PROF. LOREN MCCLENACHAN (Orcid ID : 0000-0002-9811-2742)

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Title: Shifting perceptions of rapid temperature changes' effects on marine fisheries, 1945-2017

Authors: Loren McClenachan[1], Jonathan H. Grabowski[2], Madison Marra[1], C. Seabird McKeon[3,4], Benjamin P. Neal[1,5], Nicholas R. Record[5], Steven B Scyphers[2]

Affiliations

[1] Environmental Studies Program, Colby College, Waterville ME

[2] Marine Science Center, Northeastern University, Nahant MA

[3] National Museum of Natural History, Smithsonian Institution, Washington DC

[4] Department of Biology & National Center for Integrated Coastal Research, University of Central Florida, Orlando FL

[5] Bigelow Laboratory for Ocean Sciences, East Boothbay ME

Corresponding author: Loren McClenachan, 5351 Mayflower Hill Drive, Waterville ME 04901, lemcclen@colby.edu

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Abstract: Climate-driven warming has both social and ecological effects on marine fisheries. While recent changes due to anthropogenic global warming have been documented, similar basin-wide changes have occurred in the past due to natural temperature fluctuations. Here, we document the effects of rapidly changing water temperatures along the United States' east coast using observations from fisheries newspapers during a warming phase (1945-1951) and subsequent cooling phase (1952-1960) of the Atlantic Multidecadal Oscillation, which we compared to similar recent observations of warming waters (1998-2017). Historical warming and cooling events affected the abundance of species targeted by fishing,

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the prevalence of novel and invasive species, and physical access to targeted species. Fishing communities viewed historical cooling waters twice as negatively as they did warming waters (72% vs. 35% of observations). Colder waters were associated with a decrease in fishing opportunity due to storminess, while warming waters were associated with the potential for new fisheries. In contrast, recent warming waters were viewed as strongly negative by fishing communities (72% of observations), associated with disease, reductions in abundances of target species, and shifts in distributions across jurisdictional lines. This increasing perception that warming negatively affects local fisheries may be due to an overall reduction of opportunity in fisheries over the past half century, an awareness of the relative severity of warming today, larger changes in American culture, or a combination of these factors. Negative perceptions of recent warming waters' effects on fisheries suggest that fishing communities are currently finding the prospect of climate adaptation difficult.

Keywords: climate change, climate adaptation, fisheries diversification, Gulf of Maine, historical ecology, social-ecological systems

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Introduction

Global climate change has direct effects on marine fishes and invertebrates, including changes to migration patterns, distribution, and phenology, which consequently impacts their fisheries (Roessig *et al.* 2004). The movement of marine animals poleward or to greater depths following optimal temperature conditions has been documented (Perry et al., 2005; Pinsky et al., 2013), with global shifts at the leading range edges for marine species averaging 72 km per decade (Poloczanska et al., 2013). Increases in marine pathogens with warming waters also have implications for disease in marine fisheries (Burge et al., 2014; Waples & Audzijonyte 2016).

Ecological changes have consequences for coastal fishing communities; increased seasonal variability and shifts in the distribution of target species affect the ability of fishing communities to thrive and persist (Badjeck et al., 2010; Pinsky & Fogarty, 2012; Roessig et al., 2004; Savo et al., 2017). Large-scale redistribution of marine fish has food security implications (Cheung et al., 2010) and effects at the scale of national economies are predicted in many fisheries-dependent states (Allison et al., 2009). These shifts also present new challenges for management as species move across jurisdictional boundaries (Pinksy et al. 2018). Particularly in regions identified as global hotspots of change, the ability of fishing communities to adjust to the impacts of rapid temperature changes presents major challenges, especially in areas with high dependence on fisheries for food security (Hobday & Pecl, 2014).

While the effects of modern temperature change on marine systems are predicted to increase precipitously as a result of global warming (Henson et al., 2017), rapid temperatures changes are not wholly unprecedented in recent history. A prior warming period associated with the Atlantic Multidecadal Oscillation (AMO) occurred throughout the North Atlantic in the 20th century, peaking in the early 1950s (Knudsen et al., 2011). This warming trend was strongest in the north and weakened in magnitude with decreasing latitude, with the most intense and rapid changes in water sea surface temperatures experienced in the Gulf of Maine (Shearman & Lentz, 2010). Following this rapid warming was a period of rapid cooling, with below average temperatures through the 1960s (Stearns, 1965).

The rapid temperature changes experienced in the 1940s-1960s provide an opportunity to put today's changes into a historical context. Here, we examine the ecological and social responses of marine fisheries and fishing communities during the rapid warming and cooling experienced in 1940s-1960s, and compare those to changes observed in the last two decades. Specifically, we wanted to know (*1*) how similar the historical and modern warming periods were with respect to the magnitude and rate of sea surface temperature (SST) change, (*2*) if the fishing community's observations of temperature-driven changes in marine species and fisheries aligned with SST changes, (*3*) which fisheries were described as most affected across the three time periods, (*4*) the ways in which rapid temperature changes were described as affecting fisheries, and (*5*) whether fishing communities viewed temperature driven changes

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as negative (e.g., threatening to their livelihoods) or positive (e.g., providing new opportunities). We also investigated potential links between fisher perceptions of temperature impacts and both climate change and changes to fishing opportunity over time.

Previous studies have used archival historical data—including newspapers, photographs, restaurant menus, and ships logs—to examine the top-down effects of fishing on marine ecosystems (McClenachan, 2009b,a; Rosenberg et al., 2005; Thurstan et al., 2010; Van Houtan et al., 2013), but there is also great potential to use these data to understand the effects and perceptions of past climatic changes. One concentrated and underutilized source of historical information can be found in fisheries trade publications. These publications contain information relevant to many aspects of fisheries, including observations of abundance or scarcity, speculation on drivers of change, and opinions on changes to fisheries regulations. To examine fishing communities' perspectives on temperature-driven changes, we use historical (1945-1960) and modern (1998-2017) news articles from fisheries trade publications, which were written by and for the fishing community. We examined changes across the east coast of the United States and Canada, and focused on the Gulf of Maine because this was where temperature changes were most extreme during the AMO event, and where temperatures are changing most rapidly today (Hobday & Pecl, 2014; Shearman & Lentz, 2010).

Methods

To compare the rate and magnitude of sea surface temperature (SST) change (*Question 1*), we used average monthly SST anomalies in the Gulf of Maine (Figure 1A), which were calculated from the Extended Reconstructed Sea Surface Temperature dataset (ERSST; Huang et al., 2017). Anomalies were calculated with respect to a monthly climatology—i.e. the anomaly for each month is the difference from the mean for that month over the full time series. We used the ERSST dataset because of the long timescale it covers; however, because this dataset averages over a coarser spatial scale than other SST datasets, the temperature variability and extremes are slightly reduced compared to other analyses (e.g., Pershing et al., 2015), but the variation is consistent.

To determine if the fishing community's observations of temperature-driven changes in marine species and fisheries aligned with these SST changes (*Question 2*), we extracted observations from two historical fishing newspapers: the *Maine Coast Fisherman* (1946-1960) and the *Atlantic Fisherman* (1945-1953). Our period of data collection corresponded with the period of warming and subsequent cooling that began in 1942, the availability of these historical publications, and broader historical trends (i.e., a strong focus on World War II in fishing newspapers before 1945). In 1960, these two newspapers combined and expanded to cover the US Pacific Coast under the name *National Fisherman*, which continues as a commercial fisheries trade publication today. We extracted analogous observations for our

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study region from this news source for the period of more recent warming (1998-2017). We recorded articles that described changes to a fishery that were explicitly attributed to warming or cooling waters and any instances where warming or cooling waters were associated with direct impacts to fishing practices. Additionally, we recorded all observations of novel species during the historical warming and cooling events, which we defined as those that were described as rarely or never previously seen in a locality. Finally, in the Gulf of Maine region, we recorded all observations of invasive green crabs (*Carcinus maenas,* Portunidae), as this species was observed in the historical scientific literature as increasing due to warming waters (Glude, 1955; Weslch, 1969), and their increased population abundances today have been observed to negatively affected soft-shell clam (*Mya arenaria*, Myidae) fisheries in New England (Congleton et al., 2006; McClenachan et al., 2015b). We compared both observations of novel species and the invasive green crabs to average monthly sea surface temperature (SST) anomalies. As high green crab abundances have been correlated with high January-March average SSTs for the preceding four years in Maine (Congleton et al., 2006), we used this subset of data to test the relationship between changing temperatures and observations of green crabs.

To determine which fisheries were most affected across the three time periods (*Question 3*), we recorded the number of target species affected in each of the three time periods and the relative number of observations of impacts across these fisheries. To determine the ways in which rapid temperature changes were described as affecting fisheries (*Question 4*), we categorized observations into four types: (1) *scarcity* of target species, due to changes in abundance, timing of seasonal migrations or changes in species' distribution), (2) *increases* of target species, due to the same types of changes, (3) changes in the ability to physically *access* the fishery due to weather or localized changes in the distribution of target species, and (4) changes in the *condition* of target species, such as reduced due to increased disease prevalence. To determine whether fishing communities viewed temperature driven changes as negative (e.g., threatening to their livelihoods) or positive (e.g., providing new opportunities) (*Question 5*), we categorized each as either positive, negative, or neutral, based on the description in each article. *Positive* articles were those in which the author described the temperature difference as having an observed or potential beneficial impact on local fisheries, *negative* articles were those in which the author described an observed or potential detrimental effect on local fisheries, and *neutral* articles were those that described a change related to temperature, but did not explicitly state whether that change had benefitted or harmed local fisheries. Sentiment analysis is a growing field that frequently relies on machine learning or lexicon-based approaches (e.g., Serrano-Guerro et al., 2015); however, software tools failed to accurately assess the directionality of sentiments in fisheries articles. Therefore, we instead used expert coding. Each observation was coded by two separate coders (LM, BN) and intercoder reliability was

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calculated as percent agreement (Campbell et al., 2013); those that failed to achieve agreement were excluded.

Finally, we investigated perceived links between observed changes and broader social and ecological changes. To assess broader changes to fishing opportunity that might influence fishers' perceptions, we compared landings data over time for all fisheries managed by NOAA in the Atlantic and Gulf region, and for a subset of key fisheries (NOAA 2019). Key fisheries were selected based on total value and volume of landings over time; we identified the top ten fisheries in terms of cumulative landings (million mt) and value (billion USD) from 1950-2017 for the Atlantic and Gulf of Maine regions. For all landed fish and the subset of key fisheries, we determined the year in which peak landings by volume (mt) were achieved. If opportunity had not changed, we would expect that peak landings would be within the recent time period. To assess perceived links to global warming, we identified and collated articles that linked rapid local temperature changes to global climate change.

Results

Fishing communities perceive effects of rapid sea surface temperature changes, 1945-2017

The most recent warm-water anomaly began in 1942, peaking in 1951 at an annual mean of 1.3 ° Celsius (C) above the long-term average (Figure 1A). While temperatures remained anomalously high through 1954, they began dropping in 1952, and reached a minimum in 1965 at an annual mean of 1.3 °C below the mean. In the recent warming period, water temperatures have been above the mean since 1999, with peaks of 1.8 and 1.6 °C (annual mean) above average in 2012 and 2016, respectively. While warming occurred in both periods, the recent period is longer and more pronounced. During the historical warming period, anomalously high temperatures prevailed for 12 years (1942-1954); in the recent period, they have been elevated for 18, with two of those years (2012, 2016) higher than any point in the historical time series, and six of the ten warmest years on record occurring since 2012.

These historical fishing trade publications reported both warm-water and cold-water events as impacting fisheries along Atlantic Coast of the US and Canada. We found 387 observations that described the effects of warming waters on fisheries from 1945 to 1960, 101 of which were from the Gulf of Maine. Numbers of observations peaked in 1953 with 65 observations of the effects of warm water on marine fisheries made in that year across the greater Atlantic region (Figure 1B). We found 108 observations linked to cold water from 1945 to 1960, with 57 from the Gulf of Maine. The highest number of observations (n=25) were made in 1956. Between 1998 and 2017, we found 102 observations linked to warming waters and four linked to cooling water; of these, 31 were from Gulf of Maine. These observations were temporally concentrated with 42% made in one year, 2013, the year following record-setting water temperatures (Figure 1A).

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Observations of both invasive and novel species align with SST changes (Figure 1C). We found 73 observations of invasive green crabs in the Gulf of Maine, which were described primarily in the context of their impacts on the soft-shell clam fishery. For example, in 1953, the *Maine Coast Fisherman* reported that "The green crab is the most important enemy of the soft clam …The northward extension of the distribution of green crabs is related to warmer temperatures during recent years." The number of green crab observations peaked in 1953-1954, lagging the peak in temperature. There was a significant correlation between the number of green crab observations ($r^2=0.74$, $p<0.0001$) and the average January-March temperature anomaly from the previous four years (Figure 1D).

We found 120 observations of species described as novel or rare by the fishing community, with a peak in 1951 that corresponding with the peak in temperature. There was a weak but significant correlation between the number of novel species' observations ($r^2=0.23$, $p<0.05$) and the temperature anomaly for that year. Novel species included those that were targeted by commercial or recreational fisheries such as blue crab (*Callinectes sapidus,* Portunidae), striped bass (*Morone saxatilis,* Moronidae), squid (*Loligo pealeii,* Loliginidae), round herring (*Etrumeus sadina,* Dussumieriidae), scup (*Stenotomus chrysops,* Sparidae), bluefish (*Pomatomus saltatrix,* Pomatomidae) and quahogs (*Mercenaria mercenaria,* Veneridae). In some cases, observations reflected a widespread change in distribution. For example, in 1954, the *Maine Coast Fisherman* reported that "It looks like some changes [are] coming about with... scups and other southern fish frequenting the Gulf of Maine." However, most observations were described as rare encounters with individual fish. For example, a "strange fish" that "rarely comes as far north as Maine," was confirmed to be a black seabass (*Centropristis striata,* Serranidae). Similarly, a blue crab caught in Maine in 1954 was described as "the first that has ever been seen in this location," and in 1947, a tarpon (*Megalops atlanticus*, Megalopidae) was caught in a pound net in Maryland; the *Atlantic Coast Fisherman* reported that this species is "found mostly in tropical waters, [and] sometimes wanders North." Observations also highlighted smaller scale movements of more common species, such as a striped bass that was caught in a lobster pound in northern Maine in 1949. The author noted that "Stripers are caught off the southern beaches of Maine, but few have been noted above the Penobscot River in recent years." Novel species also included observations of warm-water species not of interest to commercial or recreational fisheries, many of which were not identified to the species level. For example, in 1950, the *Maine Coast Fisherman* reported, "Howard Goddard of East Harpswell caught a 'File Fish' [Monacanthidae] in his lobster trap…. They aren't found in these waters as a rule." Similarly, in 1954, a triggerfish (Balistidae), was described as "primarily tropical" and "rarely in the Gulf of Maine." Other warm-water novel species included a sea hare (*Aplysia* spp., Aplysiidae) "native to Florida and the West Indies" caught near Martha's Vineyard, a six-gill shark (*Hexanchus* spp., Hexanchidae) caught in a drag

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net on George's Bank, and a tropical species of sea horse (*Hippocampus* spp*.,* Sygnathidae) caught in Maine.

Key fisheries affected by rapid warming and cooling

In total, 64 target species were described as affected by warming waters during the historical warming period (Table 1), with the most common being American lobster (*Homarus americanus*, Nephropidae; 8% of observations) and cod (*Gadus morhua*, Gadidae; 7% of observations). Cod were noted as experiencing reduced abundances in response to warmer waters at the southern end of their distribution, and both cod and lobster populations were noted as shifting north. Mackerel (*Scomber* spp. Scombridae), scup, striped bass, and blue crab each represented 5% of total observations. Mackerel and blue crabs were observed as having altered migrations in response to warm waters, which affected the duration of the fishing seasons associated with these species. For example, a 1949 article reported that "large schools of mackerel were running off the New Jersey coast early in March, at least a month and a half ahead of the regular season," and a 1948 article reported that "the Maryland Tidewater Fisheries Commission extended the crab season until the middle of November [1948], which is two weeks longer than usual… due to warm weather." The movement of scup and striped bass in response to warmer waters were described as reducing predictability in these fisheries. While most observations linked changes in target species directly to warming waters, others described trophic interactions, such as an increased prevalence of "bait" fish that attracted larger predators. For example, the *Atlantic Coast Fisherman* reported that, "bait runs thick, and the [striped] bass chase it," and "Bait is the thickest that most men ever saw around [Martha's Vineyard], sharks are thick alongshore, running up to a couple of hundredweight quite frequently."

In the Gulf of Maine, 25 target species were identified as affected by warming waters between 1945-1960, with the most common being soft-shell clam (12% of observations), smelt (*Osmerus mordax*, Osmeridae; 11% of observations), herring (*Clupea harengus*, Clupeidae), and lobster (10% of observations each). The effects of warming waters on clam fisheries were mixed, including improved access to clamming grounds with earlier ice melts, but also increased observations of its invasive predator, the green crab. While these observations were concentrated in Maine, they also occurred in Canada. For example, the *Maine Coast Fisherman* reported, "Green crabs arrive in New Brunswick, with a vengeance, and are ripping the heads off small clams by the thousands. Mainers have long been pestered by green crabs, but provincial fishermen hoped they wouldn't reach the Bay of Fundy! Warmer water is blamed for the appearance of the predators." The effects of warming waters on smelt fishing were observed in the reduction in ice cover on which this fishery depended; counter to clam fisheries, less ice in warm years reduced access and shortened the duration of the season. The local migration and schooling patterns of

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herring were described as affected by warm waters, with it increasing local lobster abundances overall, but also resulting in earlier molting and increased disease prevalence, both of which affected marketability (Figure 2).

During the subsequent cooling period, changes in 32 target species across the greater Atlantic region were observed. These observations were focused in the northern locations, with 90% occurring in New England and maritime Canada. The most common fisheries affected were lobster (29% of observations) and soft-shell clam (9% of observations). Lobster were noted as particularly difficult to access due to stormy weather, and were described as being scarcer and having delayed molts. Clam populations were described as rebounding in response to a decrease in invasive green crabs in severely cold winters. Observation of cold-water events from more southern locations (Virginia, North Carolina, Florida, Alabama, and Texas) included fish kills due to abnormally cold water that did not always coincide with broader annual temperature trends, as was observed for red drum (*Sciaenops ocellatus*, Sciaenidae) in Texas in 1947.

In contrast to the relatively high number of species described as affected by warming along the Atlantic coast in the 1940s and early 1950s, modern observations were limited to just 28 species (Table 1), with the two most common fisheries dominating almost half of the observations: lobster (30%) and cod (13%). Additionally, the distribution of observations was more evenly spread historically, with an overall Shannon diversity index (H') of 3.65, compared to 2.53 today, reflecting the greater concentration of observations in fewer fisheries. Modern news coverage primarily discussed temperature-related shifts in species distributions, timing differences in migration, and other aspects of life history (e.g., lobster molting), leading to abnormal market conditions that negatively affected the fishery. For example, in 2012, "a warm winter brought on the lobster shedding season earlier than anyone could remember. The glut of shedders starting in June led to a price collapse because Canadian processors, a major market in summer for soft-shelled lobsters, were not ready to buy them." Observations also included more complex trophic interactions that affected particular fisheries, such as the 2013 observation that blue crab populations were lower than expected, due perhaps to "a surging red drum population in Virginia waters, another Southern species moving north with warmer waters."

Increase, scarcity, and access: The fishing communities' perspective on change

Across the three time periods, increase, scarcity, and access dominated the fishing communities' perspectives on the effects of temperature change on fisheries (Figure 3A). During the historical warming period, the majority (62%) of observations described a local increase of target species. Many of these were linked to increases in the length of the fishing season, as was noted for alewives (*Alosa pseudoharengus,* Clupeidae) and eels (*Anguilla rostrata,* Anguillidae) in Massachusetts, oysters

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(*Crassostrea virginica,* Ostreidae) in Rhode Island and Delaware, mackerel in New Jersey, shad (*Alosa sapidissima*, Clupeidae), herring, and blue crabs in Maryland, and spotted sea trout (*Cynoscion nebulosus*, Sciaenidae), croaker (*Micropogonias undulates,* Sciaenidae), flounder (*Paralichthys* spp., Paralichthyidae), and northern kingfish (*Menticirrhus saxatilis*, Sciaenidae) in North Carolina. Increases also related to favorable conditions that resulted in better than average recruitment, such as for blue crabs in the Chesapeake Bay, or increases in prey availability, such as for striped bass in Massachusetts. Increases also included the potential for new fisheries, with the presence and survival of warm-water species noted, such as the survival of European oysters (*Ostrea edulis,* Ostreidae) that were being held experimentally to determine if a local fishery could be established in Maine.

Scarcity of target species was the next most commonly described effect of warm waters during the historical warming period (28% of observations; Figure 3A). High temperatures were linked to (1) mortality, such as for bay scallops (*Argopecten irradians,* Pectinidae) in Massachusetts; (2) failure of migratory species to appear in typical abundances, such as for Atlantic herring (*Clupea harengus*, Clupeidae) in the Bay of Fundy; and (3) the movement of target species offshore, such as the "general movement of lobsters toward deeper, colder water" observed in Massachusetts. Change in the ability to physically access a fishery was a more commonly reported effect of warming waters in the Gulf of Maine (17% of observations) than in the Atlantic (4% of observations), with many of these observations linked to reductions in the thickness, duration, and distribution of ice. Additionally, several observations described changing in schooling behavior due to warming waters that made fish harder to access. For example, shrimp in the Gulf of Mexico were described as "scattered," and in Massachusetts many different fisheries were noted as suffering from an inability to locate previously predictable schools of fish. Similarly, the *Atlantic Coast Fisherman* reported that "Hand-liners have found it difficult to make a go of things because…they run out of fish very quickly. The scup and sea-bass are both scattered." Across all observations, the effects of warming waters on fish condition represented only 3% of observations, and typically referenced reduced quality of meat (Figure 3A).

Historical cold-water observations were most often linked to scarcity (46% of observations), including acute mortality events that affected target species (e.g., test beds of European oysters in Maine; several target species in Texas), reduced recruitment success (e.g., haddock, *Melanogrammus aeglefinus*, Gadidae, in Rhode Island), changes in migration patterns (e.g., herring in Canada), and reduced local abundance as compared to previous warmer years (e.g., scup in Maine). Conversely, fewer than 3% of observations linked cold water with increases in the abundance of target species. Cold water was also commonly linked to a reduction in the ability to access fisheries (43% of observations; Figure 3A).

Loss of access included stormy winter weather that inhibited fishing activity (e.g., hauling lobster traps), weather that made it too cold to fish, and boats frozen at their moorings. For example, in Nova

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Scotia, 1959 was described as "the coldest winter in 20 years" with "sheltered harbors, coves, and inlets…frozen over with ice nearly a foot thick" that left "small longliners and other inshore craft jammed in the ice" and "inshore fishing practically at a standstill." To the south, Connecticut boats were "frozen in at the docks." These conditions were described as affecting the whole coast with the 1958 observation that "High winds and ice conditions all along the Atlantic seaboard have hurt every fishing port." There was no noted effect on fish condition.

Modern observations of warming waters were most often linked to scarcity of target species (45% of observations), followed by increases in target species (27% of observations; Figure 3A). In both cases, these changes were often due to species distribution changes in response to warming waters. For example, red hake (*Urophycis chuss*, Phycidae) were described as "once abundant in the shelf waters of the Mid-Atlantic Bight, [but] now found primarily in the western Gulf of Maine" and shrimp (Pandalid), cod and lobster in New England were all observed moving north and east. Change in fish condition was noted more often today compared to historical observations, with 17% of warm water observations linked to declines in fish condition. This included shell disease in lobsters, as well as black gill disease in South Carolina shrimp (Penaeidae) fisheries, and outbreaks of dermo disease, which is associated with warm water (Crosby and Roberts 1990), in oyster fisheries along the Mid- and South- Atlantic coasts. Change in the ability to access fisheries was the least substantial concern (11% of observations), and most observations of this type related to target species migrating to deeper waters or across jurisdictional boundaries. For example, a 2017 article described emerging regulatory issues in the surf-clam (*Spisula solidissima*, Mactridae) fishery as the "industry shifts north."

Shifting perception of effects of the rapid temperature changes

The overall effect of warming waters in the 1940s and 1950s was perceived positively by fishing communities, likely as a result of an observed link to increases in target species and the potential for new fisheries, such as the observation that "more whiting [(*Merluccius bilinearis*, Merlucciidae)] are appearing at all seasons on Georges Bank…where whiting once were known as a Summer fish." Across all historical warm-water observations, 44% were positive, 35% were negative, and 21% were neutral (Figure 3B).

In contrast, cooling waters were viewed as much more strongly negative by the fishing community, with the effects of scarcity and reduced access felt particularly in northern climates. For example, a 1960 article described the cumulative effect of cooling on Gulf of Maine fisheries: "Lobsters are so scarce that few of the lobstermen even try to haul, as the small catches do not pay for operating costs. Groundfishermen are doing little better. Fishermen are inclined to blame continued cold weather as

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the cause for the absence of the usual amount of fish." Across all observations, 70% were negative, 20% were positive and 11% were neutral (Figure 3B).

Warming waters today are viewed much more negatively than they were in the past, with links to fishery collapses, such as a 2014 *National Fisherman* article that described the role of warming waters on "the Gulf of Maine's cod problems and the collapse of the northern shrimp fishery." Across all modern warm-water observations, 72% were negative, 15% positive, and 13% neutral (Figure 3B).

Loss of fishing opportunity over time and perceived links to climate change

Our analysis of fisheries landings in the Atlantic and Gulf region suggests a loss of opportunity over time. Overall, landings peaked in 1984 at 2.1 million metric tons, and have been declining since then (Table 2). In the most recent year (2017), landings were just 58% of the peak. The timing of peak landings for fisheries contributing the highest value and volume to US east coast fisheries also suggests more fishing opportunity in the past. Peaks in landings for top fisheries occurred early; 40% peaked in the 1950s, and 73% peaked before 2000. Only one, American lobster, had a peak in landings within the last decade. These fisheries had substantial overlap with those mentioned in historical news articles; of the 15 top fisheries identified, nine were mentioned in historical newspaper articles, and four were mentioned in modern articles.

In both historical and modern periods, a small subset of articles referenced links to global climate change (Table 3). Historical observations expressed both an awareness and skepticism of climate change. For example, in 1949, a writer began a description of the effects of warm water with the disclaimer, "We hate to squawk about climatic changes" while a writer in 1952 alluded to "theory of climatic change that we hear so much about." A more credulous writer speculated that should the current warming continue, "by the end of another century, the average temperature may be 15 or 20 degrees higher than it was in 1849." While modern observations were also mixed in terms of willingness to attribute warming to climate change, articles citing climate change were generally written in a more authoritative, confirmatory tone than those from the past. For example, while a 2006 article called "The question of global warming…a matter of religion," others had no trouble citing climate change (e.g., "Climate change is starting to show real consequences") or global warming (e.g., "Why are they doing better than Southern populations? In short, global warming").

Discussion

Our results highlight similarities and differences between recent rapidly warming waters and rapid temperature changes in the mid-20th century. Data on SST demonstrate clearly that warming happened in both time periods, though the rate and magnitude of warming today has been greater than in

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the past. The fishing community noticed these changes, and reported on them in fisheries newspapers. While previous studies have demonstrated that local ecological knowledge can be a robust data source for documenting changes in fisheries population levels (e.g., Drew, 2005; Powers et al., 2013), distributions (e.g, Scyphers et al., 2015), and ecological dynamics (e.g., Boudreau & Worm, 2010), our work shows that it can also contribute to understanding the social and ecological dimensions of climate change.

Many of the same types of observations were made during both warming periods: the distributions of target species shifted, disease increased, and phenological changes occurred. Additionally, many of the same target fisheries were affected. For example, in both time periods, the top five fisheries most commonly described as affected by warming waters included lobster, cod, and blue crab. Despite these similarities, it is notable that modern observations of the effects of recent warming waters were strongly negative as compared to similar observations in the 1940s. This increasing perception that warming negatively affects local fisheries may be due to an overall reduction of opportunity in fisheries over the past half century, an awareness of the relative severity of warming today, larger changes in American culture, or a combination of these factors.

Fishing opportunity: then and now

One possible explanation for shifting perceptions over the past 72 years is reduced opportunity in marine fisheries. Our analysis of landings data suggests that fishing communities were catching more fish in the past. Overall landings for the Atlantic and Gulf peaked in 1985, declining by more than 40%, and the majority of top fisheries peaked before 1980. This net effect of reduced landings over time likely negatively affected fishers' perspectives of future possibilities in marine fisheries.

Across the region, there are two main reasons for decreases in fishing opportunity. First, management regimes have improved and formalized over time (Weber, 2002). For example, many of the earlier peaks likely reflect efforts to combat overfishing and rebuild stocks, with notable successes such as haddock, pollock, and striped bass. The formalization of management regimes has also limited the ability of fishers to switch among fisheries and to target emergent fisheries as species' distribution cross jurisdictional lines (Pinksy et al., 2018). Limited entry fisheries have become more restricted with a concentration of commercial licenses in the US northeast (Bradley, 2011), and policy makers have noted the time lag in developing management plans for fish whose distribution have expanded into more northern states (Subcommittee on Oceans Atmosphere Fisheries and Coast Guard, 2017).

The second, more insidious reason for reduced opportunity in fisheries is historical overfishing. Since the 1950s, fisheries have undergone their most dramatic changes in human history, with rapid global expansions following World War II and expansion in the US in the 1980s with the assertion of rights over the 200 mile Exclusive Economic Zone (Weber, 2002). The expansion of fishing effort and

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globalized markets led to the collapse of many formerly important fisheries (Berkes et al., 2006; Mullon et al., 2005; Pinsky et al., 2011), including cod (Myers et al., 1997), Atlantic halibut (*Hippoglossus hippoglossus*, Pleuronectidae; Grasso, 2008) and urchin (*Strongylocentrotus*; Berkes et al., 2006; Stefansson et al., 2017). In Maine, overfishing resulted in a dramatic decrease in the diversity of landings over this time period, with the lobster fishery dominating more than 80% of the landed value for the state (Steneck et al., 2011).

Reduced diversity is one of the key predictors of a loss of resilience in marine fisheries, and the ability of fishing communities to adapt to climate change (Cinner et al., 2015; Finkbeiner 2015). In our historical dataset, more than twice the number of distinct target fisheries were described as affected by warming waters than were described in the same way recently. Additionally, the distribution of observations was more evenly spread historically, reflecting the greater concentration of observations in fewer fisheries (Table 1). This overall loss of fisheries diversity and well-known history of fisheries collapse would be expected to yield reduced optimism about the opportunity for expansion to new fisheries. While warming water clearly impacts fisheries (Pershing et al., 2015), without underlying overfishing, it rarely causes collapse (Pinsky & Byler, 2015). The difference in perception of the effects of warming waters that we identified may have to do with the fact that recent warming is occurring against the backdrop of already degraded fisheries, and may be exacerbated by the fact that fisheries management is not moving as rapidly as the species being targeted (Pinsky & Fogarty, 2012). These results underscore the need to place recent observations of the effects of warming waters into the context of long-term overfishing, which reduces resilience and the potential to adapt.

Global warming: then and now

A second possible explanation for shifting perceptions of the effects of modern warming waters is a broader cultural understanding of the increased certainty, severity, and consequences of global warming. The potential effects of industrial carbon dioxide emissions on global temperature has been discussed since the late 19th century (Fleming, 1998), so the concept of global warming existed during both the historical and modern warming periods. Retrospective analyses show that warming effects were felt by the 1930s (King et al., 2016), and observed warming was described in the context of global climate change both in the contemporary scientific literature (Callendar, 1938) and the popular press (Molena, 1912; Talman, 1930). However, scientific consensus around global warming did not exist in the 1940s and 50s, and our historical observations reflect this uncertainly, expressing both an awareness and skepticism of climate change (Table 2).

In contrast, today there is clear scientific consensus around climate change (Oreskes, 2004). Additionally, the magnitude and rate of SST change are substantially higher today than they were in any

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time known in the past. The rate of recent warming is also highly anomalous in the global record back to 1900 (Pershing et al., 2015). The effects of warming on fisheries are also more clearly understood today, with a range of severe negative consequences commonly attributed to global warming, including hurricanes (Emanuel, 2005) and disease (Khasnis & Nettleman 2005; Burge et al., 2014). Scientific consensus does not mean public support, and political polarization around climate change persists in the U.S. (Hamilton, 2011; Helmuth et al., 2016). Moreover, studies have shown that while personal experiences with temperature anomalies can influence perceptions of local or regional weather trends, they do not generally trigger major shifts in beliefs related to global climate change (McCright et al., 2014).

Reflecting this disbelief, a common view in fishing communities is that warming waters observed locally are cyclical (McClenachan et al., 2019). This viewpoint may stem in part from the fact that past warming periods such as the one in the 1940s and 1950s clearly impacted fisheries. Likewise, a previous AMO-driven warming in the 1860s (Figure 1A) and the cooling of surface waters at the beginning of the 19th century may help to explain the fisheries changes that occurred during those time periods. For example, in the five years following 1816, the 'year of no summer' in New England, there was a dramatic decline in landings of fish species negatively affected by the lower temperature: alewives, shad, and herring (Alexander et al., 2017). Conversely, fisheries in the region boomed in the 1860s (Alexander et al., 2009), coincident with the warming period. The more recent 1940s and 1950s warming period is within the living memory of older fishers, and the memory of this and more distant history is passed on to younger generations in part by the fisheries trade publications themselves. For example, the *National Fisherman* publishes a monthly column highlighting notable news from decades in the past, with observances of historical warming waters featured. Given this history of well-known warming and cooling, it is not surprising that the fishing community would be aware of these cyclical patterns, and subsequently reticent to attribute warming waters to global change.

However, while modern observations were also mixed in terms of willingness to attribute warming to climate change, articles citing climate change were generally written in a more authoritative, confirmatory tone than those from the past (Table 2). Given the developments in climate science over the past 75 years, as well as the increased severity of the threat, it seems likely that the negative views of warming waters today can be partially explained by the broader cultural knowledge of global warming and its effects on fisheries.

American optimism and other possible explanations: then and now

A number of potential additional factors that could explain differences between the historical and current period are worth considering. For instance, changes in perception of warming waters could reflect

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broader changes in American culture that may also have affected views of the fishery. Post war expansionism led to optimism across sectors of the American economy, and overall changes in American society may be partially responsible for increases in negativity in the more recent time period. Corresponding with these broader cultural changes, research in psychology suggests an increase in anxiety since the 1950s (Twenge, 2000). Differences in the average age of participants in fisheries could also be a possible explanation for why perceptions differed among the two periods. Specifically, the average age of participants in many commercial fisheries in the eastern U.S. has increased through time as barriers to entry have been created to reduce overfishing; average age is an indicator of future growth in the fishery (Sustainable Measures 2010). Therefore, while our sentiment analysis was aimed at answering the question, "Does the observation indicate a negative, positive or neutral effect on fisheries?" responses may reflect broader cultural forces that we are unable to measure. However, given the higher degree of negativity associated with the cooling periods immediately following the historical warming in the 1950s and 1960s, broader cultural and demographic changes are likely not sufficient to explain large differences in perceptions of rapid temperature change.

Data and biases

This study used a novel and underutilized historical data set: newspaper articles from fisheries trade publications. In all cases, historical data must be used with caution as biases can exist in sampling, observation, recording and preservation (McClenachan et al., 2015a). With our newspaper data, preservation and recording bias are minimal, as the data derive from one consistent set of sources and there are no known incentives or disincentives to record observations of warming water effects. However, observation bias affected the data that were available, with a higher number of observations of species with economic or cultural value and a large frequency of reporting on rare species. Given our focus on fisheries effects and identification of novel species, this potential bias does not compromise our results, but limits our ability to quantify changes from these data. One clear source of bias is sampling effort, with numbers of observations inconsistent over space. For example, in a few locations, regular columnists frequently reported on changes to fisheries. Therefore, we have a disproportional number of observations from these locations when these columnists were active, which limits our ability to infer relative change across space from numbers of observation. In other words, spatial gaps in data may reflect a lack of observation rather than a lack of change.

Climate adaptation informed by history

Climate adaptation is, and will continue to be, a major global challenge. If global emission reduction goals are met, warming will be reduced, but in all scenarios, there are punctuated periods of

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rapid warming projected throughout the world's oceans (IPCC, 2013). In order to prosper under rapidly changing conditions, climate adaptation strategies will be necessary. The negative perceptions expressed in fishing newspapers of recent warming, in contrast to the warming observed in 1940s and 1950s, suggest that fishing communities are finding the prospect of adaptation more difficult. A number of conditions have changed leading to this difficulty: reduced diversity of species accessed, more rigid fisheries management, and more rapid rates of change. Our results suggest that improving any of these conditions could reduce exposure and vulnerability of fisheries to climate change. While in many respects, future changes requiring adaptation will be beyond past experience, examining historical responses to rapid changes is instructive on the conditions that are more conducive to adaptation.

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Table 1. The number and diversity (H') of fisheries mentioned as affected by warming waters in the greater Atlantic region.

Time period	Number	H'
Historical (1945-1960)	64	3.65
Modern (1998-2017)	28	2.53

Table 2. The year of peak landings for top fisheries in the Gulf and Atlantic region for federally managed fisheries. Top fisheries are those with the highest cumulative landings or value (1950-2017). Ranks within each of these top 10 lists are indicated in parentheses. Data from NOAA 2019. Fisheries with * were present in our newspaper data.

Fishery	Peak year	Total landings, million mt (*rank*)	Total value, billion USD (*rank*)
Quahog clam* (*Mercenaria mercenaria*, Veneridae)	1950	0.33	1.68 (*8*)
Brown shrimp (*Farfantepenaeus aztecus,* Penaeidae)	1951	2.84 (*4*)	9.50 (*3*)
Acadian redfish (*Sebastes fasciatus,* Sebastidae)	1951	1.50 (*7*)	0.24
Eastern oyster* (*Crassostrea virginica,* Ostreidae)	1952	1.23	4.48 (*7*)
Haddock* (*Melanogrammus aeglefinus*, Gadidae)	1952	1.48 (*8*)	0.73
Silver hake* (*Merluccius bilinearis*, Merlucciidae)	1957	1.53 (*6*)	0.47
Pink shrimp* (*Farfantepenaeus duorarum*, Penaeidae)	1964	0.45	1.53 (*9*)
Atlantic surf clam* (*Spisula solidissima*, Mactridae)	1974	1.48 (*9*)	1.38 (*10*)
Atlantic cod* (*Gadus morhua*, Gadidae)	1980	1.42 (*10*)	1.36
Menhaden* (*Brevoortia tyrannus*, Clupeidae)	1983	57.01 (*1*)	5.05 (*6*)

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Blue crab* (*Callinectes sapidus,* Portunidae)	1993	5.04 (*2*)	5.19 (*5*)
Sea scallop* (*Placopecten magellanicus*, Pectinidae)	2004	0.87	9.61 (*2*)
White shrimp (*Litopenaeus setiferus,* Penaeidae)	2006	2.02 (*5*)	8.15 (*4*)
Atlantic herring* (*Clupea harengus*, Clupeidae)	2006	4.06 (*3*)	0.74
American lobster* (*Homarus americanus*, Nephropidae)	2016	1.83	11.61 (*1*)

Table 3. Climate change or natural cycles? Both during historical and recent warming events, fishing newspapers varied in their views about whether warming trends were cyclical or more long-term.

Year	Observation
1949	We hate to squawk about climatic changes… there could be something to it.
1949	The Weather Bureau records for Boston, Mass. and vicinity show that the average annual temperature today is five degrees higher than it was a century ago. Moreover, and this is also true, the rise in temperature is faster now than it used to be, so that by the end of another century, the average temperature may be 15 or 20 degrees higher than it was in 1849.
1951	What is going to happen next we don't know. Maybe the climate will become colder.
1951	Official findings of the Oceanographic Bureau show that the average annual temperature for this general area is five degrees higher than it was a century ago. The findings continue to state that the Polar ice-caps are melting steadily, the sea level is rising…
1952	Exactly how much there may be in the theory of climatic change that we hear so much about, is probably anybody's guess as we get it. This Fall, for example, the change in the movement of the fish has been very apparent. The tautaug didn't bunch up this Fall as they usually do, and they didn't remain on the ledges as long as common either. Coming right after two consecutive seasons when the swordfish barely stopped to take on nourishment before traveling northeast, this sort of thing is bound to make you think. As we said before, this is not an argument. It is a summary of some of the known facts. If it is assumed that our local climate is warming up and that some of our common varieties of fish are moving North because of this fact, it might account for some of these things.

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1952	Allowing that the weather sharks are right, and this change of climate indicates the trend, and allowing, too, that it will mean a movement of cold-water fish to other bearings, affecting the sword, as it did last year, and maybe some other species.
2006	Setting aside the question of global warming, which with many people is more a matter of religion - they take it on faith that a catastrophic warming trend is under way - than of science, there is little question that Greenland is a more temperate place than it has been. One effect: cod are booming.
2007	A few miles east in the ocean, climate change is starting to show real consequences, scientists say. Surf clam beds off the Delmarva peninsula continued to contract in 2006 as the biomass continued a decisive trend toward the east and north, where cooler ocean floor temperatures favor new clam sets.
2013	Gradually warming water temperatures along the East Coast are well documented by oceanographers. Scientists say sea surface temperatures off the East Coast have been about 5 degrees above average in the past year.
2017	Advocates cite warming temperatures leading larger shrimp to migrate earlier. While they are cautious about labeling the problem as climate change, an increasing number of Louisiana shrimpers say they want state officials to take a closer look at how harvesting seasons are set.
2017	Why are they doing better than Southern populations? In short, global warming. Over the last 10-plus years, the Northern stocks have been benefiting from a warming Arctic.

Figure 1. The timing of change. A. Time series of temperature anomaly, Gulf of Maine with the three periods of rapid temperature change highlighted. The rest of the Atlantic experienced a similar but less pronounced pattern of temperature change. **B**. Number of observations of the effects of warm (red) and cold (blue) water on marine fisheries in the Greater Atlantic region, 1945-1960; 1998-2017. **C**. Number of observations of invasive and novel species during the historical warming period. Invasive species are represented by green crabs in the Gulf of Maine; novel species represent all observations of rare species in the Atlantic region. **D**. Correlation between observations of invasive green crabs and the temperature anomaly (January to March average).

Figure 2. Examples and locations of warm water observations in Maine, showing the diversity of effects and target fisheries affected. White dots indicate locations where temperature-driven observations were made; grey dots correspond to observations highlighted in the text. Warming water was linked to increases and the potential for new fisheries; a change in timing, such as the early molt of lobsters; fish

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condition, such as the 1955 observation that "pink tails" (disease) were observed with warming in natural holding tanks; and a change of access, such as the observations that smelt and tomcod fishing was delayed due to a lack of ice.

Figure 3. Perceived effect of rapid warming on marine fisheries, 1945-2017. A. Types of impacts of rapid temperature changes described during historical warming (1945-1952), historical cooling (1953-1960), and modern warming (1998-2017) events. Observations were categorized into those that described the scarcity of target species, increases of target species, changes in the ability to physically access the fishery, and changes in the condition of target species. **B**. Percentages of observations that were described as having an actual or potential positive, negative or neutral impact on local fisheries during historical warming and cooling and modern warming events.

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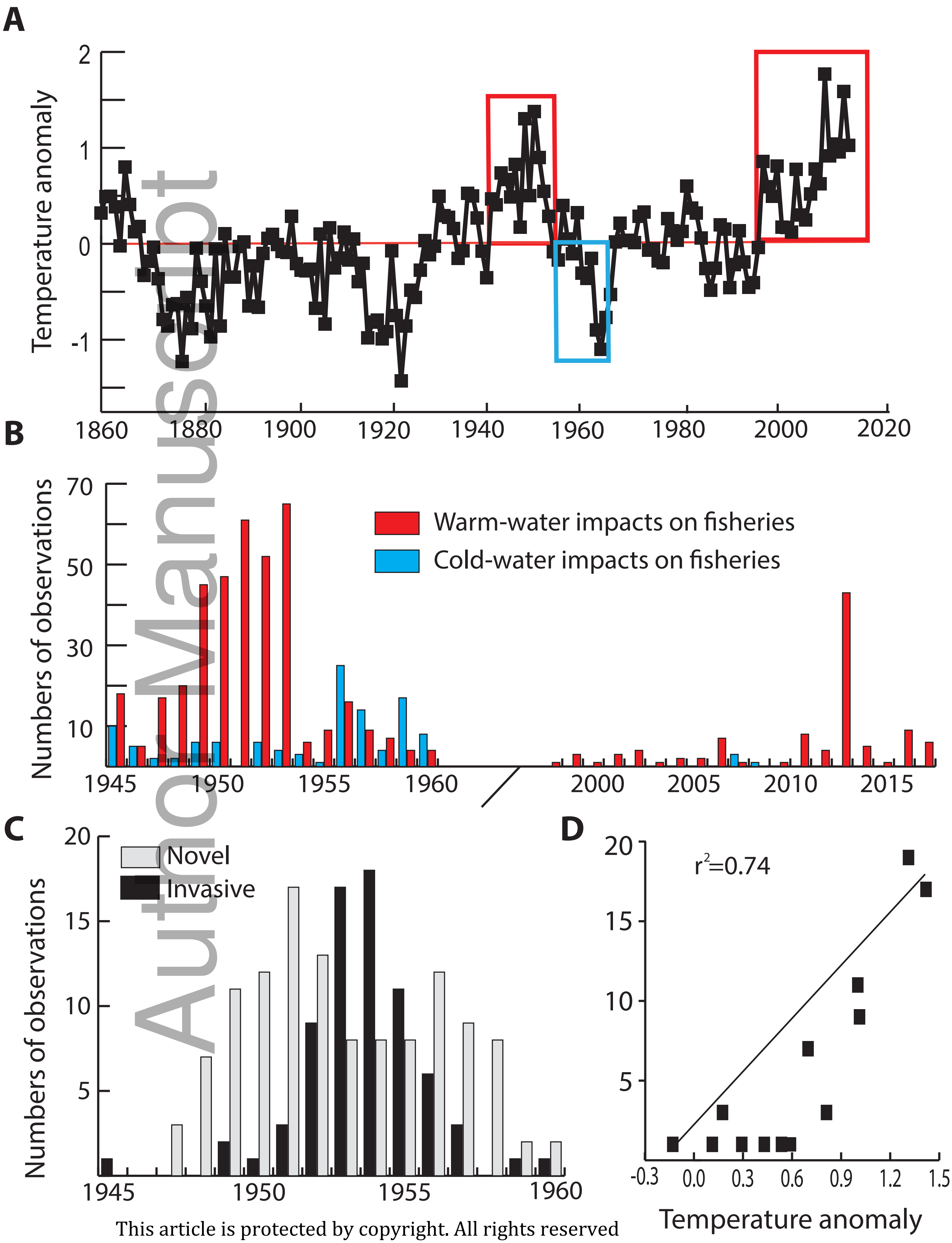

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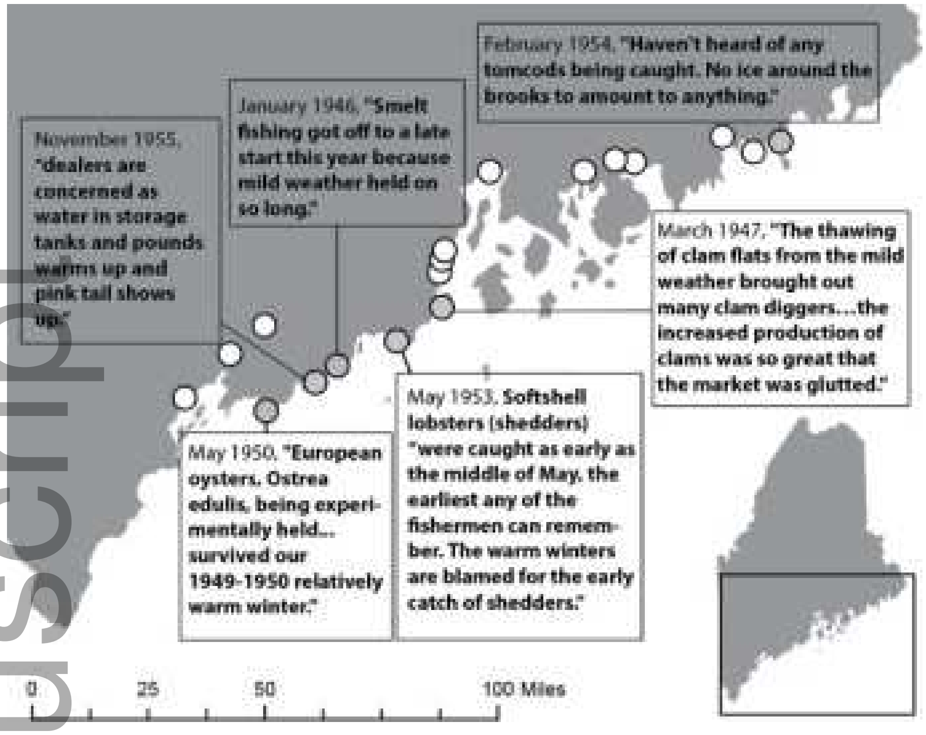

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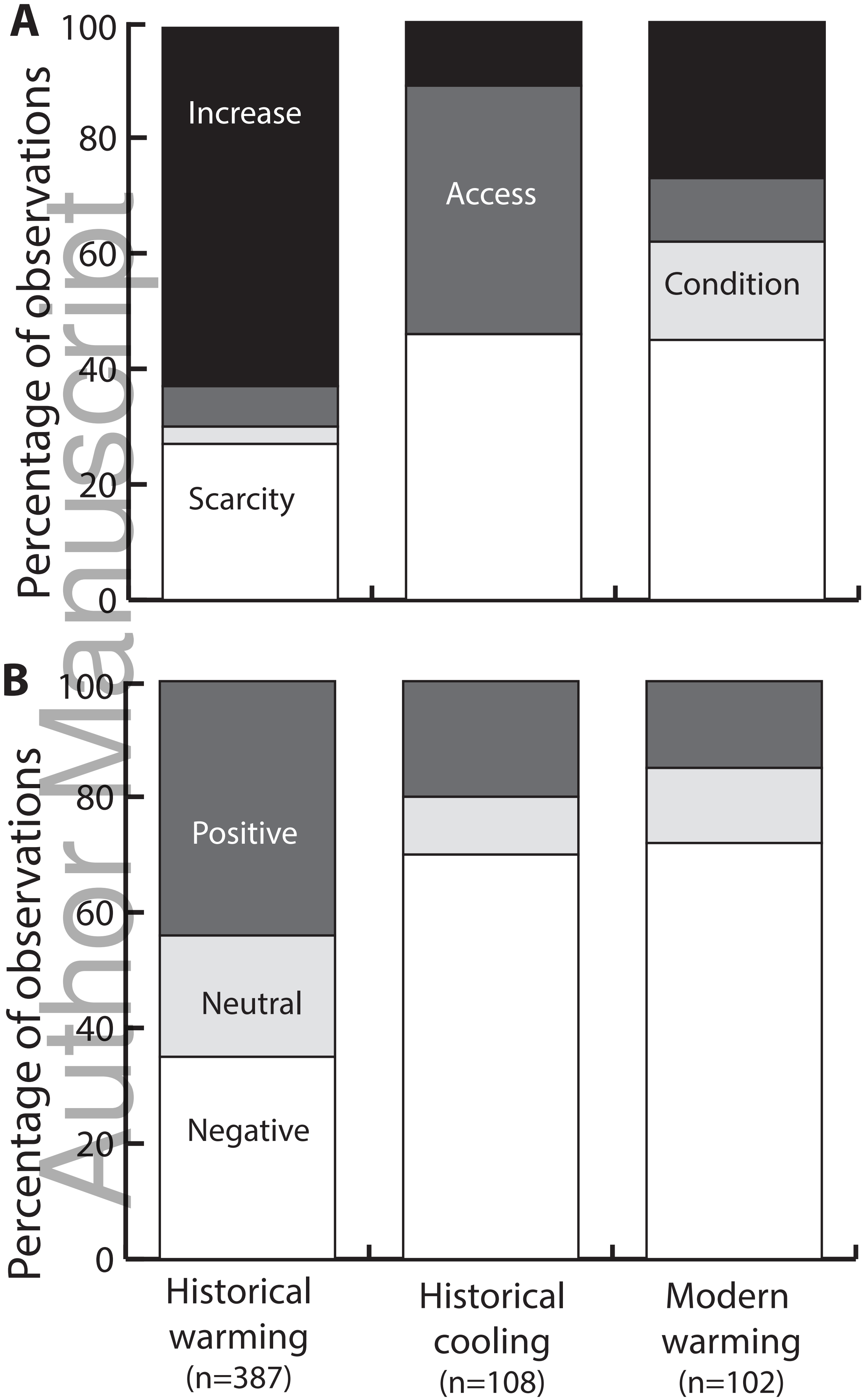

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