Climate change complicates fisheries modeling and management

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Denmark, Ireland, Norway, and multiple other nations didn't see the fish war coming. In 2011, in the waters and fjords of east Greenland, fishermen began spotting a blue-green iridescent fish. It was mackerel, a species that had never before been caught so far north. By 2014, the fish was one of Greenland's most valuable exports, generating $100 million in sales (1).

Mackerel had previously ranged in the balmier waters off the Faroe Islands, Denmark, Iceland, Norway, and Scotland. Dating back to 1999, these nations had an agreement divvying up the fishery. Then as the ocean warmed, the stock began expanding northward, first to Iceland in 2009 and then to Greenland (2).

A carefully arranged agreement was suddenly in disarray. After Iceland and Greenland set up their own quotas, the historic mackerel nations tore up their agreement and sanctioned the new entrants for daring to hunt the fish. Efforts to renegotiate a new contract and set a collective, sustainable catch limit have failed. Mackerel is now being overfished by 48% above sustainable levels (1). "The stock will decrease if the fishery continues at this rate," says Teunis Jansen, a fisheries scientist at the Technical University of Denmark. "But there is no country that has an interest in being responsible and cutting down on their national quotas."

The case of the mackerel has analogs elsewhere. The blueline tilefish, which was once found only in the southeastern United States, has shown up north of Cape Hatteras. The black sea bass, which used to be centered off Virginia, is now centered off New Jersey. As climate change has heated up the oceans, some of the world's most valuable fisheries are declining in productivity or shifting their distribution, thereby pitting nations, states, and fishermen against one another.

But there is hope. If governments manage their coastal resources well, fisheries globally could rebound by 2100, even in a warming world, according to new research based on a comprehensive modeling initiative that incorporates fisheries science, economics, and climate change. "This is added motivation to

Starting around 2009, climate-induced migration of mackerel stocks sparked squabbles among several nations that had traditionally shared the fishery. Image courtesy of Shutterstock/Rich Carey.

get our act together and fix fisheries because if we do that, the future can be more prosperous than today," says Steve Gaines, a fisheries scientist at the University of California, Santa Barbara.

Calculating the Consequences

Gaines and his colleagues are building on a 2016 study in which they found that fisheries globally could become profitable and sustainable within decades, if only nations would better manage their resources (3). Initially, the researchers did not account for the impacts of climate change, but have now redone the study to include warming.

Gaines and his colleagues used a so-called "climate upside" bio-economic model that projects how fisheries would fare both economically and biologically over the next century under various climate change and management scenarios. The model takes into account economic, fishery, and climate change data to project fishery health 100 years hence.

Global warming could affect fish stocks in two ways: it can reduce productivity if fewer juveniles enter a population relative to older fish; it could also change a stock's preferred locale, as seen in the mackerel case.

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> —Jake Kritzer

Researchers modeled the future of about 1,000 commercial stocks. The upside model projected that in a warming world under current management practices, the productivity of some stocks in 2100 would improve but others would decline. A 2 °C warming would have a slightly negative effect on overall ocean productivity, Gaines says. It could also trigger a geographical redistribution of some species, away from the tropics and toward temperate regions and the poles, the scientists found. Of some 700 commercial fish species, almost half might move from their present locations, according to Harte.

When Gaines and his colleagues input a scenario in which governments proactively manage their fisheries, the model spit out a rosier picture. If governments curb carbon emissions and manage their fisheries well, stocks in 2100 would be healthier than they are today. Fisheries' fate rests on good management, but getting it right is not easy.

Fisheries on the Edge

History has shown the potential benefits of careful management, as well as its limits. Only one in three fisheries around the world are in good biological condition today; proactive management practices have prevented things from getting worse.

But such practices do have their limitations. The yellowtail flounder stock off Georges Bank in New England, for example, is one of the less fortunate. In the mid-1990s, managers realized that groundfish stocks, including the flounder and haddock, might collapse unless they reduce catch limits and create protected refuges. The measures worked for many species, but not for the yellowtail flounder.

One reason may be climate-driven changes, says Jake Kritzer, a fisheries scientist with the Environmental Defense Fund. Sea-surface temperature in the Northeast United States has risen by 0.23 °C since 1982. Meanwhile, the Labrador Current, which carries Arctic sea ice melt into the Gulf of Maine, has brought more freshwater and made the ocean less saline. Combined with overfishing, these environmental changes have affected the productivity and distribution of many stocks, such as the yellowtail, Kritzer says. Surveys have shown that fewer yellowtail juveniles are reaching an age where they can be counted toward the fishery.

Typically, managers use stock-assessment models that simulate a species' abundance in an idealized ecosystem and set catch limits. Unlike the big-picture bioeconomic model used by Gaines and his colleagues, these models are specific to particular regions and species.

But the fisheries model for the yellowtail flounder seems to have failed because it underestimated fishing mortality and overestimated biomass, leading to uncertainty about the current status of the population. The council decided to stop using it for catch advice in 2015. "For those stocks that are not doing so well, the scientific uncertainties are incredibly problematic," Kritzer says. "It erodes confidence among the fishermen in the management measures that are being put forth, and it strains the relationship between scientists, fishery managers, and industry."

An Uncertain Future

In general, fisheries models assume that the environment varies, but only within constant bounds and in a nondirectional manner. So conditions that favor a species one year might reverse and hinder it another year, but the shifts will average out over time.

But as climate change impacts accumulate, the environment is changing in a directional manner. This fundamentally violates the assumption of environmental stability in the models, says Malin Pinsky, a fisheries scientist at Rutgers University in New Jersey. Scientists do not yet fully understand how climate shifts affects species, as some are moving toward the poles rapidly whereas others are staying put or shifting slowly. Rapid temperature changes in many parts of the world create hard-to-predict scenarios. "In many places, fisheries management hasn't been ready for that," he says.

Compounding the uncertainty, some species are inherently difficult to survey, particularly ones that are changing their distribution. Counting fish can be like "counting trees in the forest, except you can't see them and they move," says Sean Anderson, a fisheries scientist at the Pacific Biological Station in British Columbia.

Fisheries models also do not account for sudden, unforeseen population crashes—also known as "black swan events"—that routinely happen in all animal populations, says Anderson. Such events could be triggered by external causes, such as sudden climatic change or the arrival of an invasive species that damages the ecosystem (4).

Even so, the models have proved useful in managing large, commercially important fisheries for which excellent data from careful surveys are available. The models are less useful when the data quality is poor, as in tropical fisheries. And they cannot precisely answer the questions most relevant to fishermen: What does climate change mean for their fishery today and into the future?

"If fishermen say, 'How many sardines would be here in 7 years' time?' we probably couldn't say," says Michael Harte, a fisheries scientist at Oregon State University, who has served on the Pacific Fishery Management Council.

Fisheries Management 2.0

Knowledge gaps aside, there are policy tools available for managers that could help plan for a changing environment, Kritzer says.

Many managers today set catch limits such that a constant percent of the population is harvested every year. But if climate change affects the productivity of a population, it might be better to vary the fishing rate in response to population abundance, Kritzer says. When Kritzer and his colleague modeled this management scenario for stocks in New England, they found that the fishery fared better in the long run. "When we switch over to the world we think we're living in, where things are changing directionally, we actually may need to do things a different way," Kritzer says.

Tropical nations typically lack annual surveys and careful monitoring of stocks, limiting the data-driven approach. An alternate method is the "locally managed marine area," where coastal communities and fishermen manage their fishery using a mix of traditional knowledge, government buy-in, and nongovernmental organization support. For example, more than 500 communities across 15 island nations across the Pacific are managing a 12,000-square kilometer coastal zone. They have set aside 1,000 square kilometers as a no-take area where fish can reproduce and seed offspring into fishing zones.

Given arrangements like these, many scientists remain optimistic. Unlike the consequences of other complex environmental challenges, the oceans' health has shown the capacity to recover rapidly—within decades—once action is taken. "I've seen what happens when people work together to allow fish stocks to rebuild," Harte says. "The fishermen benefit, the economy benefits, the ecology benefits."

1 Jansen T, et al. (2016) Ocean warming expands habitat of a rich natural resource and benefits a national economy. *Ecol Appl* 26:2021–2032.

2 Jansen T, Frost H, Thøgersen T, Andersen JL (2015) Game theory and fish wars: The case of the Northeast Atlantic mackerel fishery. *Fish Res* 172:7–16.

3 Costello C, et al. (2016) Global fishery prospects under contrasting management regimes. *Proc Natl Acad Sci USA* 113:5125–5129.

4 Anderson SC, Branch TA, Cooper AB, Dulvy NK (2017) Black-swan events in animal populations. *Proc Natl Acad Sci USA* 114:3252–3257.