# Lumpfish, *Cyclopterus lumpus*, distribution in the Gulf of Maine, USA: observations from fisheries independent and dependent catch data

Elizabeth A. Fairchild[1*], Sophie Wulfing[1], Easton R. White[1]

[1]Department of Biological Sciences, University of New Hampshire, Durham, NH, United States

Corresponding Author:
Elizabeth Fairchild
38 Academic Way, Durham, NH, 03824 US
Email address: Elizabeth.fairchild@unh.edu

## Abstract
The Gulf of Maine (GoM) is one of the fastest-warming parts of the world's oceans. Some species' distributional shifts have already been documented, especially for commercially-important species. Less is known about species that are not currently exploited but may become so in the future. As a case study into these issues, we focus on lumpfish (*Cyclopterus lumpus)* because of the recognized and timely need to understand wild lumpfish population dynamics to support sustainable fisheries and aquaculture developments. Using occurrence data from five different fisheries-dependent and -independent surveys, we examined lumpfish distribution over time in the GoM. We found that lumpfish presence was more likely in spring and correlated with deeper waters but not bottom temperature. Since 1980, lumpfish presence has increased over time, moved farther offshore, and shifted northward. Our work provides preliminary information for resource managers to ensure that lumpfish are harvested sustainably for use in emergent lumpfish aquaculture facilities. An understanding of lumpfish occurrence patterns may enable lumpfish aquaculturists to utilize the most local populations, thus maintaining the local genetic integrity of fish slated for release into net pen salmonid farms.

Keywords: data-poor fisheries, aquaculture, range shift, climate change

## Introduction
Climate change is expected to change the distribution of many marine species, primarily with poleward shifts (Perry et al. 2005; Campana et al. 2020). The Gulf of Maine (GoM) is an interesting case study applicable to this issue as the area is one of the fastest warming bodies of water on the planet (Pershing et al. 2015). Yet, most work on species distribution shifts has focused on species of commercial interest given funding and data availability (Pershing et al. 2015; Free et al. 2019; Goode et al. 2019; Fredston-Hermann et al. 2020). Evaluating changes over time to unexploited species can be telling of ecosystem changes (e.g., marine historical ecology; Engelhard et al. 2016) yet difficult to do because these species are not usually the target of long-term fisheries surveys and are given a "data poor" designation. Often these data-poor

species appear as bycatch but only in small numbers. However, it is possible to combine multiple data sets using different gear types to ensure adequate sample sizes. For example, fisheries-independent trawl surveys, recreational fish surveys, and citizen science dive surveys were aggregated and modeled to predict temporal changes in rockfish distribution in Puget Sound, WA (Tolimieri et al. 2017). Coupling long term catch information with abiotic and biotic variables can provide insight into how these drivers affect ecological communities (e.g., Hampton et al. 2013; Rogers et al. 2019).

Lumpfish (*Cyclopterus lumpus*) are an example of a data-poor species that may be exploited in the USA in the future. Lumpfish aquaculture is one of the fastest growing aquaculture sectors in Europe and eastern Canada because lumpfish are proven “cleanerfish”: they eat or “clean” parasitic sea lice off salmonids (Atlantic salmon *Salmo salar*, steelhead trout *Oncorhynchus mykiss*) raised in ocean farms (Imsland et al. 2018; Treasurer 2018). Lumpfish as cleanerfish have revolutionized the way sea lice are treated in salmonid farms in Europe and the Canadian Atlantic Maritimes, allowing farms to reduce, or even eliminate, controversial pesticides or thermal and freshwater treatments stressful to the salmonid fish (Denholm et al. 2002; Dounia et al. 2016; Abolofia et al. 2017; George 2019). Biological delousing success by cleanerfish is optimized if approximately 10% of the caged fish biomass is a cleanerfish species (i.e., 10,000 lumpfish for 100,000 steelhead trout; Imsland et al. 2014). As a result, upwards of 50 million lumpfish are cultured each year in Canada and Europe to supply this need (Directorate of Fisheries 2020). Although salmonids reared in cages in New England waters are also susceptible to sea lice infestations, lumpfish have yet to be used in US salmonid farms, but soon will be with the operation of the first commercial lumpfish hatchery in the US for Maine Atlantic salmon farms (Cooke Aquaculture USA, Eastport, ME). Additionally, Blue Water Fisheries LLC, a steelhead trout farm proposed in New Hampshire (NH) waters, has included lumpfish in its permit applications (MAFMC 2023). Once domestic commercial lumpfish production begins, it will be imperative that wild lumpfish are managed sustainably because hatcheries still rely on wild-caught adult fish for broodstock each year. Holding and conditioning adults throughout the year to spawn in subsequent years remains unreliable and post-spawning mortality of lumpfish is high (Jonassen et al. 2017; Powell et al. 2017b; Imsland et al. 2019). In Canada and Europe, fisheries exist solely for providing live, adult (age 2+), pre-spawning lumpfish to cleanerfish hatcheries. The fish are captured mostly by gillnet and transported in live wells to the hatchery (Powell et al. 2017a).

Lumpfish are not currently regulated in US waters, and no fishery management plan exists for them. Thus, lumpfish may be susceptible to overexploitation. Powell et al. (2017a) made the case that lumpfish have a moderate- to high-vulnerability to fishing because their population doubling size time may be as long as 14 years. Given that the fishery targets larger individuals capable of spawning more eggs, lumpfish spawning stock biomass can be depleted quicky. In Canada, lumpfish are listed as Threatened due to steep population decreases most likely caused by fishing (DFO 2021). As they become exploited in US waters, lumpfish will need to be managed and, to do so sustainably, resource managers need to be informed of baseline data on fish biomass, occurrence, and distribution. Distribution information will be helpful to lumpfish hatchery managers on where to collect their broodstock each year.

In the USA, lumpfish have never been exploited, and as a result little is known about lumpfish populations in US waters (Collette and Klein-MacPhee 2002). Published information is limited to Great Bay Estuary, NH (Rackovan and Howell 2017) and Schoodic Peninsula, ME (e.g., Moring 1989, 2001). Remaining population information is inferred from studies in Canada, Greenland, and Ireland. Semi pelagic adults move inshore to rocky costs to spawn from March to May in the southwestern GoM, and May to June along the northeast Maine coast (Cox and Anderson 1922; Goulet et al. 1985; Collette and Klein-MacPhee 2002). Females spawn two to three sticky, demersal egg masses and then move offshore, while the males stay to guard and tend the eggs until hatching, which occurs after approximately six to eight weeks, depending on water temperatures (Cox and Anderson 1922; Collins 1978; Goulet et al. 1985; Martin-Robichaud 1991). Juvenile lumpfish leave the nest area in the early summer and are highly associated with macroalgae, either in tidepools or in the upper 0.5 m of the water column (Daborn and Gregory 1983; Moring 1989; Rackovan and Howell 2017), where they prey on small invertebrates including amphipods, copepods, isopods, and even small fish larvae (Moring 1989; Tully and O'Ceidigh 1989; Davenport and Rees 1993). They depend on seaweed for transportation as it passively drifts, providing protection from predators and an increased food sources (Vandendriessche et al. 2007). Lumpfish grow quickly in their first year of life, reaching approximately 35 to 70 mm in total length (TL; Martin-Robichaud 1991). During this time, most of their energy is diverted towards growth since the fish cling to algae and wait for prey to pass by (Brown 1986; Killen et al. 2007). At approximately age 1, the juveniles become mostly pelagic and begin moving offshore. Lumpfish can live up to approximately 10 to 15 years. In the wild, males reach sexual maturity in two to three years while it takes females three to four years (Albert et al. 2002; Hedeholm et al. 2014). While GoM lumpfish are considered part of a western Atlantic lumpfish stock unit, composed of US and Canadian fish (Whittaker et al. 2018), they are distinct from the Canadian populations (Langille et al. 2023).

Despite the few GoM-based lumpfish studies, numerous long-term state and federal surveys with lumpfish catch data exist. We hypothesized that for lumpfish, as an unexploited species, any distributional shift would be due to changes in water conditions, especially warming water. Thus, lumpfish is an ideal model species to understand the impacts of climate change on sustainable resource management in the GoM. Our study goals were to: 1) aggregate GoM lumpfish catch data and characterize lumpfish distribution, and 2) determine if and how water temperature has affected lumpfish distribution over time. We hypothesized that lumpfish distribution would be correlated to water temperature both temporally and spatially, shifting northeast with increases in water temperature.

## Materials & Methods

*Lumpfish source data*

We acquired historic information on lumpfish caught between 1963 (the start date depends on the dataset) and 2021 from ME, NH, Massachusetts (MA), and Northeast Fisheries Science Center (NEFSC) fisheries-independent surveys and from the fishery-dependent NEFSC observer program (Table 1). Except for the data collected by the observer program, all data are publicly available. While each data set we accessed was unique, each contained at a minimum date, location, and depth for each fish caught. All non-observer data included bottom temperature, most data sets contained fish size information (individual length, individual weight or batch weight), and some contained sex and maturity stage information. Gear types and sampling methods varied as noted below.

1. *Maine Department of Marine Resources (ME DMR) Maine-NH Inshore Trawl Survey*: A stratified random survey, separated into four depth strata and five geographic regions along the coast of Maine and New Hampshire, ranging from 5 m at the shallowest along the coast out to 19.3 km (12 miles). A total of 120 stations were randomly selected for sampling for each spring survey, then resampled again in the fall with a modified shrimp net with a 2.5 cm codend liner towed for 20 min. All catch was sorted by species, total weights taken per species, and individual lengths measured (total length (TL) for lumpfish). Selected species, including lumpfish in some years, were sampled for maturity and age. Bottom and surface temperature and salinity were measured at each tow. Survey methods are reported by Sherman et al. (2005).

2. *New Hampshire Fish and Game Department (NH F&G) Estuarine Survey of Juvenile Fish*: A monthly seine survey at 15 fixed stations in Hampton-Seabrook and Great Bay Estuaries in NH, occurring June through November each year. One haul per site per month was conducted at low tide in waters <2 m using a seine measuring 30.5 m long by 1.8 m high with 6.4 mm mesh. All catch was sorted by species and individual lengths taken. Surface temperature and salinity were measured, and bottom substrate type documented. Detailed survey results are documented in NHF&G (2020).

3. *Massachusetts Division of Marine Fisheries (MA DMF) Bottom Trawl Survey*: A stratified random bottom trawl survey in 5 regions over 6 depth zones ranging from <9 m to >55 m in both spring and fall in MA state waters. Approximately one station per 19 square nautical miles was sampled by a 20-minute tow taken with a ¾ size North Atlantic type two seam otter trawl with a 6.4 mm codend liner. All catch was sorted by species and total weight per species per tow was recorded. Bottom temperature was measured. Detailed information is found in Camisa et al. (2020).

4. *NEFSC Bottom Trawl Survey*: A spring and fall stratified random bottom trawl survey occurring most years (1963-2021), but with other seasons sampled sporadically in the past (1991-1995 summer GoM survey; 1992-2007 winter bottom trawl survey). Due to the timespan of this survey, bottom trawl gear specifications and protocols have changed slightly over the years. Generally, the survey occurs from North Carolina to Nova Scotia, but has occurred in some years as far south as Florida. However, for the purposes of this analysis, we only included lumpfish catch data from the GoM. Surveyed areas ranged in depth from 18 to 366 m with >300 tows made per survey. All catch was sorted by species and most individuals were weighed and lengths measured. Bottom temperature was also measured. Survey details can be found at: https://www.fisheries.noaa.gov/inport/item/22557.

5. *NEFSC Observer Data*: Fishery-dependent data collected by observers on board commercial fishing boats throughout the year and throughout the GoM from multiple fisheries, but lumpfish caught mostly when groundfish, herring, and sea scallops were targeted. Gear types varied but included standard bottom trawl, midwater trawl, paired midwater trawl, gillnet (both drift-sink and fixed), purse seine, and scallop dredge (Table 2). Data collected included location, depth, gear type, and for a subsample of fish, lengths were measured. For those fish measured,

individual fish weights were also recorded, otherwise fish were batch weighed and sample size not recorded. For some trips, surface temperature was recorded. Data are available by request directly from the Observer Program: [https://www.fisheries.noaa.gov/new-england-mid-atlantic/fisheries-observers/fisheries-monitoring-operations-northeast](https://www.fisheries.noaa.gov/new-england-mid-atlantic/fisheries-observers/fisheries-monitoring-operations-northeast).

*Data cleaning and analysis*

We combined datasets to include tow data such as latitude and longitude (decimal degrees) of catch, date, season, and depth of catch when present in the data. We included environmental variables, such as bottom and surface water temperature (ºC), air temperature (ºC), and bottom and surface water salinities (ppt), where available. Catch data included number of lumpfish caught, fish length (TL), as well as several fish weight (kg) categories. Some datasets reported weights of individual fish, whereas other datasets aggregated the weight of all lumpfish in each tow. We used the most precise weight data when available. For fish lacking individual weights, we estimated weights using the Bayesian length-weight relationship: Weight = $\alpha$ Length $^{\beta}$. These were calculated using alpha and beta values of $\alpha = 0.02630$ (0.01101 - 0.06285) and $\beta = 2.99$ (2.77 - 3.21) (Froese et al. 2014). From these calculations, we also estimated the age of lumpfish by separating them into Young-of-Year (< 7 cm TL), Juvenile (7 – 17 cm TL), and Adult (> 17 cm TL) categories (Collins 1979).

To better understand the range shifts of lumpfish, we mapped the distribution of lumpfish over each season, as well as the bottom temperature (where available) where each lumpfish was located when caught. We defined seasons as winter (December through February), spring (March through May), summer (June through August), and fall (September through November). Using the NEFSC bottom trawl surveys, which included effort, we built a series of generalized linear models with Binomial error distributions to understand potential correlates of lumpfish catch over time. We accounted for spatial autocorrelation with a smoothing function of latitude and longitude using an exponential decay for correlation. We verified model assumptions by visually inspecting residual plots.

## Results

Across the five datasets, we identified over 12,000 instances of lumpfish being caught across the five datasets, including 9,910 in the 1989-2021 NEFSC Observer data (Table 1). Most of the datasets only indicate positive catch records and not true catch-per-unit effort (although we explore the NEFSC Bottom Trawl data further below to address this point). There was enormous variability in the spatial and temporal scales of catch between the datasets (Fig. 1, Table 1). The NEFSC Observer and Bottom Trawl programs caught lumpfish over the largest range, which is in line with expectations given sampling protocols due to the other datasets fishing efforts focused nearshore. (Fig. 1). NEFSC Observer data were the most consistent throughout the year. The NEFSC Bottom Trawl and most state surveys were conducted only during spring and fall. Most lumpfish were caught by various types of trawl gear or gill nets (Table 2).

Lumpfish were caught at bottom temperatures ranging from 2° C to 17.6° C and at depths ranging from 2 meters to 393 meters (Fig. 2). Most fish caught were adult individuals, however, NH F&G surveys only caught YOY fish (Figs. 3-4). New Hampshire Fish & Game surveys occurred closer to shore and only in estuaries, which often act as nursery habitats for lumpfish. Further, NEFSC Observer surveys rarely caught juvenile and YOY individuals due to gear selectivity as they use standard legal fishing gear, which have larger mesh sizes than the fishery-independent surveys (Fig 4a). Adult lumpfish were caught throughout the GoM whereas juvenile and YOY fish were mostly caught inshore (Fig. 5). Adult individuals were also the age group caught the most throughout each of the seasons, with very few juvenile and YOY individuals caught in the winter season (Figs. 3-4).

Using data from the NEFSC BT surveys (which also included effort), we assessed which covariates might affect lumpfish presence in catch. While accounting for spatial autocorrelation, we found that lumpfish presence increased over time ($\beta=0.01$, $p<0.0001$). Here, the estimate indicates a 0.01 increase in log-odds (or 1.01 odds) for each increase in year. Lumpfish presence was also more likely in spring ($\beta=0.18$, $p<0.0001$) compared to fall surveys. We also found lumpfish presence was more likely in deeper ($\beta=-0.00063$, $p<0.0001$) and warmer bottom depths ($\beta=0.0092$, $p=0.0006$). Although all the variables were significant, the effect size for depth was relatively small compared to the other parameters. Using a separate set of analyses, we found that the yearly latitude of lumpfish presence in catch increased over time ($\beta=0.0175$, $p=0.018$). In other words, lumpfish presence was more likely at higher latitudes over time (Fig. 6). In addition, lumpfish presence shifted farther offshore over time ($\beta=0.0254$, $p=0.014$).

## Discussion

Although lumpfish are relatively uncommon in catch data in the GoM, we were able to identify 12,142 instances of catch when combing five disparate datasets spanning five decades (Table 1). Our findings are in line with past studies (e.g., Collette and Klein-MacPhee 2002) showing that adult lumpfish inhabit the GoM broadly both temporally and spatially, whereas YOY and juvenile lumpfish, for the most part, are found nearshore (e.g., Moring 2001; Rackovan 2017). The predominance of younger fish nearshore during summer and fall, as evidenced from NH F&G and ME DMR surveys, indicates lumpfish spawn and egg nests are built in these waters. Surprisingly, these life stages were also found offshore indicating that adults are spawning offshore too (Fig. 5c). Multiple studies have shown seasonal inshore-offshore movements of adult lumpfish associated with spawning, both in the GoM (Davenport 1985) and elsewhere (e.g., Iceland: Kennedy et al. 2014; Kennedy and Olafsson 2019; Norway: Mitamura et al. 2012). However, lumpfish spawning and completing the life cycle offshore is not well documented. We show clear differences in catch composition given differences in sampling design and between the five monitoring programs. There were differences in this catch composition for nearshore versus offshore surveys, by season, and with gear type.

We found support for our hypothesis that lumpfish distribution has shifted northward and offshore in the past few decades (Fig. 6). The GoM is one of the fastest warming bodies in the world (Pershing et al. 2015; Balch et al. 2022; GMRI 2024). Lumpfish are a cold-adapted species, so a distributional shift with temperature aligns with their life history characteristics (Collette and Klein-MacPhee 2002). Within the region, there have been other accounts of species moving in relation with warming waters (Le Bris et al. 2018; Friedland et al. 2023). Past work has shown that some species may see range expansions (e.g., spiny dogfish and American lobster) while other more northern species (e.g., Acadian redfish, American plaice, Atlantic cod, haddock, and thorny skate) will experience range constrictions (Kleisner et al. 2017). For lumpfish, the GoM is towards the southern end of their range and, as it continues to warm, will likely become increasingly less suitable for lumpfish (Rodríguez-Rey and Whittaker 2023). Additional work is needed to understand how changes in other oceanographic variables (e.g., nitrate, salinity, productivity; Rodríguez-Rey and Whittaker 2023) may interact with temperature increases (Pershing et al. 2021) and changes to fishing pressures to affect GoM species in the future.

Over the course of five decades of data, there were changes in sampling protocols within and across our five datasets. Also, effort data were not associated with all the datasets, which limited our ability to conduct more detailed analyses. Future work could use more sophisticated approaches (Fletcher et al. 2021) to combine these disparate datasets more formally. We had associated metadata (e.g., bottom temperature, salinity) for only some of the datasets we used. Future work could collate and combine similar types of metadata from other available sources. Further, consideration could be given to sea temperature data as bottom temperature may not be the strongest driver to predict marine species' shifts, but rather a temperature composite of the water column (Friedland et al. 2023). We also did not address how large perturbations (e.g., storm events) may affect population trends differently than long-term oceanographic changes. We also did not study how behavioral responses by harvesters may change with seafood demand. There could also be additional work to understand how socio-ecological dynamics may interact with extreme events (White and Wulfing 2023) to affect lumpfish. Finally, we only examined linear trends in lumpfish catch and distribution over time. Future work could examine how population dynamics may be changing in nonlinear ways (Bruel and White 2021, Boënnec et al. 2024). Given predicted demand for lumpfish in aquaculture, our findings highlight the need for further research on the status of lumpfish in the GoM. If exploited, proper management must ensure lumpfish are harvested responsibly and overfishing prevented, especially because adults return to the same spawning areas (Davenport 1985; Kennedy et al. 2015) at the same times (Kennedy and Olafsson 2019) each year and discrete lumpfish populations exist (Lagille et al. 2023).

## Conclusions

Lumpfish in the USA present a rare opportunity to understand the population dynamics of a species that has never been exploited and provide information for sustainable harvesting practices. We found support for our hypothesis that lumpfish occurrences are shifting offshore and northward with increases in temperature. We also found that the probability of catching lumpfish increased over time and there were higher catches during spring and at greater water depths. We hope this paper provides a foundation for future work on lumpfish, geared towards this emergent aquaculture sector, including lumpfish movements, genetic structure, stock assessments, and latitudinal population effects. We also hope this paper provides a template for investigations into other data-poor species.

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Data and Code Availability:
All data are available from the original data providers. We have also included code for all analyses https://github.com/swulfing/TeamLump.

Table 1. Lumpfish catch data from fish surveys in the Gulf of Maine.

| **Location** | **Agency** | **Survey Name** | **Gear Used** | **Date Range** | **Total Lumpfish** |
|---|---|---|---|---|---|
| ME/NH | Maine Dept of Natural Resources | Maine-NH Inshore Trawl Survey | Bottom trawl | 2000-2021 | 1,357 |
| NH | New Hampshire Fish & Game Dept | Estuarine Survey of Juvenile Fish | Seine | 1997-2021 | 104 |
| MA | Massachusetts Division of Marine Fisheries | Bottom Trawl Survey | Bottom trawl | 1978-2021 | 120 |
| Federal Waters | NEFSC | Bottom Trawl Survey | Bottom trawl | 1963-2021 | 649 |
| Federal Waters | NEFSC | Observer Data | Multiple | 1989-2021 | 9,910 |

Table 2. Number of lumpfish caught 1989-2021 by various commercial gear types as documented by fisheries observers. Gear type descriptions are federal observer program codes.

| **Gear Type – Observer Data** | **Total Lumpfish** |
|---|---|
| Trawl, otter, bottom, fish | 8,885 |
| Gill net, fixed or anchored, sink, other/unspecified | 640 |
| Trawl, otter, midwater paired | 103 |
| Dredge, scallop, sea | 58 |
| Trawl, otter, midwater | 54 |
| Trawl, otter, bottom, shrimp | 48 |
| Trawl, otter, bottom, haddock separator | 47 |
| Gill net, drift-sink, fish | 46 |
| Trawl, otter, bottom, twin | 10 |
| Trawl, otter, bottom paired | 6 |
| Longline, bottom | 5 |
| Pot/trap, lobster offshore nk | 2 |
| Trawl, otter, bottom, Ruhle | 2 |
| Dredge, other/nk species | 2 |
| Trawl, shrimp, twinned | 1 |
| Handline | 1 |
| **All gears combined** | **9,910** |

**Figure 1.** Seasonal lumpfish catch in the Gulf of Maine from state and federal surveys spanning 1963-2021. Winter = Dec-Feb; Spring = March-May; Summer = June-Aug; Fall = Sept-Nov. See Table 1 for additional information about data sources.

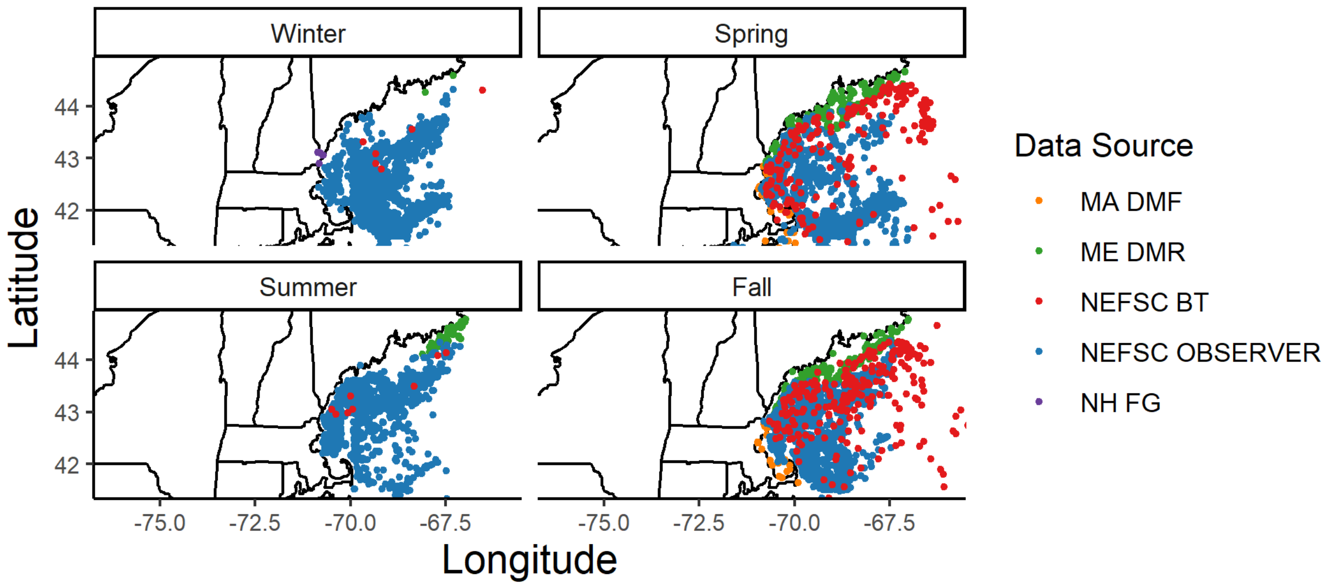


**Figure 2.** Bottom temperature (°C) where lumpfish were caught in the Gulf of Maine from 1963-2021. Bottom temperature only was recorded for surveys conducted by MA DMF, ME DMR, and the NEFSC.

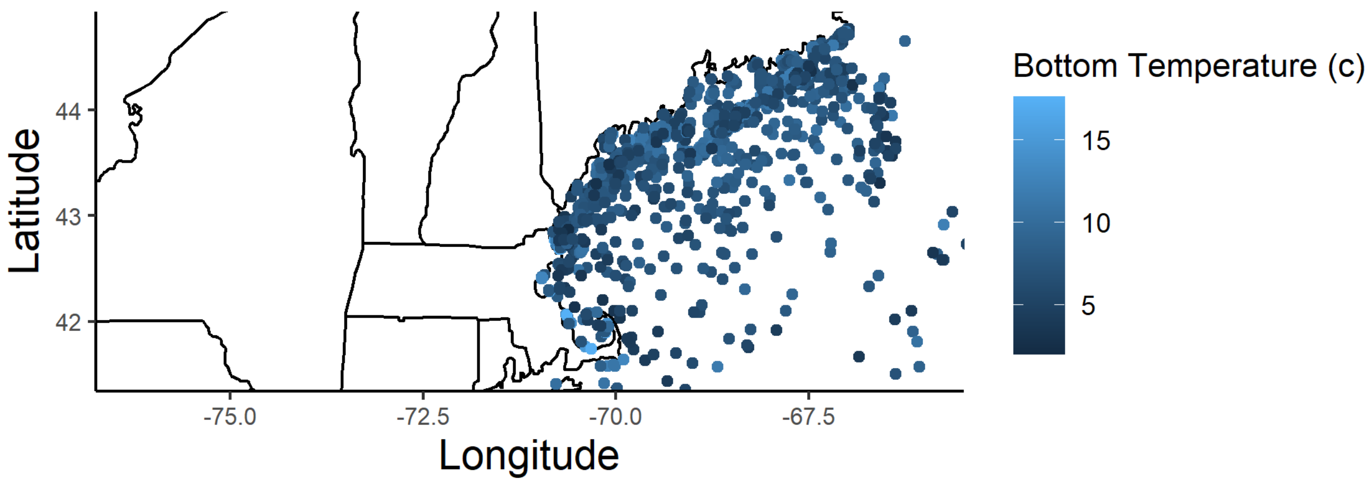


**Figure 3.** Mean calculated Bayesian weights (kg) of lumpfish caught by source. MA DMF data are not included as lumpfish lengths were not reported.

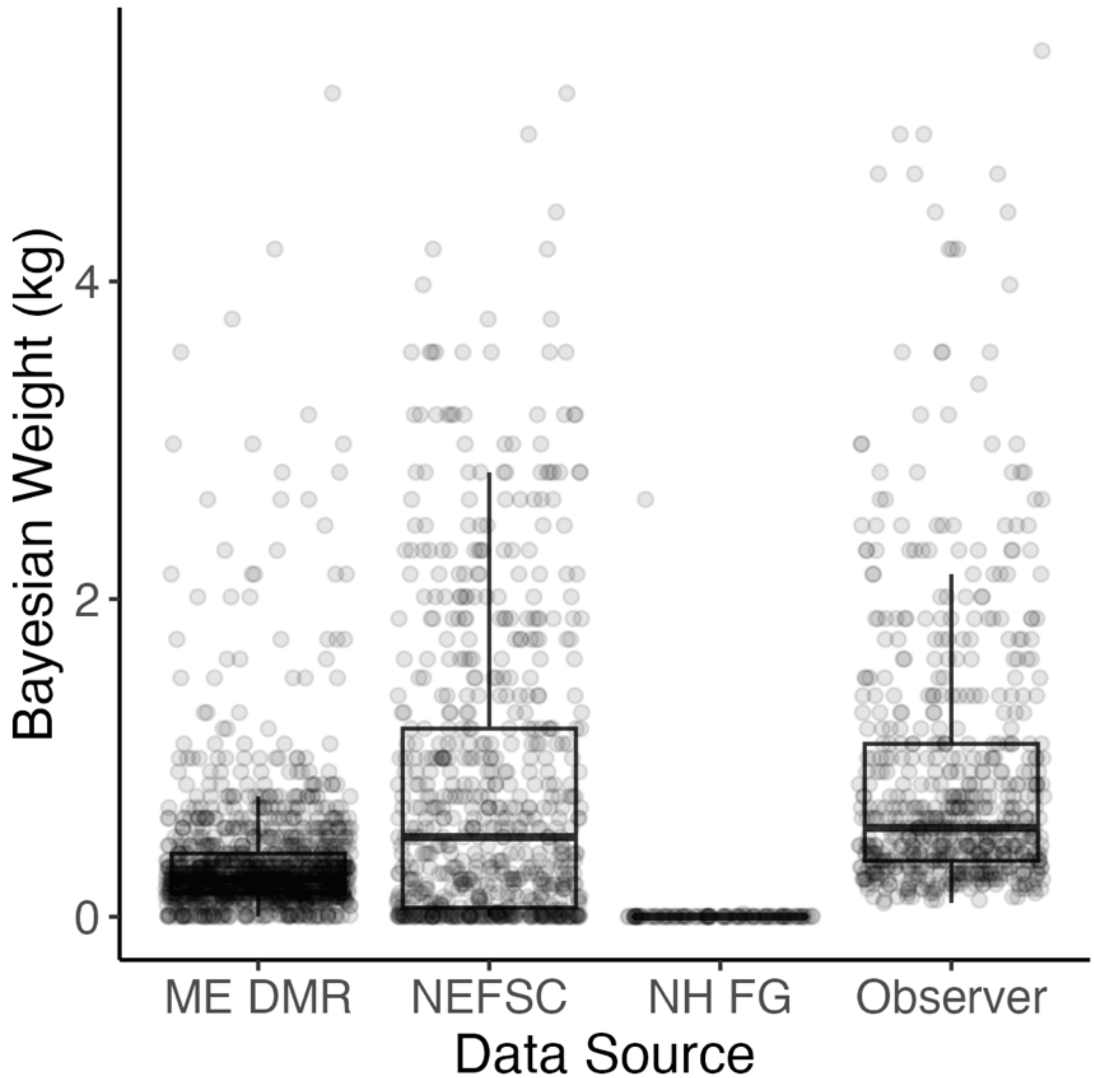


**Figure 4.** Number of lumpfish caught by year in the Gulf of Maine from 1963-2021 from all state and federal surveys depicted by (A) age, (B) proportion, and (C) season. MA DMF data are not included as lumpfish age data could not be calculated.

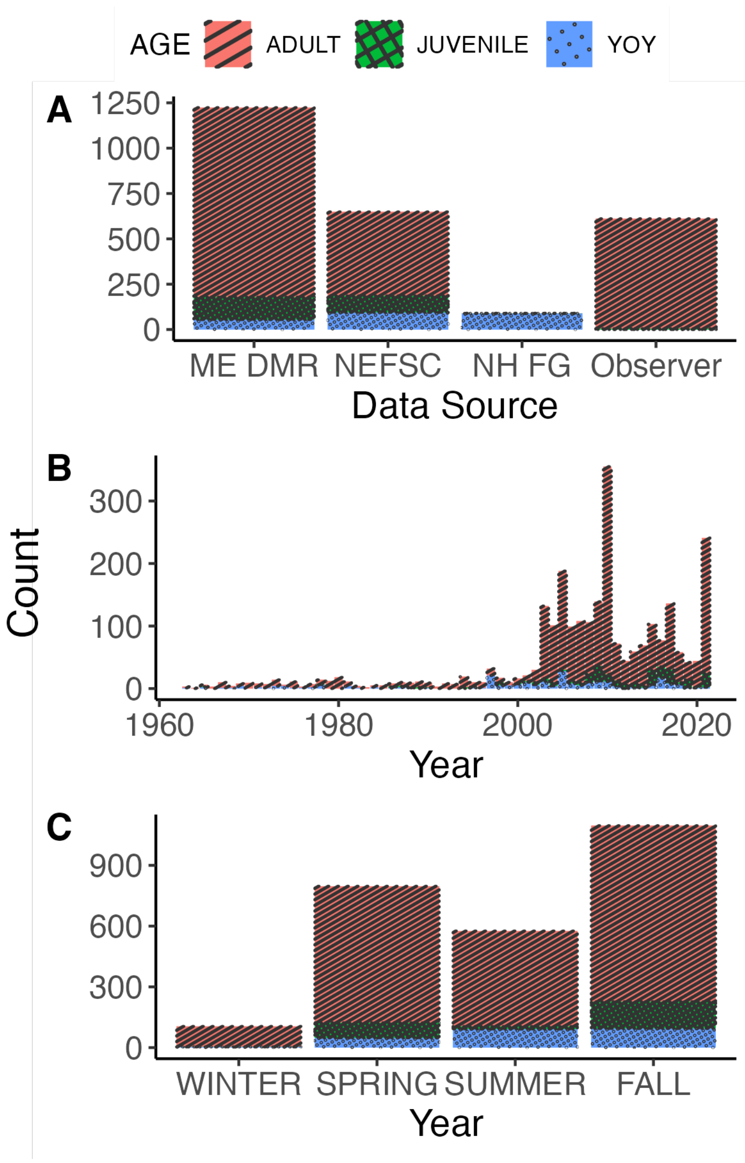


**Figure 5.** Distributions of (A) YOY, (B) juvenile, and (C) adult lumpfish caught in the Gulf of Maine from 1963-2021 from all state and federal surveys. MA DMF data are not included as lumpfish age data could not be calculated.

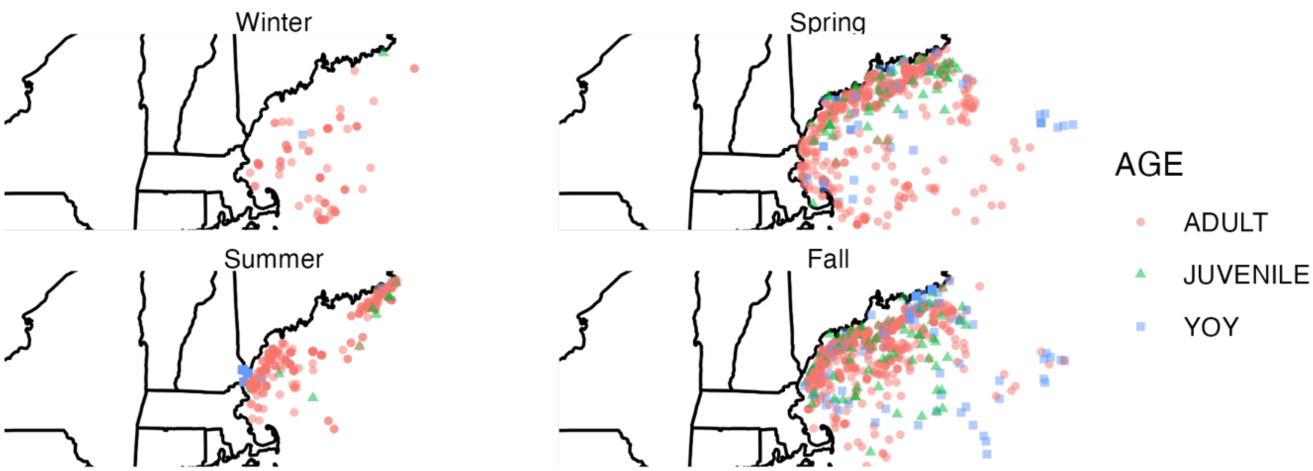
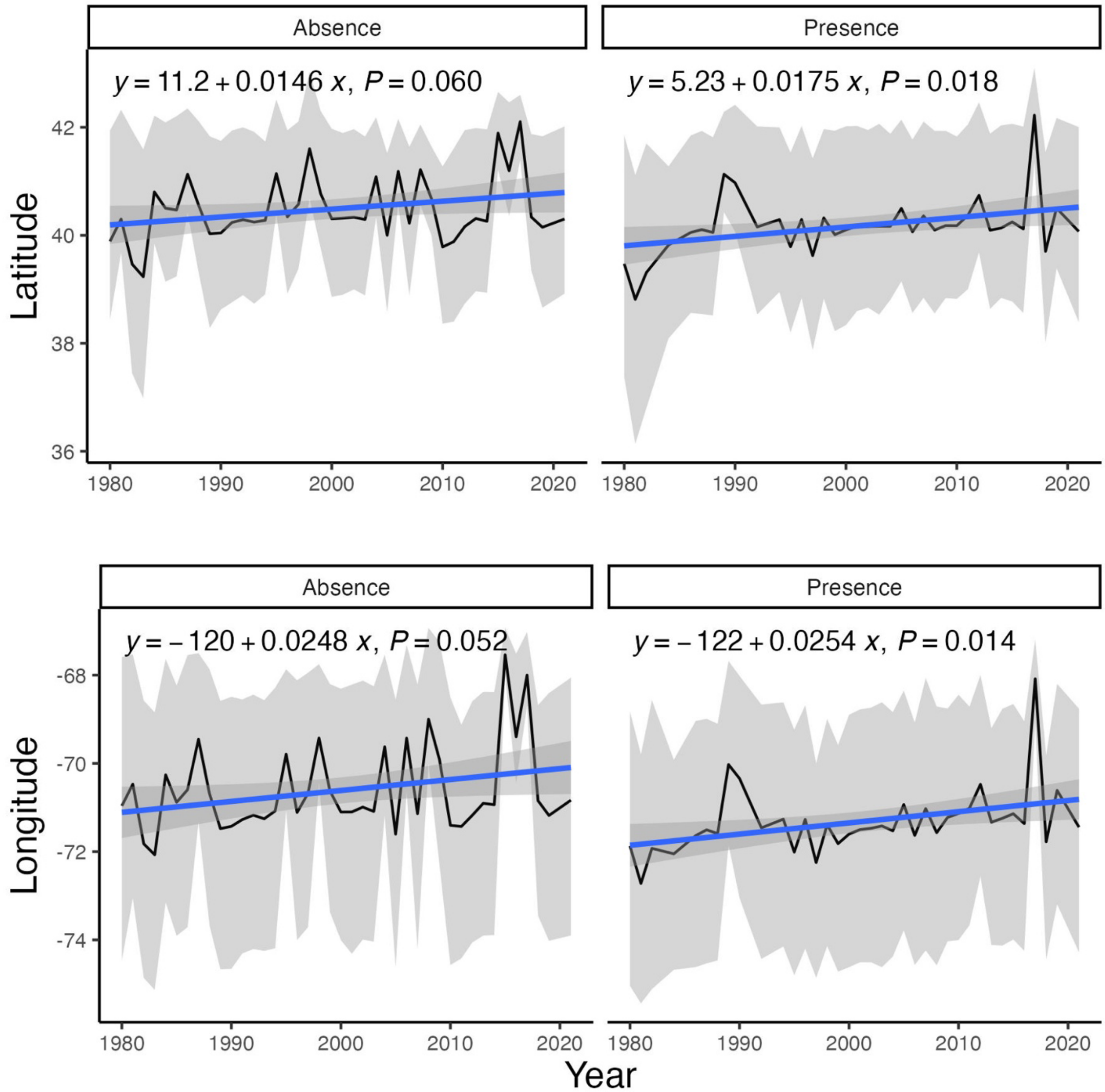


**Figure 6.** Time series of latitude and longitude of surveys where lumpfish were either absent or present in the NEFSC BT surveys from 1980 – 2021.



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