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Identifying New England's underutilized seafood species and evaluating their market potential in a changing climate

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Developing and diversifying market opportunities for lesser known yet abundant seafood species has been a successful strategy for seafood businesses in the Northeast United States. Since climate change and other stressors are currently threatening the economic vitality of New England's seafood industry, it is important to identify if there are lesser-known species that could simultaneously support additional market opportunities and remain resilient in a warming climate. We developed a quantitative definition for the term "underutilized species" based on five criteria derived from science-based sustainable fishing metrics. Using this definition, we evaluated 47 stocks in the Northeast United States during the initial time period of 2013-2017 to identify seven underutilized finfish species that could be considered for new market opportunities as part of a climate-smart approach: 1) Acadian redfish *(Sebastes fasciatus)*, 2) Atlantic pollock *(Pollachius virens)*, 3) butterfish *(Peprilus triacanthus)*, 4) haddock *(Melanogrammus aeglefinus)*, 5) scup *(Stenotomus chrysops)*, 6) silver hake *(Merluccius bilinearis)*, and 7) white hake *(Urophycis tenuis)*. The climate resiliency of these resulting seven species was then evaluated using a framework consisting of species-specific metrics on climate sensitivity, directionality (of responses to climate impacts) and future habitat availability under warming scenarios. Our results show that assessing underutilized species on a regular basis and evaluating their ongoing responses to climate change can be a part of a climate-smart approach towards building more diversified and adaptive markets.

KEYWORDS

fisheries, sustainable, underutilized species, seafood, climate change, northeast, food, Atlantic

1 Introduction

1.1 Climate change impacts on fish and fisheries

Rapid warming along the Northeast United States (Karmalkar and Horton, 2021) has elevated concerns about the future stability of regional fish populations and fisheries (Pershing et al., 2015; Colburn et al., 2016; Pershing et al., 2021). Fish populations are responding to warming temperatures in diverse ways such as shifting their abundance, distribution, and phenology (Nye et al., 2009; Staudinger et al., 2019; Langan et al., 2021). While geographical range and phenological shifts demonstrate fishes' ability to adapt to changing environmental conditions, these shifts can alter ecosystem-level interactions (Weiskopf et al., 2020; Staudinger et al., 2021) and complicate management policies (e.g., regional allocation of quota, fishing locations, etc.) when fish populations span management boundaries (Pinsky et al., 2018).

Climate-induced changes in marine species have created socioeconomic consequences for the seafood industry in New England and beyond (Mills et al., 2013). Overhead and operational costs increase when fishers need to travel farther to capture species that shift away from fishing ports (Pinsky and Fogarty, 2012; Young et al., 2019) into deeper waters or more northern habitats (Nye et al., 2009; Kleisner et al., 2017). Warming waters have also created unstable supply and demand relationships for fishers and seafood businesses (Garcia and Rosenberg, 2010; Mills et al., 2013). Financial challenges from climate change are magnified by pricing pressure from increasing amounts of cheaper imported seafood with high carbon footprints (Keithly et al., 2006; Stoll et al., 2015; Shamshak et al., 2019). Small boat fishers may also experience fewer days to safely operate their businesses since climate models predict more frequent and intense storms in the Northeast U.S. (Dupigny-Giroux et al., 2018).

1.2 Building resilience with adaptive markets

Climate change is one of several recognized stressors that is prompting New England's seafood industries to adjust their operations (Colburn et al., 2016; Pershing et al., 2018). New England's fisheries, including those for groundfish, seasonal finfish, and highly migratory pelagic species, are heavily regulated and managed through a complex set of controls including harvest limits, gear specifications, seasonal restrictions, and spatial and temporal closures. Regulation changes that protect other marine life (e.g., Atlantic Large Whale Take Reduction Plan impacting lobster and other pot/trap fisheries) and the global COVID-19 pandemic have also challenged the vitality of New England's seafood businesses (Smith et al., 2020). New England's seafood industries have a history of creating successful new economic opportunities for lesser-known and low-value marine foods, especially when facing financial stressors and uncertainties. For example, lobster in the mid-1800s and certain tuna species in the early 1900s are notable New England seafood items that were transformed from low-value catch to high-value delicacies with canning technology and creative marketing (Seaver, 2017). Squid (as calamari) only recently became a menu favorite in the early 1990s, when proper processing infrastructure and advertising were established to encourage consumers to expand their preferences beyond overharvested groundfish populations (Frank, 2014). Expanded and diversified markets for lesser-known local seafood species were also observed during the COVID-19 pandemic when animal proteins were difficult to access due to breakdowns in the supply chain (Smith et al., 2020; Stoll et al., 2021). Research from Eating with the Ecosystem shows that New England's total catch portfolio is not reflected in the region's marketplace (Masury and Schumann, 2019), and therefore there are lesser-known seafood species that may be able to support expanded market opportunities.

These current and historical perspectives suggest that an abundant population, collaboration throughout the supply chain (point of origin to the end consumer), and heightened interest in the marketplace are all key ingredients when building lasting markets for lesser-known seafood species. Moving forward, establishing diverse, and long-term markets will also require that marketed species be consistently accessible in a changing climate. If New England seafood businesses and resource managers incorporate up-to-date information on past, current, and future impacts of climate change on fish stocks, fishers and seafood businesses could better anticipate fish population responses and therefore implement climate adaptation plans and policies to create more adaptive and resilient fisheries and food systems.

Here, we offer a climate-smart approach to building adaptive market opportunities. We identify finfish species landed in New England that are underutilized and based on current information, evaluated the potential of these finfish populations to remain productive, stable, and accessible in a changing climate. To date, the term "underutilized species" has been a generalized marketing term used to describe any regional seafood item that is abundant in the wild but is not well-known or widely used, even if it is valued in international markets or by culinary professionals (McClenachan et al., 2014; Witkin, 2014). If the term "underutilized" continues to be used arbitrarily or based solely on the species' visibility in the marketplace, seafood providers and advocacy groups may create demand for species independent of each other and independent of best available management and climate information, which could risk creating demand for species that are experiencing overfishing or are overfished. However, a measurable definition for "underutilized" that incorporates management metrics, alongside updated information about the species response to climate change, could help regional fisheries and advocacy groups identify, prioritize, and market their region's unique underutilized species in alignment with each other to create a more climate-smart seafood system. Our definition for "underutilized" expands upon the Food and Agriculture of the United Nation (FAO) metrics of "underfished" (when a fish population is more than what would produce maximum sustainable yield (MSY)), and "underfishing" (when the catch (F) is less than the ideal proportion of catch that will generate MSY) (Hilborn, 2020; FAO, 2021).

We developed quantifiable criteria to identify underutilized seafood species managed by the New England and Mid-Atlantic

Fishery Management Councils during two time periods (2013-2017 and 2015-2019). We then designed a weighted evidence assessment to evaluate the climate resilience of each identified underutilized species. Results were coupled with economic data and consumer marketing reports to create accompanying species-specific, public-friendly, climate-informed species profiles to complement communication and outreach initiatives. Here we provide New England's seafood industries with: 1) a definition for the term `underutilized species' that is measurable based on specific quantifiable criteria, 2) criteria for evaluating climate resilience of each underutilized species, 3) a rating of species that New England seafood businesses can consider for expanded market opportunities based on their underutilized status and climate resilience, and 4) public-friendly species profiles that share science-based sustainability information with the seafood industry, advocacy groups, and consumers. While this framework has been developed and demonstrated with a focus on finfish managed and landed in the Northeast United States, the framework could be adopted by other managed fishing regions within or outside of the United States with resources to support ongoing updates.

2 Methods

2.1 Identifying underutilized species

We established a measurable definition for underutilized finfish species as any managed finfish species or stock that: 1) is allowed to be landed, 2) is not overfished, 3) is not experiencing overfishing, 4) has a population at or above target levels, and 5) 50% or less of the annual catch limit (either sub-annual catch limit or quota, depending on species) has been caught in at least three out of the past five years. Criteria in this definition were based on science-based sustainable fishing metrics that can be derived from NOAA stock assessments, management regulations, and catch reports. Such metrics included catch limits, cumulative catch (weight kept + weight of discards), fishing status (e.g., overfishing is or is not occurring), and population status (e.g., overfished or not overfished; at, below, or above target levels). These metrics are routinely calculated and reviewed (typically once every 1-3 years) by fishery management bodies in the United States, which ensures the specified definition of underutilized species can be applied and evaluated consistently across regions and time periods. The annual catch limit threshold in criteria #5 is intentionally set low at 50% and covers a span of time to allow the underutilized definition to highlight stocks that are repeatedly underfished and would likely not experience overfishing [based on definitions in FAO (2021)] if additional fishing pressure was applied in an effort to expand market opportunities for the species.

Stock assessments and annual catch monitoring reports were reviewed to evaluate which finfish stocks managed by the New England and Mid-Atlantic Fishery Management Councils (Figure 1) were underutilized for two sliding 5-year periods (2013-2017 and 2015-2019). Stock assessment reports stated the following statuses for each stock: overfished (Yes, No, or Unknown), overfishing (Yes, No, or Unknown), and population level (Below, At, or Above Target Level) (NEFSC, 2014; NEFSC, 2017; NOAA, 2021). Data-poor stocks were disqualified from a full evaluation if stock statuses were listed as "unknown". Annual catch monitoring reports detailed whether each species was allowed to be landed, and the annual cumulative catch (landings + discards). For consistency, cumulative catch weights were converted from pounds (lb.) to metric tons (mt.) as needed. Annual catch limits are different for every species, and different stocks of the same species have separate annual catch limits. Annual catch limits for all species/stocks managed under the Northeast Multispecies Fishery Management Plan (FMP) and Small-Mesh Multispecies FMP were the sub-Annual Catch Limits (sub-ACL), which reflect stock distinctions. Sustainable annual catch limits for all other species were the species-specific coast-wide quotas. Catch limits changed annually for all species except scup, which had separate seasonal quotas (Winter I, Summer, and Winter II). Annual *cumulative catch*, *quota*, and *sub-ACL* for 2013-2017 were gathered from catch monitoring reports and online databases and then organized into a separate database. Data sources can be found in Supplementary Material.

If not already provided in each species' monitoring report, annual *percent catch limit caught* was calculated as:

$$\textit{Percent catch limit caught} = (\textit{Cumulative Catch}/\textit{subACL or Quota}) * 100$$

Our process affirmed that if the median *percent catch limit caught* within a five-year window for a species was below 50%, less than 50% of the ACL or quota was used in at least three out of the five years. By using the median percent caught over five years (as opposed to the mean), annual information could not collectively be influenced by other years.

Annual catch reports were initially evaluated in 2019 for the five-year window of 2013-2017 since 2017 was the most recent annual data available. Species identified as underutilized were re-evaluated for the five-year window, 2015-2019, in late 2021. The 2015-2019 re-evaluation was limited in scope since annual catch monitoring reports from 2018 and 2019 were only considered finalized for species within the Northeast Multispecies complex.

2.2 Assessing climate resilience

Climate resilience was assessed for each underutilized species identified in each five-year window. Published reports were gathered on three indicators of climate resilience - biological sensitivity, directionality, and future habitat availability. Biological sensitivity and directionality scores were derived from a recent Climate Change Vulnerability Assessment that focused on Northeast finfish species (Hare et al., 2016). Overall biological sensitivity (low, moderate, high, or very high) was determined in Hare et al. (2016) by a logic model that considered scores from 12 biological attributes representing traits of the species that influence its responsiveness to environmental change. Directionality indicated whether climate change impacts on population productivity were anticipated to be negative, neutral, or positive.

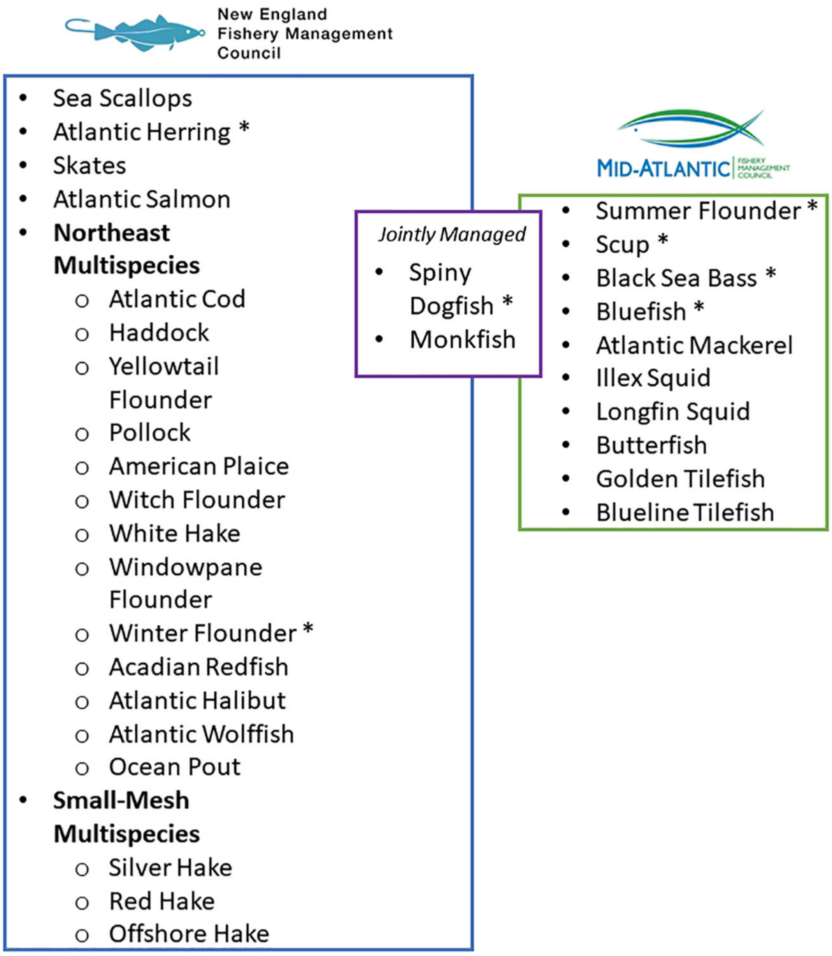

FIGURE 1
A list of all fish species managed independently, and jointly, by the New England Fishery Management Council and the Mid-Atlantic Fishery Management Council. Management responsibilities are also shared with the Atlantic States Marine Fisheries Commission for fish marked with an asterisk (*).

Future habitat availability was derived from two recent modeling studies: 1) Kleisner et al. (2017) projected gains and losses in seasonal habitat abundance under a carbon dioxide doubling scenario implemented using the CM2.6 model developed by the NOAA Geophysical Fluid Dynamics Laboratory; and 2) Allyn et al. (2020) projected seasonal relative biomass in 2055 with habitat conditions from the CMIP5 climate model ensemble run under the RCP 8.5 scenario. Mean model results for the Gulf of Maine and Southern New England/Mid-Atlantic Bight regions during the fall and spring reported in Allyn et al. (2020) were used for the future habitat availability metric.

The climate resilience assessment weighted the biological sensitivity, directionality, and habitat availability metrics across a spectrum from "-1" to signal relatively lower resiliency to "+1" to indicate relatively higher resiliency. A score of "0" indicated stability or no substantive changes detected and a "NA" indicated that the species was not evaluated in a specific study. When two or more studies commented on the same resilience indicator (e.g., habitat availability), each study received its own score and then the mean of the two scores was used as an aggregate score (Table 1).

The total weight of evidence (W) was calculated as the average score of the three indicators. Higher values for total weight of evidence indicates greater confidence (W>0.33) in each underutilized species' resilience under future climate conditions, while lower values indicate neutral confidence ($-0.33 \le W \le 0.33$) and ($W < -0.33$) lower confidence in their climate resilience (Table 1). The short term and long-term market potential of each underutilized species was deduced based on the climate resilience score. Underutilized species with 'high' climate resilience ratings were associated with long-term market potential; those species with 'neutral' or 'low' ratings were determined to have short-term market potential if markets could align with their availability as climate conditions continue to change.

2.3 Climate informed profiles

Public-friendly climate-informed profiles were also constructed for each identified underutilized species to help communicate results to diverse (i.e., non-technical) audiences with interests in

TABLE 1 A scoring rubric showing how resilience indicator results from literature were converted into weighted scores from -1 to 1 for the climate resilience assessment.

Resilience Indicator	Data Source	If the result was....		...then weighted score in the assessment was
Sensitivity	Hare et al. (2016)	low		1
		moderate		0
		high or very high		-1
Directionality	Hare et al. (2016)	positive		1
		neutral		0
		negative		-1
Habitat Availability	Kleisner et al. (2017); Allyn et al. (2020)	Habitat Abundance (Kleisner et al., 2017)	Relative Biomass (Allyn et al., 2020)	
		a significant gain in both fall and spring	significant gain in both regions during both seasons	1
		a significant gain in only one season, no substantive changes in other season	significant gain in both regions during one season, marginal loss or gain in both regions in other season	0.5
		no significant loss or gain in either season	no significant loss or gain in either region in either season	0
		a significant loss in only one season, no substantive changes in other season	significant loss in both regions during one season, marginal loss or gain in both regions in other season	- 0.5
		a significant loss in both fall and spring	significant loss in both regions during both seasons	-1

Higher weighted scores reflect sensitivity, directionality, and habitat availability responses that demonstrate relatively high resilience (e.g., low sensitivity, positive directional effect, and gains in habitat availability) while lower scores indicate relatively low resilience. A score of "0" indicated stability or no substantive changes detected and a "NA" indicated that the species was not evaluated in a specific study.

fisheries management and marketing. Life history and socio-economic information were gathered from the primary literature, government publications, Essential Fish Habitat Source Documents (Cargnelli et al., 1999; Chang et al., 1999; Cross et al., 1999; Pikanowski et al., 1999; Steimle et al., 1999; Lock and Packer, 2004; Brodziak, 2005), and a market analysis report (Masury and Schumann, 2019). Additional climate research was compiled from a subset of previously published studies that documented and projected range and other shifts for regional fish species (Collie et al., 2008; Nye et al., 2009; Bell et al., 2015; Henderson et al., 2017; Morley et al., 2018).

A colored "gauge" display in each profile communicates how each species' underutilized status may have changed across different time periods and as new science-based population data became available. A full bright green gauge with a 5/5 reading communicates that the species met all five criteria to be considered underutilized. Incomplete gauges with warm colors (yellow-orange-red) convey the species did not meet one or more underutilized criteria. Gauges and climate-informed species profiles were envisioned to be integrated into other existing public awareness campaign materials such as sustainable seafood guides (e.g., Seafood Watch from the Monterey Bay Aquarium), or support communication efforts by seafood retailers or by organizations (e.g., Our Wicked Fish) that promote underutilized species.

3 Results

3.1 Identifying underutilized species

Our initial evaluation of the 2013-2017 time period identified seven species (eight out of 47 fish stocks) as underutilized in the Northeast U.S.: 1) Acadian redfish *(Sebastes fasciatus)*, 2) Atlantic pollock *(Pollachius virens)*, 3) butterfish *(Peprilus triacanthus)*, 4) Georges Bank and Georges Bank East stocks of haddock *(Melanogrammus aeglefinus)*, 5) scup *(Stenotomus chrysops* (only during their Winter II harvest season), 6) the northern stock of silver hake *(Merluccius bilinearis)*, and 7) white hake *(Urophycis tenuis)* (Figures 1–3) (Supplementary Material-Table 1). When these seven species were re-evaluated during the 2015-2019 time period, five out of seven previously identified underutilized species were still characterized as underutilized. Butterfish were disqualified because the population status dropped below the target level between the two time periods (NOAA, 2021). White hake were disqualified during the second time period because: 1) more than 50% of the white hake ACL was used in three out of the five years during 2015-2019, and 2) the 2019 stock assessment report stated white hake as both below the target population level and overfished. Results from the 2019 stock assessment report qualified the southern silver hake stock to be an underutilized species because

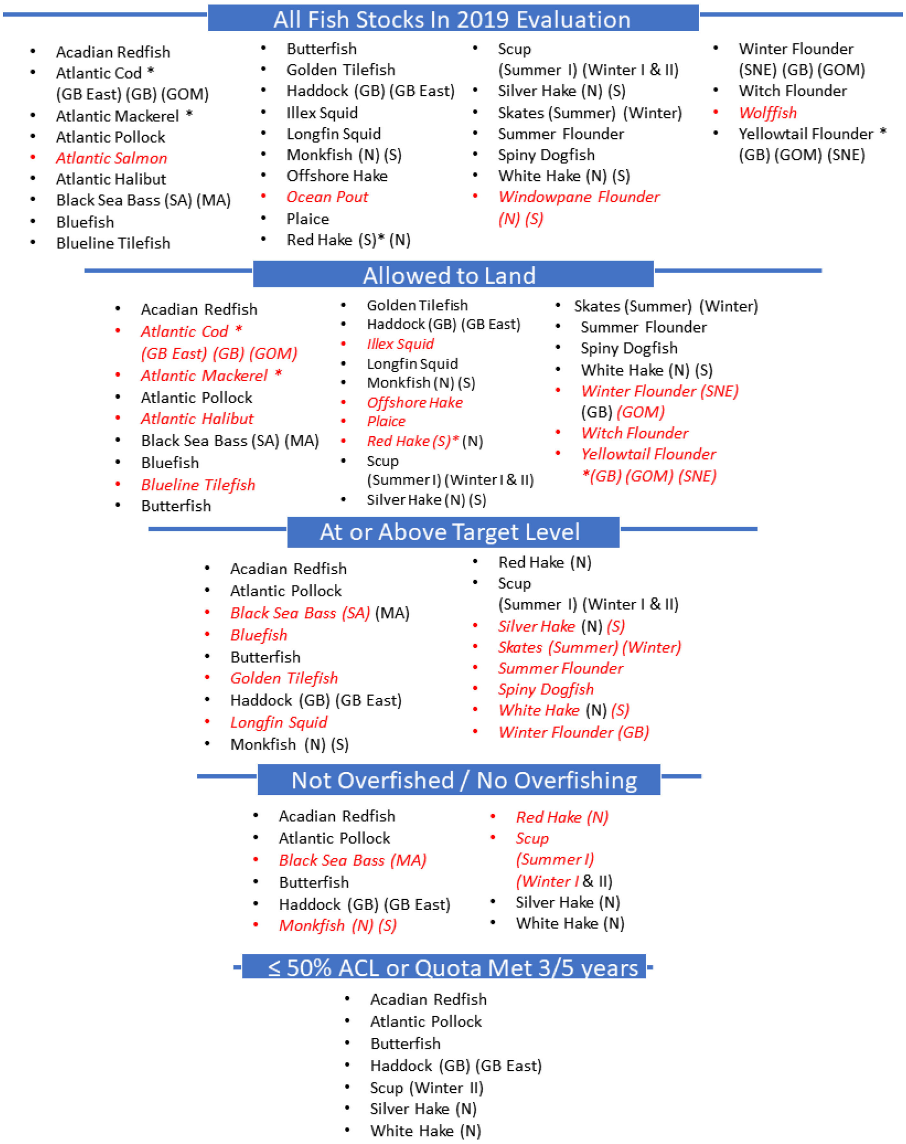

FIGURE 2
A flowchart showing how each fish stock performed in the initial underutilized species evaluation conducted for the time period of 2013-2017. Stocks italicized in red indicate where in the evaluation process they became ineligible. For example, while all Atlantic cod stocks were allowed to be landed, none of the stocks were at or above target level; therefore, they were not eligible to continue in the evaluation process. When a status was "unknown", the stock could not continue in the evaluation. Statuses were unknown either because the management organization did not have enough information to decide or the data available were insufficient (e.g., northern red hake). Abbreviations for stocks include N, northern; S, southern; MA, Mid-Atlantic; SA, Southern Atlantic; GB, Georges Bank; GBE, Georges Bank East; GOM, Gulf of Maine; SNE, southern New England. Additional data can be found in Supplementary Material.

its population improved to be above the target level. For the remainder of the paper, we will refer to all species that qualified as underutilized in at least one of the two evaluations as an underutilized species.

3.2 Climate resiliency assessment

Biological Sensitivity - The biological sensitivity of scup, butterfish, silver hake, and haddock were rated as low. White hake, Acadian redfish and Atlantic pollock received moderate biological sensitivity ratings due to relatively higher sensitivity pertaining to effects on population growth rates, spawning cycles, early life requirements, stock status, and/or adult mobility.

Directional Effect - Scup and butterfish were expected to benefit from higher productivity with climate change (i.e., positive directional effect), while productivity was expected to decline for the other underutilized species (i.e., negative directional effect) (Table 2).

Habitat Availability- Kleisner et al. (2017) projected that butterfish, haddock, silver hake, white hake, and Acadian redfish will lose significant habitat abundance in both spring and fall by 2060-2080, while scup was projected to lose habitat abundance only during the fall (Kleisner et al., 2017). Allyn et al. (2020) projected

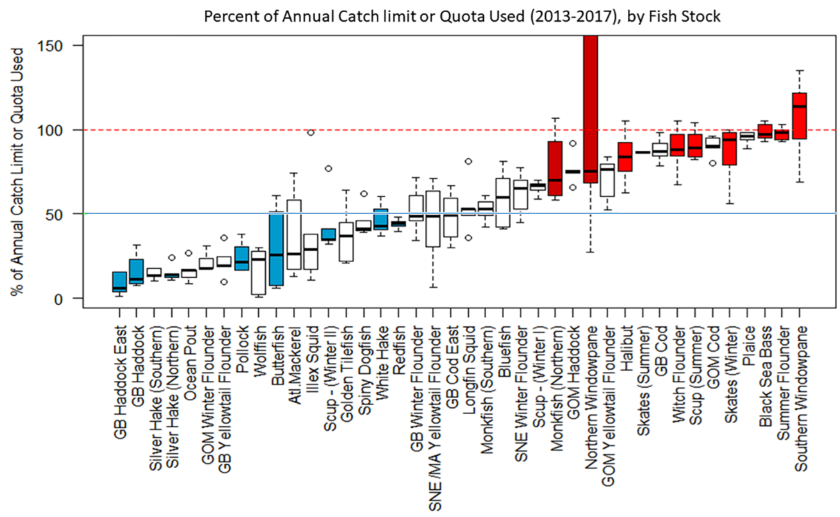

FIGURE 3
Boxplots showing percent of annual catch limit (ACL) or quota used from 2013-2017 for stocks managed by the New England Fishery Management Council and the Mid Atlantic Fishery Management Council. Stocks plotted in blue had 50% or less of the annual catch limit caught in at least three of the five years, satisfying criteria #5 of the underutilized species definition. Red plots highlight stocks that experienced more than 100% of their ACL or quota met at least once during 2013-2017. The blue solid line marks 50% of the ACL or quota and the red dash line marks 100% of the ACL or quota. Fish stock abbreviations include GB, Georges Bank; GB East, Georges Bank East; GOM, Gulf of Maine; SNE, Southern New England; MA, and Mid-Atlantic.

that haddock, white hake, Acadian redfish, and Atlantic pollock would decline in relative biomass by 2055. Silver hake was projected to decline in the fall only, while scup was projected to increase in the spring only (Allyn et al., 2020) (Table 2).

Final Weighted Results - Results from the climate resiliency assessment (Figure 4; Table 2) show scup (W=0.67) as the only species out of seven underutilized species with a high resilience rating. Butterfish (W= 0.33), silver hake (W= -0.25), and haddock (W= -0.33) all received neutral resilience ratings. Acadian redfish (W= -0.67), Atlantic pollock (W= -0.67), and white hake (W= -0.67) received the lowest resilience scores out of the seven underutilized species. Based on these climate resilience determinations, scup is a candidate species with long-term market potential. Other underutilized species may have shorter-term market expansion potential but their lower resilience to climate change may make it harder to maintain their availability to local and regional markets as climate conditions continue to change.

3.3 Climate-informed species profiles

Consumers and the seafood industry can access the climate-informed species profiles in Supplementary Material and at www.ourwickedfish.com/climate-informed-profiles. The top section of the profile showcases if the species underutilized status has changed over time. The colored gauges in the example profile (Box 1) show how white hake was initially considered underutilized during the 2013-2017 evaluation but became ineligible when updated data

TABLE 2 Results of the climate resiliency assessment.

Underutilized Species	Sensitivity	Directionality	Habitat Abundance	Relative Biomass	Aggregate Habitat Score	Final Weighted Resilience Score (W)	
Scup	1	1	-0.5	0.5	0	0.67	High
Butterfish	1	1	-1	N/A	-1	0.33	Neutral
Silver Hake	1	-1	-1	-0.5	-0.75	-0.25	Neutral
Haddock	1	-1	-1	-1	-1	-0.33	Neutral
White Hake	0	-1	-1	-1	-1	-0.67	Low
Acadian Redfish	0	-1	-1	-1	-1	-0.67	Low
Atlantic Pollock	0	-1	N/A	-1	-1	-0.67	Low

The final weighted resilience score (W) for each species was calculated as the mean of the sensitivity, directionality, and aggregate habitat score. Purple coloration highlights a low final resilience score, yellow a neutral score, and green a high resilience score.

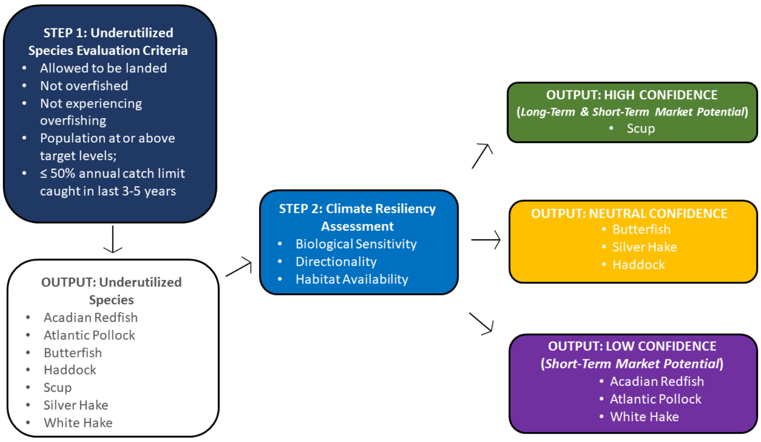

FIGURE 4
The overall framework for identifying underutilized species (Step 1), evaluating their resiliency with the climate resiliency assessment (Step 2), and categorizing the species with high confidence (green), neutral confidence (yellow), and low confidence (purple) of resilience.

from 2018-2019 were included and three criteria were not met. Profiles also include data on the observed and expected changes for the species in a warming climate, landings, value, and possible opportunities for expanding markets. A complimentary narrative and references are included with each profile.

4 Discussion

This study develops a two-step framework for determining market potential of fish species by assessing (1) whether they are underutilized and (2) their resilience in the context of projected climate conditions (Figure 4). Our quantitative definition for underutilized species allows regional fisheries and advocacy groups to evaluate fish stocks at least once every two years with familiar and readily available science-based fishery metrics. Species that are determined by this definition to meet current management goals and are not harvested to their full potential provide opportunities for the seafood industry and consumers to align efforts and develop markets with a science-based strategy. Species that are identified as underutilized and resilient to future climate conditions through this framework could then be targeted for market expansion. Species profiles demonstrate how this information could be used to inform consumers and the seafood industry of potential new opportunities. Species' profiles communicate whether their populations are healthy, meet management goals, and provide information on their climate resilience. The climate resilience assessment evaluates which fish stocks have the highest potential to withstand increased harvest levels under warming conditions. Two studies were available with multispecies results to assess future habitat availability when this study was conducted (Kleisner et al., 2017; Allyn et al., 2020); however, our framework can be updated as new information becomes available. In addition, the presentation of results from multiple studies captures agreement or disagreement among methodologies as well as different climate scenarios or projections of future time periods. Our approach can also signal which species could be considered underutilized with additional management intervention. For example, during the 2013-2017 evaluation period, spiny dogfish (*Squalus acanthias*) and golden tilefish (*Lopholatilus chamaeleonticeps*) fulfilled all criteria to be considered underutilized species except they were below their target levels (Figure 2). Policies that improve their population levels could alter their 'underutilized' determination in future evaluations and make them a contender for future climate resilience assessments.

There are some limitations to our approach that should be considered before widespread implementation. First, the definition of 'underutilized' can only be applied to data-rich species that are frequently monitored and managed using benchmarks that align with the specified criteria (e.g., stocks with catch records, catch limits, stock status determinations). Offshore hake (*Merluccius albidus*), American plaice (*Hippoglossoides platessoides*), winter flounder (*Pseudopleuronectes americanus*), witch flounder (*Glyptocephalus cynoglossus*), and northern red hake (*Urophycis chuss*) could not be fully evaluated during the 2013-2017 time period due to the lack of a stock assessment report or undetermined stock status (i.e., no stock target levels or overfished/overfishing determinations) (Figure 2). Additionally, applying this definition relies on accurate and accessible information. Sourcing, validating, and compiling catch data for each species was challenging, in part because stock-specific information was divided by different fishing periods, or frequently updated, and distributed throughout disparate management websites or portals. These challenges may hinder other parties or fishing regions from adopting and implementing our approach. However, our evaluation could transform from a heavily manual process into a straightforward annual process (opposed to every other year) if there was an online database that aggregated the annual sub-ACL or quota, cumulative catch, and stock statuses for all species across different management councils, or if NOAA included percent of sub-ACL or quota used in their annual Status of the Stocks report.

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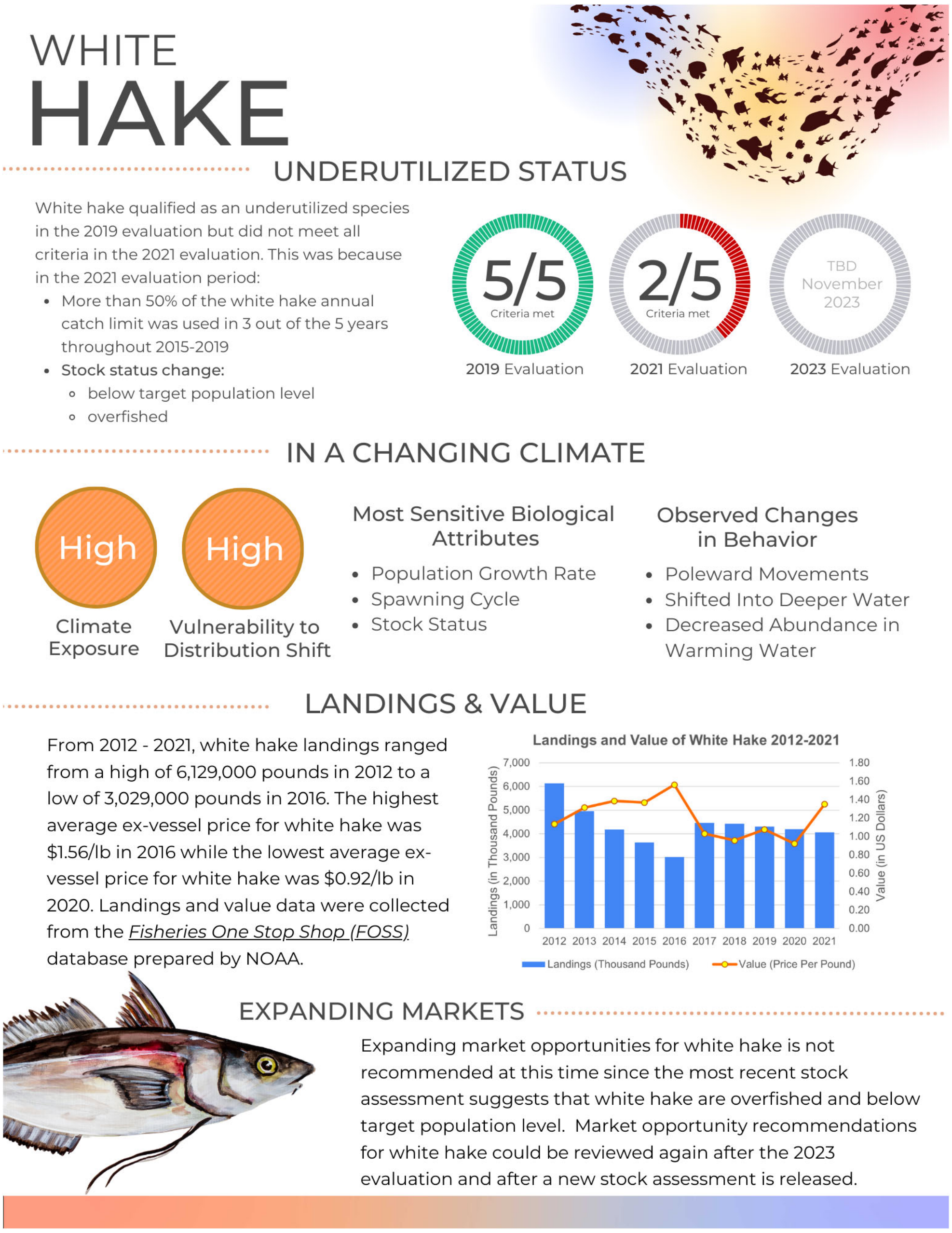
BOX 1 The climate-informed profile for white hake. The complete green gauge shows that white hake was an underutilized species during the 2019 evaluation but that it did not meet all 5 criteria during the 2021 evaluation. The profile also includes information about the species sensitive biological attributes, observed changes in behavior, historical landings and value, and an overview of the species life history. Climate informed profiles for all underutilized species can be found at www.ourwickedfish.com/climate-informed-profiles.



4.1 Resiliency & long market potential timelines for underutilized species

Species-specific climate resilience and market potential information are detailed for each of the seven underutilized species for scientists, managers and the fishing industry to consider as they review the results of this study.

Scup - Scup appears to have the greatest short and long-term market potential compared to all other underutilized species given its high climate resilience score and healthy population. Scup are expected to be both abundant and accessible in future climate conditions and they have a low price point (NMFS 2014, 2016, 2018, 2020), which may be attractive to consumers and chefs. Scup were only underutilized during their Winter II harvest season (November – December) (Figure 3). If not already done, the seafood industry may want to assess if scup harvested during Winter II have different market characteristics (size, flavor, filet texture and quality, etc.) than scup harvested in other seasons. Scup face several marketplace challenges including their small size, bony structure, and being sold whole rather than as a filet, which offers convenience to consumers (Masury and Schumann, 2019). While there are current efforts to create a filet market for scup, consistent filet quality has been a key issue (CFRF, 2019). Collaborations with food scientists could lead to solutions that overcome the undesirable effects of freezing scup filets or develop promising alternative preparations (e.g., canning, smoking, etc.).

Butterfish - Butterfish earned the second highest climate resiliency score, but their underutilized population status changed to below target level in the most recent stock assessment. The seafood industry will likely have ample time to increase the butterfish population size and make butterfish attractive to consumers given its higher climate resilience rating. Beyond their small size and bony structure, butterfish face several obstacles for expanding market opportunities including sharing an "Acceptable Market Name" of 'butterfish' (FDA, 2020) with at least nine other species including escolar *(Lepidocybium flavobrunneum)*, a fish that has been known to make consumers sick. Encouraging consumers to better recognize whole butterfish through appearance and their seasonal availability could reduce the possibility of market confusion and mistrust.

Silver hake - Silver hake may have short-term market potential as an underutilized species under changing climate conditions, but because their populations are moving northward rapidly, long-term markets would need to be strategically planned to align with future distribution predictions.

Haddock - Even though the haddock population has produced several strong year classes under warming conditions, it earned a neutral climate resiliency score. Continued research and monitoring of haddock's climate response could be meaningful to fisheries and markets since haddock appear to face fewer obstacles in the marketplace than other underutilized species. Unlike most underutilized species, haddock does not need to overcome the challenge of consumer familiarity (Masury and Schumann, 2019). However, much of the haddock in the U.S. marketplace is imported, and haddock is decreasing in value. For example, in 2018, the U.S. landed 6,557 metric tons of haddock (out of an allowable sub-ACL of 58,721 metric tons) while importing 20,224 metric tons of haddock from other countries such as Norway and Iceland (NMFS, 2020). It is unclear whether low haddock prices reflect increased landings, pricing pressure from imports, quality, or a combination of these or other factors.

White hake - White hake appear limited to short-term market potential because it earned a low resiliency score and did not qualify to be an underutilized species in the 2015-2019 re-evaluation. The white hake stock could improve in upcoming years. The seafood industry could consider the results of 2023 stock assessment to strategically plan expanding short-term markets that align with future distribution predictions.

Acadian Redfish - Acadian redfish had a low resiliency score and have a narrower window of opportunity to broaden markets compared to the other underutilized species. This designation was determined because Acadian redfish are slow growing, mature later, have a lower fecundity (Pikanowski et al., 1999), exhibited range contractions (Nye et al., 2009), and are projected to lose suitable thermal habitat in the Northeast U.S. (Kleisner et al., 2017; Allyn et al., 2020). A small market for Acadian redfish exists. Further expanding market opportunities for Acadian redfish would have to be done soon, and carefully, with input from the fishing industry and fisheries scientists to avoid overfishing.

Atlantic pollock - Atlantic pollock had a low climate resilience score in part due to loss of suitable habitat. Parallel markets for Atlantic pollock and Acadian redfish could be developed since Atlantic pollock are considered bycatch in the Acadian redfish fishery (Pol et al., 2015) and exhibit similar responses to climate change. Developing new markets with cohesive messages for Atlantic pollock and Acadian redfish together would provide additional short term financial opportunities for fishers while helping the industry improve catch diversity, and potentially reduce bycatch.

4.2 Alternatives to increasing fishing pressure

Landing more of the available catch limit or quota for each underutilized species does not necessarily require increased fishing pressure. Discarded catch and catch limit policies for choke species (a term to describe any incidentally caught species with a low quota and when all fishing for the targeted species must stop because the low quota for the choke species has been met) are both factors that may be limiting landings of underutilized species (McQuaw and Hilborn, 2020). For example, Atlantic Cod is a choke species that can limit the catch of haddock (Lacasse, 2018), and some haddock within the Georges Bank and Georges Bank East stock are also discarded over the course of the fishing season (2013-2017 average discards were 604 mt/year and 90.7 mt/year, respectively) (NOAA, 2023). Using discarded catch or adjusting catch limit policies for choke species are alternatives that could increase landings of underutilized species without increasing fishing pressure. However, regulatory changes, policy initiatives, infrastructure support, and marketplace incentives would all be necessary to achieve this outcome. Fishing gear technology advancements (DeCelles et al., 2017) and additional social, economic, and policy research could uncover other approaches to land more of the catch limits without increasing fishing pressure or compromising a population's productivity.

4.3 Monitoring and research needs

Uncertainties remain about how all underutilized species may respond to climate change through distribution changes, physiological effects, and indirect effects that affect populations across community and ecosystem scales (Chang et al., 1999; Henderson et al., 2017; NEFSC, 2017). For example, butterfish have ecological importance as a prey species for both small and large commercial fish (Bigelow and Schroeder, 1953; Cross et al., 1999). Emerging species moving into northern areas from the mid-Atlantic due to warming waters (e.g., silver hake) (Nye et al., 2009) have the potential to increase predatory demand on butterfish therefore influencing their overall resilience to changing conditions. Alternatively, climate or fishing-induced declines in predator populations could release butterfish and other prey populations from some natural mortality, possibly bolstering their overall resilience through increased stock levels. Future monitoring and research efforts are needed to better capture how changes in species interactions and phenology create immediate and lagged population and trophic effects that directly and indirectly influence regional fisheries, especially those managed with seasonal quotas (Henderson et al., 2017; Staudinger et al., 2019). These research efforts could help the regional fishing industry and marketplace better measure resilience, anticipate changes in supply, and prepare for system-level effects. If markets or total catch expanded for these underutilized species, then additional monitoring could help track how the combined effects of fishing and climate change could impact their populations.

4.4 Marketplace needs and opportunities

Consumers have reacted positively to Acadian redfish, Atlantic pollock, silver hake, haddock, and scup in taste studies (Masury and Schumann, 2019), likely because they fit the familiar culinary, white-fleshed fish profile, and because they are often less expensive than other more common whitefish species such as Atlantic cod (NMFS 2014, 2016, 2018, 2020). Still, for some underutilized species, research and development may be needed to achieve market-ready products. In addition to advocacy groups, extension organizations like NOAA Sea Grant and the Commercial Fisheries Research Foundation (CFRF) are playing instrumental roles in introducing, testing, and engaging the fishing industry and consumers in new and expanding markets. These groups' research and development projects, along with newer seafood companies like True Fin Seafood and Chatham Harvesters Cooperative that specialize in partnering directly with fishers, are demonstrating that expanding markets for underutilized species is possible. Outreach and marketing efforts may want to explore if those in the Millennial generation (those born between 1981-1996) and Generation Z (e.g. Gen-Zers) (those born between 1997-2012) are more interested in purchasing underutilized species than other generations since these age-groups have not been the explicit focus of sustainable New England seafood research, despite being the largest purchasing power of any currently living generation in the United States (Conley and Lusk, 2019; Fry, 2020).

Climate-informed profiles (Box 1) (Supplementary Material) were created for seafood businesses and advocacy groups that want to track information about current underutilized species in a changing climate or prioritize marketing plans for these species. Our profiles may also be valuable to marketing professionals who are interested in testing climate-smart messaging. Incorporating climate-smart messaging into popular seafood marketing tools such as ecolabels (e.g., Marine Stewardship Council, Gulf of Maine Responsibly Harvested), sustainability guides (e.g., Seafood Watch from the Monterey Bay Aquarium) (Kemmerly and Macfarlane, 2008), and chef-centered commitment programs like Smart Catch (James Beard Foundation, 2020) may help expand markets for underutilized species. This concept would need to be introduced carefully since some seafood marketing tools have been correlated with confusion among consumers (Roheim, 2009) and decreased seafood sales at grocery stores (Hallstein and Villas-Boas, 2013).

Adaptation approaches and policy recommendations that emerged from the industry following experiences during the COVID-19 pandemic could also help produce new or expanded markets for underutilized species (Smith et al., 2020; Stoll et al., 2021). These include: 1) financial incentives for domestic seafood purchasing and consumption prioritizing sustainable stocks, 2) simplified regulatory requirements for harvesters to sell directly to consumers and retail outlets, 3) heightened marketing assistance at local, regional, and national levels, and 4) infrastructure improvements that would help scale up smaller operations (Stoll et al., 2021). All these actions could increase agility and adaptability of the fishing industry to uncertain and volatile conditions, including a changing climate.

5 Conclusion

Expanding and developing new market opportunities for underutilized seafood species could be part of a climate-smart resiliency strategy for the New England fishing industry and regional food system. While our approach was initially developed for Northeast U.S. fisheries, it could be applied to other managed regional fisheries outside the United States. Our quantitative definition for underutilized species repeatedly assesses fish stocks with science-based fishery metrics that fishery managers are already familiar with. The seven identified underutilized fish species exhibited a range of climate resiliency scores, with scup scoring the highest confidence in resilience under future climate conditions. Based on prior studies of climate vulnerability and future responses, we determined all seven species have short-term market potential, but each has its own unique challenges within the marketplace for long-term success. History demonstrates that creating and expanding marketplaces for lesser known species is possible especially with collaboration among industry, management, and attractive advertising (Frank, 2014; Seaver, 2017). Future research efforts could test underutilized species in market scenarios, evaluate how climate-induced shifts could create cascading impacts within regional fisheries, and ultimately, consider how industries could adapt to system-wide effects.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

Each author contributed significantly to the conceptualization, methodology, data analysis, and writing of this manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1226219/full#supplementary-material

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