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

Malin L. Pinsky (corresponding author)

Department of Ecology and Evolutionary Biology, Princeton University, 106A Guyot Hall, Princeton, NJ 08544

609-258-7436 (phone)

609-258-6819 (fax)

pinsky@princeton.edu

Michael Fogarty

Northeast Fisheries Science Center, National Marine Fisheries Service, Woods Hole, MA 02543

Keywords: *fisheries, range shifts, coupled natural-human systems, ecosystem services*

Abstract: 170
Main Text: 2,887
Figures: 2
Tables: 1
References: 30

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.

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 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 socio-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 1982-2006, 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.

Methods

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 mostly 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.

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.

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.

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.

Results

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 (Figure 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 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 degrees (Table 1). Landed value also shifted little: only 0.13-0.39 degrees 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.

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 ($p = 4 \times 10^{-8}$).

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.

Discussion

Over the forty 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 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 1960-2009 (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 & 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.

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 & Butler 2001).

Because fishing is a socio-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.

Acknowledgements

We thank Andrew Applegate for help understanding the red hake fishery, Mary Ruckelshaus and Peter Kareiva for insightful conversations during the development of this manuscript, and the many scientists, economists, and others who collected the bottom trawl and fisheries landings data analyzed in this paper. M.L.P. was supported by the David H. Smith Conservation Research Fellowship Program.

References

Anonymous (2010) Mackerel wars: overfished and over there. The Economist, September 4, 2010,

Azarovitz TR (1981) A brief historical review of the Woods Hole Laboratory trawl survey time series. Canadian Special Publication of Fisheries and Aquatic Sciences 58:62-67

Belkin IM (2009) Rapid warming of Large Marine Ecosystems. Prog Oceanogr 81:207-213

Burrows MT, Schoeman DS, Buckley LB, Moore PJ, Poloczanska ES, Brander KM, Brown CJ, Bruno JF, Duarte CM, Halpern BS, Holding J, Kappel CV, Kiessling W, O'Connor MI, Pandolfi JM, Parmesan C, Schwing FB, Sydeman WJ, Richardson AJ (2011) The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. Science 334:652-655. doi:10.1126/science.1210288

Caputi N, Melville-Smith R, de Lestang S, Pearce A, Feng M (2010) The effect of climate change on the western rock lobster (Panulirus cygnus) fishery of Western Australia. Can J Fish Aquat Sci 67:85-96. doi:10.1139/F09-167

Cheung WWL, Lam VWY, Sarmiento JL, Kearney K, Watson R, Zeller D, Pauly D (2010) Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Global Change Biol 16:24-35

Collie JS, Wood AD, Jeffries HP (2008) Long-term shifts in the species composition of a coastal fish community. Can J Fish Aquat Sci 65:1352-1365

Coulthard S (2009) Adaptation and conflict within fisheries: insights for living with climate change. In: Adger WN, Lorenzoni I, O'Brien KL (eds) Adapting to Climate Change: Thresholds, Values, Governance. Cambridge University Press, Cambridge, UK, pp 255-268

Dalton MG (2001) El Niño, Expectations, and Fishing Effort in Monterey Bay, California. J Environ Econ Manage 42:336-359. doi:10.1006/jeem.2000.1158

Dulvy NK, Rogers SI, Jennings S, Stelzenmller V, Dye SR, Skjoldal HR (2008) Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. J Appl Ecol 45:1029-1039. doi:10.1111/j.1365-2664.2008.01488.x

Ecosystem Assessment Program (2012) Ecosystem Status Report for the Northeast Shelf Large Marine Ecosystem - 2011. U.S. Dept. Commer, Northeast Fish Sci Cent Ref Doc. 12-07. National Marine Fisheries Service, Woods Hole, MA

Grafton RQ, Hilborn R, Ridgeway L, Squires D, Williams M, Garcia S, Groves T, Joseph J, Kelleher K, Kompas T, Libecap G, Lundin CG, Makino M, Matthiasson T, McLoughlin R, Parma AM, San Martin G, Satia B, Schmidt C-C, Tait M, Zhang LX (2008) Positioning fisheries in a changing world. Mar Policy 32:630-634. doi:10.1016/j.marpol.2007.11.003

Hamilton LC, Butler MJ (2001) Outport adaptations: social indicators through Newfoundland's Cod crisis. Research in Human Ecology 8:1-11

Hare JA, Alexander MA, Fogarty MJ, Williams EH, Scott JD (2010) Forecasting the dynamics of a coastal fishery species using a coupled climate-population model. Ecol Appl 20:452-464

Henson SA, Sarmiento JL, Dunne JP, Bopp L, Lima I, Doney SC, John J, Beaulieu C (2010) Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. Biogeosciences 7:621-640

Hilborn R, Walters CJ (1992) Quantitative fisheries stock assessment: choice, dynamics, and uncertainty. Kluwer Academic Publishers, Boston

Lenoir S, Beaugrand G, Lecuyer É (2010) Modelled spatial distribution of marine fish and projected modifications in the North Atlantic Ocean. Global Change Biol

Link JS, Nye Ja, Hare Ja (2011) Guidelines for incorporating fish distribution shifts into a fisheries management context. Fish Fish 12:461-469. doi:10.1111/j.1467-2979.2010.00398.x

Lucey SM, Nye JA (2010) Shifting species assemblages in the Northeast US Continental Shelf Large Marine Ecosystem. Mar Ecol Prog Ser 415:23-33. doi:10.3354/meps08743

McCay BJ, Weisman W, Creed C (2011) Coping with Environmental Change: Systemic Responses and the Roles of Property and Community in Three Fisheries. In: World Fisheries: A Socio-Ecological Analysis. pp 381-400

NEFMC (1998) Monkfish Fishery Management Plan. New England Fishery Management Council, Saugus, MA

NEFMC (2003) Northeast Multispecies FMP Amendment 12.152

Nye JA, Link JS, Hare JA, Overholtz WJ (2009) Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. Mar Ecol Prog Ser 393:111-129

Pauly D, Christensen V, Guenette S, Pitcher TJ, Sumaila UR, Walters CJ, Watson R, Zeller D (2002) Towards sustainabilty in world fisheries. Nature 418:689-695

Perry AL, Low PJ, Ellis JR, Reynolds JD (2005) Climate change and distribution shifts in marine fishes. Science 308:1912-1915

Silvert W (1977) The Economics of Over-Fishing. Trans Am Fish Soc 106:121-130

Steneck RS, Hughes TP, Cinner JE, Adger WN, Arnold SN, Berkes F, Boudreau SA, Brown K, Folke C, Gunderson L, Olsson P, Scheffer M, Stephenson E, Walker B, Wilson J, Worm B (2011) Creation of a gilded trap by the high economic value of the Maine lobster fishery. Conserv Biol 25 (5):904-912. doi:10.1111/j.1523-1739.2011.01717.x

Sumaila UR, Cheung WWL, Lam VWY, Pauly D, Herrick S (2011) Climate change impacts on the biophysics and economics of world fisheries. Nature Climate Change:1-8. doi:10.1038/nclimate1301

Worm B, Barbier EB, Beaumont N, Duffy JE, Folke C, Halpern BS, Jackson JBC, Lotze HK, Micheli F, Palumbi SR, Sala E, Selkoe KA, Stachowicz JJ, Watson R (2006) Impacts of biodiversity loss on ocean ecosystem services. Science 314:787-790

Worm B, Hilborn R, Baum JK, Branch TA, Collie JS, Costello C, Fogarty MJ, Fulton EA, Hutchings JA, Jennings S, Jensen OP, Lotze HK, Mace PM, McClanahan TR, Minto C, Palumbi SR, Parma AM, Ricard D, Rosenberg AA, Watson R, Zeller D (2009) Rebuilding global fisheries. Science 325:578

Figure Legends

Figure 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.

Figure 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).

Tables

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

Figure 1

Click here to download line figure: Fig1.pdf

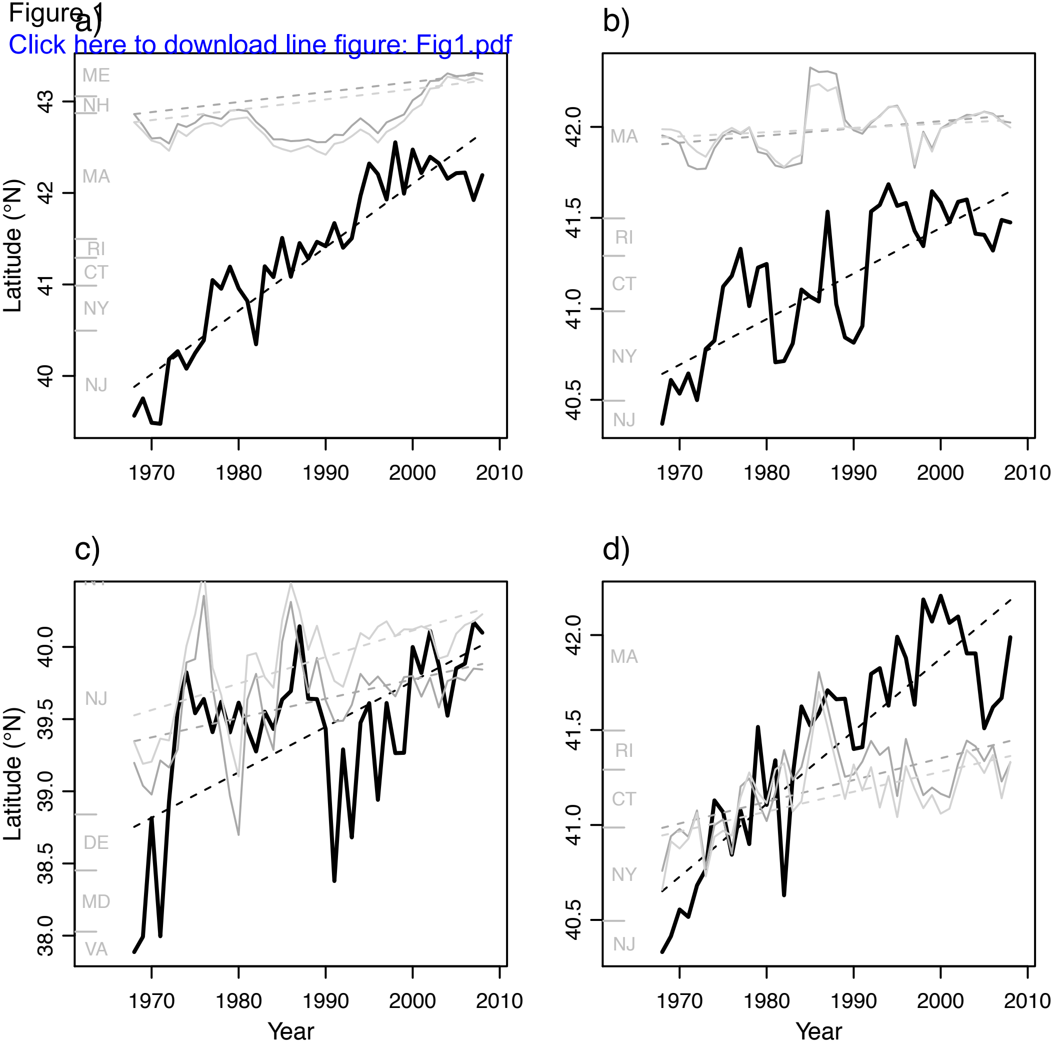
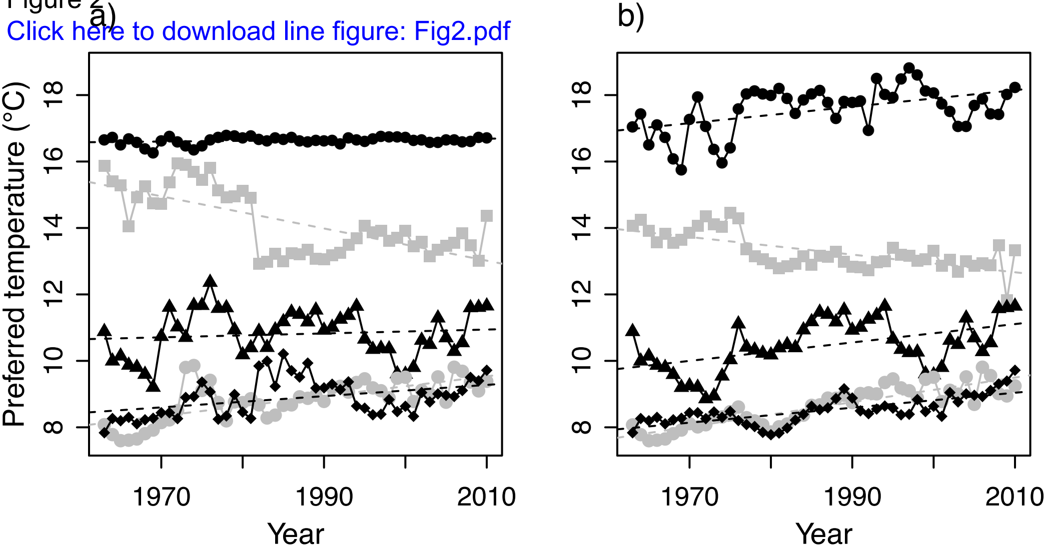


Figure 2

Click here to download line figure: Fig2.pdf



Supplementary Information

Table S1. Preferred temperature by taxon (mean of minimum and maximum).

Scientific name	**Common name**	**Preferred temperature (°C)**	**Source**
Alosa aestivalis	Blueback herring	9	(Collie et al. 2008)
Alosa pseudoharengus	Alewife	9	(Collie et al. 2008)
Amblyraja radiata	Thorny skate	3.5	(Scott 1982)
Ammodytes americanus	American sand lance	4	(Scott 1982)
Anarchichas lupus	Atlantic wolfish		(Scott 1982)
Arctica islandica	Ocean quahog	11	(Cargnelli et al. 1999e)
Argopecten irradians	Bay scallop	14	(Brun et al. 2008)
Brevoortia tyrannus	Menhaden	16.5	(Hall et al. 1991)
Brosme brosme	Cusk	8	(Scott 1982)
Callinectes sapidus	Blue crab	20	(Booth and McMahon 1992)
Cancer borealis	Jonah crab	14.5	(Collie et al. 2008)
Cancer irroratus	Atlantic rock crab	14.5	(Collie et al. 2008)
Centropristis striata	Black seabass	18.25	(Drohan et al. 2007)
Clupea harengus	Atlantic herring	7	(Collie et al. 2008)
Crassostrea virginica	Eastern oyster	25	(Barnes et al. 2007)
Cynoscion regalis	Weakfish	21.8	(Collie et al. 2008)
Dipturus laevis	Barndoor skate	10.6	(Barnes et al. 2007)
Gadus morhua	Atlantic cod	7	(Fogarty et al. 2007)
Glyptocephalus cynoglossus	Witch flounder	6.5	(Cargnelli et al. 1999c)
Hippoglossoides hippoglossus	Atlantic halibut	6	(Scott 1982)
Hippoglossoides	Atlantic plaice	4.5	(Johnson 2004)

platessoides			
Homarus americanus	American lobster	11	(Collie et al. 2008)
Illex ilecebrosus	Northern shortfin squid	13.9	(Hendrickson and Holmes 2004)
Katsuwonus pelamis	Skipjack tuna	25.5	(NMFS 2006)
Leucoraja erinacea	Little skate	8.5	(Collie et al. 2008)
Leucoraja garmani	Freckled skate	12.5	(McEachran and Musick 1975)
Leucoraja ocellata	Winter skate	7	(Scott 1982)
Libinia emarginata	Spider crab	11.5	(Collie et al. 2008)
Limanda ferruginea	Yellowtail flounder	8	(Johnson et al. 1999)
Limulus polyphemus	Horseshoe crab	30	(Collie et al. 2008)
Loligo pealeii	Longfin squid	12	(Collie et al. 2008)
Lophius americanus	Goosefish	9	(Steimle et al. 1999a)
Lopholatilus chamaeleonticeps	Golden tilefish	13	(Steimle et al. 1999b)
Malacoraja senta	Smooth skate	5.5	(Scott 1982)
Melanogrammus aeglefinus	Haddock	5.5	(Cargnelli et al. 1999a)
Mercenaria mercenaria	Quahog	12.5	(Ansell 1968; Murphy 1983)
Merluccius bilinearis	Silver hake	10	(Collie et al. 2008)
Micropogonias undulatus	Atlantic croaker	20.3	(Miglarese et al. 1982)
Morone saxatilis	Striped bass	17.8	(Nelson et al. 2010)
Mya arenaria	Softshell clam	13.15	(Newell and Hidu 1986)
Mytilus edulis	Blue mussel	16	(Newell 1989)
Paralichthys dentatus	Summer flounder	15.5	(Collie et al. 2008)
Paralichthys oblongus	Fourspot flounder	11.4	(Collie et al. 2008)
Peprilus triacanthus	Butterfish	13	(Collie et al. 2008)

Placopecten magellanicus	Sea scallop	12.5	(Packer and Chute 1999)
Pollachius virens	Pollock	7	(Cargnelli et al. 1999b)
Pomatomus saltatrix	Bluefish	13.5	(Collie et al. 2008)
Pseudopleuronectes americanus	Winter flounder	8.8	(Collie et al. 2008)
Raja eglanteria	Clearnose skate	18	(McEachran and Musick 1975)
Scomber scombrus	Atlantic mackerel	11.55	(Studholme et al. 1999)
Scophthalmus aquosus	Windowpane	13.4	(Collie et al. 2008)
Sebastes fasciatus	Acadian redfish	7.5	(Pikanowski et al. 1999)
Spisula solidissima	Atlantic surf clam	13.5	(Cargnelli et al. 1999d)
Squalus acanthias	Spiny dogfish	10.5	(McMillan and Morse 1999)
Stenotomus chrysops	Scup	14.5	(Collie et al. 2008)
Tautoga onitus	Tautog	13.5	(Collie et al. 2008)
Tautogolabrus adspersus	Cunner	14.5	(Collie et al. 2008)
Thunnus alalunga	Albacore tuna	17.5	(NMFS 2006)
Thunnus albacares	Yellowfin tuna	24.5	(NMFS 2006)
Thunnus obesus	Bigeye tuna	21	(NMFS 2006)
Thunnus thynnus	Bluefin tuna	21	(Muhling et al. 2011; NMFS 2006)
Urophycis chuss	Red hake	8.5	(Collie et al. 2008)
Urophycis tenuis	White hake	9.5	(Chang et al. 1999)
Xiphius gladius	Swordfish	20	(NMFS 2006)
Zoarces amercanus	Ocean pout	7.5	(Scott 1982)
	Skates	9.37	Average of *Dipturus laevis*, *Raja eglanteria*, *Leucoraja erinacea*, *Leucoraja*

			garmani, *Malacoraja senta*, *Amblyraja radiata*, *Leucoraja ocellata*
	Squids	12.95	Average of *Loligo pealeii* and *Illex ilecebrosus*

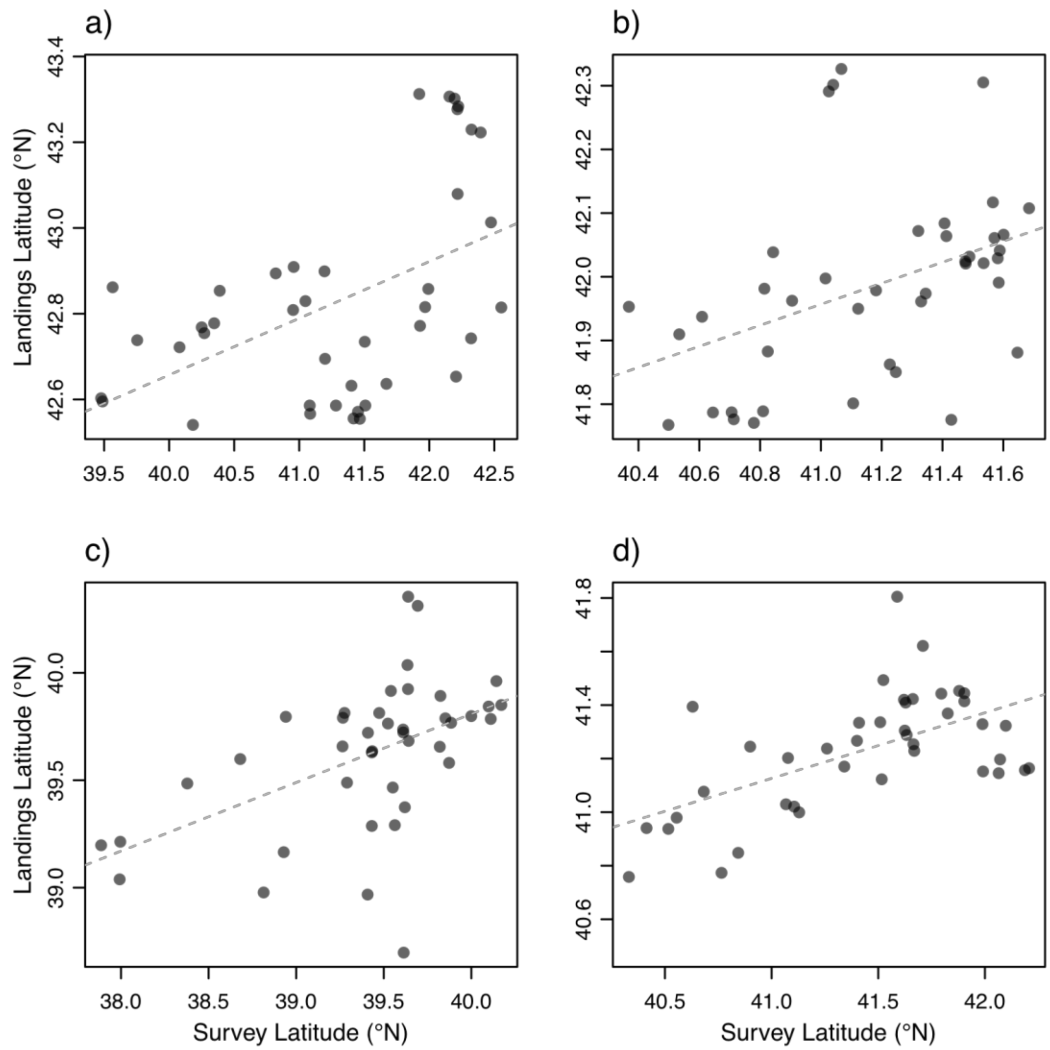


Figure S1. Average latitude of landings plotted against average latitude of species in the research surveys. A linear regression is shown as a grey, dashed line. Subplots are the same species as in Fig. 1.

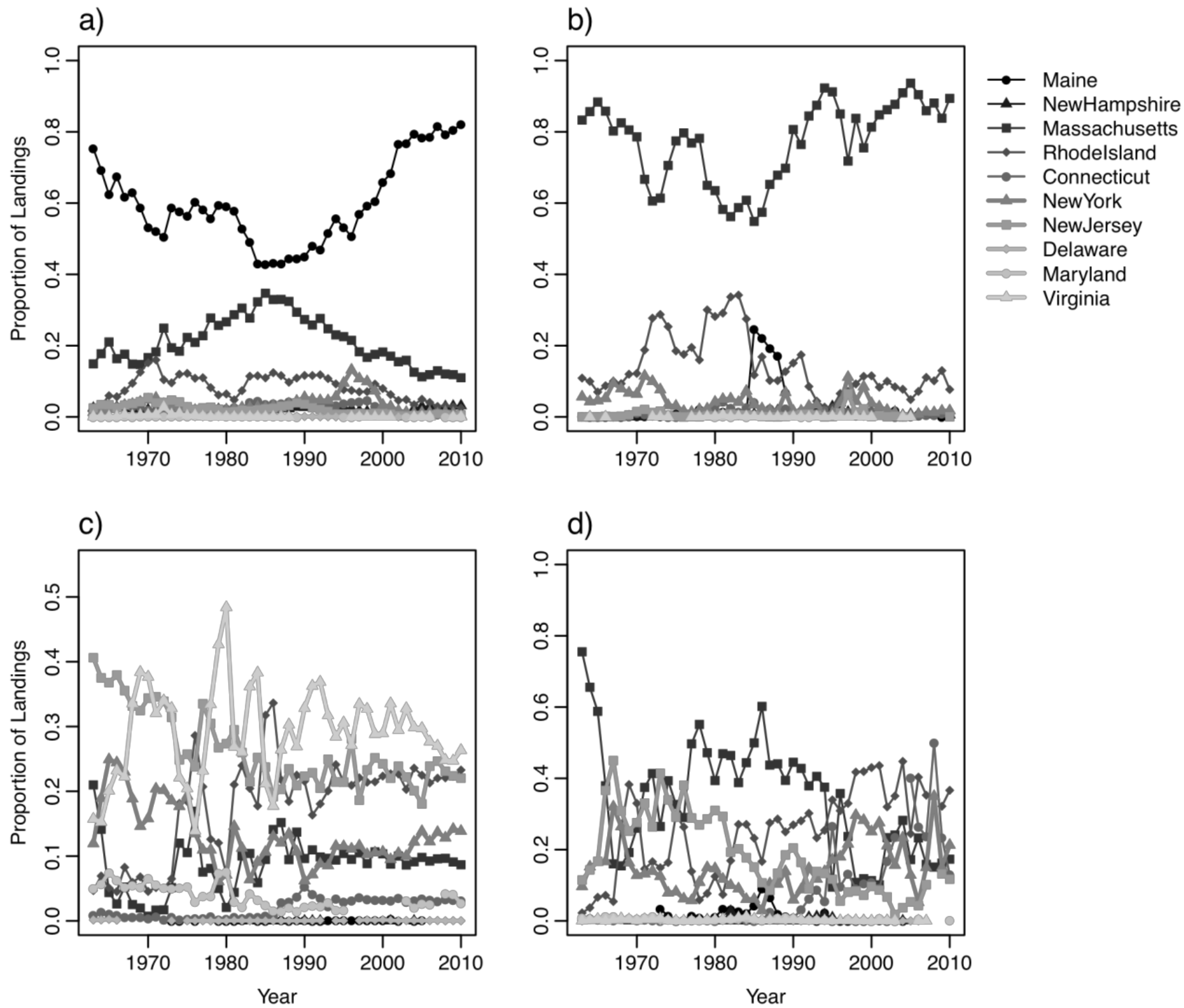


Figure S2. Relative commercial fishery landings from 1963-2010, organized by state in which the species was landed. The species are a) American Lobster (*Homarus americanus*), b) yellowtail flounder (*Limanda ferruginea*), c) summer flounder (*Paralichthys dentatus*), and d) red hake (*Urophycis chuss*).

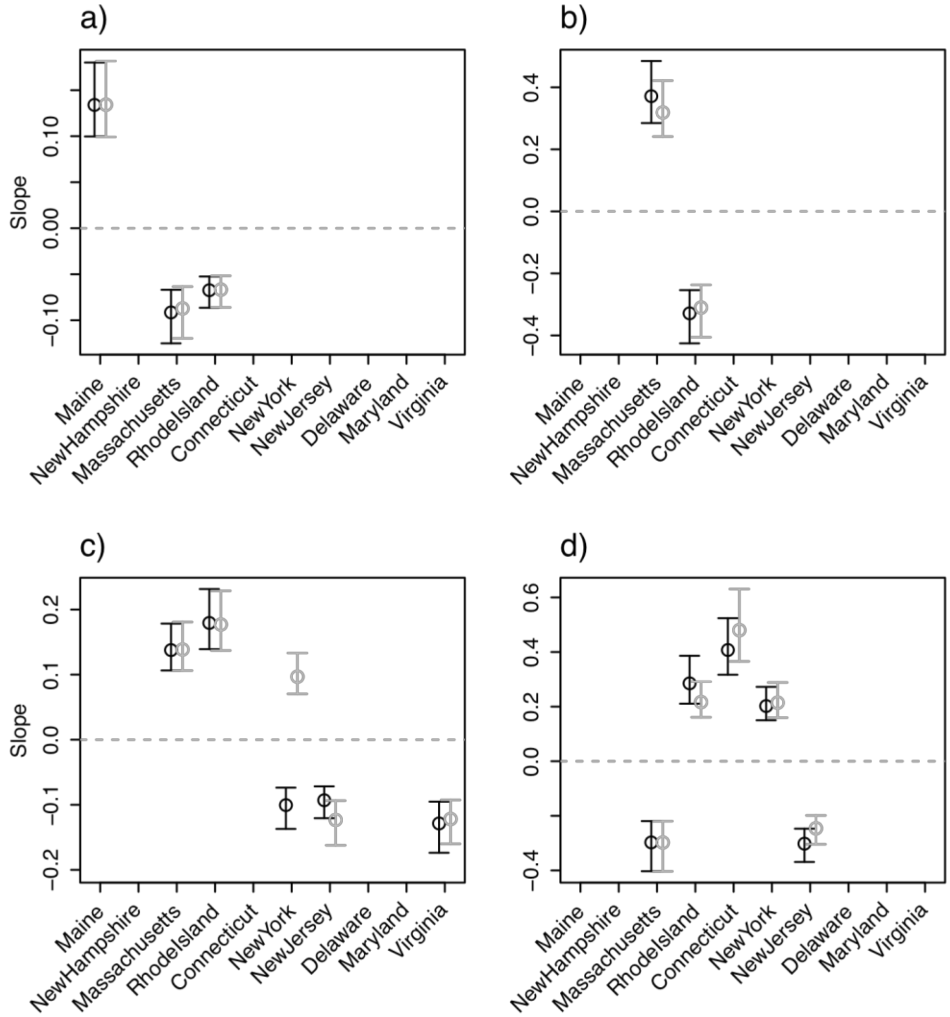


Figure S3. Slope of the relationship between each state's share of total landings (black) or share of total landed value (grey) and each species' mean latitude from research surveys. A positive slope indicates that a given state received a higher proportion of landings as the species shifted northward, while a negative slope indicates that the state received a smaller share. States are arranged from northernmost (Maine) on the left to southernmost (Virginia) on the right. Species in each panel are as in Fig. 1 and 2.

Supplementary References

Ansell A.D. (1968) The rate of growth of the hard clam, *Mercenaria mercenaria* (L) throughout the geographical range. *ICES J Mar Sci* **31**, 364-409.

Barnes T.K., Volety A.K., Chartier K., Mazzotti F.J., Pearlstine L. (2007) A habitat suitability index model for the Eastern oyster (*Crassostrea virginica*), a tool for restoration of the Caloosahatchee Estuary, Florida. *J Shellfish Res* **26**, 949-959.

Booth C.E., McMahon B.R. (1992) Aerobic capacity of the blue crab, *Callinectes sapidus*. *Physiol Zool* **65**, 1074-1091.

Brun N.T., Bricelj V.M., MacRae T.H., Ross N.W. (2008) Heat shock protein responses in thermally stressed bay scallops, *Argopecten irradians*, and sea scallops, *Placopecten magellanicus*. *J Exp Mar Biol Ecol* **358**, 151-162.

Cargnelli L.M., Griesbach S.J., Berrien P.L., Morse W.W., Johnson D.L. (1999a) Essential fish habitat source document: Haddock, *Melanogrammus aeglefinus*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-128. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.

Cargnelli L.M., Griesbach S.J., Packer D.B., Berrien P.L., Johnson D.L., Morse W.W. (1999b) Essential fish habitat source document: Pollock, *Pollachius virens*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-131. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.

Cargnelli L.M., Griesbach S.J., Packer D.B., Berrien P.L., Morse W.W., Johnson D.L. (1999c) Essential fish habitat source document: Witch flounder, *Glyptocephalus cynoglossus*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-139. U.S. Dept. Comm. Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.

Cargnelli L.M., Griesbach S.J., Packer D.B., Weissberger E. (1999d) Essential fish habitat source document: Atlantic surfclam, *Spisula solidissima*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-142. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.

Cargnelli L.M., Griesbach S.J., Packer D.B., Weissberger E. (1999e) Essential fish habitat source document: Ocean quahog, *Arctica islandica*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-148. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin, Nat. Mar. Fish. Serv., Woods Hole, MA.

Chang S., Morse W.W., Berrien P.L. (1999) Essential fish habitat source document: White hake, *Urophycis tenuis*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-136. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.

Collie J.S., Wood A.D., Jeffries H.P. (2008) Long-term shifts in the species composition of a coastal fish community. *Can J Fish Aquat Sci* **65**, 1352-1365.

Drohan A.F., Manderson J.P., Packer D.B. (2007) Essential fish habitat source document: Black sea bass, *Centropristis striata*, life history and habitat characteristics. 2nd ed. NOAA Tech. Mem. NMFS-NE-200. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.

Fogarty M., Incze L., Hayhoe K., Mountain D., Manning J. (2007) Potential climate change impacts on Atlantic cod (Gadus morhua) off the northeastern USA. *Mitigation and Adaptation Strategies for Global Change* **13**, 453-466.

Hall L.W., Fischer S.A., Sullivan J.A. (1991) A synthesis of water quality and contaminants data for the Atlantic menhaden, *Brevoortia tyrannus*: Implications for Chesapeake Bay. *Journal of Environmental Science and Health Part A: Environmental Science and Engineering and Toxicology* **26**, 1513-1544.

Hendrickson L.C., Holmes E.M. (2004) Essential fish habitat source document: Northern shortfin squid, *Illex illecebrosus*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-191. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.

Johnson D.L. (2004) Essential fish habitat source document: American plaice, *Hippoglossoides platessoides*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-187. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.

Johnson D.L., Morse W.W., Berrien P.L., Vitaliano J.J. (1999) Essential fish habitat source document: Yellowtail flounder, *Limanda ferruginea*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-140. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.

McEachran J.D., Musick J.A. (1975) Distribution and relative abundance of seven species of skate (Pisces: Rajidae) which occur between Nova Scotia and Cape Hatteras. *Fish Bull* **73**, 110-136.

McMillan D.G., Morse W.W. (1999) Essential fish habitat source document: Spiny dogfish, *Squalus acanthias*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-150. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin, Nat. Mar. Fish. Serv., Woods Hole, MA.

Miglarese J.V., McMillan C.W., Shealy M.H., Jr. (1982) Seasonal abundance of Atlantic croaker (*Micropogonias undulatus*) in relation to bottom salinity and temperature in South Carolina estuaries. *Estuaries* **5**, 216-223.

Muhling B.A., Lee S.-K., Lamkin J.T., Liu Y. (2011) Predicting the effects of climate change on bluefin tuna (*Thunnus thynnus*) spawning habitat in the Gulf of Mexico. *ICES J Mar Sci* **68**, 1051-1062.

Murphy D.J. (1983) Freezing resistance in intertidal invertebrates. *Annu Rev Physiol* **45**, 289-299.

Nelson G.A., Armstrong M.P., Stritzel-Thomson J., Friedland K.D. (2010) Thermal habitat of striped bass (*Morone saxatilis*) in coastal waters of northern Massachusetts, USA, during summer. *Fish Oceanogr* **19**, 370-381.

Newell C.R., Hidu H. (1986) Species profiles: life histories and environmental requirements of coastal fish and invertebrates (North Atlantic): softshell clam. U.S. Fish. Wildl. Serv. Biol. Rep. 82 (11.53), U.S. Army Corps of Engineers TR EL-82-4. p. 17.

Newell R.I.E. (1989) Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (North and Mid-Atlantic): blue mussel. U.S. Fish. Wildl. Serv. Biol. Rep. 82 (11.102), U.S. Army Corps of Engineers TR EL-82-4.

NMFS. (2006) Final consolidated Atlantic highly migratory species fishery management plan. p. 1600. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Silver Spring, MD.

Packer D.B., Chute A.S. (1999) Essential fish habitat source document: Sea scallop, *Placopecten magellanicus*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-189. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.

Pikanowski R.A., Morse W.W., Berrien P.L., Johnson D.L., McMillan D.G. (1999) Essential fish habitat source document: Redfish, *Sebastes* spp., life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-132. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.

Scott J.S. (1982) Depth, temperature and salinity preferences of common fishes of the Scotian Shelf. *J Northwest Atl Fish Sci* **3**, 29-39.

Steimle F.W., Morse W.W., Johnson D.L. (1999a) Essential fish habitat source document: Goosefish, *Lophius americanus*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-127. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.

Steimle F.W., Zetlin C.A., Berrien P.L., Johnson D.L., Chang S. (1999b) Essential fish habitat source document: Tilefish, *Lopholatilus chamaeleonticeps*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-152. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.

Studholme A.L., Packer D.B., Berrien P.L., Johnson D.L., Zetlin C.A., Morse W.W. (1999) Essential fish habitat source document: Atlantic mackerel, *Scomber scombrus*, life history and habitat characteristics. NOAA Tech. Mem. NMFS-NE-141. U.S. Dept. Comm., Nat. Ocean. Atmos. Admin., Nat. Mar. Fish. Serv., Woods Hole, MA.