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Fishers' Local Ecological Knowledge Reveals Complex Food Web Dynamics With Rapidly Warming Waters

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ABSTRACT

Local ecological knowledge (LEK) can provide insight into ecosystem change, particularly in dynamic ecological conditions, such as those driven by climate change. In New England lobster fisheries, warming waters have the potential to disrupt food webs, as range-shifting species introduce novel ecological interactions. Here we use interviews with lobster fishers in Maine and Massachusetts to understand lobster fishers' LEK of dynamic food webs, taking a mental modelling approach to construct LEK food web models under rapidly warming waters. We find that fishers are observing a remarkable range of ecological interactions across habitats, collectively reporting knowledge of > 35 species that interact trophically with lobster across larval, juvenile, and adult life stages, ranging from terrestrial species like mink (*Neovison vison*) to deep sea species like redfish (*Sebastes fasciatus*). Our LEK food webs demonstrate perceptions of warming water altering species' abundances and interactions, with an overall negative impact on lobster fisheries. Fishers also report knowledge of complex interactions, including predation, competition, and habitat loss mediated by warming waters and changing species' abundances. Finally, we identify and categorise three main pathways that contribute to fishers' LEK, including observation, word of mouth, and inference. Our findings demonstrate that active fishers have complex understandings of food web interactions in dynamic ecosystems that are changing rapidly. With management unable to keep pace with climate-driven change, fishers' LEK is an invaluable source of knowledge, whose use could improve the ability to understand the diverse impacts of warming waters on coastal ecosystems.

1 | Introduction

Marine ecosystems are changing rapidly, with warming waters causing changes in species' distributions, phenologies, and disease prevalence (Harvell et al. 1999; Parmesan and Yohe 2003; Pinsky et al. 2013). The result of these changes is altered species interactions and ecosystem dynamics. For example, range-shifting species that are moving poleward due to warming waters have the ability to disrupt food webs, thereby increasing predation on or competition with local species (Harley et al. 2006). These disruptions are occurring against a backdrop of other changes including invasive species (Sorte et al. 2010), pollution and bottom water hypoxia (Diaz and Rosenberg 2008), overfishing (Jackson et al. 2001), and coastal habitat loss (Beck et al. 2011; Lotze et al. 2006). Notably, range shifts have exceeded the ability of management efforts to keep pace, resulting in challenges for fisheries trying to adapt to changing ecosystems (Pinsky et al. 2021).

Local ecological knowledge (LEK) can provide valuable insight into ecosystem change, particularly in contexts with rapidly changing ecological dynamics. LEK reflects the lived experiences of individuals and their relationship with the environment, and is particularly valuable when derived from fishing communities (Beaudreau and Levin 2014; Brook and McLachlan 2008; Rubio-Cisneros et al. 2023). Fishers' LEK can be a cost-effective monitoring tool for fisheries in data-limited systems, as it can help to describe species distributions (Lopes et al. 2019), spatial and temporal patterns (Moller et al. 2009), and food web interactions (Garavito-Bermúdez and Boonstra 2023). These observations are highly relevant to science and management, with application across a range of contexts (Anbleyth-Evans and Lacy 2019; Stephenson et al. 2016; Zukowski et al. 2011). LEK is particularly valuable in data-limited contexts, where observations of short- and long-term changes can provide critical missing information relevant to management (McClenachan et al. 2024). As fisheries are increasingly impacted by rapid, unpredictable, and non-linear effects of climate change, experienced fishers can provide both time-sensitive information on changes that are outside the natural range of variability and a baseline to which these changes can be compared. For example, in Alaska, local Indigenous knowledge has provided insight into both past and ongoing change in the Pacific cod fishery, which helps to document and assess population-level responses to a recent marine heat wave (West et al. 2025).

One useful lens for understanding fishers' LEK is that of mental models. A mental model is an internal representation of a given system, which can be represented graphically and mathematically using fuzzy cognitive mapping (FCM) (Gray et al. 2015; Özesmi and Özesmi 2004). Cognitive maps can be used to compare perceived relationships among concepts at the community level, as well as explore the logical consequences of future scenarios based on perceptions of system dynamics (Gray et al. 2015). FCMs have been used for various purposes in conservation research, including coastal restoration and assessments of adaptive capacity in fisheries under warming water scenarios (Drew et al. 2021; McClenachan et al. 2020). They have been used effectively as a mechanism for participatory research and to capture stakeholders' knowledge of complex ecological systems. For example, FCMs have been used with anglers and commercial fishers to help understand the factors influencing changes in the qualities and quantities of populations of targeted species (Gray et al. 2015), such as the effects of climate change (LaMere et al. 2020). While many FCMs used in marine conservation and fisheries contexts have focused on social-ecological systems, they can also be used effectively to explore LEK of food web dynamics. For example, in British Columbia, FCMs were used to harness experts' perceptions of herring food webs to improve decision-making processes (Stier et al. 2017). In both the North and Baltic Seas, a similar approach was used to construct food webs, compare perceptions across stakeholder groups, and test management scenarios (Olsen et al. 2023; Uusitalo et al. 2020).

The New England lobster fishery is an ideal case study to examine LEK of rapidly changing ecosystems for several reasons. First, the Gulf of Maine is warming faster than 99% of global oceans (Pershing et al. 2021) and several range-expanding species have recently arrived in the Gulf of Maine, including black sea bass (*Centropristis striata*) and blue crab (*Callinectes sapidus*) (Cheng et al. 2025; Manomet 2025). These species have been identified as potential food web disrupters through their predation on and competition with lobsters and other local species (McMahan et al. 2020; McMahan and Grabowski 2019). Second, coastal communities in the region are highly dependent on fisheries, with disruptions representing large economic and cultural impacts (Steneck et al. 2011). Finally, the dispersed, community-based, small-boat nature of the lobster fishery means that there are large numbers of individuals on the water making observations across a wide spatial extent of the coast that contribute to well-developed local ecological knowledge in this social-ecological system (McClenachan and Neal 2023). Likewise, there is a lot of inherited generational knowledge—or Traditional Ecological Knowledge (TEK)–because lobstering is often a family business passed from one generation to the next (Acheson 1988).

Previous interview-based work has demonstrated that New England lobster fishers are concerned about warming waters' impacts on lobster fisheries (McClenachan et al. 2020, 2022). Likewise, related work has shown that range-changing species are moving poleward, with potential impacts on lobster fisheries (Cheng et al. 2025; McMahan and Grabowski 2019). Yet gaps in knowledge remain around the details of food web interactions and potential mechanisms for disruption, such as predation, competition, and habitat alteration. Likewise, the relative importance of food web disruptions by range-changing species in the context of other impacts from warming waters is poorly understood. These include migration of lobsters to follow cold water, increased disease prevalence in warming waters, and disruptions to reproduction (Casey et al. 2023; Groner et al. 2018).

This case study has relevance more broadly, as fisheries around the world are impacted by warming waters, often in ways that are complex and hard to predict. Shifting species ranges and phenologies—against a backdrop of historical and ongoing exploitation—make it difficult for scientists and managers to understand and effectively plan for future change (Kortsch et al. 2015; Lindegren and Brander 2018; West et al. 2025). For example, shifting species distributions affect fisheries access, with a need to allocate licences equitably as species move across management jurisdictions (Pinsky et al. 2021). A lack of clarity about the degree to which range-shifting species impact or are impacted by food web dynamics further complicates efforts of managers to keep pace with these climate-driven changes. Efforts to understand the food-web mediated effects of climate change on marine ecosystems include those based on ecosystem modelling (Du Pontavice et al. 2020), controlled experiments (Amundrud and Srivastava 2019; Ullah et al. 2018), and field observations (Byrnes et al. 2011). In this context, observations of fishers add to a toolbox of methods relevant to understanding these complex changes to coastal ecosystems.

Our research addresses the question: What do fishers' LEK reveal about food web dynamics under rapidly warming waters? Specifically, we investigate the diverse interactions that fishers observe, their perceptions of the mechanisms for warming waters' impacts on lobster, and their observations of range-changing species and their impacts on the central fisheries species in the region, the American lobster (*Homarus americanus*). Taking a mental modelling approach, we construct LEK food webs in order to identify ways in which warming waters and range-changing species are perceived to alter the food web dynamics that affect lobsters, which we compare across the two regions of the Gulf of Maine. We also consider complex interactions, investigating the wider range of ecological interactions that fishers observe, including predation, competition, and habitat alteration. We conclude by considering and categorising the types of knowledge that contribute to this type of LEK.

2 | Methods

We conducted pilot interviews during July 2022 with ten active lobster fishers in coastal Maine. We recruited fishers to participate using a snowball sampling technique, and by approaching fishers on loading docks after fishing. In these semi-structured conversations, we asked fishers which species had the largest trophic impact on lobsters, the degree to which range-shifting species posed a threat to food web dynamics, and the relative importance of food web dynamics as compared to other warming waters' impacts. These interviews took place in person, lasting from 20 to 90 min. These pilot interviews were used to develop our structured FCM survey tool, which we used beginning in July 2023.

We conducted our structured interviews between July 2023 and March 2024. We targeted fishers who had an interest in warming waters and range-shifting species, as these fishers were more likely to have LEK that relates to our analysis. We recruited participants to participate in our in-person interviews by first sending a request to participate in an online survey, which asked fishers to report the number of black sea bass and blue crabs encountered in the 2022 season, their opinion about whether warming waters had or would affect lobster populations, and specifically whether it would affect lobster populations via (a) reproduction, (b) changing food web dynamics, (d) increase in disease, and (e) change to migration. Fishers were asked to provide contact information if they would like to participate in our in-person survey and were offered a $50 USD gift card as compensation. This survey was sent to all lobster licence holders in Maine limited-entry lobster fishing Zones E, F, and G. Additionally, we recruited fishers from northern Massachusetts to participate who had completed a previous survey in 2021 on the effects of range-expanding species on the lobster fisher and indicated willingness to participate in follow-up interviews and focus groups. Finally, we interviewed lobster fishers during the annual Massachusetts Lobstermen's Association's Annual Weekend and Trade Show in March 2024.

In person interviews lasted between 25 and 75 min. We began the interviews with semi-structured questions. We first asked fishers to confirm the responses they had given to the online survey, with the follow up question, "How do you know that warming waters are having an impact?" This question was aimed to elicit conversation about observations of warming waters with minimal biases. We also asked fishers at this point about the area where they fished, how long they had been fishing, and their home port.

In the structured FCM component, fishers were shown a partial food web that represented lobster and the seven taxa identified most commonly as lobster predators during our pilot interviews. These were Atlantic cod (*Gadus morhua*), black sea bass, striped bass (*Morone saxatilis*), seals (*Phoca vitulina*, *Halichoerus grypus*), blue crabs, green crabs (*Carcinus maenas*), and native crabs (*Cancer* spp.). Fishers were asked which of these species interacted with lobsters. For any species indicated, we asked whether the interaction was strong, moderate, or weak, and whether the taxon consumed adult, juvenile, or larval lobsters. We then asked fishers to identify other lobster predators they considered to be important, and whether these predators consumed any of the other taxa previously mentioned. For any species and interaction identified, we asked the same set of follow-up questions about interaction strength and life stage. Next, we asked which of these species were currently affected by warming waters in the areas where the interviewee fished. For any taxa identified, we again asked if that effect was strong, moderate, or weak. Information from respondents was transcribed during the interview by the interviewers on a working illustration of the food web, which was confirmed with the respondents.

Data analysis for the FCMs involved determining average centrality values for our core concepts and average interaction strength among those concepts. Interaction strength was coded as a value between −3 and +3, with negative values indicating predation, or a negative effect of warming waters when warming waters was the driving concept. For instance, 0 indicates no predation or warming affect, −1 indicates weak predation or weak negative warming effect, −2 indicates moderate predation or moderate negative warming effect and −3 indicates strong predation or strong negative warming effect. In some cases, responses were more nuanced than is easily captured by this simple scale. For example, one fisher reported that warming water has a "weak positive impact on lobster below 25 fathoms (45 m), and strong negative impact above." In these cases, we took an average of the values expressed. For example, this interaction was coded with a moderate negative impact (average: +1, −3 = −2). We include quotes from our interviews alongside the FCM results to help add nuance into the results.

We determined all species perceived to have a direct trophic impact on lobsters, including both species in our original FCM and those added by fishers during the interview process. To compare across this larger species pool, we derived weighted average interaction strengths for species not included in the original FCM. That is, we weighted the average reported interaction strengths by the number of respondents mentioning each taxa to derive equivalent interaction strengths. Next, we used online software (https://www.mentalmodeler.com/ (Gray et al. 2015)) to run scenarios of increasing warming water, in order to determine how the collective FCM implied that taxa would respond, considering food web dynamics. Our interaction strength values were scaled from −1 to +1 to run scenarios to align with the scale used by the software. Finally, we compared average FCMs between the two geographic regions (Maine and Massachusetts), testing for significant differences using simple t-tests.

We further analysed our qualitative interview data by coding descriptions of diverse interactions, mechanisms of change, descriptions of complex interactions (e.g., predation, competition, habitat change). Finally, we categorised responses to the question "How do you know that warming waters are having an impact?" into a range of observation types, including direct observation and word of mouth. We report these responses with direct quotes attributed to lobster fishers alongside the quantitative FCM results.

3 | Results

We interviewed 45 lobster fishers using our structured survey, 20 in Maine and 25 in Massachusetts. Half of our interviewees (51.1%) were between the ages of 55 and 74, with 40.0% between 35% and 54% and 8.9% between 18 and 35. These demographics largely track the industry, which is characterised by long wait times for licences and fishers who maintain licences and continue to fish into their 80s (McClenachan and Moulton 2022). The majority (80.0%) of respondents had more than 20 years of experience fishing lobster, while 6.7% had 10 to 20 years of experience, and 13.3% had less than 10 years.

3.1 | Fisher Observations of Food Web Interactions

3.1.1 | Observations Across a Diversity of Habitats and Species

Our interview results demonstrate that New England lobster fishers' collectively possess LEK that spans a remarkable variety of species and habitats (Figure 1). Lobster fishers operate by setting baited traps, to which they return up to several times a week for hauling. Fishers typically set their traps in the same location over many seasons, which results in repeated daily observations of marine environments, often over decades. Collectively, New England lobster fishers operate across a range of habitats, from shallow (2 m) water within sight of shore to over a hundred kilometres offshore in up to 200 m of water. In the process of this work, fishers make observations in habitats including nearshore terrestrial, estuarine, coastal marine, and offshore pelagic and deep sea habitats. In particular, fishers who operate lobster traps across depths possess knowledge about ecological differences across a range of habitats. For example, one lobster fisher who operates in waters up to 100 m in depth said that the "food web changes with

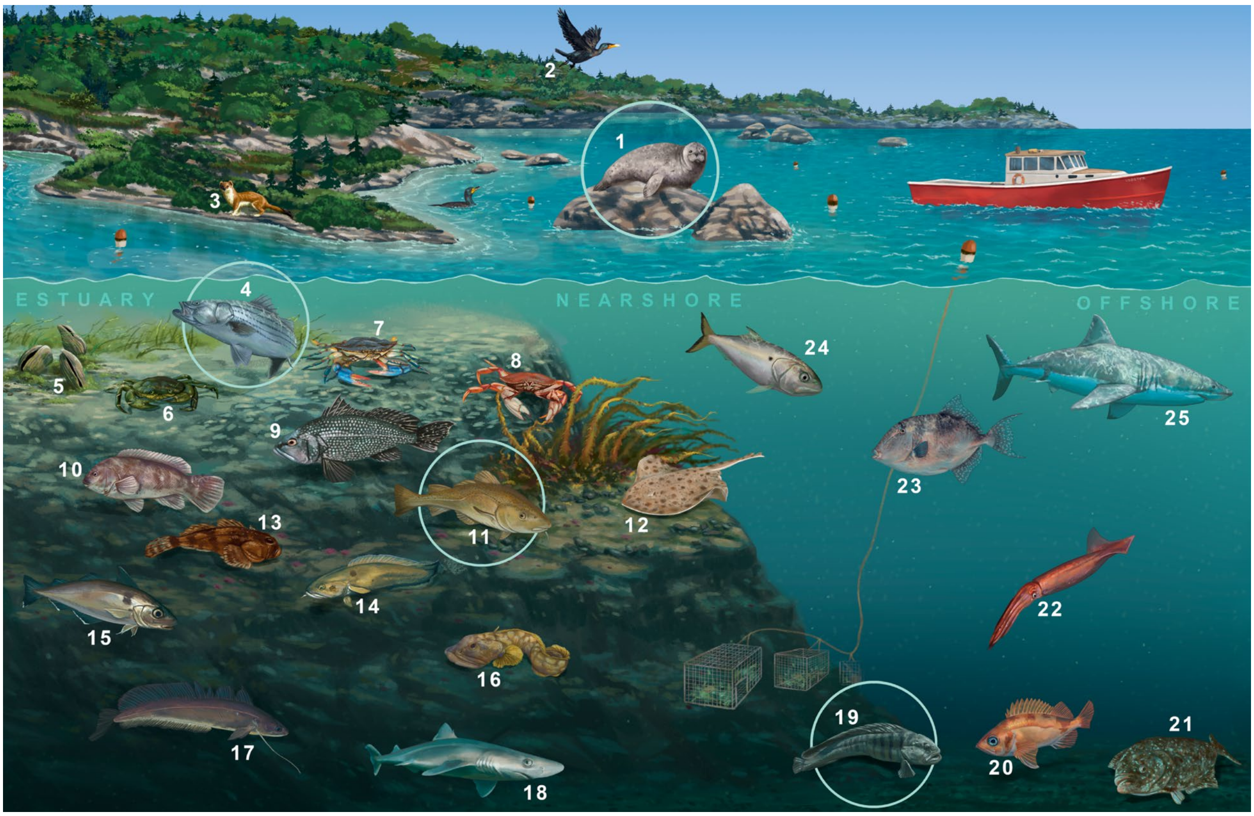

FIGURE 1 | Species observed by active lobster fishers. Based on in-person interviews ($n = 45$). Fishers observe a diversity of species across a range of marine habitats, including estuarine, nearshore, and offshore. More than 35 taxa were mentioned by at least one respondent; the subset of species represented here demonstrates the diversity of species observed, with key predators across estuarine, nearshore, and offshore habitats indicated with circles. Key: 1 Harbour seal (*Phoca vitulina*), 2 Cormorant (*Nannopterum auritu*), 3 Weasel (*Mustela erminea*), 4 Striped bass (*Morone saxatilis*), 5 Oysters (*Crassostrea virginica*), 6 Green crab (*Carcinus maenas*), 7 Blue crab (*Callinectes sapidus*), 8 Native crab (*Cancer* spp.), 9 Black sea bass (*Centropristis striata*), 10 Tautog (*Tautoga onitis*), 11 Atlantic cod (*Gadus morhua*), 12 Skate (Rajidae), 13 Sculpin (*Myoxocephalus* spp.), 14 Cusk (*Brosme brosme*) 15 Haddock (*Melanogrammus aeglefinus*), 16 Ocean pout (*Macrozoarces americanus*), 17 Red hake (*Urophycis chuss*), 18 Dogfish (*Squalus acanthias*), 19 Wolfish (*Anarhichas lupus*), 20 Acadian redfish (*Sebastes fasciatus*), 21 Halibut (*Hypoglossus hypoglossus*), 22 Shortfin squid (*Illex illecebrosus*), 23 Triggerfish (*Balistes* spp.), 24 Menhaden (*Brevoortia tyrannus*), 25 White shark (*Carcharodon carcharias*). Full species list and frequencies are shown in Table S1. Art by Jennifer Claussen.

depth, at every 5 fathoms," or approximately 10 m. He further described a distinct shift in the food web "below 20 or 25 fathoms," or approximately 40 m. In particular, fishers reported that different lobster predators exist at different depths. One respondent said "black sea bass can be found a lot deeper than [striped bass]" which are constrained to "40 fathom or less," or approximately 70 m. Another concurred, adding that "codfish are only deep."

The breadth of collective LEK results in observations of a diversity of marine, estuarine, and terrestrial species. Across all our interviews, fishers identified > 35 taxa while fishing for lobster (Table S1). Most taxa were observed in lobster traps, while others were observed in the course of operations. Species observed included terrestrial mammals like weasel (*Mustela erminea*) and mink (*Neovison vison*), as well as seals, all of which were observed taking either lobsters or lobster bait from nearshore traps. One respondent said harbour seals "eat mostly bait and can open [lobster trap] doors." Observations were also made of animals, including seals and striped bass, feeding on lobsters while traps were being hauled. One fisher reported that striped bass "follow [the boat] like dogs. And they also eat the trap spills [small lobsters coming out from the trap's vents] as the trap comes up." Fishers also observed species entering traps and becoming stuck within them. These typically included finfish species, including menhaden (*Brevoortia tyrannus*), striped bass, wolffish (*Anarhichas lupus*), and red hake (*Urophycis chuss*), but one fisher reported that he once caught a weasel in his trap. Fishers frequently keep a running estimate of the number of individuals caught, which allows them to assess relative abundance over time and across species. For example, one said that he sees 100 striped bass a year in his traps, and another saying that menhaden (known locally as pogies), "have been getting caught in lobster traps, up to one hundred pogies a haul." Another noted that red hake appeared to be increasing at depth, as he "sees a lot more in 60 fathom [110 m]" reporting up to ten per trap.

Lobster fishers used these observations to draw conclusions about predation, identifying lobster predators across a range of habitats and ecosystems. Key lobster predators (Figure 1, circles) included striped bass in inshore marine and estuarine habitat, seals in pelagic nearshore environments, cod in demersal inshore and offshore habitats, and wolfish in benthic inshore and offshore habitats. Fishers drew conclusions about predation by directly observing predation events, and also by directly observing the stomach contents of species caught in lobster traps. One said that when ocean pout (*Macrozoarces americanus*) and sculpin (*Myoxocephalus* spp.) are brought to the surface from depths in lobster traps, the pressure difference causes them to invert their stomachs, and that he "has seen them vomit lobsters." Fishers also reported cutting open finfish bycatch, and observing stomach contents in this process, with some reporting that they selectively used particular bycatch species as bait based on their perceptions of the predatory impact on lobsters. One said that he "throws everything back except sea robins [(*Prionotus* spp.)] and sculpin because they eat lobster" and so he uses them for bait. Several fishers reported throwing back Atlantic cod, rather than cutting them open to observe stomach contents, because they would like to see historically depressed populations recover.

3.1.2 | LEK Food Webs

We were primarily interested in fishers' LEK about lobster predators. Therefore, our FCM food web included seven key lobster predators: seals, striped bass, black sea bass, Atlantic cod, blue crabs, green crabs, and native crabs. During our interviews, fishers were asked to identify additional species that were part of lobster food webs, either by directly preying on lobster or indirectly by consuming another species that is part of the FCM food web. Due to the open-ended nature of this question, different levels of taxonomic detail were offered. For example, some fishers identified flatfish (Pleuronectidae, Scophthalmidae) as lobster predators, while others specifically identified halibut (*Hypoglossus hypoglossus*). Likewise, in some cases, common names refer to a suite of species. For example, sculpin (*Myoxocephalus* spp.) and sea robin (*Prionotus* spp.) were sometimes used interchangeably. Therefore, our taxonomic groupings collapse species for which different levels of taxonomic precision were offered or that fishers referred to interchangeably during our interviews. Details of species groupings are found in Table S1. Through this process, fishers identified 30 additional taxa with direct or indirect consumptive effects on lobster (Table S1), with nine taxa identified as having links to the lobster food web by four or more respondents (Table 1).

Striped bass was the most significant predator identified, with an average interaction strength of −2.42, representing "moderate to strong" predation (Table 1 and Figure S1). This was followed by Atlantic cod (−1.51), seals (−1.47), and black sea bass (−1.16), all of which were perceived to have weak to moderate predation effects on lobster. Of the seven taxa included in our FCM, blue crab had the smallest perceived predation impact on lobsters (−0.16).

For the nine additional taxa identified as lobster predators by four or more respondents, we calculated average interaction strength among the respondents that identified them, which ranged from four to 16 individuals. In order to more directly compare interaction strengths of these nine taxa with the seven original species included in the FCM, we also calculated a weighted average interaction strength, which accounts for fishers who did not identify this species. The most significant predators that emerged were wolffish (−1.88 average reported, −0.67 weighted average), sculpin (−1.86, −0.58.), flatfish (−1.56, −0.31) tautog (−1.71, −0.27), and cormorants (−1.38, −0.24) (Table 1 and Figure S1). All five of these had weighted interaction strengths greater than that of blue crabs, the lowest-ranking predator in our original FCM. Additional species identified as predators by four or more respondents were dogfish (*Squalus acanthias*), red hake (*Urophycis chuss*), triggerfish (*Balistes* spp.), and cusk (*Brosme brosme*).

We also asked fishers to report on consumptive effects throughout the food web, for example, as seals consumed a range of finfish and invertebrate species. When accounting for these interactions, lobsters, striped bass, and seals were perceived to be the most significant interactors, with centrality scores of 9.39, 8.22, and 7.93, respectively. Blue crabs were the least significant interactor, with a centrality score of 2.60 (Figure 2A and Table S2).

TABLE 1 | Direct consumptive effects on lobster. Average reported interaction strengths were weighed by the number of respondents for those not included in the original FCM to derive equivalent interaction strengths.

Species	Average reported interaction strength	*N*	Weighted average interaction strength
Striped bass (*Morone saxatilis*)	−2.42	45	n/a
Atlantic cod (*Gadus morhua*)	−1.51	45	n/a
Seals (*Phoca vitulina*, *Halichoerus grypus*)	−1.47	45	n/a
Black sea bass (*Centropristis striata*)	−1.16	45	n/a
Native crabs (*Cancer* spp.)	−1.05	45	n/a
Green crabs (*Carcinus maenas*)	−0.67	45	n/a
Wolffish (*Anarhichas lupus*)	−1.88	16	−0.67
Sculpin (*Myoxocephalus* spp.)	−1.86	14	−0.58
Flatfish (Pleuronectidae, Scophthalmidae)	−1.56	9	−0.31
Tautog (*Tautoga onitis*)	−1.71	7	−0.27
Cormorant (*Nannopterum auritu*)	−1.38	8	−0.24
Blue crabs (*Callinectes sapidus*)	−0.16	45	n/a
Dogfish (*Squalus acanthias*)	−1.50	4	−0.13
Red hake (*Urophycis chuss*)	−1.50	4	−0.13
Triggerfish (*Balistes* spp.)	−1.20	4	−0.11
Cusk (*Brosme brosme*)	−1.00	4	−0.09

3.1.3 | Predation on Lobsters at Different Life Stages

Lobster fishers identified predation on lobsters throughout larval, juvenile, and adult life stages (Table S1). The largest number of taxa ($n = 32$) were identified as consuming juvenile lobsters. Eleven taxa were identified as consuming adult lobsters, including seals, striped bass, and crabs. One respondent said, "Big crabs can take a market lobster down in the traps" and another said, "Big stripers are able to eat adults on the bottom." One respondent identified oysters as a predator of lobster larvae, saying "Oyster aquaculture is having an impact, eating lobster eggs." Four additional taxa were identified as having an indirect effect on lobster food webs through consumption of other species in the lobster FCM food web. The most commonly mentioned of these was white sharks (*Carcharodon carcharias*), which were described as connected to lobster via their consumption of seals.

3.2 | Dynamic Food Web Interactions Under Warming Waters

3.2.1 | Warming Waters Across the Foodweb

Fishers perceived the effects of warming waters throughout the food web (Figure 2A and Table S2). Increasing warming water was believed to have the largest overall negative impact on lobster (−0.84), and largest overall positive impact on black sea bass (+1.44). They also indicated that warming water would cause the abundance of several species to increase, including striped bass (+0.82), green crabs (+0.78), blue crabs (+0.64), and seals (+0.22), and a decrease in abundance of cod (−0.13), and native crabs (−0.11). Warming waters' impact on lobster reflects average perceptions across habitats (including as defined by depth strata), which were often quite different. For example, one fisher reported that warming water has a "weak positive impact on lobster below 25 fathoms (45 m), and strong negative impact above." Another reported that lobsters were strongly affected by warming waters inshore, while offshore populations thrived.

Mental modeller scenarios allow for a quantification of perceived impacts, based on reported interaction strengths across the food web (Figure 2B). Our analysis revealed that fishers perceive that warming waters will result in a 20% increase in black sea bass, a 10% increase in green crab and striped bass, and a 5% increase in seal populations. They also indicated that warming waters would cause a 10% decrease in lobster and a 5% decrease each in cod and native crab populations. Interview responses reflect the perception that the combination of increased warming water and predation would have negative impacts on lobsters. One respondent summarised, 'Warmer water fish—black sea bass—are showing up here. [They are] voracious feeders that will have an impact'.

3.2.2 | Regional Differences

For both predation and warming waters, there were a few significant ($p < 0.05$, Table S3) differences between locations (Figure S2). The most important predator was identified as striped bass in Maine and seals in Massachusetts. In Maine, striped bass were perceived to have a significantly stronger predation impact on several species (black sea bass, cod, blue crabs, native crabs, and green crabs), while in Massachusetts, seals were perceived as having a stronger impact on black sea bass, blue crabs, native crabs, and green crabs than they did in Maine. There were also significant differences between locations in the relative importance of both native crabs and green crabs, with both considered significantly more central to food webs in Maine than in Massachusetts. All crab species were perceived to have a significantly stronger negative effect on lobsters in Maine. Finally, in Maine, lobster had a significantly higher centrality than in Massachusetts, due to

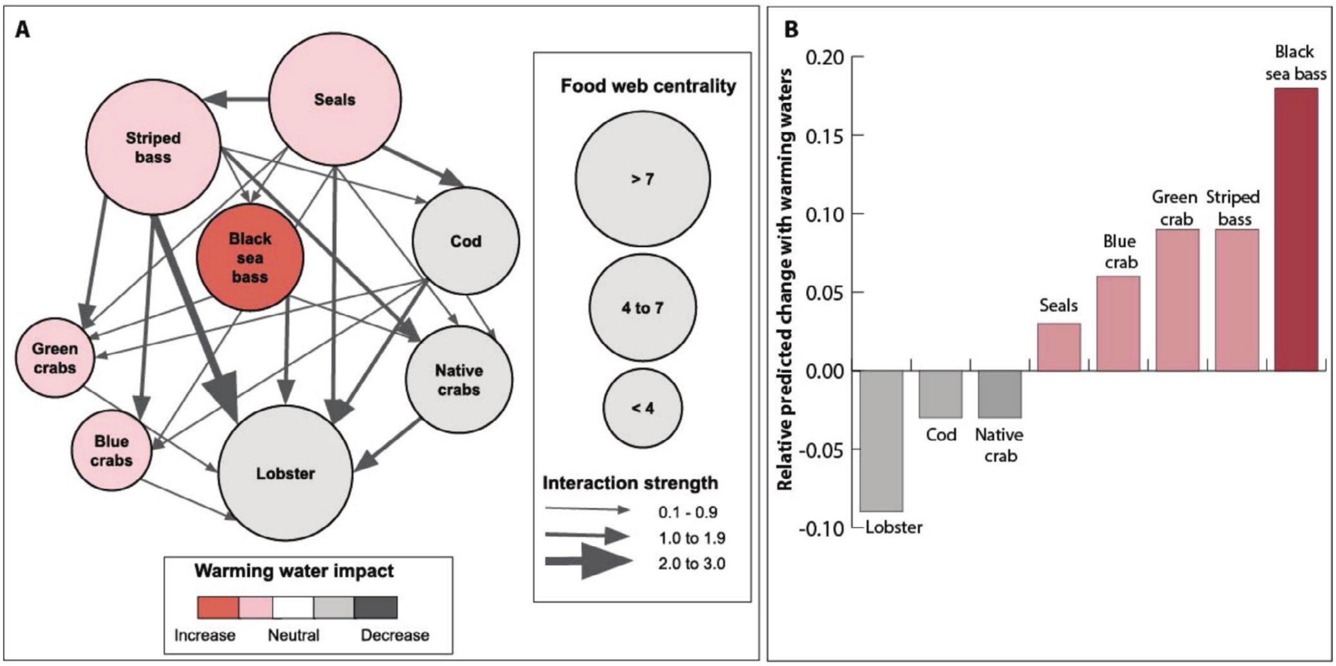

FIGURE 2 | LEK food webs under warming. (A) Perceived food web interactions, with warming water impacts. Food web centrality ranged 2.60–9.39 and interaction strengths ranged 0–2.42. (See Table S2 for all values). Warming water was perceived to strongly impact black sea bass (increase), and moderately impact seals, green crabs, blue crabs (increase), lobster, cod, and native crabs (decrease). (B) Mental modeller scenarios suggest the relative perceived change in these same taxa that fishers expect with warming waters.

higher perceived consumption across the food web. Warming waters were perceived to have stronger impacts throughout the food web in Maine as compared to Massachusetts, with significant differences in warming water's impact on striped bass, native crabs, and green crabs (Table S3).

Some of these regional differences in perceived impacts may be related to varying degrees of exposure to warming waters and two range-expanding species, black sea bass and blue crabs (Table S4). Fishers in both Maine and Massachusetts reported observation of these two species, but there were substantial differences between the two locations, with more observations of both species in Massachusetts. All fishers in Massachusetts reported observing black sea bass, with a median of 150 individuals encountered in a season. In contrast, only 73% of Maine lobster fishers reported black sea bass interactions, with a median of 5 individuals. Fewer respondents reported interactions with blue crabs in both locations, with 40% of fishers in Massachusetts and 29% in Maine reporting interacting with blue crabs, and a median of 0 individuals observed in both locations. These observations likely had some impact on the perception of the role of these species in lobster-centered food webs.

3.2.3 | Observations of Complex Ecological Interactions and Knowledge Pathways

In addition to direct predation, fishers identified complex ecological interactions including predation across multiple trophic levels, competition, and habitat alteration (Table 2). Complex predation relationships that involved three or more species included those at the top of the food web, such as interactions among white shark, harbour seals, grey seals, and lobsters. One respondent described increasing white sharks "only eating gray seals, not harbor seals," with impacts on lobster food webs as the two seal species were described as having different diet preferences, with grey seals being more voracious lobster predators, while "harbor seals only eat lobsters when they're desperate because they prefer bait." These predator–prey relationships also included observations related to complex interactions at the base of the food web. One respondent described increasing oyster populations as having a food web impact, as oysters both eat lobster eggs and also filter plankton with the result being "less phytoplankton, which makes it easier for other predators to see lobster larvae."

The driver of many of these complex predation interactions was warming waters, as new predators become more prevalent. These changes can have both negative and positive impacts on lobster. For example, one respondent reported a net positive impact with the addition of squid to local coastal ecosystems: "Squid are increasing due to warming. They eat fish, which eat lobster." Other drivers include increasing aquaculture, overfishing and the recovery of anadromous fish populations. One respondent described increases in seals as due to alewife (*Alosa pseudoharengus*) restoration, saying "There are more seals, which impacts lobsters because when they're done feeding on alewives in June, they will start feeding lobster that are migrating inshore." Some of these complex predation and phenological interactions were identified as having a negative impact on lobster populations, with the others being positive or neutral.

Fishers also described complex interactions involving species competition, habitat loss, and environmental change, all of

TABLE 2 | Descriptions of complex interactions described by lobster fishers, based on in-person interviews ($n = 45$). Example observations are based on direct quotes from interviews; interaction type, driver, species involved, and impact on lobster were inferred from additional information provided in that interview.

Interaction type/species involved	Example observation, number of respondents describing this interaction	Driver	Lobster impact
Predation: Oysters, phytoplankton, lobsters	Oyster aquaculture is having an impact, eating lobster eggs, cleaning up water, less phytoplankton, easier for other predators to see lobster larvae ($n = 1$)	Aquaculture	Decrease
Predation: Squid, fish (unspecified species), lobsters	Squid are increasing due to warming, eat fish, which eat lobster ($n = 1$)	Warming waters	Increase
Predation: Seals, herring, lobsters	Seals turned to scavenging on the bottom for lobsters much more after the inshore herring were wiped out by the mid-water trawlers ($n = 1$)	Overfishing	Decrease
Predation: Seals, alewives, lobsters	There are more seals, which impacts lobsters because when they're done feeding on alewives in June, they will start feeding on lobsters that are migrating inshore. There are more seals, but it's not because of temperature. It's because of alewife restoration. ($n = 1$)	Species recovery	Decrease
Predation: Seals, menhaden, plankton, lobsters	Seal predation is not happening anymore, pogies (menhaden) are feeding them now, which is an indirect positive effect on lobsters… Pogie abundance is mediated by plankton availability, which is temperature mediated ($n = 1$)	Warming waters	Increase
Predation: Sharks, grey seals, harbour seals, lobsters	Sharks used to be here during the 1970s which was also a warm time. Sharks are only eating grey seals, not harbour seals. Harbour seals only eat lobsters when they're desperate, they prefer bait. Grey seals eat lobster but the population is low ($n = 1$)	Warming waters	Not specified
Competition: Green crabs, mussels, clams	Green crabs eat mussels and clams, competing with lobsters… Used to freeze in bays which changes the survivorship of green crabs ($n = 4$)	Warming waters	Decrease
Competition: Blue crabs	Blue crabs compete for food and space with lobster, no direct predation ($n = 2$)	Not specified	Decrease
Competition: Native crabs	Native crabs displace lobster. Crabs take over whole pieces of bottom and lobsters will move to the shoals, and then they just switch ($n = 2$)	Not specified	Decrease
Competition: Spider crabs	[Spider crabs] push out the lobster, they're either competing for bait or just filling up traps. In the last 10 years the populations exploded. The closer inshore, the bigger. ($n = 1$)	Warming waters	Decrease
Habitat loss/Environmental change: Green crabs, eelgrass	Green crabs are changing eelgrass habitat into muddy shorelines, which indirectly impacts lobsters ($n = 2$)	Invasive species	Decrease
Habitat loss/Environmental change: Kelp, urchins, lobster	Kelp is reduced, possibly due to urchins, which is reducing lobster habitat ($n = 1$)	Not specified	Decrease
Habitat loss/Environmental change: Fresh water, lobster	Rain has been a significant impact this year, visibility even offshore in over 30 fathoms is less than 2 fathoms. Dark freshwater layer staying on the surface through all of State waters ($n = 3$)	Increased precipitation	Decrease

which were described as having a negative impact on lobster. Competition with crabs was mentioned by several respondents. For example, one respondent said, "Green crabs eat mussels and clams, competing with lobsters." Competition for space was also mentioned, with one respondent reporting, "Native crabs displace lobster. Crabs take over whole pieces of bottom and lobsters will move to the shoals, and then they just switch." Another specifically noted spider crabs displacing lobster, saying "They push out the lobster, they're either competing for bait or just filling up traps. In the last 10 years, the populations exploded." These competition interactions were reported as driven by warming waters in some cases.

Complex interactions involving habitat loss and environmental change included changes to kelp, eelgrass, and water quality. For example, one respondent noted, "Green crabs are changing eelgrass habitat into muddy shorelines, which indirectly impacts lobsters." Three respondents noted that an increase of freshwater–associated with increased and less predictable rainfall patterns–affects lobster. One observed a "dark freshwater layer staying on the surface" throughout all state of Maine waters, and another said the freshwater impacts lobsters as they "move offshore and die in tanks" holding lobsters at the surface after being caught. One of the three fishers who reported increased rainfall as an impact on lobster suggested it may be due to changing global climate patterns, saying "If temperature affects rainfall, then there is a big negative effect."

Finally, we identified several types of LEK pathways that fishers expressed throughout their responses. These knowledge pathways collectively related to observations of species presence, abundance and movement, species interactions, and drivers of change (Table S5). First, direct observations described knowledge based on personal observations and related most commonly to observations of species abundance, presence, and movement. For example, observations of species presence or relative abundance were frequently based on direct observations, such as the observation made by one fisher that he had seen black sea bass in low abundances for 20 years. Knowledge of species interactions and drivers of change also drew from direct observations, such as the observation of stomach contents including lobster, and observations of temperature shifts, such as one fisher who said he remembered "walking out on sea ice as a kid, and there is none at all now."

A second LEK pathway was word of mouth, which is information based on peer-to-peer information sharing and related both to species presence and trophic interactions. For example, one Massachusetts fisher said "I've heard from friends in Maine that they are seeing more blue crabs" and another who reported hearing that someone cut open a lumpfish and found small lobsters, suggesting predation. A third LEK pathway was indirect observations or inference, which was an observation of a proxy of the phenomenon of interest or knowledge based on observations of analogous events (e.g., other species or time periods). Drivers of change were often inferred. For example, one fisher reported that "sharks used to be here during the 1970s which was also a warm time" as a reason to think that a recent increase in sharks was temperature driven. Species interactions were also inferred, such as the report that "Red squid eat shrimp, so will also eat juvenile lobsters."

4 | Discussion

Fishers' local ecological knowledge (LEK) is known to be a valuable source of information around the world (Drew 2005; Rosa et al. 2014). Here, we found that New England lobster fishers display a remarkable range of LEK due to the nature of the fishery. In particular, repeated observations in the same habitat by individuals –often over decades and using the same fishing gears–coupled with the diversity of habitats and ecosystems that lobster fishers collectively interact with make them especially valuable as providers of LEK. Our results demonstrate that fishers observe a range of ecological interactions–including predation, competition, and habitat alteration–and are actively tracking the varied and non-linear impacts of warming waters, all through the lens of the lobster fishery. Fishers spend long hours on the water over decades and have an economic interest in tracking changes that affect lobsters. Therefore, their observations are closely made and often insightful about very specific parameters affecting single-species targets.

LEK has been used in a variety of fisheries management and conservation contexts across fisheries sectors, including commercial, recreational, and Indigenous (Anbleyth-Evans and Lacy 2019; Eckert et al. 2020; Pita et al. 2020; Zukowski et al. 2011). One of the key contributions of this work is underscoring the value of LEK food webs to improving management in an era of rapid warming. In particular, direct LEK food webs provide insights into dynamic ecological changes and are especially valuable as climate-driven changes are happening faster than the ability of scientists and managers to track them. Possible applications in this context include the inclusion of fishers' observations of range-changing species in NOAA's State of the Ecosystem reports and through real-time reporting of observations. For example, regional nonprofit fisheries organisations in Maine have developed a reporting mechanism for blue crabs (Manomet 2025) and are working to develop a similar observation reporting dashboard for lobster fishers to report black sea bass sightings. Both state and federal fisheries management agencies have expressed interest in using this information in decision-making. Together, our results demonstrate the value of fishers' LEK in tracking dynamic ecological responses that impact a fishery, and thus are valuable for fisheries management that is struggling to keep pace with climate-driven changes (Pinsky et al. 2021).

This interview-based work dovetails with other approaches to understand the impact of range-changing species on lobster fisheries. Our results agree with both ecological and social science research suggesting that as the northwest Atlantic rapidly warms, range-expanding species such as black sea bass and blue crabs are becoming more abundant in the region, especially in the southwestern reaches of the Gulf of Maine. For instance, diver surveys and opportunistic collections of black sea bass throughout New England demonstrate highest abundances in Rhode Island, intermediate in northern Massachusetts, and lowest in Maine (McMahan 2017; McMahan et al. 2020). A 2021 survey of lobster fishers noted that fishers are observing black sea bass throughout much of the Gulf of Maine, with highest abundances observed during recent warm years and throughout a greater portion of the year in northern Massachusetts than in Maine (Cheng et al. 2025). These studies collectively have filled a data gap given that black sea bass is not adequately sampled by any scientific surveys in the region, and highlight the value of quantifying fishers' local ecological knowledge, especially in a rapidly changing world.

Our analysis also has limitations. It is important to note that our quantitative FCMs reflect perceptions of species interactions. As we describe, these perceptions are based on a range of knowledge pathways, including observations of stomach contents, conversations with peers, and observations of habitat changes over decades. This is rich knowledge with insights into changes on a scale that is typically not possible by ecological studies, but it is also not consistent or standardisable in the way that ecological data typically are. Within the FCMs themselves, it is important to note that perceived abundance is conflated with perceived importance in the food web; these values can differ, especially with respect to historically important predators, which are currently not abundant but were once important. For example, populations of Atlantic cod are widely known to have collapsed in abundance following overfishing, with reduced roles in the ecosystem (McClenachan and Neal 2023). However, where they are found, they are important predators on a range of benthic invertebrates, including lobsters. While many fishers independently volunteered the perception that cod are less abundant than other predators, we did not ask this question directly, and as a result our FCMs do not distinguish between perceptions of cod abundance and predation. Finally, lobster fishers view the ecosystem through the lens of lobster, which means that species interacting with lobster are in sharper focus than others that may have important but less visible roles in the ecosystem. Gray et al. (2015) found similar degrees of focus within members of angling communities, with fishers' view of the ecosystem and associated drivers of change shaped by the target species. These considerations do not limit the applicability of the findings, but should be used in comparing them to results derived from other knowledge pathways.

Finally, fishers' observations can provide new and testable ideas for scientists and managers to investigate further, in collaboration with fishing communities. Through just a handful of interviews in the course of this study, the lobster industry generated several observations (Table 2) worthy of potential research projects. In New England, there is a long history of collaboration between lobster fishers and research scientists, and fisheries science often benefits from the hypotheses that the industry generates through their observations. For example, observations reported by lobster fishers led to initial ecological research on range-changing species in the Gulf of Maine, including black sea bass diet analysis and predator–prey experiments with lobster and black sea bass (McMahan et al. 2020; McMahan and Grabowski 2019). Similarly, it was also their belief that they are farming lobsters in the Gulf of Maine that led to research on bait impacts on lobster diet and growth (Grabowski et al. 2010). Some of the observations made in the course of our interviews are not currently the subject of scientific inquiry, but could be developed as collaborative research. For example, it was reported that egg shedding behaviour by female lobsters has changed, with only males migrating into shallower (warmer) waters, while females remained below a thermocline threshold, and therefore in some cases farther offshore. Adaptations to behaviours such as brood and aeration have recently been shown experimentally in response to changing environmental conditions (Sisti et al. 2024), but this has not been shown in field conditions for lobsters. Ontogenetically specific changes in horizontal and vertical migration related to environmental conditions thus represent one possible hypothesis to come from these interviews.

The core concepts and theoretical framework of this case study have broader global relevance, as they underscore the value of LEK in understanding changes in contemporary coastal ecosystems affected by climate change. Our study shows that fishers observe complex interactions across a wide range of species and habitats, often of phenomena that impact both the fisheries in which they work and marine ecosystems more broadly. Such rich ecological knowledge has provided insight into both short and long-term changes across a range of ecosystems and fisheries contexts, from the Baltic Sea to the Caribbean (Garavito-Bermúdez and Boonstra 2023; Rubio-Cisneros et al. 2023). Experienced fishers often hold knowledge of long-term change not captured by ecological or fisheries data; these observations of change are particularly relevant in regions with limited baseline fisheries data, where repositories of LEK often remain overlooked by managers and authorities (McClenachan et al. 2024). At the same time, experienced fishers are able to compare decades of accumulated knowledge of species' distributions, abundance, and trophic interactions to contemporary observations and note specific changes that are outside of the range of variability, generating knowledge that is essential to managing climate-ready fisheries (West et al. 2025). In a warming world that is changing rapidly and unpredictably, these observations and the hypotheses they generate will be increasingly valuable.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are not available due to restrictions on sharing under the Institutional Review Board's Research Ethics protocols.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** faf70021-sup-0001-Supinfo01.docx.