LETTER

Lagged social-ecological responses to climate and range shifts in fisheries

Malin L. Pinsky · Michael Fogarty

Abstract While previous research has documented marine fish and invertebrates shifting poleward in response to warming climates, less is known about the response of fisheries to these changes. By examining fisheries in the northeastern United States over the last four decades of warming temperatures, we show that northward shifts in species distributions were matched by corresponding northward shifts in fisheries. The proportion of warm-water species caught in most states also increased through time. Most importantly, however, fisheries shifted only 10–30 % as much as their target species, and evidence suggested that economic and regulatory constraints played important roles in creating these lags. These lags may lead to overfishing and population declines if not accounted for in fisheries management and climate adaptation. In coupled natural-human systems such as fisheries, human actions play important roles in determining the sustainability of the system and, therefore, future conservation and climate mitigation planning will need to consider not only biophysical changes, but also human responses to these changes and the feedbacks that these responses have on ecosystems.

1 Introduction

Some of the most important ecosystem services derived from the ocean are the seafood, employment, and support to local economies provided by marine fisheries. Substantial attention has focused on the impact that overfishing, habitat destruction, and other stressors have had on these services (Pauly et al. 2002; Worm et al. 2006), and on the value that can be gained by rebuilding overfished populations (Worm et al. 2009). Fisheries, however, also

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M. L. Pinsky (✉)
Department of Ecology and Evolutionary Biology, Princeton University, 106A Guyot Hall, Princeton, NJ 08540, USA
e-mail: pinsky@princeton.edu

M. Fogarty
Northeast Fisheries Science Center, National Marine Fisheries Service, Woods Hole, MA 02543, USA

rely upon species and populations that are sensitive to climate change (Sumaila et al. 2011). Substantial evidence suggests that warming climates are already pushing marine fishes poleward and deeper in ecosystems around the world (Dulvy et al. 2008; Nye et al. 2009; Perry et al. 2005), and models suggest that these shifts will continue (Hare et al. 2010; Lenoir et al. 2010; Cheung et al. 2010).

It is less clear, however, what impacts these biophysical shifts will have upon local fisheries and fishery-dependent economies and communities (Coulthard 2009). Fisheries are inherently social-ecological systems, and changes in management, technology, social structure, and economics have historically played dominant roles in determining the status of fisheries and the value we derive from them (Hamilton and Butler 2001; McCay et al. 2011; Grafton et al. 2008). Technology and fisherman behavior, for example, might buffer coastal communities from many of the impacts of shifting species ranges. For fishermen that already travel extensively to fishing grounds, following the fishing grounds poleward may be a low-cost climate adaptation strategy, particularly because switching to new species can be expensive, require new skills, or be difficult given existing processing, transportation or marketing infrastructure (Sumaila et al. 2011; Coulthard 2009). On the other hand, for fishermen that travel little, perhaps because of vessel size constraints or fuel cost considerations, shifts in species distributions may force them to switch to new species or leave the fishery entirely. In addition, regulatory or economic constraints may limit the adaptation strategies available to fishermen.

Previous research has shown that changes in climate impact fisheries, even though integrating climate into standard fisheries management has been substantially more challenging (Hilborn and Walters 1992). For example, fishermen in Monterey Bay catch more albacore (*Thunnus alalunga*) and albacore receives a higher price during warm El Niño conditions (Dalton 2001). In Chile and Peru, the 1997–98 El Niño led to a 50 % decline in fishmeal export that cost the economy \$8.2 billion (Sumaila et al. 2011). In Australia, lobster fishermen have traveled to deeper water in recent years, possibly because warming temperatures drove lobsters deeper (Caputi et al. 2010). Despite this evidence, it remains unclear how closely fisheries follow shifts in species' ranges and what factors affect their responses, particularly when those shifts occur across large spatial scales that span many different fisheries ports.

To test the extent to which shifting species ranges drive changes in fisheries, this paper examines coincident shifts in selected fish and marine invertebrate distributions and landings over the last 40 years in the northeastern United States. Sea surface temperatures warmed at 0.23 °C/decade from 1982 to 2006, or close to twice the global average (0.13 °C/decade), making this region a useful example for how fisheries and marine ecosystems may respond to global warming (Belkin 2009). By examining the distribution of both fish and fisheries, we detect effects on fisheries at broad scales, though without detailed data on fishermen behavior, we do not attempt to identify specific coping mechanism.

2 Methods

2.1 Species data

We chose lobster (*Homarus americanus*), yellowtail flounder (*Limanda ferruginea*), summer flounder (*Paralichthys dentatus*) and red hake (*Urophycis chuss*) for this analysis because these four species have exhibited significant poleward shifts in both

spring and fall bottom trawl surveys conducted by the National Marine Fisheries Service. Lobsters are relatively sedentary invertebrates primarily caught with pots in New England, while yellowtail flounder are relatively sedentary fish primarily caught in large-mesh otter trawls that target a range of demersal fishes. Summer flounder are seasonally migratory fish caught with otter trawls, primarily in southern New England. Red hake also migrate seasonally and are primarily caught with small-mesh otter trawls.

The bottom trawl surveys have been conducted since the 1960s on the continental shelf from Cape Hatteras, North Carolina to the Gulf of Maine. We only used data from survey regions consistently sampled throughout the survey. Further details of the sampling method can be found in Azarovitz (1981).

We characterized species distributions in each year by their mean latitude. Mean latitude was calculated as a biomass-weighted average latitude at which the species appeared in research survey tows. For simplicity of presentation, we averaged mean latitude across the spring and fall surveys.

2.2 Landings data

Commercial landings (metric tons) and value (dollars) were collated by state by the National Marine Fisheries Service for all coastal states from Maine to Virginia. Nominal value was converted to real value in 2010 dollars using the Consumer Price Index (All Items, Northeast). We calculated mean latitude of landings as the average latitude of the states in which the species was caught, weighted by biomass landed. We also calculated mean latitude of landed value. Latitude for each state was based on the location of its primary fishing ports.

2.3 Preferred temperature of species in landings

We also examined the preferred temperatures of species landed in each state (e.g., Collie et al. 2008). We conducted a literature review to determine the annual range of temperatures preferred by adults of the most abundant species in each state (Table S1). We used the midpoint of these ranges as the preferred temperature of each species. For each state in each year, we then calculated the averaged preferred temperature of species in the landings, weighted by either biomass of landings or by real dollar value of landings.

2.4 Analysis

We compared mean latitude from landings or landed value against mean latitude from surveys using standard linear regression. If fisheries shifted poleward at the same rate as the target species, we would expect a slope close to one.

We also used linear regression to relate the proportion of landings within each state to the mean latitude of each species. Our hypothesis was that northern states would receive a higher proportion of total landings as the species moved north (positive slope of landings vs. mean latitude) while southern states would receive a lower proportion (negative slope). Alternatively, there could be no relationship, or southern states could receive a higher proportion of the landings. The latter could occur if overfishing in the south caused the species to shift north. Proportional landings were arc-sin transformed to improve normality.

3 Results

3.1 Shifts in fisheries and shifts in species

Over the last four decades, all four species shifted northward, while landings and landed value also showed northward shifts (Fig. 1). Overall, the mean latitudes of landings and of the species were significantly correlated (Table 1, Figure S1), suggesting that both fisheries and their target species shift together.

However, landings and landed value showed much weaker shifts than did the target species. For example, landings of lobster and yellowtail flounder were centered in northern states from the beginning of the time series, even though the biomass of the target species was centered much further south. Landings then shifted northward only slightly as the species shifted north. Red hake landings were initially centered in southern states and
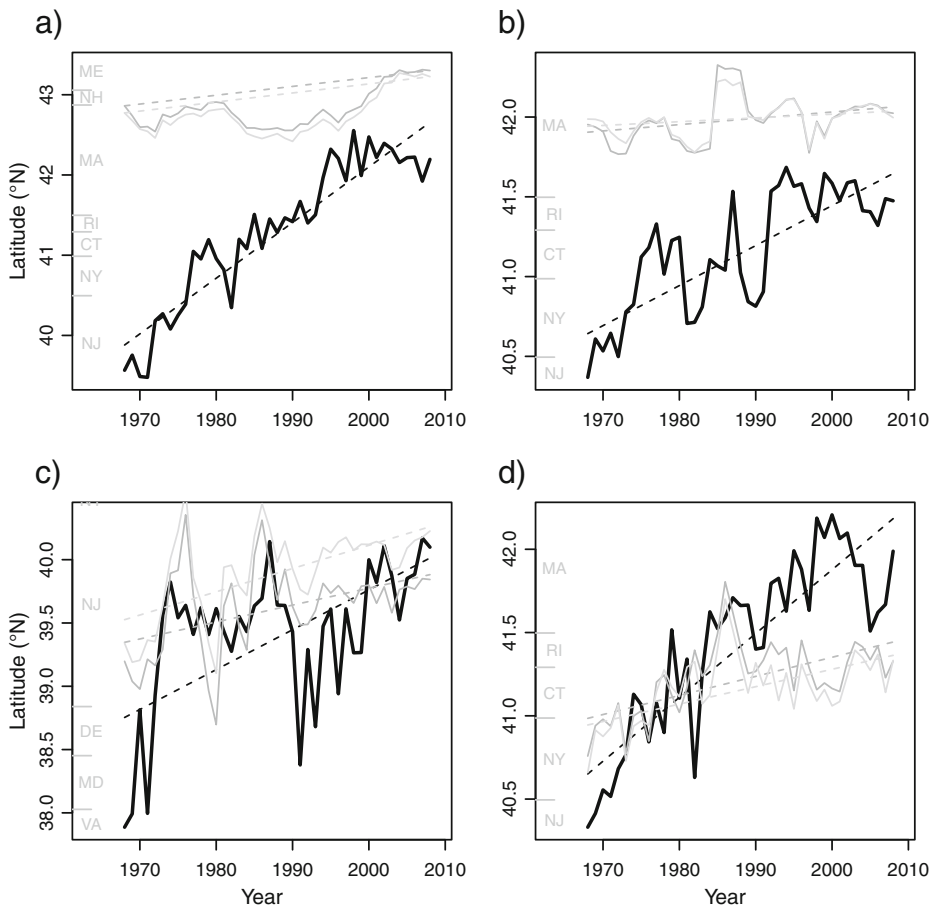

Fig. 1 Average biomass-weighted latitude from research surveys (*black*), average biomass-weighted latitude of the fisheries landings (*dark grey*), and average dollar-weighted latitude of the fisheries landed value (*light grey*). The species are **a**) American lobster (*Homarus americanus*), **b**) yellowtail flounder (*Limanda ferruginea*), **c**) summer flounder (*Paralichthys dentatus*), and **d**) red hake (*Urophycis chuss*). The latitudinal range of each state is shown on the left for reference. *Dotted lines* are best fits from linear models with autoregressive noise of order 1

Table 1 Relationship between the mean latitude of landings (or landed value) and the mean latitude of the species as determined from research surveys

Species	Metric	Δ° lat/Δ° lat in surveys	p-value
American lobster	Landings	0.132	0.001
	Landed value	0.125	0.003
Yellowtail flounder	Landings	0.165	0.007
	Landed value	0.110	0.021
Summer flounder	Landings	0.319	0.0006
	Landed value	0.386	<0.0001
Red hake	Landings	0.245	<0.0001
	Landed value	0.200	0.0005

showed a strong northward shift only until 1985, despite a substantial northward shift in the species' biomass that continued long after 1985. On average, for each degree of latitude that a species shifted, landings shifted only 0.13–0.32° (Table 1). Landed value also shifted little: only 0.13–0.39° per degree latitude shift in the species.

The shift in landings was also apparent when comparing the allocation of landings among states to the mean latitude of each species (Figure S2, S3). For lobster, yellowtail flounder, and summer flounder, northern states increased their proportion of total landings (positive correlation) and southern states decreased their proportion (negative correlation) as each species shifted northward. The exception was red hake landings in Massachusetts, which showed a proportional decline as red hake shifted northward.

3.2 Preferred temperature in state landings

Over time, the preferred temperature of species caught in Virginia, Rhode Island, Massachusetts, and Maine tended to increase from 1963 through 2010 (Fig. 2a). The trend was significant in Massachusetts and Maine ($p<0.004$), but not in Virginia ($p=0.059$) or Rhode Island ($p=0.43$). In contrast, New Jersey tended to catch more cold-water species over time ($p=4\times10^{-8}$).

Menhaden (*Brevoortia tyrannus*) dominated the landed biomass of Virginia and New Jersey and was also important in Rhode Island in the 1970s. Without menhaden, the preferred temperature of Virginia's landings increased significantly ($p=0.0003$), as did Rhode Island's ($p=0.0002$) (Fig. 2b). New Jersey's landings trended less strongly towards colder-water species without menhaden.

4 Discussion

Over the 40 years and the four cases we examined, fisheries in many ways responded predictably to poleward shifts in their exploited species. Northward shifts in the species were mirrored by northward shifts in fisheries landings and landed value, as has been predicted by models but rarely shown empirically. Northern states also received a higher proportion of the total landings and the total landed value as species shifted poleward. Finally, the mix of species landed in most states tended towards warmer-water species during a period when average water temperatures warmed. While a range of economic, social, regulatory, and biological factors affect fisheries landings, the relationships that we found imply that species
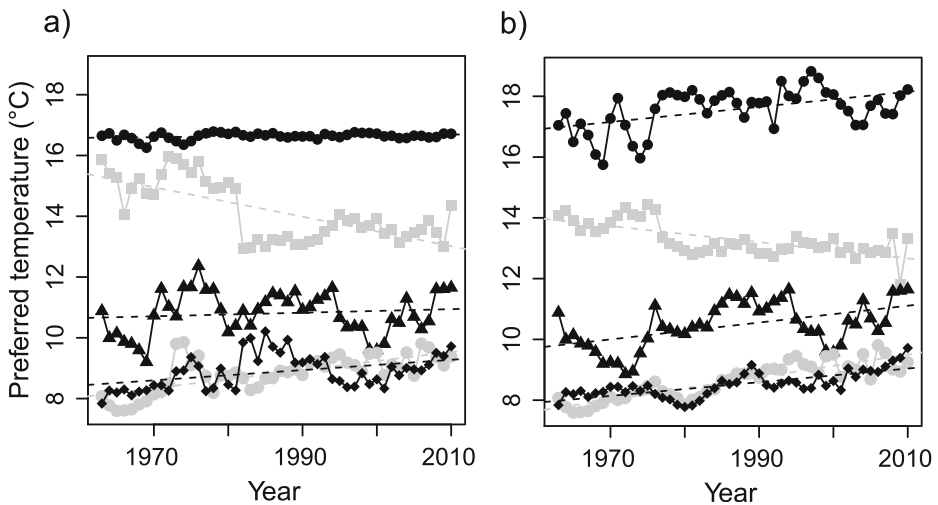
a)

b)

Fig. 2 Weighed mean preferred temperature of the species landed in each state for **a**) all species and **b**) all species except menhaden (*Brevoortia tyrannus*). States from top to bottom in each graph are Virginia (*black circles*), New Jersey (*grey squares*), Rhode Island (*black triangles*), Massachusetts (*black diamonds*), and Maine (*grey circles*)

range shifts have a strong and quantifiable impact that can already be observed in the fishing communities and coastal economies of the northeastern U.S.

At the same time, our analysis revealed exceptions to this general rule that highlight the important role of social, economic, and historical factors in mediating the ability of fisheries to respond to species range shifts. First, landings and landed value appear to have shifted poleward more slowly than did the exploited species. In the northeast U.S., climate velocity moved at rates of 20–100 km/decade from 1960 to 2009 (Burrows et al. 2011). This is approximately how quickly the four species we examined shifted northward (0.24–0.70° latitude/decade, or about 27–78 km/decade), but this is substantially faster than fisheries landings (0.03–0.08° latitude/decade, or 3–9 km/decade). For a fishery to shift northward, either individual fishermen have to change the primary port they use for landing fish or travel further from their current ports, poleward fishermen have to catch more fish, or equator-ward fishermen have to catch fewer fish. Given that fish are shifting north, but southern fishermen are not catching as many fewer fish as we would expect, this may imply that southern fishermen are fishing harder for those remaining fish. There is some evidence to suggest this has happened: while overall effort in northeastern demersal fisheries has declined in recent years as part of programs to halt overfishing, effort has declined more slowly in southern than in northern New England (Ecosystem Assessment Program 2012). This has shifted relative effort to the south, perhaps compensating in part for northward shifts in the target species. While this compensating behavior can slow the transition for a time, it will actually hasten the eventual shift if it leads to overfishing of southern populations.

In addition, regulations may limit the opportunities available to fishermen to shift poleward. For example, the red hake fishery did not shift northward as quickly as its target species, particularly as the species shifted into Massachusetts (Fig. 1d). Red hake is part of the "Small-mesh multispecies" fishery, and is excluded from most of the Gulf of Maine and northern Georges Bank due to bycatch concerns. The fishery therefore remains small in

Massachusetts, leading to few buyers and more generally, economic, regulatory, and practical barriers to entering the fishery (Andrew Applegate, personal communication, January 30, 2012). Similar restrictions are likely to affect other species when range shifts move populations across stock management boundaries (Link et al. 2011). In addition, the reduced fishing effort on the northern stock of red hake has likely helped it to increase rapidly as environmental conditions there have improved, further speeding the species' shift north. More generally, this reveals the substantial impact that regulatory and economic considerations can have in mediating a fishery's response to shifting species, and perhaps more importantly, the feedback that this fishery response can have on the exploited species.

The cooling trend in New Jersey landings also stands out as a surprise, but appears unrelated to changes in regional temperatures. In particular, Lucey and Nye (2010) analyzed the fish community in the Mid-Atlantic Bight (as sampled by scientific surveys) and found an increase in its mean preferred temperature since the 1960s, in direct contrast to the landings trend. Instead, the cooling trend in landings that we found appears to result from a number of coincident but unrelated social and economic factors. For example, consolidation in the menhaden industry led to the closing of a large processing plant in the early 1980s, causing a dramatic decline in landings for what had been the state's largest fishery, and one for a particularly warm-water species (NEFMC 2003). In addition, a lucrative export market for goosefish (*Lophius americanus*) developed in the mid-1970s (NEFMC 1998) and the offshore ocean quahog (*Arctica islandica*) and Atlantic mackerel (*Scomber scombrus*) fisheries recovered. These are all relatively cool-water species in New Jersey. For these reasons, the cooling trend in New Jersey landings appears to result from a confluence of economic and social events that reversed the general warming trend we saw in other states and that has been observed in the fish community offshore from New Jersey.

4.1 Projecting forward: economic and social impacts of shifting ranges

The historical range shifts we discuss are consistent with the types of changes we expect to become more common as the global climate warms, even if unambiguous attribution of these past changes to global warming is difficult at the moment (Henson et al. 2010). Studies predict the loss or severe decline of many iconic fisheries species from the northeast U.S. (Lenoir et al. 2010), while others predict the growth of fisheries for warm-water species (Hare et al. 2010). These trends may, in the short term, increase travel time for fishermen as previously nearby fishing grounds shift poleward, thereby increasing costs (Sumaila et al. 2011). Over the longer term, fishermen and the fishing industry more broadly will face the challenges and costs of adapting processing and fishing infrastructure as well as fishing gear to take advantage of the opportunities provided by new species.

In the face of uncertainty, fishermen have many coping strategies, including diversification among fisheries, joining together in cooperatives, and diversifying among sources of income (Coulthard 2009). Because species shift at different rates in response to climate, diversification among species should also smooth the adaptation of local fishermen to shifting species ranges. This will be easier for some fishermen than for others, depending in part on the specialization of their gear. Fishing for yellowtail flounder, summer flounder, and red hake requires similar boats (though different nets), and so there are fewer barriers to transitioning among species. Heavy investment in specialized gear for lobsters, on the other hand, limits these fishermen's options and may favor exiting the fishery altogether (Steneck et al. 2011). Other management measures that can foster adaptation include vessel buybacks, gear restrictions, reduction of perverse subsidies, and endowment funds (Sumaila et al. 2011). While new fishing opportunities provide an important replacement for declining

species, such transitions can also change the social dynamics of fisheries. For example, Newfoundland's transition from a largely cod-focused fishery to one targeting shrimp and invertebrates led to a greater concentration of fishing activities among fewer people, increased inequality between regions and between communities, and hastened outmigration of residents from fishing communities (Hamilton and Butler 2001).

Because fishing is a social-ecological system, the impacts of climate change must be considered in light of feedbacks between the behavior of fishermen and the species they exploit. Reduced fishing on newly arrived species will hasten their establishment, for example, and may prove beneficial in the long run if it allows a viable fishery to develop more quickly. On the other hand, continued fishing on trailing edge populations might prolong an existing fishery and ease the economic transition to new species, but may also trigger a disruptive population collapse. Under the knowledge that a trailing edge population will be extirpated, the individual incentive is to overfish the population before climate drives it to low abundance (Silvert 1977). While rational, however, that outcome may reduce the ability of other, poleward fishermen to exploit the species. The problem is exacerbated if the shift is across management boundaries. The "Mackerel Wars" in 2010 demonstrated this problem quite vividly: Icelandic fishermen began fishing a northward-shifting mackerel population while British fishermen resisted a reduction in their fishing quotas, thereby jointly threatening to overfish the population (Anonymous 2010). Future research will be needed on strategies that allow both fisheries and the species they exploit to adapt smoothly to global climate change, particularly in light of the feedbacks between the two.

In conclusion, we found clear evidence that changes in species distributions have bottom-up controls on the location and value of fisheries, but that social and economic factors introduce important lags and constraints on the ways that fisheries respond. Further efforts to plan ahead for impending changes will help to ensure that fisheries continue to sustain coastal economies as global temperatures warm.

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