fecund female fish," or lobster in this case, has been proposed before as a fisheries management and marine conservation approach. The fecundity contribution of large individuals can make marine reserves more profitable for fisheries management (14); has played a key role in arguments for "balanced fishing" across species and fish sizes; and can mitigate fisheries-induced evolution of small, early-maturing fish. The presence of large fish also reduces population variability and makes populations less sensitive to climate variations (15). The advance contributed by Le Bris et al. (2) is to show quantitatively that these same strategies not only mitigate the negative impacts of long-term warming but also accentuate the positive benefits when warming is a net benefit. Conservation of large individuals can therefore be a powerful climate adaptation strategy. Other strategies that have been proposed include dynamic adjustment of fishing levels, efforts to maintain spatial and functional diversity within populations, efforts to protect habitat, and the use of precautionary harvest levels (16).

Many climate adaptation strategies rely upon predicting future conditions. The northwest Atlantic, and particularly the Gulf of Maine, is a global "hotspot" of ocean warming (6). These hotspots provide valuable natural laboratories for understanding the complex impacts of climate change on marine ecosystems and the coupled social-ecological systems of which they are a part (17). Regional temperature trends have to be interpreted carefully, however, in part because they are the combination of both anthropogenic warming and natural climate variation like that from El Niño, the Pacific Decadal Oscillation, or the Atlantic Multidecadal Oscillation (AMO). Such climate variability signals appear more strongly at regional scales than in global averages. A warming hotspot right now is therefore not necessarily going to continue warming rapidly.

Even though the unique oceanography of the northwest Atlantic suggests that this particular region will warm rapidly over the long term (18), this region has also experienced a half-century of warming driven by the AMO (an ∼50- to 60-y climate cycle) and is now in a particularly warm phase. Interesting questions remain whether a switch to an AMO cooling phase would provide decade-scale cooling, even though it would not prevent long-term warming driven by greenhouse gas emissions. Global climate projections, which do not attempt to account for climate variability in any detailed way, suggest that the Gulf of Maine will hit +2 °C by 2060 (as measured relative to the 1982–2011 average temperature) (19). In contrast, observations suggest that the Gulf of Maine is already +1–2 °C (6), implying that midcentury conditions are already being experienced but may not persist. These discrepancies between reality (which includes climate cycles) and average climate projections (which often do not) illustrate some of the challenges of basing climate adaptation decisions in fisheries or other sectors around attempts at a detailed knowledge of the future. The future is unlikely to have monotonic changes in temperature, and especially in complex social-ecological systems, the future is almost guaranteed to produce surprises. Generic adaptation strategies that work well under a wide range of conditions, such as the conservation of large individuals, are a better bet than solutions optimal under a narrow range of conditions.

As the research community continues to understand how coupled social-ecological systems adapt to climate change, important progress will also be made by focusing attention on how humans respond to ecological change. This is not an area Le Bris et al. (2) examine, but the dynamics of human behavior and their responses to environmental change can qualitatively alter the outcomes that are possible (20). Existing research has begun to suggest common features of how fisheries respond to climate change, including fisheries that lag behind ecological changes (21). Other fascinating social, political, and cognitive dimensions influence how scientific evidence is interpreted in fisheries management and translated into goals and management measures (22). We are already headed down the rabbit hole of climate change, and how we choose to adapt, or not, to the ongoing changes will determine whether the oceans continue to provide abundant seafood, support vibrant coastal economics, and provide inspiration for generations.

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