COMMENTARY

Diversification spins a heatwave safety net for fisheries

Malin L. Pinsky[a,1]

Both stock markets and ecosystems experience shocks. Some shocks spark dramatic recessions or ecological collapse; others are just small bumps in the road of history. Understanding why some systems are fragile and others resilient to shocks is a major question across research fields, from economics to engineering, ecology to climate science (1). In PNAS, Fisher et al. (2) leverage a natural experiment involving crabs, fishing communities, and an extreme climate event to provide insight. The findings provide lessons for adaptation to climate change and an elegant validation of predictions from network theory. A key finding is that the least vulnerable systems are those that are more connected, are more modular, and rely on a larger set of resources.

Despite the relatively steady global increase in temperatures, most ecological and social impacts occur during extreme climate events like storms, floods, and heatwaves that push ecological and social systems beyond their typical tolerances (3). Unfortunately, heatwaves in the ocean have already become 20-fold more frequent as a result of anthropogenic climate change (4). Because fisheries directly harvest wild animals, they are tightly coupled to oceanographic and biological conditions. This fact makes disruptions from extreme events particularly clear in fisheries.

One particularly notable heatwave nicknamed the "Blob" struck the Northeast Pacific from 2014 to 2016, with cascading ecological impacts that ranged from very low ocean productivity to high mortality in seabirds and salmon, altered whale migrations, and a harmful algal bloom along the West Coast of the United States (5, 6). The algae were then eaten by Dungeness crabs and other animals, contaminating the meat with toxic domoic acid and forcing the closure of the lucrative crab fishery for months. With a massive closure to one of the most valuable fisheries on the West Coast, the economic shock to coastal communities and individuals was potentially extreme. The question is how they coped and who was most affected.

To answer this question, Fisher et al. (2) dig into more than 286,000 records from individual fishing trips to quantify fishing vessel behaviors. Vessels generally responded to the closure in one of three ways: catching a species other than crab, moving to a new location to continue fishing, or temporarily stopping fishing altogether. More than half of all boats in Northern California stopped all fishing, a clear indication of the disruption caused by the closure. This "duck-and-cover" strategy is simple to use, but cannot be tolerated for more than short disruptions. Overall, these three strategies mirror bottom-up adaptation behaviors observed across a wide range of fisheries (7). Changing to catch new species or moving to new locations are both

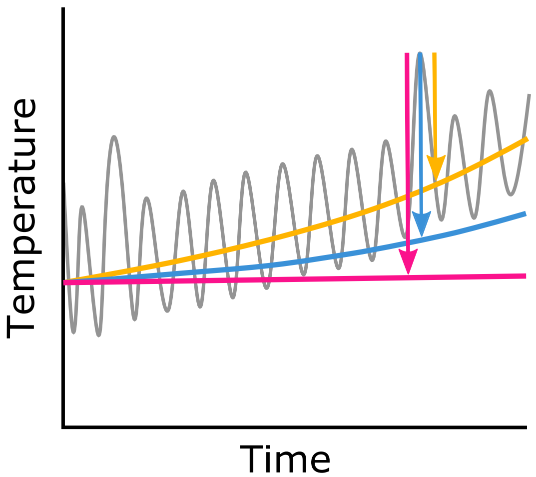

Fig. 1. The ecological and societal impacts of future heatwaves depend not only on responses to each single event but also on long-term adaptation to climate change. In this conceptual figure, gray represents temperature through time with two heatwaves shown (early on the left and later on the right). If ecosystems, human institutions, and economic systems remain structured for the average climate of the past (flat magenta line), heatwaves in the future will have even more drastic impacts than are experienced now (magenta arrow). If ecosystems and societies adapt to new average conditions (yellow line), impacts will be similar to today (yellow arrow). Reality is likely to be somewhere in between (blue line and arrow).

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promising responses because they allow fishing and income generation to continue, but these behaviors are often difficult to implement in practice (8). Catching new species can require new equipment, new knowledge, or new permits, all of which are often not available on short notice. Moving to new locations requires local ecological knowledge for how to fish in the new area, and may require new permits and leaving behind social ties, family, or friends.

Fisheries are sometimes caricatured (and managed) as a single species of fish caught by a group of similar boats, each owned and operated by a captain coming from a single port. In reality, fisheries are complex webs of interactions. Fish and other animals compete, eat, and are eaten. Boats often catch many species, either at the same time or at different times, and work out of many ports. Captains and crew may work on one or many boats and may be different from the owners. Supply chains stretch across the world to deliver materials to the fishing boats and to transport their catch to processors and markets. These interactions mean disruptions in one place (e.g., the Dungeness crab fishery) can ripple outward to affect other species, other places, and other people (9).

Rather than breeding chaos, however, the key insight is that such complexity can actually make the system more predictable. As network theory posits, the topology of these interactions provides clues as to where the impacts of climate shocks will be felt most strongly. Fisher et al. (2) construct participation networks that reveal which fishing vessels catch which species in which ports. The nodes in these networks represent a fishery, defined for this purpose as a set of species caught with a particular type of fishing gear from a particular port or group of nearby ports. The lines connecting them are vessels that participate in both fisheries. In some fishing communities, vessels participate in many fisheries, and the networks have what is called high connectedness (many edges). Other networks have low connectedness, and vessels participate in just one or a small number of fisheries.

This connectedness provides a key predictor for where climate shocks will be felt most extremely. In communities with high connectedness before the heatwave, vessels used existing patterns of behavior to shift away from Dungeness crab during the heatwave and catch other species instead. In communities with low connectedness, disruptions were more acute, including more vessels that stopped fishing entirely. Connectedness, in this case, provides a metric of diversification, and greater diversity has been linked to greater stability across a range of ecological and social–ecological systems (10–12). Network size (the number of nodes) is another metric of diversification that was also linked positively to fewer fishery disruptions during the heatwave.

Beyond diversification, however, concepts of contagion are also important. Modularity refers to the extent to which networks are divided into subgroups of tightly connected nodes that are then weakly connected to other subgroups. Modular networks tend to contain the impacts of a shock to the subgroup (low contagion), without the shock propagating throughout the entire network (high contagion). The 2007–2008 global financial crisis has become a key example of contagion: Without modularity in the finance system, a financial crisis in part of the US economy quickly spread to engulf nearly all economic sectors around the world (13). Among fishing communities, smaller disruptions from the crab fishery closure were felt in communities with greater modularity.

These disruptions from the northeast Pacific heatwave and the features that made fishing communities more resilient can be seen as a test run for the future. Marine heatwaves are already more common than in previous decades, and events that used to happen only once every hundreds to thousands of years may happen every year or decade with 3 °C of further global warming (4). These short return times may devastate not only fisheries but also coral reefs and other ecosystems around the world (14). However, marine heatwaves are becoming more common primarily because average temperatures are increasing, and, therefore, natural variation around those higher averages is more likely to exceed a given threshold (Fig. 1) (4, 15). Increased heatwave frequency is generally not attributed to greater variability around the mean.

Understanding why some systems are fragile and others resilient to shocks is a major question across research fields, from economics to engineering, ecology to climate science. In PNAS, Fisher et al. leverage a natural experiment involving crabs, fishing communities, and an extreme climate event to provide insight.

To understand the impact of future heatwaves, we therefore need to think about not just the acute heatwave events but also the slow processes of social–ecological adaptation to increasing average temperatures (Fig. 1). Fisheries and other social–ecological systems may remain configured as they are today (Fig. 1, magenta line), with fishing boats geared up to catch species that become increasingly rare in the local ocean as they shift poleward, local markets only ready to accept these traditional species, and regulations only allowing or incentivizing targeting such species. Regulations for some species on the East Coast of the United States and in Europe, for example, allocate fisheries access based on fixed historical rather than current conditions (16). In this case, future marine heatwaves will be huge disruptions from an increasingly distant historical state (Fig. 1, magenta arrow).

On the other hand, social–ecological systems could adapt smoothly to the new mean states, with species expanding poleward as conditions become favorable, fishing vessels equipped to catch these new species, markets ready to buy them, and permits available to access them legally (Fig. 1, yellow line). Transferable quotas like those used for some tunas could provide a useful adaptation mechanism within fisheries (17, 18). In this idealized case, marine heatwaves would be no more disruptive than they are now (Fig. 1, yellow line).

Reality is likely to be somewhere in between (Fig. 1, blue line and arrow). Ecosystems have both fast-adapting components like phytoplankton and slow-adapting components like long-lived rockfishes or slow-dispersing kelps. Fishing vessels often change behavior quickly, but regulations and laws change much more slowly (7, 19).

For these reasons, the lessons from the Dungeness crab fisheries will become even more critical over the coming years and decades, and more attention and research on strategies for incentivizing diversification and modularity is needed. In addition, suitable forecasts of climate and ecosystem states over months, years, and decades will be important for informing not just fishers but people and institutions throughout society (20).

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1 R. M. May, S. A. Levin, G. Sugihara, Complex systems: Ecology for bankers. *Nature* **451**, 893–895 (2008).
2 M. C. Fisher, S. K. Moore, S. L. Jardine, J. R. Watson, J. F. Samhouri, Climate shock effects and mediation in fisheries. *Proc. Natl. Acad. Sci. U.S.A.*, 10.1073/pnas.2014379117 (2020).
3 D. R. Easterling *et al.*, Climate extremes: Observations, modeling, and impacts. *Science* **289**, 2068–2074 (2000).
4 C. Laufkötter, J. Zscheischler, T. L. Frölicher, High-impact marine heatwaves attributable to human-induced global warming. *Science* **369**, 1621–1625 (2020).
5 L. Cavole *et al.*, Biological impacts of the 2013–2015 warm-water anomaly in the northeast Pacific: Winners, losers, and the future. *Oceanography (Wash. D.C.)* **29**, 273–285 (2016).
6 R. M. McCabe *et al.*, An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophys. Res. Lett.* **43**, 10366–10376 (2016).
7 T. Young *et al.*, Adaptation strategies of coastal fishing communities as species shift poleward. *ICES J. Mar. Sci.* **76**, 93–103 (2019).
8 G. D. Murray, T. R. Johnson, B. J. McCay, K. St. Martin, Creeping enclosure, cumulative effects and the marine commons of New Jersey. *Int. J. Commons* **4**, 367–389 (2010).
9 E. C. Fuller, J. F. Samhouri, J. S. Stoll, S. A. Levin, J. R. Watson, Characterizing fisheries connectivity in marine social-ecological systems. *ICES J. Mar. Sci.* **74**, 2087–2096 (2017).
10 M. Loreau, C. de Mazancourt, Biodiversity and ecosystem stability: A synthesis of underlying mechanisms. *Ecol. Lett.* **16** (suppl. 1), 106–115 (2013).
11 D. E. Schindler *et al.*, Population diversity and the portfolio effect in an exploited species. *Nature* **465**, 609–612 (2010).
12 T. J. Cline, D. E. Schindler, R. Hilborn, Fisheries portfolio diversification and turnover buffer Alaskan fishing communities from abrupt resource and market changes. *Nat. Commun.* **8**, 14042 (2017).
13 A. G. Haldane, R. M. May, Systemic risk in banking ecosystems. *Nature* **469**, 351–355 (2011).
14 T. P. Hughes *et al.*, Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science* **359**, 80–83 (2018).
15 M. A. Alexander *et al.*, Projected sea surface temperatures over the 21st century: Changes in the mean, variability and extremes for large marine ecosystem regions of northern oceans. *Elementa* **6**, 9 (2018).
16 B. A. Dubik *et al.*, Governing fisheries in the face of change: Social responses to long-term geographic shifts in a U.S. fishery. *Mar. Policy* **99**, 243–251 (2019).
17 M. L. Pinsky *et al.*, Preparing ocean governance for species on the move. *Science* **360**, 1189–1191 (2018).
18 T. Aqorau, J. Bell, J. N. Kittinger, Good governance for migratory species. *Science* **361**, 1208–1209 (2018).
19 M. L. Pinsky, M. J. Fogarty, Lagged social-ecological responses to climate and range shifts in fisheries. *Clim. Change* **115**, 883–891 (2012).
20 D. Tommasi *et al.*, Managing living marine resources in a dynamic environment: The role of seasonal to decadal climate forecasts. *Prog. Oceanogr.* **152**, 15–49 (2017).