Bluefish Ecosystem and Socioeconomic Profile

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Executive summary

An Ecosystem and Socioeconomic Profile (ESP) was used as a framework to address TOR1 in this research track assessment. ESP is a standardized framework to facilitate the inclusion of ecosystem and socioeconomic information in the stock advice process; it leverages existing information to understand the ecological and socio-economic drivers of stock dynamics and to incorporate this diverse information into the stock advice process through the creation of ecosystem and socioeconomic indicators. This standard framework also facilitates the interpretation of data and allows future working groups to update the existing indicators in addition to creating and assessing new indicators.

The ESP process begins with (1) a systematic review of existing ecosystem and socioeconomic literature and identification of problem statements for the stock, followed by (2) development of conceptual models to outline the major drivers on the stock, (3) creation of indicators relevant to stock performance, (4) analysis of select indicators, and, lastly, (5) reporting out scientific advice. The scientific advice provided by an ESP can come at multiple levels of complexity, ranging from providing additional context and research recommendations, to suggesting new covariates to include as covariates to inform assessment modeling.

The bluefish ESP includes a comprehensive literature review of bluefish life history and related ecosystem considerations relating to bluefish habitat, distribution, diet, predators, competitors, growth, and survival at each life stage, as well as a review of the history of the bluefish stock assessment and relevant biological information that is used to make decisions relating to the assessment modeling. Diet data collected from multiple scientific surveys were analyzed to determine the major prey and predators of bluefish, supplementing the literature review with the most recent data. Distributional and environmental data from multiple state and federal surveys were analyzed to understand where, when, and under what conditions bluefish of multiple life stages and size classes were found. Ecosystem and socioeconomic indicators were developed to better understand metrics of ecosystem and socioeconomic status, as well as to begin to probe potential mechanistic linkages between the environment and the status of the bluefish stock.

Background

Life history

Spawning

Bluefish are multiple spawners with indeterminate fecundity and asynchronous oocyte development (Robillard et al. 2008). Although the number of spawning events per individual per year is not known, multiple batches per female per year is likely (Robillard et al. 2008). Each female produces several hundred thousand eggs per batch (range 114,513 - 920,746, mean 402,247; Robillard et al. 2008). There is high variability in the relationship between female length or weight and fecundity, so a length-fecundity or weight-fecundity relationship has not been established (Robillard et al. 2008); the relationship between fecundity and age has also not been quantified (Shepherd and Packer 2006).

Spawning begins in the spring in the South Atlantic Bight (SAB), and progresses northward into the Mid Atlantic Bight (MAB) in the summer (Shepherd and Packer 2006, Austin et al. 1999, Wilk 1977). Gonadosomatic indices of adult bluefish, as well as egg and larval abundances, indicate that spawning is protracted and progresses northward throughout the spring and summer (Hare and Cowen 1993). Gonad status of female bluefish indicates that spawning occurs in Florida and North Carolina in March and April and continues northward to Virginia through New York in April until August (Robillard et al. 2008). Observations of bluefish eggs in the MarMAP cruises (1977-1987) indicated that spawning began in May near Cape Hatteras, extended northward to southern New England by July, and tapered off in August (Berrien and Sibunka 1999). The timing and age of young-of-the-year (YOY) bluefish appearing in coastal Maine suggest that there may be additional spawning sites closer to Maine than the MAB (Creaser and Perkins 1994). The peak in female gonadosomatic index occurs in June and July, with a low period from January to March (Robillard et al. 2008), although varying numbers of larvae are observed in every month, indicating some degree of spawning year round (Kendall and Walford 1979). Spawning occurs approximately 55-148 km offshore, on the outer half of the continental shelf, at temperatures of 18-25.6°C and salinities above 26.6 ppt (Norcross et al. 1974). Optimal temperature and salinity for spawning are 25.6°C and 31 ppt, respectively (Norcross et al. 1974). The minimum temperature at which spawning was observed was lower when the salinity was higher, implying possible interactive effects of temperature and salinity (Norcross et al. 1974).

Two main length cohorts are observed in the YOY population, which are commonly termed the spring and summer cohorts. The spring cohort is comprised of the fish spawned in March, April, and May in the SAB (Shepherd and Packer 2006, Austin et al. 1999), and the summer cohort is comprised of the fish spawned in June, July, and August in the MAB (Shepherd and Packer 2006, Austin et al. 1999). In some years, an intermediate cohort, spawned in early summer, appears in the MAB (Callihan et al. 2008); this may be due to warmer water temperatures in the MAB favoring spawning (Callihan et al. 2008). Multiple cohorts have also been observed during the summer in New Jersey (Taylor and Able 2006), and a fall cohort may be present in some years in the SAB (Juanes et al. 1996, 2013). There is no evidence that any of these length cohorts are produced by different spawning stocks. All bluefish found in the Northwest Atlantic are a single genetic stock (Shepherd and Packer 2006, Austin et al. 1999, Graves et al. 1992). Additionally, age-1 bluefish spawning in the summer in the New York Bight had lengths consistent with being spawned themselves the prior spring (Chiarella and Conover 1990), indicating connectivity between the spring and summer length cohorts.

It is not known whether the two subannual length cohorts are produced by discrete spatio-temporal spawning events, or whether the appearance of two cohorts is created due to the differential mortality of individuals spawned throughout the spring and summer (Shepherd and Packer 2006). In late spring and early summer, oceanographic conditions may be unfavorable for recruitment to estuaries (Hare and Cowen 1993). Alternatively, spawning may slow as adults migrate north in the late spring and early summer (Wuenschel et al. 2012). Adult condition may be reduced following their migration, limiting spawning in the summer (Wuenschel et al. 2012). It is also possible that older bluefish may overwinter offshore of the MAB, rather than in the SAB, and therefore only contribute to the summer cohort (Wuenschel et al. 2012).

The relative importance of each length cohort is not well understood. Seasonal pulses of eggs and larvae may reduce recruitment variability (Secor 2007). The relative abundance of each length cohort within the YOY varies from year to year, with the spring cohort being more numerous in the 1970s and 1980s, whereas the summer cohort was more numerous in the 1990s and early 2000s (Conover et al. 2003, Secor 2007). However, the majority of adult bluefish from these year classes appear to be from the spring cohort (Conover et al. 2003). Poor overwinter survival of summer-spawned YOY combined with fewer spring-spawned YOY could be contributing to the observed population decline (McBride et al. 1995).

Eggs

Bluefish eggs are oceanic (Shepherd and Packer 2006), with 88% of eggs being found more than 55 km offshore (Norcross et al. 1974). Eggs may be geographically concentrated or more widely distributed, depending on the year (Able and Fahay 1998). Most eggs are found at less than 30 meters depth, and no eggs are distributed below 70 meters depth (Shepherd and Packer 2006). Eggs have a diameter of approximately 1mm (Shepherd and Packer 2006, Deuel et al. 1966, Wilk 1977).

Eggs can tolerate temperatures of 8-26°C, but the optimal temperature is above 13°C. In the Northwest Atlantic MARMAP survey of the MAB, eggs were found at surface temperatures of 16-28°C, with a peak at 19-21°C (Smith et al. 1994). Eggs hatch in two days at temperatures of 18-22°C (Shepherd and Packer 2006, Deuel et al. 1966). In the Gulf of Mexico, bluefish eggs were found to hatch in 30-36 hours at 25°C (Ditty and Shaw 1995). 86% of eggs were found in water with salinity above 29 ppt (Norcross et al. 1974). Eggs are found continuously throughout the spring and summer in the MAB (Hare and Cowen 1993).

Larvae

Larvae are oceanic and are found at shallow depths (<4m) during the day, and slightly closer to the surface at night (Shepherd and Packer 2006, Kendall and Naplin 1981). Larvae feed on a yolk for the first two days after hatching (Deuel et al. 1966) and eventually transition to feeding on copepods (Shepherd and Packer 2006), fish eggs (Marks and Conover 1993), invertebrate eggs, and cladocerans (Kendall and Naplin 1981). At hatching, larvae are 2.0-2.6mm in length (Shepherd and Packer 2006, Deuel et al. 1966, Wilk 1977), and they grow at a rate of 0.3-0.8mm/day (Juanes et al. 1996). The larval stage lasts for 18-25 days, and larvae are 10-12mm in length when they metamorphose to juveniles (Hare and Cowen 1993). 10mm has been used as the upper length limit of bluefish larvae (Kendall and Walford 1979), and the largest larva included in the analysis of Norcross et al. (1974) was 17mm.

Feeding larvae prefer temperatures of 17-26°C (Shepherd and Packer 2006). Larvae are found in MAB waters with temperatures of 18-26°C and salinity of 30-32 ppt, and in SAB waters with temperatures of 20-26°C and salinity of 35-38 ppt (Kendall and Walford 1979). 15°C may be a lower thermal limit for bluefish larvae (Kendall and Walford 1979).

Some larvae are seen in the MAB and/or SAB in every season, but most larvae are observed in spring and summer (Kendall and Walford 1979). In the spring, most larvae are found in the SAB, while in the summer, most larvae are found in the MAB (Kendall and Walford 1979). At their peak abundance in the spring, larvae are distributed throughout the SAB (Powles and Stender 1976).

Larvae are transported northward by the Gulf Stream and possibly also by warm core ring streamers (Hare et al. 2002). Larvae may actively move inshore as they age; larvae under 4mm in length were found only on the outer shelf, while larger larvae were also found on the inner shelf (Collins and Stender 1987). However, larvae do not enter estuaries (Able et al. 2011).

Pelagic juveniles

Relatively little is known about the pelagic juvenile phase. Larvae transition into pelagic juveniles approximately 18-24 days after hatching, at a length of 10-12mm (Shepherd and Packer 2006). At this point, the juveniles are growing at approximately 0.8mm/day (Juanes et al. 1996). Pelagic juveniles spawned in the spring grew more slowly than pelagic juveniles spawned in the summer (McBride and Conover 1991). Given this growth rate, the pelagic phase lasts for approximately five weeks, as juvenile bluefish are approximately 40mm in length when they begin to enter estuary habitats (Juanes et al. 1996).

The diet of pelagic bluefish larvae is mediated by their size (Shepherd and Packer 2006). Until bluefish reach 30mm in length, their diet includes primarily copepods (Shepherd and Packer 2006, Juanes et al. 1996, Marks and Conover 1993). When bluefish reach 30mm in length, their diet begins to include fish, and may become mostly fish by the time they reach 40mm in length (Shepherd and Packer 2006, Juanes et al. 1996), which also coincides with their entry to coastal and estuarine habitats (Juanes et al. 1996). There are no morphological changes associated with the start of piscivory (Marks and Conover 1993).

Estuarine/coastal juveniles

Habitat and distribution

YOY bluefish are transported from spawning regions to nearshore juvenile habitat through a combination of physical processes and active swimming. The Gulf Stream transports larvae and early juveniles from the SAB towards the MAB (Hare and Cowen 1996), and physical processes help move the bluefish inshore. These physical processes may include warm-core ring streamers (Hare and Cowen 1996) and winds (Munch and Conover 2000). Once the shelf-slope temperature front dissipates in the spring, the juveniles swim inshore (Hare and Cowen 1996, Hare et al. 2001). Bluefish arrival in nearshore habitats in the MAB coincides with the appearance of their piscine prey, and this northward migration pattern may have developed because it allows the bluefish to access a beneficial diet (Juanes et al. 1994, Juanes and Conover 1995).

Juvenile bluefish are broadly distributed along the eastern United States. In the spring, juvenile bluefish begin to recruit to estuaries and coastal regions in the Mid Atlantic Bight, possibly responding to a temperature or diet cue (Scharf et al. 2004). Although estuaries are the best-known juvenile habitat, juveniles are also found at many coastal beaches (Taylor et al. 2007, Wuenschel et al. 2012, Woodland et al. 2012). The summer-spawned cohort in particular has been observed at several coastal beaches (Able et al. 2013, Wilber et al. 2003), often being more abundant at coastal beaches rather than in nearby estuaries (Wuenschel et al. 2012, Callihan et al. 2008, Taylor et al. 2007). In contrast, spring-spawned YOY bluefish were more abundant in estuaries compared to nearshore beaches (Taylor et al. 2007). Bluefish also use oyster reef habitat (Harding and Mann 2001a, 2001b, Pfirrmann and Seitz 2019). In the Chesapeake Bay region, bluefish abundance was sometimes (Harding and Mann 2001a, 2001b), but not always (Pfirrmann and Seitz 2019), higher on oyster reef habitat compared to other coastal habitat. Higher abundance on oyster reefs may be linked to a more diverse diet (Harding and Mann 2001b). Juveniles tolerate all dissolved oxygen levels above 2 mg/L, but are rarely found when dissolved oxygen is below 2 mg/L (Howell and Simpson 1994).

Juveniles do not enter estuaries until water temperatures are above 13-15°C (Shepherd and Packer 2006), and become abundant in estuaries when temperatures approach 20°C and warmer (Hagan and Able 2003, Taylor et al. 2007). Juvenile bluefish may have a lower temperature limit between 10°C (where they lose weight) and 12°C (where growth is low but positive) (Morley et al. 2013). Cold temperature reduces the number of prey attacks made by bluefish, thereby reducing their ingestion rates (Morley and Buckel 2014). Bluefish actively avoid cold water, but will enter cold water to feed (Olla et al. 1985). Bluefish are generally observed at salinities of 29-36 ppt (Shepherd and Packer 2006), but they have also been found at salinities as low as 5 ppt (Able et al. 2009).

Juveniles enter North Carolina estuaries beginning in April (McBride et al. 1993, Wuenschel et al. 2012) and enter New York Bight estuaries beginning in late May (McBride et al. 1993) through June and July (Wuenschel et al. 2012). These juveniles are estimated to be around 60-76 days old and 60mm in length (Shepherd and Packer 2006). Juveniles spawned the previous summer may also enter North Carolina estuaries in the spring (Wilk 1977). Another wave of juveniles begins to enter New York Bight estuaries in July (Wuenschel et al. 2012) and

August (Shepherd and Packer 2006). Juvenile bluefish have been observed as far north as Maine (Furey and Sulikowski 2011, Creaser and Perkins 1994, Bigelow and Schroeder 1953).

As temperatures cool in the fall, the coastal and estuarine nurseries in the MAB become less suitable for bluefish, and YOY begin to migrate southward (Juanes et al. 1996). The larger, spring-spawned individuals begin migrating first (Morley et al. 2013). Juveniles in the New York Bight move southward during the fall (Wuenschel et al. 2012) and eventually reach North Carolina in October (McBride et al. 1993, Wuenschel et al. 2012). Some juveniles continue southward to overwinter off of Florida (Stormer and Juanes 2018), while others remain in North Carolina estuaries (Morley et al. 2013). Possible bluefish migration patterns are shown in Figure 1.

Diet

Juvenile bluefish are opportunistic predators capable of eating a variety of prey (Shepherd and Packer 2006, Festa et al. 1979, Bigelow and Schroeder 1953). Bluefish begin to consume fish when they have a length of 30-40mm (Marks and Conover 1993), and by the time they reach 80mm, their diet is primarily fish (Able et al. 2003, Creaser and Perkins 1994). This shift to piscivory occurs as the bluefish are beginning to enter coastal and estuarine habitats (Juanes et al. 1996). The entry of juvenile bluefish into estuaries also coincides with the appearance of menhaden (Scharf et al. 2004), striped bass (Juanes et al. 1994), bay anchovy (Taylor et al. 2007), and silversides (Juanes and Conover 1995), some of their primary dietary species. Reported daily consumption rates for age-0 fish can approach 33% of body weight (Juanes and Conover 1994). Additionally, Buckel and Conover (1996) observed gastric evacuation rates, expressed as time to 90% evacuation, ranging from ~5h at 30ºC to ~10h at 21ºC, which suggests that bluefish are capable of feeding 2-4 times per day.

Bluefish are visual predators (Olla et al. 1985), and their gut fullness typically peaks in the evening and reaches a minimum in the morning (Marks and Conover 1993). Bluefish have been recorded to eat many species of fish and invertebrates, including (but not limited to) silversides and striped bass (Buckel and Stoner 2000), Atlantic menhaden (Scharf et al. 2004, Uphoff and Sharov 2018), bay anchovy and mysid shrimp (Stormer and Juanes 2017), winter flounder (Manderson et al. 2006), striped anchovy (Gartland et al. 2006), killifish (Buckel and Stoner 2004), spot (Miltner et al. 1995), squid (Buckel et al. 1999b), copepods (Creaser and Perkins 1994, Marks and Conover 1993, Buckel et al. 1999b), blue crab (Festa et al. 1979), and crab zoea (Buckel et al. 1999b). Smaller juvenile bluefish also eat caridean shrimp, grass shrimp, and polychaetes (Festa et al. 1979), and increased predation on commercially important invertebrates such as blue crabs (Callinectes sapidus) may occur when fish prey are less available (Scharf et al. 2004). Stomach contents of bluefish caught in the NEAMAP and ChesMMAP trawl surveys, two inshore surveys that overlap with juvenile bluefish habitat, frequently contain bay anchovy and other small forage fish (Table 2, 3). The spring-spawned cohort overlaps with multiple prey species, while the summer-spawned cohort relies primarily on bay anchovy (Scharf et al. 2006). Natural mortality for young-of-year striped bass in the Hudson River has been attributed almost entirely to Bluefish predation (Buckel et al. 1999a).Cannibalism has also been documented, and therefore bluefish predation may influence recruitment of conspecifics (Bell et al., 1999).

Both seasonal and inter-annual differences in diet have been observed. These differences are likely attributed to differences in prey availability, but also due to inter-annual variability in timing of estuarine arrival (Nyman and Conover, 1988). Feeding may also be constrained by thermal gradients (Olla et al., 1985).

Juvenile condition is highest when their diet contains more fish, rather than invertebrate prey (Friedland et al. 1988), and feeding efficiency and growth are reduced when eating invertebrate prey compared to fish prey (Scharf et al. 2009). Bluefish select fish prey over shrimp prey if given a choice (Juanes et al. 2001). Bluefish predation may represent a large portion of the natural mortality of their prey species, including Atlantic menhaden (Uphoff and Sharov 2018), Atlantic silverside (Gleason and Bengtson 1996), striped bass (Buckel et al. 1999c), and bay anchovy (Buckel et al. 1999b).

Bluefish are unique among piscivores in that they are able to consume prey that are relatively large compared to their own body size (Scharf et al. 2002). If the prey is larger than 35% of the bluefish's own size, the juvenile bluefish will bite the prey into pieces (Scharf et al. 1997). Juvenile bluefish have a high capture success even on large prey, and prey that was 30% (Scharf et al. 1998) to 50% (Scharf et al. 2002) of the bluefish's own size was the most profitable. Review of bluefish diet data from the NMFS bottom trawl for the 2015 Atlantic menhaden assessment showed that bluefish consumed prey up to approximately 60% of their own body size, with a peak in selectivity around 20% of their own body size.

Predators and competitors

Juvenile bluefish are eaten by a variety of seabirds, including Atlantic puffin, Arctic tern, common tern, and roseate tern (Shepherd and Packer 2006). Bluefish are opportunistically consumed by elasmobranchs, including smooth dogfish, clearnose skate, and bullnose ray (Woodland and Secor 2011). Cannibalism is unlikely, as the abundance of the spring- and summer-spawned cohorts is positively correlated (Munch and Conover 2000), and age-1 bluefish have low capture success (<20%) on age-0 bluefish (Bell et al. 1999); however, cannibalism has been observed in limited instances (Lassiter 1962, Table 1-3). Few bluefish have been observed in predator stomachs taken in the NEAMAP and ChesMMAP trawl surveys, and the only recorded bluefish predators in these data sets are sandbar shark and striped bass (Tables 2, 3).

Juvenile bluefish do not have many competitors. There is little intraspecific competition between cohorts, as they have low dietary overlap (Hartman and Brandt 1995, Stormer and Juanes 2017). However, a large spring-spawned cohort may result in less food availability for the summer-spawned cohort (Scharf et al. 2006). There is dietary overlap between bluefish and weakfish during the summer and between bluefish and weakfish, summer flounder, and striped bass during the winter (Wuenschel et al. 2013). However, there was no evidence for competition between bluefish and striped bass in the New York Bight (Buckel and McKown 2002). The two species had low habitat overlap and low diet overlap (Buckel and McKown 2002, Buckel et al. 2009), and a mesocosm experiment showed no difference in growth rates when bluefish and striped bass were kept together or separate (Buckel and McKown 2002). Growth estimates from the field were not correlated with the abundance of the competitor (Buckel and McKown 2002). Bluefish switch to piscivory at a smaller size than striped bass and consume larger fish relative to their own size (Scharf et al. 2006, Hartman 2000). When feeding on similarly-sized prey under laboratory conditions, bluefish have more efficient feeding and outcompete striped bass (Scharf et al. 2009).

Growth and survival

Juvenile bluefish grow at approximately 0.5-2mm/day (McBride et al. 1993, Juanes and Conover 1994, Juanes et al. 1996, Creaser and Perkins 1994, Able et al. 2003), and they grow to nearly one third of their maximum length by age 1 (Richards 1976, Wilk 1977). They grow fastest when eating a fish diet (Juanes and Conover 1994, Buckel et al. 1998). Prior study has found no effects of sex, year, or region on juvenile bluefish growth (Robillard et al. 2009, Working Paper 5 Truesdell et al. 2022). The spring- and summer-spawned cohorts have similar size-at-age, although this means that the spring-spawned cohort is larger at any given point in time (McBride et al. 1993).

At the beginning of winter, the spring-spawned cohort has more energy stored than the summer-spawned cohort (Stormer and Juanes 2017, Morley et al. 2007); however, the spring-spawned cohort only has greater survival than the summer-spawned cohort when overwintering under starvation conditions (Slater et al. 2007). The summer-spawned cohort stores more lipid per body mass (Stormer and Juanes 2017), and by February, both the spring- and summer-spawned cohorts have similar energy density (Morley et al. 2007).

Even when starved, juvenile bluefish survival over winter was greater than 50%, and comparison between field samples and laboratory starved samples showed that field-caught bluefish are in better energetic condition than starved bluefish (Slater et al. 2007). Cold temperatures reduce bluefish feeding, and at 10°C, consumption rates are only slightly above zero (Morley et al. 2013). Size-selective overwinter mortality may occur in years when temperatures drop below 12°C (Morley et al. 2013). Juvenile bluefish leave their estuarine habitats when temperatures drop below 15°C (Juanes et al. 1996).

Adult

Bluefish maturity was analyzed in the 2015 benchmark assessment (working paper B2) using a large dataset compiled from several pre-existing studies and surveys. The results showed that bluefish reached 50% maturity at a length of 30.4cm (northern bluefish) or 24.0cm (southern bluefish). Females were approximately 0.6cm larger than males at maturity. At age 1, 40% of fish were mature; at age 2, 97% of fish were mature; and at age 3 and onward, all fish were mature. Updated maturity estimates including data through 2021 are presented in Working Paper 5 (Truesdell et al. 2022). This data corresponds well with prior studies that used macroscopic observations (e.g., Salerno et al. 2001). Robillard et al. (2008) used female-only histological samples and estimated lower age-at-maturity for ages 1-3. Maximum age is approximately 14 years (2015 assessment, working paper B2), and maximum size is approximately 110cm length and 4.5-6.8 kg (Shepherd and Packer 2006). The sex ratio of the bluefish population is approximately 1:1 (Shepherd and Packer 2006); however, in Australia, the sex ratio increased to 1.58 females per 1 male after exploitation on the stock was reduced (Schilling et al. 2019).

Analyses done in the 2015 benchmark assessment concluded that southern fish (collected between North Carolina and Florida) were slightly larger in both length- and weight-at-age compared to northern fish (collected in Virginia and states northward), although the effect size seemed to be small. These analyses also showed that bluefish collected in the spring had less body mass at a given length, compared to bluefish collected in the fall.

Adult bluefish are pelagic, and their distribution broadly covers coastal, nearshore, and continental shelf regions (Bigelow and Schroeder 1953), although the specifics are not well known. Bluefish travel in schools with similarly-sized bluefish (Wilk 1977, Bigelow and Schroeder 1953) and can swim up to 5km per day when migrating (Shepherd et al. 2006). Larger adult bluefish may be distributed more northward as compared to smaller adult bluefish (Shepherd and Packer 2006), and the northern edge of their range has historically been variable, sometimes extending north into the Gulf of Maine and sometimes remaining in southern New England (Bigelow and Schroeder 1953). Smaller bluefish migrate north-south nearshore, while larger fish are more likely to also have an inshore-offshore component to their migration, and they may not migrate as far south (McBride 2014, Shepherd et al. 2006). Tagging of adult bluefish between 1963-2003 identified three groups of bluefish with distinct spatiotemporal patterns (Shepherd et al. 2006). Bluefish that were distributed in the northern MAB (Delaware to Massachusetts) in the late spring to late fall overwintered on the east coast of Florida if they were less than 45cm in length and overwintered offshore in the MAB if they were over 45cm in length (Shepherd et al. 2006). Bluefish in the southern MAB (North Carolina to Maryland) consisted of both transients and residents (Shepherd et al. 2006). Bluefish from these two groups that were tagged in the MAB tended to return to the same location in following years (Wilk 1977). Lastly, bluefish found in southern Atlantic Florida were mostly less than 45cm and had the highest abundance in winter (Shepherd et al. 2006). Bluefish tagged in Florida tended to return to the same location only for one year (Wilk 1977). Bluefish did not seem to use the nearshore waters in Georgia or South Carolina (Shepherd et al. 2006). Some bluefish may also overwinter offshore in the northern MAB, as historical sources recorded trawling bluefish off of Martha's Vineyard and New York in the winter (Bigelow and Schroeder 1953). This age-specific difference in distribution may lead to a non-genetic structuring of the stock (McBride 2014). The cue for migration may be related to the photoperiod, as bluefish swim faster when the day length is longer (Wilk 1977). Possible bluefish migration patterns are shown in Figure 1.

Some bluefish are also caught in the U.S. states adjacent to the Gulf of Mexico; however, it is not known definitively whether these fish are part of the same stock as the Atlantic bluefish, or whether these fish mix with Atlantic bluefish. The catch of these Gulf of Mexico bluefish is negligible in comparison to the Atlantic bluefish; see Appendix I to Working Paper 10 (K Drew 2022b) for more details.

Bluefish have been found at depths up to 400 meters (Shepherd and Packer 2006). They seem to prefer complex bottom habitats, especially oyster reefs when they are inshore (Harding and Mann 2001a, 2001b). The lower temperature limit of adult bluefish is around 14°C (Shepherd and Packer 2006, Wilk 1977, Bigelow and Schroeder 1953), and they have been observed in salinities down to 12ppt (Grouthues and Able 2007).

Bluefish are opportunistic foragers, and the composition of adult bluefish diet depends largely on the available prey (Shepherd and Packer 2006). Adult bluefish diets are similar to juvenile bluefish diets, described above. Bluefish have long been recognized as a notable predator of forage fish (Storer 1853, Bigelow and Schroeder 1953). Bluefish are a key predator of Atlantic menhaden, and may be responsible for most of the natural predation on menhaden

(Uphoff and Sharov 2018, Garrison et al. 2010). However, at 50,000 metric tons consumed per year, bluefish consume less menhaden than the amount fished by humans (Buckel et al. 1999c), and the amount of menhaden fished by humans is not expected to affect bluefish (Buchheister et al. 2017). Bluefish consume squid (Staudinger 2006), and remove approximately 100,000 metric tons of longfin squid each year, which is more squid than the amount removed by humans (Buckel et al. 1999c). Bluefish also consume approximately 100,000 metric tons of butterfish each year, more than the amount removed by humans (Buckel et al. 1999c). Notably, all of these diet estimates were calculated prior to the revision of the MRIP catch data in 2018, which resulted in a large increase in historical estimates of bluefish catch. Consequently, bluefish biomass is now thought to have been ~20-50% higher than the levels assumed in these studies, so estimates of bluefish removals of prey species would likely need to be revised upwards.

Almost no cannibalism has been observed among adult bluefish (Buckel et al. 1999b). Larger bluefish have been shown to consume larger mean prey-sizes (Sharf et al., 2004), while prey capture success has been reported to decline linearly with increasing prey length/predator length ratio (Buckel et al. 1998).

Similar to juvenile bluefish (described above), adult bluefish are eaten by large pelagic fish, including sharks, tuna, and billfishes (Oliver et al. 1989, Shepherd and Packer 2006), and other elasmobranchs, including smooth dogfish, clearnose skate, and bullnose ray (Woodland and Secor 2011). Bluefish account for more than 85% of shortfin mako shark diet in the Northwest Atlantic, and each mako shark consumes approximately 500 kg of bluefish each year (Wood et al. 2009). Mako probably consume more bluefish than the amount removed by the fishery (Wood et al. 2009), although, as noted above, the 2018 revision of MRIP data resulted in higher historical bluefish catch estimates. However, bluefish may not be sensitive to changes in the mako shark population, while mako are likely sensitive to changes in bluefish abundance (Harford 2013). Bluefish make up <20% of tuna diet (Chase 2002).

Additional qualitative information on bluefish predators was provided by personal communication from Cami McCandless and Kathy Duffy (NEFSC). Sampling of the stomachs of sharks caught in New York recreational tournaments (1972-2019) is the main source of shark diet information in the Northwest Atlantic. Due to increasing shark regulations, few samples are collected each year, hence the qualitative nature of this information. These records date back to the 1970s, when many more sharks were caught and analyzed each year. Mako shark diet consistently includes a large number of bluefish, although in recent decades, the proportion of bluefish has decreased from approximately 90% of the diet to 80%, even though the number of bluefish consumed has increased; the average weight of each bluefish present in mako shark stomachs is smaller in recent decades compared to historical data. This trend may reflect reduced overlap of mako sharks and large bluefish, potentially supporting the theory that large bluefish are moving offshore. Alternatively, the shift in mako shark diet may reflect changes in relative abundance of bluefish compared to other prey species. Blue shark and thresher shark diets also included bluefish, although to a lesser extent than mako diet. There was no change in the size of bluefish in blue shark and thresher shark stomachs over time, but the sample size was lower than for mako sharks. It appears that mako actively target bluefish, while blue sharks and thresher sharks only consume bluefish opportunistically.

Similar to juvenile bluefish (described above), adult bluefish compete with many seabirds, including common terns (Safina 1990, Bugoni and Vooren 2004) and roseate terns (Safina 1990). Bluefish also compete with humans for Atlantic menhaden, but modeling has shown that menhaden fishing scenarios have little effect on bluefish biomass (Buchheister et al. 2017). Other large pelagic fish that are likely competitors of bluefish include Spanish mackerel, king mackerel, striped bass, large weakfish, Atlantic bonito, and little tunny (Oliver et al. 1989).

Stock assessment

History of the stock assessment

Bluefish was assessed through SAW23 (1997) using the CAGEAN (Catch at AGE ANalysis) model, a catch-at-age model that used commercial and recreational catch tuned by recreational CPUE and survey catch-at-age data. The assessment found that bluefish were at historically low levels of spawning stock biomass and overexploited. It recommended that fishing mortality should be reduced to halt the decline in SSB.

In 2004, the SAW WG put forward an ASPIC (A Stock Production model Incorporating Covariates) surplus production model at SARC-39. This assessment was not accepted as a basis for fishery management because the recreational CPUE did not correctly handle live-release data, creating a “severe” bias, the NEFSC data used as an index of fishable biomass represented only age-0 and age-1 fish, and the residuals in the commercial catch rate data showed strong autocorrelation, indicating model misspecification.

The Technical Committee and Working Group continued work on the assessment, returning in 2005 with an age-structured assessment at SARC 41. The NFT ADAPT (NOAA Fisheries Toolbox ADAPTive) version of VPA (Virtual Population Analysis) was used as an initial model. The committee felt that the VPA model produced satisfactory results, but the assumption of no error in the catch-at-age matrix and the ADAPT method of modeling selectivity could produce misleading results. Therefore, a statistical catch-at-age model, ASAP (Age Structured Assessment Program) from the NFT models, was used as the primary assessment tool. Many of the results coming out of the ADAPT VPA model were used as input starting values for ASAP. The ASAP model was brought to review and was accepted by two out of three reviewers. The third reviewer was extremely critical of the way the model had been configured and the way some inputs and assumptions were handled.

The current assessment model for bluefish has provided management advice since 2005 and was accepted at the Stock Assessment Workshop 41 review (NEFSC 2005). After reviewing several model types including a modified Delury model, a surplus production model, a VPA and statistical catch-at-age models, the Bluefish Technical Committee concluded that a statistical-catch-at-age (ASAP) model was the most appropriate for the bluefish assessment.

The 2015 stock assessment made several updates to the model structure. The recreational and commercial industries were modeled as separate fleets. Maturity values were updated from estimates to calculated values based on newly analyzed age-maturity data. Fleet selectivity was estimated rather than fixed.

In July 2018, the Marine Recreational Information Program (MRIP) replaced the existing estimates of recreational catch with a calibrated 1981-2017 time series that corresponds to new survey methods that were fully implemented in 2018.The recreational landings and discards from the new MRIP calibration were incorporated into the 2019 operational assessment using data through 2018 and the 2015 assessment model. The large increase in recreational landings and discards from the new MRIP calibration has further increased the importance of the recreational data to this assessment.

Model parameters

Bluefish recruitment indices are derived from YOY fish caught in state and federal scientific surveys. No surveys specifically target bluefish, but bluefish are observed in several state and federal surveys. Bluefish eggs and larvae are pelagic (Shepherd and Packer 2006) and are not consistently sampled, and therefore the understanding of survival from egg to juvenile is not well understood due to a lack of data.

There are few data sources to characterize natural mortality of bluefish. The main predators of bluefish are large, highly migratory species that are sparsely sampled. Most determinations of natural mortality are derived from modeling and ecological theory. Natural mortality calculations for bluefish are detailed in Working Paper 6 (Tyrell and Truesdell 2022).

Release mortality has been characterized in several studies, which are summarized in Working Paper 11 (Valenti 2022b). Bluefish are generally believed to be resilient to mortality after being released by anglers, and an updated recreational release mortality estimate continues to reflect this.

Maturity is discussed in Working Paper 5 (Truesdell et al. 2022).

Because adult bluefish are pelagic and sparsely sampled by existing survey gear, changes to bluefish observations may be caused by changes in distributions rather than by a change in the population size. The 2015 benchmark assessment (2015 working paper B4) investigated bluefish distribution and availability to surveys. Data collected in 2008-2014 from the NEAMAP and NEFSC bottom trawl surveys were used to train a thermal niche model, and data from before 2008 was used for validation. This study concluded that the amount of available habitat did not appear to be changing over time and that the surveys consistently sampled similar amounts of suitable habitat. Therefore, the availability of bluefish to these surveys did not appear to change over time.

Aging

The 2005 benchmark assessment used a catch-at-age model (ASAP) to model the bluefish stock. Ages were calculated using either scale or otolith data, depending on when the fish were collected; ages of fish sampled in 1982-1997 were calculated based on scale information. In addition, only data from North Carolina and Virginia were used to create age-length keys. Therefore, the 2015 benchmark assessment (2015 working paper B6) made several updates to improve the ageing protocol.

The Robillard et al. (2009) study was conducted to validate and standardize ageing procedures. In agreement with past studies (Barger 1990, Sipe and Chittenden 2002), they found that otolith ageing provides the most accurate bluefish ages, with the least variation between readers. In comparison, scales were not as reliable, and other studies have found that vertebrae and other methods are similarly not reliable (Barger 1990, Sipe and Chittenden 2002).

Robillard et al. (2009) also validated the otolith ageing procedure using marginal increment analysis, confirming that otolith ageing is the preferred method. Historical scale data was retained in the 2015 benchmark assessment, with updates to make the data more compatible with the more accurate otolith data. Most notably, age 0 North Carolina samples taken in the spring were moved to the age 1 year class (2015 working paper B6).

To improve the geographical distribution of samples used for ageing, the Bluefish Technical Committee convened a workshop in 2011 to standardize the ageing procedures across states. Additionally, the Northeast Fisheries Science Center began to use otoliths for ageing bluefish caught in the bottom trawl surveys beginning in 2014. The 2015 benchmark assessment had access to age data collected by the states of Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Virginia, North Carolina, South Carolina, Georgia, and Florida. Analysis of this geographic data determined that there were regional differences in age-length keys (2015 working paper B8), size-at-age, and catch-at-age (2015 working paper B7). However, model outputs with the updated age-length keys were all within 2 percentage points of the outputs created from the historical Virginia-only age-length keys. The regional differences in age-length keys could be caused by differing gear selectivity across states; northern data was collected mostly by commercial gear, while southern data was collected mostly by recreational gear. The seasonal movements of bluefish can also cause regional patterns in size at age, as age is only determined to the year class and does not account for monthly differences.

Age data from 1985-1995 is based on commercial scale samples collected from North Carolina and NMFS port sampling, as well as CT Long Island Sound Trawl and NEFSC trawl scale samples. From 1996 onwards, age data is based almost exclusively on otolith samples collected from multiple fisheries dependent and independent sources. Age data from 1996-2000 is based on commercial otolith samples collected from North Carolina. From 2012 to 2020, state collection of age data has been mandated for states catching more than 5% of the total bluefish harvest, which improves the coastwide sampling of bluefish ages; in 2021, the standard was changed to states that account for more than 4%[1] of total coastwide bluefish removals (recreational and commercial landings and dead discards).

Human dimensions

Recreational fishery

The recreational fishery for bluefish accounts for the majority of bluefish catch and landings, with approximately 87% of landings by weight coming from the recreational fishery (ASMFC 2019). The recreational sector is currently allocated 86% of the bluefish Acceptable Biological Catch (Amendment 7 to the Interstate Fishery Management Plan for Bluefish, 2021). Due to the broad geographical range of bluefish, states on the Atlantic coast between Maine and Florida all report some recreational bluefish landings nearly every year. Since 2020, there has been a bag limit of three fish for private anglers and five fish for anglers on for-hire vessels

[1] 4% was selected as the threshold because it would maintain all of the states that previously met the Addendum I threshold percentage while also accounting for inclusion of additional states as a result of MRIP calibration. As was done in Addendum I, Virginia would be required to maintain its biological monitoring program to support the age data collection effort.

in most states. Prior to 2020, the bag limit was either 10 or 15 fish for all recreational anglers in most states. A recreation demand model could be used to better estimate how these and other management changes will impact angler effort and therefore can inform managers of the likely economic and biological implications of alternative regulatory and stock conditions; however there are no resources currently allocated to developing this type of model for bluefish (ESP Appendix 1). The time series high in recreational harvest occurred in 1986, when 151.46 million pounds were harvested; the current annual recreational harvest is at historic lows and generally below 30 million pounds per year. This is partially attributable to an increase in releases of bluefish, as an average of two thirds of bluefish catch have been released since 1999.

Despite lower catches in recent years, bluefish remains one of the top recreational fisheries on the U.S east coast in terms of total catch, and therefore helps support a robust recreational fishing industry. Recreational fishing sales constitute a large industry on the Atlantic coast, with sales between 2014 to 2018[2] ranging from $13.2 billion in 2015 to $17.9 billion in 2018 (Figure 2). Of the coastal Atlantic states, East Florida had the highest average sales in 2018 with $5,217 million (Figure 3), followed by North Carolina ($2,205 million) and New Jersey ($2,010 million). The states with the four lowest average recreational sales were New Hampshire ($53 million), Maine ($112 million), Delaware ($163 million), and Georgia ($250 million).

We briefly summarize patterns in recreational bluefish catch from the North Atlantic (NA), Mid-Atlantic (MA), and South Atlantic (SA) states over 2010-2021 (Figure 4).[3] These summaries were informed using the Marine Recreational Information Program (MRIP) query tool[4], which relies on survey microdata to produce statistical catch estimates across various categories. Here, catch refers to recreational harvested and released fish which corresponds to "Total Catch" (A+B1+B2) in the MRIP data summaries. Catch is reported in the number of fish as opposed to pounds or tons and all 2021 MRIP data are preliminary. For additional information on MRIP methods and terms, please see the Data User Handbook (2021).

North Carolina and Florida have the highest median recreational bluefish catch with median values of 10.6 and 9.8 million fish, respectively, when assessed over 2010-2021 (Figure 5). Florida has the highest variation in catch over time, ranging from 4.05 million to 20.7 million fish; in comparison, North Carolina ranged from 2.93 million to 11.43 million bluefish over the same time period. New Jersey and New York had the third and fourth highest median recreational bluefish catches (7.63 million and 7.04 million bluefish, respectively). All other states had median recreational bluefish catch less than or equal to 2.50 million fish; the lowest medians were reported from Georgia, Maine and New Hampshire (0.18 million, 0.01 and <0.01 million fish, respectively). The majority of states incurred the lowest bluefish recreational catches during or after 2017. No state incurred a time series high of recreational bluefish catch in 2020 or 2021.

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[2] Recreational sales values were obtained from the Fisheries Economics of the United States Reports 2014-2018. Values are reported in 2020 constant dollars, adjusted using the Gross Domestic Product Implicit Price Deflator (2012=100).

[3] States included in the NA include: Maine, New Hampshire, Massachusetts, Rhode Island, and Connecticut; MA states include: New York, New Jersey, Delaware, Maryland, and Virginia; and SA states include: North Carolina, South Carolina, Georgia, and East Florida.

[4] The MRIP query tool is accessible at https://www.fisheries.noaa.gov/data-tools/recreational-fisheries-statistics-queries

The number of directed[5] recreational bluefish trips off the Atlantic Coast were consistently low in the last 4 years in the time series relative to the entire 11-year period (Figure 6). The annual number of directed trips from 2010 to 2017 ranges from 4.29-7.86 million trips, with an average of 6.74 million directed trips. From 2018-2021, the number of directed trips ranges from 4.29-5.33 million trips, an average of 5.06 million trips annually.

Over the past decade, recreational bluefish catch has been primarily caught by shore-based fishing efforts or on private/rental boats across the Atlantic Coast (Figure 7). In the NA, about half of the total regional recreational bluefish catch was caught from shore angling (50.4%) and the other half from private/rental boats (46.8%) when averaged over 2010-2021. Shore based activities resulted in 65.9% of total annual MA recreational bluefish catch and 31.5% of catch came from private/rental boats. In the SA, an average of 84% of annual recreational bluefish catch resulted from shore angling and 15% came from private/rental boats. For each region, less than 3.0% of recreational bluefish catch resulted from charter boats (2.51%, 1.70% and 0.61% for NA, MA and SA, respectively) and less than 1% resulted from party boat activities (0.35%, 0.89% and n.a. for NA, MA and SA, respectively), when averaged over 2010-2021. In 2020, 863 party/charter permits were issued for bluefish, and 258 vessels reported landing bluefish (Bluefish Fisheries Information Document, 2021).

The season in which the most bluefish are caught recreationally differs across the regions (Figure 8). The majority of annual recreational bluefish is caught in July/August for both the NA and MA (NA: 48.5% and MA: 40.0% when averaged over 2010-2021). Another large proportion of annual bluefish catch is caught in September/October for both regions, with an average of 41.0% and 34.9% of average annual bluefish in the NA and MA, respectively. May/June shows a slightly higher proportion of catch in the MA (19.0%) relative to the NA (9.3%), on average. In the NA and MA, the lowest proportions of bluefish are caught in November/December (NA: 1.3% and MA: 3.2%) and March/April (NA: 0.1% and MA: 3.8%); recreational catch is not reported in the NA and MA in January/February. The South Atlantic (SA) is more even in its distribution of annual bluefish catch proportions across months and does not follow the same temporal catch trends as the other two regions. In the SA, about 24% of recreational bluefish are caught in March/April, followed by November/December (20.5%), September/October (20.2%), May/June (18.1%), January/February (10.3%) and July/August (8.1%).

In 2010, bluefish catch comprised 10.3% of total recreational catch when averaged over the 3 Atlantic coastal regions (NA:11.7%, MA: 8.5% SA: 10.7%), which decreased to an average of 4.3% in 2021 (NA:3.8%, MA: 3.6% SA: 5.5%) (Figure 9). Further analysis would be required to determine the drivers of this decline; management could be a contributing factor, as the Acceptable Biological Catch of bluefish has decreased by approximately 50% between 2010 and 2021. Overall, the North Atlantic had the highest average proportion of bluefish when averaged over the entire time series with 7.5% of total recreational catch, closely followed by the MA and (7.0%) and the SA (6.5%).

On the state level, there is variation in recreational bluefish catch as a percentage of total recreational catch (Figure 10). Connecticut had the highest average percentage of bluefish catch relative to other species (13.5% of recreational catch), which is driven by the highest inter-

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[5] Here, directed trips refers to the primary target species in the MRIP data which provides an effort estimate for all trips on which an angler identified bluefish as their primary target.

annual state maximum of bluefish catch as a percent of total recreational catch (29.8%) in 2011. When assessing median percent bluefish catch, Connecticut had the third highest catch (9.6%), surpassed only by New Jersey (10.9%) and North Carolina (11.0%). Georgia, Maine, and New Hampshire had the lowest mean and median percentages of recreational bluefish catch, with median values of 1.2%, 0.7% and 0.2% and means of 1.1%, 0.1% and 0.1%, for each state, respectively.

Commercial fishery

The commercial bluefish fishery is less substantial in comparison to the recreational sector. Bluefish meat does not transport well due to quick spoilage, which makes bluefish a less commercially viable product (ASMFC, 2019). The commercial sector is allocated 14% of the total catch, with each state allocated a proportional quota based on historical landings between 2009-2018 and a minimum state quota of 0.1% of the total commercial catch (Amendment 7 to the Interstate Fishery Management Plan for Bluefish, 2021).

The Bluefish Fisheries Information Document (2022) provides information about the state of the commercial fishery in 2021. In 2021, 2,291 commercial federal permits were issued for bluefish, and dealer reports identified 248 vessels that landed bluefish (Bluefish Fisheries Information Document, 2022). There were 141 federal dealers that were permitted to buy bluefish, and 119 of those dealers reported buying blufish (Bluefish Fisheries Information Document, 2022). Commercial bluefish landings were caught by gillnet (59%), otter trawl/bottom trawl (7%), handline (5%), and unknown or other gear (26%) (Bluefish Fisheries Information Document, 2022). In 2021, 2.07 million pounds of bluefish were landed in the commercial fishery. Across states, 2021 commercial landings were the highest in North Carolina with 0.85 million pounds of bluefish landed, followed by New York at 0.32 million pounds and Rhode Island at 0.25 million pounds. Maine, New Hampshire, South Carolina, and Georgia did not land any bluefish commercially. The top port for commercial bluefish landings was Wanchese, NC, which landed 17% of commercial bluefish, followed by Hatteras, NC (15%), Port Judith, RI (10%), Montauk, NY (7%), Point Pleasant, NJ (6%), and Boston, MA (6%). No other ports landed more than 5% of commercial bluefish landings (i.e., more than 100,000 pounds). A small number of vessels were responsible for the landings at the two North Carolina ports, resulting in average landings per vessel of more than 20,000 pounds. In contrast, the more northern ports reported landings from more vessels, with average landings per vessel being between 2,000 and 10,000 pounds.Total ex-vessel value of bluefish were $1.94 million in 2021, and has ranged between approximately $2-3.5 million per year from 1996 to present. Bluefish revenue accounted for less than 1% of all commercial fishery revenues along the Atlantic coast in 2021.

Additional commercial economic metrics dating from 2004 to 2021 developed by the Social Sciences Branch of the Northeast Fisheries Science Center provide additional context for the commercial bluefish fishery.[6] These analyses used dealer data in combination with vessel trip reports to identify trips that targeted bluefish and to develop additional metrics associated with those trips. Because this analysis was more selective in assigning a vessel to the bluefish fishery, these metrics differ from those presented in the Fisheries Information Document. The metrics suggest that 2018 through 2021 had the lowest number of vessels and trips participating

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[6] See https://apps-nefsc.fisheries.noaa.gov/socialsci/pm/index.php/programs/3

in the commercial bluefish fishery. Between 2018 and 2021, 95-115 vessels participated each year, down from 155-197 vessels participating per year in previous years (2004-2017). There were 477-814 total trips per year, down from 1,130-1,308 trips per year in previous years. Days at sea are also at a series low in 2018-2021, with 149-240 days at sea, down from 341-533 days at sea in earlier years. Total commercial bluefish revenues have been at a series low during 2018-2021, with an average of $430k cumulative bluefish revenues per year.[7] In prior years, total bluefish revenues ranged from $682k - $1.4M per year. In contrast, the past four years have had the highest time series ex-vessel bluefish prices, ranging from $0.99 - $1.17 per pound. In years prior to 2018, bluefish ex-vessel prices ranged from $0.42-$0.94 per pound. Bluefish revenue per vessel was the lowest in the time series in 2021 at $3,750, while revenue per trip and day at sea were close to the time series low at $778 per trip, and $2,500 per day at sea in 2021.

Diet analysis

Methods

Northeast Fisheries Science Center (NEFSC)

NEFSC bottom-trawl sampling occurs twice annually in the spring (March-May) and fall (September-November). The survey area encompasses about 293,000 square km of continental shelf from Cape Hatteras, NC, to Nova Scotia, Canada in depths from 8-400 m. Food habits sampling has been conducted since 1973, and bluefish have been collected as a "secondary" priority species from 1977-1980 and from 1985-present (Smith and Link, 2010). Bluefish stomachs are collected in small (<30 cm), medium (31-70 cm), and large (>70 cm) size strata. Over 4,500 bluefish stomachs have been collected to date from over 1,400 survey tows. Predator length ranged in size from 3 to 118 cm. Stomachs are collected at sea by NEFSC, and have been primarily analyzed at sea since 1981. Total stomach volume is estimated, each prey item is identified and sorted to the lowest possible taxonomic level, and the proportion of each prey item is estimated. Detailed methods are described in Link and Almeida (2000).

In this analysis, we examined data for the entire Northeast US shelf. Bluefish diet was evaluated in 10 year blocks across all seasons, regions, and size classes of bluefish. Data was acquired from the NEFSC Diet Data shiny app, Fish Trophic Ecology of the Northeast U.S. Continental Shelf, by Smith B.E. & Rowe S., dated 9/20/2021. These data were pulled 7 October 2021 and were saved in the datfromshiny folder in this repository.

Prey composition percent by weight[8] was calculated using a weighted mean ($\underline{w_{ijs}}$) (Link and Almeida, 2000) to estimate mean weight of prey i in predator j for statistical group s:

$$(1)\ \underline{w_{ijs}} = \frac{\sum_{t=1}^{N_{ts}} N_{jts}\underline{\underline{w_{ijts}}}}{N_{ts}}$$

[7] All monetary values in this section are presented in 2020 constant U.S. dollars, adjusted using the GDP implicit price deflator.

[8] Prey volumes are used as proxies for prey weight.

where t represents an individual bottom trawl tow, N_{jts} is the number of predator j stomachs in tow t for statistical group s, N_{ts} is the number of tows in statistical group s, and

$$(2)\ \underline{w_{ijts}} = \frac{\sum_{k=1}^{N_{jts}} \underline{\underline{w_{ijtsk}}}}{N_{jts}}$$

Virginia Institute of Marine Science (VIMS) – NEAMAP & ChesMMAP

The Virginia Institute of Marine Science (VIMS) conducts two fishery-independent bottom trawl surveys; namely, the Chesapeake Bay Multispecies Monitoring and Assessment Program (ChesMMAP) and Northeast Area Monitoring and Assessment Program, Mid-Atlantic/Southern New England (NEAMAP M-A/SNE) Trawl Surveys. Both programs are designed as multispecies surveys and collect bluefish for diet analysis, and other biological data, throughout their spatial and temporal ranges. ChesMMAP samples the main stem of the Chesapeake Bay from Poole's Island, MD to the Virginian Capes, and collects bluefish from throughout the bay during the May, July, September, and November cruises, which reflects the temporal residency of this species in the estuary. The ChesMMAP Trawl Survey has been sampling the Chesapeake Bay since 2002. NEAMAP has been sampling the nearshore waters of the Mid-Atlantic Bight and Southern New England since the fall of 2007. This survey conducts two cruises per year, one in the spring and one in the fall, mirroring the efforts of the NEFSC Bottom Trawl Survey offshore. Sampling occurs from Martha's Vineyard, MA, to Cape Hatteras, NC, and between the 18m and 36m depth contours to the north and east of Montauk, NY, and the 6m and 18m contours to the south and west. The offshore extent of the NEAMAP effort aligns with the inshore extent of the NEFSC survey. Bluefish are collected throughout the sampling area in both the spring and fall cruises.

Bluefish stomach samples collected at sea by ChesMMAP and NEAMAP are labeled and preserved in Normalin®. Processing occurs at the shore-based laboratories at VIMS. Stomach samples for both surveys were analyzed according to standard procedures (Hyslop 1980). Specifically, each stomach was individually weighed (±0.001 g), the contents were emptied, the empty stomach was weighed, and all prey items were identified to the lowest possible taxonomic level. Each prey item was then enumerated, weighed (±0.001 g), and individual length measurements (±0.1mm) were taken when possible.

It is well known that fishes distribute in temporally and spatially varying aggregations. The biological and ecological characteristics of a particular fish species collected by fishery-independent sampling activities inevitably reflect this underlying spatio-temporal structure. Intuitively, it follows then that the diets (and other biological parameters) of individuals captured by a single gear deployment (e.g., ChesMMAP or NEAMAP tow) will be more similar to one another than to the diets of individuals captured at a different time or location (Bogstad et al. 1995).

Under this assumption, the diet indices percent by weight (%W) and percent by number (%N) for bluefish can be represented using a cluster sampling estimator since trawl collections essentially yield a cluster (or clusters if multiple size groups are sampled) of the species at each sampling site. The equation for $\%W$ of prey type k is given by (Bogstad et al. 1995, Buckel et al. 1999):

$$(3)\ \%W_k = \frac{\sum_{i=1}^{n} M_i q_{ik}}{\sum_{i=1}^{n} Mi} * 100$$

where

$$(4)\ q_{ik} = \frac{w_{ik}}{w_i}$$

and where n is the total number of clusters collected of the fish species of interest, M_i is the number of that species collected in cluster i, w_i is the total weight of all prey items encountered in the stomachs of the fish collected and processed from cluster i, and w_{ik} is the total weight of prey type k in these stomachs. Estimation of $\%N_k$ uses the same equation by replacing the biomass values with count data. These cluster estimators were used to quantify the diet compositions of the bluefish collected by NEAMAP and ChesMMAP. While the diet descriptions provided reflect a combination of data collected across years for each survey, presentations of diet by sub-area, year, cruise, size, age, etc., are possible.

Results

NEFSC

The proportion of empty stomachs ranged from 20-40% in the ten year blocks. In each ten year period, around 60-70 bluefish prey items were identified. Anchovies are significant prey of bluefish across all time periods, as are butterfish and squids (Figure 11). Other prey have varying importance across time, including sandlances, herrings, bluefish, and scup (which has increased in the past two decades). Drums have also recently increased in bluefish diets. Figure 11 shows changes in prey categories by decade for bluefish from the NEFSC diet database, as updated from the 2015 SAW 60 Working Paper.[9] Supplemental figures and tables with bluefish diet overall, by season, by region, and by size category from the NEFSC diet database are available at the end of this document and online.

There were relatively few records of bluefish as prey. From 1973-2020, 42 bluefish were identified as prey in fish sampled for diet. Of these, bluefish were themselves the most common bluefish predator, accounting for 52.4% of all observed bluefish consumption.

NEAMAP

The number of bluefish sampled annually for diet analysis has ranged from 403 to 666 specimens, covering the 6.5 to 78.5 cm FL size range (Figure 12). Prey from a total of 3,362 bluefish stomachs have been analyzed (Figure 13). Overall, NEAMAP staff encountered 86 prey types in the 2,379 bluefish stomachs that contained prey to date. Diet composition by weight and by number were similar. Fishes were the main bluefish prey in the nearshore waters of the Mid-Atlantic and Southern New England regions (Figure 13), comprising >96% of bluefish diet by weight and 92.6% of bluefish diet by number. Bay anchovy (53.9%W), butterfish (7.4%W), and striped anchovy (6.2%W) accounted for the bulk of the prey consumed. For the invertebrates, the longfin inshore squid was the main identifiable prey type. Invertebrates were

[9] For interactive plots with downloadable tables, please see https://sgaichas.github.io/bluefishdiet/DietSummary.htm

slightly more important in the bluefish diet using %N, likely due the large numbers of small-bodied invertebrates (e.g., crab megalope and mysid shrimps) that were encountered on several occasions.

ChesMMAP

Sample sizes for diet from ChesMMAP have ranged from 8 to 74 bluefish annually, and fish from 11.9 to 53.7 cm FL (Figure 14) were collected. A total of 443 bluefish have been sampled and analyzed for diet from this survey since 2002, and 54.0% of these have had prey items in their stomach. Although sample size and the size-distribution of bluefish are somewhat small, this survey likely provides a useful representation of the diet composition of bluefish in Chesapeake Bay, as large bluefish have been absent from the Chesapeake for several decades.

ChesMMAP scientists have analyzed 455 bluefish stomachs to date. Fishes again dominated the diet of bluefish collected from Chesapeake Bay (Figure 15), and diet composition by weight and by number were similar. Fishes comprised approximately 87.7% of the bluefish diet by weight and 84.6% of bluefish diet by number. Bay anchovy (39.9%W), spot (18.8%W), and Atlantic menhaden (9.1%W) accounted for the bulk of the fishes consumed by bluefish. Silver perch and weakfish each accounted for 2.4% of the diet by weight. Of the invertebrates, the mysid shrimp was the main identifiable prey type. Invertebrates accounted for 13.7% of bluefish diet by count. The remainder of bluefish diet was unidentifiable items.

Summary

Overall, the diet of bluefish both in the Chesapeake Bay and the coastal ocean, from Cape Cod to Cape Hatteras, is dominated by fishes, regardless of the index by which the diet is quantified. These findings correspond with those of past studies that have sought to characterize bluefish diet in estuarine and ocean environments. In particular, diets collected and analyzed as part of the South Carolina Department of Natural Resources (SCDNR) Southeast Area Monitoring and Assessment Program (SEAMAP-SA) identified 49 different types of bluefish prey between 2011 and 2013, with the majority being fishes (93.5%W), including anchovies (49.8%W), Atlantic bumper (3.2%W), and sciaenid fishes (1.2%W). Penaeid shrimp, loliginid squids and cubozoan jellyfish contributed in highest proportions among the invertebrates. A full summary of SEAMAP-SA bluefish diet was reported in the 2015 benchmark assessment, but could not be updated in the present assessment as funding for SEAMAP-SA diet analysis ended in 2015 (K Spanik (SC-DNR), pers. comm., August 2021).

Environmental, distribution, and cohort analyses

Methods

Existing state and federal survey data was analyzed to better understand bluefish distribution, environmental conditions, and YOY cohorts. Bluefish presence/absence in these surveys, as well as MRIP catch data, was analyzed to infer the regions where bluefish were present over the course of the year.

MRIP catch data (in numbers) was assessed to better understand seasonal bluefish distributions. We present recreational catch and catch per unit effort (CPUE) information collected in two-month waves by the MRIP program. Estimated catch data by state and wave is provided by MRIP. The mean proportion of coastwide catch by state and MRIP wave was determined for East Coast states from Maine to Florida. Catch per trip was calculated but rejected as a metric of abundance because the directed trip information provided by MRIP did not include estimates of length of trip, which may vary over time. Instead, mean predicted catch per unit effort (CPUE) was calculated by state and by wave using the generalized linear model that had been created to standardize the MRIP data (see Working Paper 13 Drew 2022d).

Several state and federal surveys collect environmental data, which were assessed to determine the environmental conditions at which bluefish were most commonly found. Summary statistics of temperature, salinity, and dissolved oxygen (mean, median, standard deviation, minimum, maximum, 2.5% quantile, and 97.5% quantile) were analyzed on three groups of data: sites where bluefish were not captured, sites where bluefish were captured, and sites where bluefish were captured, weighted by the number of bluefish observed. Summary statistics were calculated for each set of data from each survey within each state for all months that had more than 10 recorded sampling events over the time series.

Bluefish distribution in multiple federal surveys was mapped by month. Egg data from 1977-1987 was collected in the Marine Resources Monitoring, Assessment and Prediction (MARMAP) program, and additional data was collected in 1993 by the Ecosystem Monitoring program (EcoMon). Larval data has been collected every year since 1977 in a combination of surveys, including the Herring and Sand Lance Program (1988-1994), Georges Bank Global Ocean Ecosystems Dynamics (1995-1999), MARMAP (1977-1987), and EcoMon (1992 – present). Juvenile and adult data is collected in the NMFS bottom trawl survey, which has sampled most years since 1963, primarily in the spring and fall, but also occasionally in summer and winter. Bluefish were classified in three size groups: small fish were up to 30.3cm, medium fish were between 30.3cm and 50.0cm, and large fish were 50.0cm or larger. The 30.3cm cutoff represents the mean size at age 1 from the empirical life history data, while the 50.0cm cutoff represents the mean size at age 3; fish ages 3 and older are fully sexually mature. For each survey, the total number of individuals observed in each month was divided by the number of tows in that month to determine the mean number per tow. All of these surveys have environmental data for some (but not all) of their samples. When temperature and salinity data was available, the mean temperature and salinity were calculated, weighted by the total number of fish in each observation.

Length density data of small bluefish was visually assessed to determine whether multiple young-of-the-year cohorts were visible in state and federal surveys.

Results

Eggs

Egg distribution is shown in Figure 16. Out of the twelve years of egg surveys, bluefish eggs were only collected in two tows in May, both of which were taken off the coast of North Carolina.

In June, bluefish eggs were observed in four out of ten years of data collection. Eggs were found between North Carolina and New Jersey.

The highest abundance of eggs was observed in July, with eggs collected in eight out of 11 years. The geographic range of the eggs extended north to Southern New England.

Eggs were also observed throughout the MAB in August in eight out of 11 years, although the total abundance of eggs was lower than that observed in July.

No eggs were found in any other months. Bluefish eggs were found at mean surface temperatures of 20-24°C (range 17-28°C), with warmer temperatures occurring in August (Table 1). Mean salinities were 31-33 (range 30-35) (Table 1). A lack of egg surveys from the 1990s to present means that recent data is not available.

Larvae

Larval distribution is shown in Figure 17, with summaries in Table 2. Bluefish larval data has been collected on the east coast since 1977, with variation in the areas and months surveyed each year; notably, most South Atlantic Bight samples were taken in the 1980s. The month of first observation of bluefish larvae is variable by year, due at least partly to the differing sampling months over time, but the first observation of bluefish larvae tends to be recorded in May, June, or July. Every year that the first larva observation occurred in August was missing sampling in July, and the one year when the first larva was observed in September did not have sampling in August. Additionally, the limited sampling in the SAB may further obscure conclusions about the timing of the spawning season. Only one year contained observations of bluefish larvae in April (out of 26 years with April sampling), when 13 tows collected bluefish larvae off of North Carolina, South Carolina, and Florida. In May, 11 out of 38 years of sampling recorded observations of bluefish larvae in the MAB and SAB. Bluefish larvae were found in the MAB in June in 17 out of 34 years, with some being found as far north as Massachusetts Bay in 2010 and 2011. By far, the highest abundance of bluefish larvae was observed in July, despite July having the fewest years of sampling, with 17 out of 21 years of sampling containing bluefish larvae. Bluefish larvae were also widely distributed in the MAB in August, and 27 out of 31 years contained observations of larvae, although the total number of larvae recorded in August was lower than the number recorded in July. There are a small number of observations of bluefish larvae on Georges Bank in July and August, indicating potential spawning in this region. Additionally, both July and August have sparse sampling in several years, limiting the inferences that can be made about bluefish spawning. Bluefish larvae are consistently observed in September, but at much lower abundances, appearing in 19 out of 42 years. Bluefish larvae were observed off the coast of Cape Hatteras in one tow in January 1986.

A decrease in mean larval size was observed from July to August and could indicate the presence of a late summer cohort. However, further analysis would be needed to determine whether this decrease is attributable to a consistent influx of smaller larvae in August of each year, or whether it may simply reflect larval arrival being delayed in some years. The mean temperature at which bluefish larvae have been found ranges from 22-25°C depending on the month, with August being the warmest month and May being the coolest (range 8-28°C) (Table 2). Mean salinities are 31-32 (range 25-36) (Table 2).

Juveniles and adults

MRIP

Maine and New Hampshire have a very low amount of catch year-round, although unstandardized CPUE is slightly higher in May through October compared to other months (Figure 18). Massachusetts, Rhode Island, and Connecticut all show a domed pattern with higher catch, proportion of coastwide catch, unstandardized CPUE, and standardized CPUE in May through October compared to other months (Figure 18).

The Mid Atlantic states of New York, Delaware, Maryland, and Virginia show similar domed patterns in the MRIP data, with higher catch, proportion of coastwide catch, unstandardized CPUE, and standardized CPUE in May through October compared to other months (Figure 19). New Jersey has a slightly different pattern in both standardized and unstandardized CPUE, with values being mostly linear and generally higher than the values in the other states throughout the year (Figure 19).

The southern states of North Carolina, South Carolina, Georgia, and Florida show roughly opposite trends compared to the Northern and Mid Atlantic states. All of the southern states have low standardized and unstandardized CPUEs in July/August, with higher CPUEs in the other months (Figure 20). Florida has the largest proportion of coastwide catch in November through April, with North Carolina at a distant second (Figure 20).

This catch data qualitatively supports the seasonal migration from southern locations in cold months to northern locations in warmer months that has been documented in bluefish literature.

NMFS bottom trawl

Juvenile and adult bluefish are sampled in the NMFS bottom trawl, which has been running since 1963. March, September, and October are the months with the most consistent sampling, but some data has been collected in all months of the year.

The monthly distributions of small bluefish 30.3cm in length and smaller are illustrated in Figure 21. 30.3cm is the mean length of an age 1 bluefish. Bluefish under this length were recorded off the coast of North Carolina in December and in February through May (no observations were recorded in January, a month with limited sampling). June had very limited sampling. In July through November, samples of these small bluefish were recorded from Massachusetts down to the southernmost point of the survey (which ranged from Florida to North Carolina, depending on month). By far the most small bluefish were recorded in September and October. The mean temperature at which small bluefish have been found ranges from 12-26°C depending on the month, with July being the warmest month and March being the coolest (range 6-30°C) (Table 3). Mean salinities are 31-35 (range 22-36) (Table 3).

The monthly distributions of medium bluefish between 30.3-50.0 cm in length are illustrated in Figure 22. Medium sized bluefish between 30.3cm and 50.0cm (mean length at age 3) followed similar distribution patterns to small bluefish, with some nuanced differences. In March, medium bluefish were found more along the shelf break, compared to the small bluefish, which were found spanning the range between the shelf break and the coast. In September and October, more medium bluefish were found on Georges Bank compared to the small bluefish, which were closer to the coast. The mean temperature at which medium bluefish have been found ranges from 8-26°C depending on the month, with July being the warmest month and April being the coolest (range 6-29°C) (Table 4). Mean salinities are 31-34 (range 20-37) (Table 4).

The monthly distributions of large bluefish 50.0cm in length and larger are illustrated in Figure 23. Large bluefish above 50.0cm in length are typically fully mature. These fish exhibited a different distributional pattern compared to the small and medium bluefish. January, May, June, and December all had few or no observations of large bluefish, likely resulting from the limited amounts of sampling in these months together with the difficulties associated with capturing large bluefish with trawl gear. In February and March, large bluefish were observed near the shelf break in the Mid Atlantic Bight. In July through November, large bluefish were observed along the coast between Maryland and Cape Cod, as well as on Georges Bank. In October, large bluefish were also observed in Massachusetts Bay. The mean temperature at which large bluefish have been found ranges from 10-22°C depending on the month, with May through September being similar in warmth and February being the coolest month (range 6-26°C) (Table 5). Mean salinities are 32-34 (range 28-36) (Table 5).

The overall length distributions of bluefish in the NMFS bottom trawl are illustrated in Figure 24. Some bluefish have been observed in all months except January. Fish observed in February are approximately 30-60cm. In March, there are peaks in observations of fish 15-30cm and 35-50cm, as well as several larger fish also observed. April is similar to March, with more fish under 15cm observed. There are very few observations in May and June. In July and August, there is a peak in fish under 15cm and in fish around 20cm, as well as some larger fish above 50cm. September and October are the months with the most frequent sampling, with bluefish of all sizes observed. The largest peaks in abundance occur around 10cm and 20cm, although there are also many fish larger than 30cm. November also shows a similar pattern, although with fewer fish observed, and only a small number of fish have been observed in December. These results are undoubtedly affected by the survey effort in each month, with March, September, and October having the highest number of cruises.

State surveys

Here we summarize when and where bluefish of various sizes have been observed in state scientific surveys. However, it is important to note that a lack of observations of bluefish in a particular survey does not confirm an absence of bluefish in that region at that time of year. Bluefish data was aggregated by state and survey program. Only state-programs with more than 20 fish observed over 3 or more years are considered as a reliable "bluefish observation" programs and described here.

New Hampshire collects bluefish length data in one program, the Juvenile Finfish Survey, which has sampled every year since 1997 and has recorded bluefish in eight of those years. New Hampshire catches a small number of bluefish under 25cm in length. The first bluefish of the season, which are generally under 5cm in length, may be caught as early as June in some years (Figure 25). More bluefish of approximately 5-15cm in length are caught in July and August in some years (Figure 25), suggesting an influx of recently spawned fish from a spring cohort. In September and October 2018, fish under 10cm were observed (Figure 25), suggesting the recruitment of recently spawned fish (i.e., a summer cohort). These New Hampshire bluefish support the existence of a summer-into-fall cohort spawned in August and September.

Massachusetts bluefish length data is collected in three programs: the Massachusetts inshore bottom trawl survey, federal port sampling, and the Sportfish Angler Data Collection Team (volunteer recreational anglers). The majority of bluefish in Massachusetts were caught by the bottom trawl survey in September, which has been running since 1978 (Figure 26). These fish are generally under 25cm in length, with a peak around 10cm (Figure 26), and most are taken south of Cape Cod in Buzzards Bay and Nantucket Sound. These fish likely represent a late summer cohort of bluefish spawned in August. The port sampling and volunteer angler data, collected in April through October, generally shows a peak in fish approximately 35-75cm (Figure 26). State volunteer angler reporting for bluefish began in 2021, and federal port sampling began in 2013.

Rhode Island bluefish length data is collected in three programs: NEAMAP, port sampling, and the RI Department of Marine Fisheries survey. Federal port sampling is the only method that collects fish in every month, and it is the only program to record fish in December through April (Figure 27). Port sampled fish are usually 32-75cm; no bluefish under 32cm length are recorded in port samples (Figure 27). In some years, the RI survey shows a peak in bluefish under 15cm length in June or July, and NEAMAP shows a peak of bluefish between 10-25cm in September and October (Figure 27). Bluefish between 40-80cm are seen in the RI survey in May through December (Figure 27).

Connecticut bluefish length data is collected in four programs: the Long Island Sound Trawl Survey (LISTS), and three recreational angler data collection programs. Connecticut records the most bluefish in September and October in the LISTS (Figure 28), which has been running since 1984. In these months, there are sometimes two peaks in length frequency, one under 25cm, and one between 40-50cm (Figure 28). In October, more fish larger than 60cm are also observed (Figure 28). The LISTS also has recorded fish in May through August and in November in several years; most of these are larger than 30cm (Figure 28). There is a small peak in fish 50-60cm in June and a small peak in fish 35-50cm in August (Figure 28). Bluefish under 32cm length are recorded only in the Long Island Sound Trawl Survey (Figure 28). Recreational fishery samples were only recorded in June 2012-2014 and showed fish around 40-60cm (Figure 28). The Black Hawk recreational program recorded bluefish around 40-60cm in June 2015 and 2016, in September 2021, and in October 2016, 2018, and 2021 (Figure 27).

New York bluefish length data is collected in five programs: NEAMAP (2007 - present), federal port sampling (1985 - present), the NYS DEC fishery dependent sampling program (2012 - present), the Peconic Bay small mesh trawl survey (1987 - present), and the Western Long Island seine survey (1986 - present). Only port samples were recorded in December through March in a few years, most of which were 25-55cm (Figure 29). In April, the NYS fishery dependent sampling program also recorded bluefish in the same length range as the federal port sampling program, approximately 30cm and larger (Figure 29). Bluefish under 25cm in length are observed sometimes starting as early as May in the Western Long Island Sound survey, with increasing numbers typically observed in June in both the Western Long Island and Peconic Bay surveys and persisting through July, August, September, and October (Figure 29). The NEAMAP survey also observes bluefish in the 10-20cm size range in October (Figure 29). Many of these small fish are taken in coastal regions both on the north and south shores of Long Island, such as Hempstead Harbor, Jamaica Bay, Little Neck Bay, Manhasset Bay, and Oyster Bay. Larger bluefish are also observed in New York. There is also a peak in fish 32-75cm in length in several months, mostly coming from federal and state port sampling (Figure 29). NEAMAP has also collected a few larger fish in this size range (Figure 29).

New Jersey bluefish length data is collected in three programs: state biological sampling (2010 - present), NEAMAP (2007 - present), and NMFS port sampling (1985 - present). In January through March, most samples come from the port sampling program, with a small number of biological samples taken in January. These winter fish are generally 32-75cm (Figure 30). In April through November, the biological sampling program collects bluefish, sometimes with bimodal peaks around 35 and 70cm (Figure 30). Relatively few fish under 32cm are recorded. New Jersey observes the most bluefish under 25cm in October, when the NEAMAP survey records data (Figure 30). The lack of observations of smaller fish may be due to the sampling methods used and the survey timing.

Delaware bluefish length data is only collected by NEAMAP (2007 - present), which typically samples during May and October. There is a peak in observed numbers around 15-25cm in some years in May and in most years in October (Figure 31). No fish over 32cm are observed, although fish around 30cm length are more often observed in October rather than May.

Maryland bluefish length data is collected in two programs: ChesMMAP (2002 - present) and NEAMAP (2007 - present). ChesMMAP recorded fish between 10-40cm in some years May through September and in November, although the total number of fish was very small (Figure 31). NEAMAP recorded fish in May, October, and some Novembers, showing a small peak in fish 15-25cm in May, and a relatively larger peak in October (Figure 32). Few fish above 32cm are observed.

Virginia bluefish length data is collected in four programs: ChesMMAP (2002 - present), NEAMAP (2007 - present), federal port sampling (1985 - present), and the VMRC program (1999 - present). Only the VMRC program recorded samples in all months of the year. ChesMMAP and NEAMAP both showed a peak in fish 10-30cm in the months they collected data, which typically included May, October (NEAMAP only), and November (Figure 33). A peak in fish 15-32cm was seen in the VMRC data in April through October, with some larger fish above 50cm length also observed (Figure 33). Fish larger than 32cm were typically more numerous in November and December in the VMRC data, although in some years larger fish were also relatively abundant in May and June (Figure 33).

North Carolina bluefish data is collected by three programs: state ageing samples (1983 - 2000, 2006 - present), NEAMAP (2007 - present), and the South Carolina DNR coastal trawl SEAMAP survey (2002 - 2010). Bluefish are observed in all months in North Carolina, and the state ageing samples typically show a peak around 30cm length, along with several larger bluefish in many years. A peak in fish 10-20cm is seen in April in the SCDNR SEAMAP survey and this peak is also seen to a lesser extent in NEAMAP (Figure 34). The SCDNR SEAMAP survey also recorded additional small bluefish in July (Figure 34). Both NEAMAP and the SCDNR SEAMAP survey show a peak between 10-25cm in October and November (Figure 34).

South Carolina data comes from the South Carolina Department of Natural Resources (SCDNR) SEAMAP survey (1984 - present), which utilizes several capture methods, including trawls and recreational tournaments. Some fish are observed in all months. South Carolina records some fish under 20cm starting in April in some years (Figure 35), with a peak around 15cm, which are mostly recorded in the coastal trawl. This peak of smaller bluefish is also seen in May, June and July in some years. There is a peak in fish 30cm and larger in July through December and January through March. Few fish above 50cm are observed.

Georgia bluefish length data is recorded only in the SCDNR coastal trawl SEAMAP survey (1999 - 2010), which recorded bluefish observations in April through August, October, and November (Figure 36). There was a peak in fish under 30cm in April and May. Few fish were observed in July, but the fish observed were around 20-30cm in length. A peak in fish around 20-32cm was seen in October. No fish over 32cm are observed.

Florida bluefish length data is collected in many programs: FIN-BIOSTAT (2000 - 2006), HB Biostat (2005 - 2016), HB survey (1981 - 2019), MRFSS (2000 - 2004), the SCDNR coastal trawl SEAMAP survey (2002 - 2010), SEAMAP (2011 - present), and TIP (1986 - present). Bluefish are recorded in all months. In the 1980s, the HB survey recorded a peak in fish around 75cm in March and April. In the 1990s, the HB survey and the TIP program both recorded fish around 25-60cm, mostly in September through April. In nearly every month of the 2000s, all programs reporting samples recorded fish around 25-60cm; July samples came from the SCDNR SEAMAP survey (Figure 37). In the 2010s, programs recorded fish around 25-60cm in September through May.

Cohort timing

Based on the length distributions of bluefish observed in the state surveys, there is qualitative evidence of prolonged spawning over a wide geographic range, which may be resolved into distinct subannual cohorts. Due to the variable timing and location of sampling across states, a comprehensive quantitative analysis of cohorts is not pursued at this time. We instead summarize when and where small bluefish have been observed as a qualitative step towards understanding potential cohort timing. However, it is important to note that a lack of observations of bluefish in a particular survey does not confirm an absence of bluefish in that region at that time of year. These suggested cohorts need to be verified with otolith analysis to determine the precise dates of spawning.

Bluefish data were aggregated by length group, state, year, and month. Only months with more than 20 bluefish under 30.3cm observed over 3 or more years are considered as a reliable "bluefish observation" and described here. This analysis is more selective than the state survey analyses described above, which aggregated all bluefish length data by state and program to determine sufficient sample sizes.

Fish under 15cm were spawned within approximately the past three months. Therefore, these fish presumably represent a recent subannual cohort of bluefish. These small fish are observed in April in North Carolina (Figure 38), indicating that the first spawning of the year may occur in the SAB and/or southern MAB. In May and June, small bluefish are observed in North Carolina and New York (Figure 38), indicating that spawning has moved northward. Small fish are fairly widespread along the coast for the remainder of the summer, with small bluefish observed in July in North Carolina, New York, and New Hampshire (Figure 38), in August in New York, Massachusetts, and New Hampshire, and in September in all states between New York and New Hampshire (Figure 38). In fall, small fish observations become more sparse again, with small bluefish observed in October in most states between North Carolina and Rhode Island, and in November in North Carolina and Virginia (Figure 38). There are no recorded observations in January, February, March, or December (Figure 38).

Bluefish between 15-30cm have been spawned between three and six months prior. These fish presumably represent older young-of-the-year fish, or age 1 fish spawned at the tail end of the prior calendar year. These medium-small fish are observed in December, January, February, and March in North Carolina and Florida (Figure 38), which likely represents overwintering of fish spawned the prior summer/fall. In April, medium-small fish are observed in every state between Virginia and Florida (Figure 38), indicating a northward movement of the age 1 fish. In May through October, medium-small fish are observed in most states between Massachusetts and Florida (Figure 38). The medium-small fish observed in spring and early summer are most likely age 1 fish spawned the previous summer/fall, while the medium-small fish observed in summer and fall are likely young-of-the-year fish spawned in the current spring/summer. In November, medium-small fish are observed in Virginia, North Carolina, and Florida (Figure 38), indicating a movement southward.

The presence/absence of small bluefish can indicate when and where recently-spawned bluefish are found, but resolving this information into distinct bluefish cohorts, rather than continuous spawning, is more difficult. In order to identify multiple cohorts, there must be clear modality in the lengths of the small bluefish observed. Unfortunately, many surveys only have a few years of data on small bluefish, or may not consistently sample enough bluefish lengths to reliably determine if there is bimodality. In many surveys, observations of small bluefish are too sparse to reliably distinguish potential length cohorts in a given year. MA, RI, and CT only sample bluefish in a limited number of months, and may therefore miss sampling all cohorts. NJ, NC, FL, and the NEFSC bottom trawl do not often catch numerous bluefish under 15cm, although they do catch many fish around 30cm in length, which may be young of the year, but were likely spawned several months or even a year prior. However, there are a few datasets where the size distributions can be followed over the months to resolve the presence and growth of the spring and summer cohorts.

New Hampshire frequently samples small bluefish in the NH Juvenile Finfish Survey. There is no evidence of bimodality in the New Hampshire data, but the growth of the cohort over the season can be clearly seen (Figure 39).

New York consistently samples small bluefish, so the New York data was investigated more closely (Figure 40, 41). The New York data comes from three surveys, the NEAMAP survey, the Peconic Bay Small Mesh Trawl Survey, and the Western Long Island Seine Survey. Length densities were plotted by year and month (Figure 40, 41). Bimodality of lengths is clearly evident in many of the WLISS samples. There is a distinct cohort that appears in June, and a second cohort sometimes appears in August or September (Figure 40). The Peconic Bay survey frequently records slightly larger fish in June compared to the WLISS survey (Figure 41), which may indicate either the presence of an early spring cohort, or these fish may be small age 1 fish that were spawned the previous year.

Small bluefish are also seen in NEAMAP (Figure 42) and SEAMAP (and its precursor the SDNR coastal trawl) (Figure 43). Fish in the 0-10cm length range are not well represented, but fish above 10cm are sampled fairly consistently. NEAMAP and SEAMAP both typically capture bluefish with median length around 15cm in April and May (Figure 42, 43), which likely indicates a spring-spawned cohort. In years with scientific survey sampling through the summer and fall, the median fish length increases over months as the cohort grows (Figure 42, 43). Bimodality is visible in some, but not all, years, and patterns differ by state.

Northern cohorts summary

New York is the only state that consistently observes bluefish less than 5cm. These observations occur in every month between May and August, indicating that bluefish likely spawn at sites near New York in April through July, which would allow the eggs approximately one month to mature into juveniles and travel to the locations where they were observed in May through August. Examination of the length frequencies in the New York data show that the first (spring) cohort likely arrives in May (ex., 2009) or June (ex., 1986), while the second (summer) cohort arrives in August (ex., 1998, 2009) or September (ex. 2020) (Figure 41). Although many years show length bimodality consistent with multiple cohorts, not all years have bimodal length frequencies (ex. 1986) (Figure 40, 41).

Bluefish between 5-15cm length are observed in Massachusetts, Rhode Island, Connecticut, New Jersey, and Maryland in late summer and/or early fall, but there is not enough data to reliably determine whether multiple cohorts are present. Some years do show bimodality (ex., 2013 Connecticut data).

Finally, the data from New Hampshire show that young-of-the-year bluefish recruit to New Hampshire sites in some years. The NH Juvenile Seine Survey has sampled every month between June and November from 1997 to the present. Young-of-the-year under 5cm length were observed in New Hampshire in June in 2012, and slightly larger bluefish (under 10cm) have been found in July and August in New Hampshire in many years (Figure 39). These data suggest that bluefish may become active at spawning sites near New Hampshire in the early summer or even late spring. The NMFS bottom trawl has observed bluefish 50cm+ on Georges Bank between July and October, and these fish could be a potential source of the young-of-the-year observed in New Hampshire. In 2018, no young-of-the-year blufish were recorded in the spring, but fish under 5cm were found in September, indicating that there may be additional spawning sites close to New Hampshire that are active in late summer, as has also been hypothesized by Creaser and Perkins (1994) due to the occurrence of small bluefish in Maine surveys, which were not considered in this assessment.

Southern cohorts summary

Data from southern states (North Carolina and south) are more sparse. Fish under 15cm are found in North Carolina in April through November (Figure 24, 38), broadly indicating the potential for one or more spring/summer cohorts and a fall cohort. However, most years only have one or two months of observations with few fish under 15cm observed in each year, which makes it difficult to determine whether multiple cohorts are present, or if a single cohort has a varying arrival month.

No other southern states record substantial amounts of bluefish under 15cm (Figure 35-37, 43), so it is difficult to determine whether bluefish cohorts recruit to these regions. The most evidence for southern cohorts occurs in the SCDNR data in South Carolina in May and June and in Florida in April and July, when small fish under 15cm are observed in some years. The presence of small bluefish under 30.3cm in southern states, primarily in the spring and fall, may indicate either locally spawned fish or the migration of small bluefish into these regions.

Spring and summer cohorts

Conover et al. (2003) proposed that changes in the relative abundance of the spring-spawned and summer-spawned young-of-the-year bluefish may be important in determining overall bluefish abundance, with lower abundance of the spring-spawned cohort since 1992 being correlated with general population decline. Therefore, we investigated bluefish length data to determine whether spring- and summer-spawned cohorts could be distinguished and whether there has been a change in the relative contribution of each cohort over time.

State survey length data did not yield conclusive information. As discussed above, only New Hampshire, New York, and North Carolina consistently sample bluefish under 15cm, and although multiple cohorts can be distinguished in several years, there is not enough data to support a shift in the relative abundance of each cohort. Furthermore, bluefish growth is fast and variable, generally ranging from 1-2mm/day, which results in a wide range of possible recruitment dates for a bluefish of a given size.

We also investigated the NMFS bottom trawl data (Figure 44), similar to the analysis of Conover et al. (2003). When pooling all samples taken in the fall (September - December), it is true that the shorter length cohort, when present, was relatively less abundant in comparison to the longer length cohort in all years prior to 1992. Between 1992 and 2008, there were seven years where the summer cohort appeared to be equally or more abundant than the spring cohort. However, there were several years both before and after 1992 when there was only one peak in length frequency, meaning that two cohorts were not observed. In unimodal years, the size of the single cohort appeared to align with the size of the spring cohorts of other years in most (but not all) cases. Additionally, in years with sample collection in both September and October, there were sometimes conflicting cohort patterns; for example, in 1980, the spring cohort was more numerous than the summer cohort in September, but the summer cohort was more numerous than the spring cohort in October. In 2003, the opposite pattern was present. When resolved at a monthly timestep, it is apparent that the fall sampling has shifted from occurring primarily in October in the 1970s and 1980s to occurring primarily in September from the 1990s to present. This variation in the timing of sampling further confounds the interpretation of cohort patterns, as it suggests that the relative abundance of spring- and summer-spawned cohorts may change month-to-month.

After 2008, the NMFS bottom trawl survey strata changed to exclude inshore strata, which makes the data post 2008 less representative of the small bluefish length frequencies. The NEAMAP survey continued to collect inshore strata information, and several years of bimodal length cohorts can be seen in the NEAMAP data (Figure 42), although the low sample sizes limit the inference of which cohort may be most numerous.

Lastly, late summer and early fall spawning may be poorly documented in fall surveys taking place in September and October (as many fall surveys do), as the recently-spawned bluefish may be too small to be captured; this further complicates any analysis of annual variations in seasonal bluefish cohort strength.

Environmental conditions

The temperatures at which bluefish were found in the NMFS bottom trawl survey generally reflected seasonal patterns (Tables 6-8). In the winter, bluefish were found at mean temperatures of 10-14°C. In the spring, they were found at the broadest range of mean temperatures, 8-22°C. In the summer, they were found at mean temperatures of 17-26°C, and in fall they were found at mean temperatures of 14-21°C. Medium bluefish were generally found at temperatures 1-3°C colder than small bluefish, and large bluefish were found at temperatures 1-3°C colder than medium bluefish. Mean salinities were between 31-35 ppt.

State survey data showed that there is a geographic component to the temperatures at which bluefish are found, with cooler temperatures observed in the more northern states, especially in fall and winter. In these states with more variable and cooler temperatures, bluefish tended to be found at warmer sites compared to the sites that were surveyed but did not record bluefish. This pattern was evident year-round in New Hampshire, and was also noted in New York and Delaware in winter.

The maximum temperature where a bluefish was found was 33.6°C, and the minimum temperature was 5.6°C. No states recorded more than 10 bluefish sampling events with surface temperature measurements in January and February. In March, North Carolina observed bluefish at 16°C; these sites where bluefish were observed were 3-7°C warmer than sites without bluefish on average. New Jersey conducted surveys with surface temperature measurements in March, but did not sample any bluefish. Data collected from April through November generally covered most states on the Atlantic coast. Bluefish tended to be found at warmer surface temperatures in more southern states, with greater temperature differences between northern states and southern states in spring and fall. Mean surface temperatures where bluefish were found were 10-21°C in April, 13-23°C in May, 17-27°C in June, 22-29°C in July, 23-29°C in August, 20-26°C in September, 16-25°C in October, and 15-22°C in November. In December, North Carolina observed bluefish at 15°C. New Jersey conducted surveys with surface temperature measurements in December but did not record any bluefish sampling events. Bottom temperatures where bluefish were found were generally similar to surface temperatures.

Sites with bluefish in North Carolina, South Carolina, Georgia, and Florida sampled by the SEAMAP program had mean surface salinities of 31-35, regardless of month of sampling. New Jersey sampled in all months of the year with surface salinities consistently 30-32, although bluefish were only observed in April, June, August, and October. Salinities in North Carolina sampling in the Pamlico Sound varied from a low of 18 in April to 20-23 in all other months (except January, which had no sampling). Bottom salinity measurements showed a similar pattern, with the NEAMAP survey consistently sampling saline sites with bottom salinity 31-33 and other surveys sampling less saline sites with salinities of approximately 20. Notably, the New Jersey Delaware Seine Survey sampled several sites with bluefish that had bottom salinities near zero. The Virginia Striped Bass Seine Survey also sampled bluefish at low bottom salinity sites. There were no systematic differences in the salinities at sites with and without blufish that would suggest a salinity preference.

Dissolved oxygen was less variable, with most blufish being found between 5-9 mg/L oxygen. Sites with bluefish had very slightly higher oxygen concentrations in the winter compared to summer and in northern states compared to southern states, reflecting the temperature trends in oxygen saturation.

Indicator analysis

Indicator selection

An in-depth literature review was conducted to inform ecosystem indicators. A literature search on the Web of Science using the terms '*("Pomatomus saltatrix" OR "bluefish") AND ("marin* environ*" OR ecolog* OR plankton* OR ecosystem* OR "estuarin* habitat*" OR "estuarin* nurseri*" OR "estuarin* system*" OR "small* pelag*" OR "surfac* temperatur*" OR "water* column*" OR "abiot* factor*" OR "climat* chang*" OR pollut* OR "advect* process*" OR "aquat* ecosystem*" OR "boundari* current*" OR "dissolv* oxygen*" OR "local* ecolog* knowledg*" OR "physic* factor*" OR "predat* pressur*" OR "trophic* dynam*" OR "water* qualiti*"\))*' and a second more general search of the terms '*("Pomatomus saltatrix" OR "bluefish") AND (Atlantic OR "United States")*' identified 368 relevant papers. Based on content, these papers were narrowed down to 154 papers that were reviewed in depth. Information from the papers was used to develop a conceptual model of the life history of bluefish, which identified the habitat and distribution, phenology, age, length, and growth patterns, energetics, diet, and predators and competitors of each bluefish life stage from egg to adult (Figure 45). The conceptual model was then used to determine relevant ecosystem linkages that could impact bluefish, and these linkages were developed into a list of potential ecosystem indicators. Research recommendations from the prior bluefish assessment were also considered and developed into potential indicators where possible.

Socioeconomic indicators were informed by indicators published in multiple Alaska Stock Assessment and Fishery Evaluation (SAFE) reports (Dorn et al. 2019, Armstrong et al. 2020, Barbeaux et al. 2020, Goethel et al. 2020) and expanded upon by NEFSC Social Sciences Branch economists to capture information relevant for bluefish in the Northeast U.S.. Socioeconomic indicators were split into three main categories: commercial, recreational, and social. In the Alaska ESPs, the primary focus was on commercial indicators, however, the development of recreational indicators was necessary for bluefish due to high recreational participation. The socioeconomic indicators were conceptualized as either an indicator that can directly describe the change in fishing pressure (angler or commercial fishing effort) or as a descriptive indicator of the overall socioeconomic status of the fishery that provides context.

Indicator selection criteria

After reviewing the best practices for indicator development in Rice and Rochet (2015), indicator selection criteria were developed to help the working group conceptualize the value of the proposed indicators and prioritize indicator development. The four criteria were: (1) data quality of the indicator, (2) effort to create the indicator, (3) theoretical basis of the indicator, and (4) interpretability of the indicator. A scoring rubric guided the assessment of each criterion, with qualitative scoring levels. The "low" level was unfavorable, "medium" was neutral, and "high" was favorable. These qualitative scores were further defined for each criterion to guide decision making (Table 6).

A low score for the data quality criterion was defined as, "The data may be inaccurate or imprecise. Data may be missing or cover a sparse spatial or temporal scale. The data is not sufficient for passing peer review." A medium score was defined as, "no major red flags in data," and a high score was defined as, "The data have been collected with peer-reviewed methods and are expected to be accurate and/or precise enough for their purpose. There are no concerns about spatial or temporal data coverage."

A low score for the theoretical basis criterion was defined as, "The literature shows that the indicator has a weak/hard to detect response to the underlying pressure/mechanism." A medium score was defined as, "There is no existing literature information on the indicator, but peer-reviewed literature sources support the inclusion of a similar indicator, or of the same indicator affecting similar species; or, there may be conflicting reports in the literature. Alternatively/ additionally, the indicator may reflect multiple underlying mechanisms (i.e., there are multiple interpretations of indicator change)." A high score for the theoretical basis criterion was defined as, "Multiple peer-reviewed literature sources support the inclusion of this indicator. The indicator has a high/ well-defined response to an underlying pressure. The indicator is a clear reflection of an identifiable mechanistic process (i.e., indicator change has a single/streamlined interpretation)."

A low score for the interpretability criterion was defined as, "An abstract concept that requires detailed explanation; a general audience is not familiar with the indicator." A medium score was defined as, "The indicator represents a familiar concept, but might require explanation to fully understand its utility in the specific context." A high score was defined as, "An intuitive concept; the general audience has heard of the indicator and seen related data before."

Effort differed from the other criteria in that a "low effort" indicator would receive a "high" score according to the scoring rubric. This maintained the definition of a low score being unfavorable and a high score being favorable. Accordingly, an indicator would score "low" on the effort criterion if "The indicator already exists, or can be easily created from existing data." A medium score was defined as, "The indicator could be created from a more detailed analysis of one or more existing data sources," and a high score for the effort criterion was defined as, "the indicator would require extensive calculations, or the collection of new data."

Following the February 2022 data meeting, the working group ranked the scoring criteria from most important to least important: data quality, theoretical basis, effort, and interpretability. These rankings helped guide decisions on how to move forward with indicator creation and prioritization.

Proposed indicators and working group comments

The working group discussed the indicators listed in the following section at the data workshop in February 2022. A follow-up survey was conducted shortly after the workshop to capture working group members' comments on the proposed indicators.

Ecosystem indicators

1. Indicators of distribution
    a. Maximum latitude of bluefish observations in NEFSC bottom trawl
        i. Linkage to bluefish: Proxy for the northern range of bluefish
        ii. Relevance to management: Changes to bluefish distribution could inform state quotas, may impact where and when bluefish spawn, may impact where bluefish are caught
        iii. Rating: neutral to favorable
        iv. Rating rationale: The data is available, and the bottom trawl has good coverage of the northern range of bluefish.
    b. Recreational catch by state
        i. Linkage to bluefish: Bluefish are not well sampled in scientific surveys, so catch data may provide additional context about bluefish distribution
        ii. Relevance to management: Changes to bluefish distribution could inform state quotas, may impact where and when bluefish spawn
        iii. Rating: neutral to favorable
        iv. Rating rationale: Lower scores were given in the interpretability and theoretical basis categories due to the number of confounding variables that could impact catch, such as changes in regulations.
    c. CPUE by state
        i. Linkage to bluefish: The MRIP CPUE index is one of the only measurements of older year classes of bluefish
        ii. Evidence for linkage: N/A
        iii. Relevance to management: The MRIP CPUE index is used to quantify adult bluefish abundance, and therefore any factors other than bluefish abundance that affect this index will affect the assessment and should be taken into account.
        iv. Rating: generally neutral to favorable
        v. Rating rationale: The inclusion of effort was seen as both a potential positive (because it would account for changes in effort) and a negative (because it could be impacted by regulations or other external factors).
    d. Minimum latitude of bluefish observations in NEFSC bottom trawl
        i. Linkage to bluefish: Proxy for the southern range of bluefish
        ii. Relevance to management: Changes to bluefish distribution could inform state quotas, may impact where and when bluefish spawn, may impact where bluefish are caught
        iii. Rating: Ratings were lower than for maximum latitude

        iv. Rating rationale: The southern extent of bluefish range extends farther south than the bottom trawl.

    e. Center of gravity
        i. Linkage to bluefish: Proxy for the midpoint of the range of bluefish
        ii. Relevance to management: Changes to bluefish distribution could inform state quotas, may impact where and when bluefish spawn, and may impact bluefish availability to the fishery and location of catches
        iii. Rating: Neutral to favorable
        iv. Rating rationale: It was mentioned that the catchability of bluefish in the NEFSC bottom trawl is low, which may affect observations.
    f. Assessment of Florida bluefish
        i. Linkage to bluefish: Seasonal sizes of bluefish in Florida may improve understanding of bluefish migrations
        ii. Relevance to management: Seasonal migrations and distribution may impact where and when bluefish spawn, may impact where bluefish are caught
        iii. Rating: Mixed responses
        iv. Rating rationale: There was concern that the size of bluefish caught might not be representative of the sizes of bluefish inhabiting the area.
2. Climate indicators
    a. Date when average MAB surface temperature reaches 18°C
        i. Linkage to bluefish: 18°C has been identified as the lower temperature bound for bluefish spawning. The time when this temperature is reached could affect the length of the spawning season and therefore the number of individuals spawned.
        ii. Evidence for linkage: Norcross et al. 1974
        iii. Relevance to management: Improved estimates of spawning could inform the stock-recruit relationship and improve model performance
        iv. Rating: Mixed responses.
        v. Rating rationale: The spatial scale of the indicator may be too large to see any correlations with young-of-the-year indices, which are more regional.
    b. Location of 22C isotherm in July
        i. Linkage to bluefish: 22°C is the temperature at which spawning peaks. If the isotherm is located seaward of the continental shelf, environmental conditions are not optimal for spawning.
        ii. Evidence for linkage: Norcross et al. 1974
        iii. Relevance to management: Improved estimates of spawning could inform the stock-recruit relationship and improve model performance.
        iv. Rating: Mixed responses.
        v. Rating rationale: As with the MAB temperature indicator, there were concerns that the spatial scale of the indicator may be too large to see any correlations with young-of-the-year indices, which are more regional.
    c. Location of 29ppt isohaline in July

i. Linkage to bluefish: 86% of spawning occurred above 29 ppt. If the isohaline is located seaward of the continental shelf, environmental conditions are not optimal for spawning.
ii. Evidence for linkage: Wilson and Degnbol 2002; Sbragaglia et al. 2020; Sabates et al. 2012.
iii. Relevance to management: In order to estimate abundance indices, we need to know where bluefish are living.
iv. Rating: Mixed responses.
v. Rating rationale: As with the other climate indicators, there were concerns that the spatial scale of the indicator may be too large to see any correlations with young-of-the-year indices, which are more regional.

d. Velocity of winds in April and May
   i. Linkage to bluefish: Winds may help transport larvae and juveniles inshore.
   ii. Evidence for linkage: Norcross et al. 1974
   iii. Relevance to management: Improved estimates of spawning could inform the stock-recruit relationship and improve model performance.
   iv. Rating: Neutral to unfavorable
   v. Rating rationale: Unfamiliarity with the data and concern that there wasn’t enough support in the literature.
e. Number of warm core rings in March - September
   i. Linkage to bluefish: Warm core rings could help transport bluefish larvae and juveniles north and towards the shelf break, affecting recruitment
   ii. Evidence for linkage: Hare et al. 2002, Hare and Cowen 1996, Able and Fahay 2010
   iii. Relevance to management: Improved recruitment estimates would improve projections
   iv. Rating: Neutral to unfavorable
   v. Rating rationale: Unfamiliarity with the data and concern that the effort required would be too high.

3. Indicators of mortality
   a. Large predator index, mako shark index
      i. Linkage to bluefish: Large predators (especially mako shark) eat bluefish and high abundance of large predators could increase natural mortality of bluefish.
      ii. Evidence for linkage: Shepherd and Packer 2006, Wood and Wetherbee 2009, Chase 2002, MacNeill et al. 2005
      iii. Relevance to management: Improved estimates of natural mortality could improve model performance
      iv. Rating: Mixed leaning towards unfavorable
      v. Rating rationale: The data quality and effort required were viewed as generally unfavorable to neutral.
   b. Condition

i. Linkage to bluefish: Bluefish with poor condition may be more susceptible to predation and disease, resulting in higher natural mortality
ii. Relevance to management: Changes in natural mortality would affect population dynamics
iii. Rating: Mixed ratings
iv. Rating rationale: this indicator requires more calculations. Additionally, condition could either be directly connected to mortality, or there could be an indirect connection via reproductive effects.

Socioeconomic indicators

1. Recreational indicators
   a. Total annual recreational catch
      i. Linkage to bluefish: This metric can serve as an indicator of future bluefish fishing activity as catch in other fisheries is linked to fishing satisfaction and the likelihood of an individual's willingness to fish (Carr-Harris and Steinback, 2020).
      ii. Relevance to fishing effort: Increased catch may increase angler satisfaction and drive additional fishing effort.
      iii. Rating: neutral to favorable
      iv. Rating rationale: Lower scores were given in the interpretability and theoretical basis categories due to the number of confounding variables that could impact catch, such as changes in regulations and effort.
   b. Annual number of directed recreational bluefish trips
      i. Linkage to bluefish: This indicator describes the number of directed recreational trips which target bluefish and may indicate future trends in effort as well as serve as an indicator of economic health in the recreational sector.
      ii. Rating: Generally neutral to favorable.
      iii. Rating rationale: The working group members expressed concerns pertaining to identifying a “bluefish trip” and noted that it might be difficult if a methodology more complicated than direct analysis of MRIP survey results was desired.
   c. Average annual price of fuel ($/gallon)
      i. Linkage to bluefish: Increases in fuel prices can increase the prices for recreational party and charter business operations and the resulting cost incurred for recreational fishing patrons.
      ii. Relevance to fishing effort: Potential inverse relationship between fuel prices and quantity of fishing trips demanded as the equilibrium price of a fishing trip increases.
      iii. Rating: Generally neutral to favorable
      iv. Rating rationale: The price of fuel may not have as strong or the same effect for shore-based fishing, which constitutes much of the recreational fishery.
   d. Average annual percentage of trips targeting bluefish

i. Linkage to bluefish: The percent of trips taken which specifically target bluefish can indicate the recreational effort specifically associated with bluefish and serve as a more direct link to economic effects stemming from bluefish trip activity.
ii. Relevance to fishing effort: An indirect measure of economic impact due to bluefish-related fishing activities which can lend insight into future trends and bluefish fishing effort.
iii. Rating: Generally neutral to favorable.
iv. Rating rationale: Concerns were raised by the working group regarding the identification of a "bluefish trip" such that it might be difficult if a methodology more complicated than direct analysis of MRIP survey results was desired, or that respondents may have categorized bluefish as a target species only after encountering them, as MRIP surveys are conducted at the end of trips.

2. Commercial indicators
   a. Annual aggregate commercial landings
      i. Linkage to bluefish: Commercial landings of bluefish is an economic indicator of the economic performance of the fishery.
      ii. Relevance to fishing effort: Commercial landings can lend insight into stock assessment findings and can also be an indicator of future fishing effort if trends are assessed over time.
      iii. Rating: favorable
      iv. Rating rationale: Commercial landings directly translate into revenues which can contribute to understanding the economic performance of the commercial fishery and commercial landings directly contribute to bluefish mortality.
   b. Annual average fuel price ($/gallon).
      i. Linkage to bluefish: To the commercial sector, increases in operating costs can change immediate fishing practices as these costs need to be covered in order for at-sea operation to occur.
      ii. Relevance to fishing effort: Fuel prices are expected to have an inverse relationship with fishing effort.
      iii. Rating: Neutral to favorable
      iv. Rating rationale: The negative correlation between fuel price and commercial fishing effort is expected to be stronger than that between fuel price and recreational effort and may help describe fluctuations in fishing pressure over time.
   c. Average annual ex-vessel bluefish price ($/lb.)
      i. Linkage to bluefish: Ex-vessel prices are inversely related to commercial bluefish landings but may also absorb changes in the prices of substitutes or compliments which may help describe changes in fishing behavior.
      ii. Relevance to fishing effort: Ex-vessel prices could be argued to impact a fishermen's decision to fish (Holland 2008)
      iii. Rating: Neutral to favorable

iv. Rating rationale: Ex-vessel prices could be argued to impact a fishermen’s decision to fish and also play a role in overall revenues and profits.

d. Total number of commercial vessels landing bluefish, annually
    i. Linkage to bluefish: Number of commercial vessels landing bluefish is an indication of economic performance and capital of the fishery and can be used to better understand consolidation and commercial bluefish dependence.
    ii. Relevance to fishing effort: The number of commercial fishing vessels is positively correlated with fishing effort.
    iii. Rating: Generally neutral to favorable.
    iv. Rating rationale: It was thought that the data quality may be poor if looking at the total number of permits, because a vessel could have a permit for bluefish but might not land bluefish due to the open access nature of the commercial fishery which is why landing data is necessary to define the number of vessels landing bluefish.

3. Social indicators
    a. Average annual recreational fishing reliance scores
        i. Linkage to bluefish: Indication of social dependence on recreational fishing.
        ii. Relevance to fishing effort: Higher reliance can indicate higher fishing pressure and has links to social implications.
        iii. Rating: Generally neutral to favorable
        iv. Rating rationale: The data quality could be viewed as low because the existing data are not specific to bluefish, but rather is a general index of all recreational fishing.
    b. Average annual recreational fishing engagement scores
        i. Linkage to bluefish: Indication of social well-being related to recreational activities.
        ii. Relevance to fishing effort: Higher engagement can indicate higher fishing pressure and social implications.
        iii. Rating: Generally neutral to favorable
        iv. Rating rationale: The data quality could be viewed as low because the existing data are not specific to bluefish, but rather is a general index of all recreational fishing.

Indicators selected for development

Based on working group feedback on the indicators described above, combined with necessary modifications to indicators due to data or analysis constraints, the following indicators were developed.

Ecosystem indicators

1. Distribution

   a. Center of gravity of small, medium, and large bluefish in the fall NMFS bottom trawl in eastings and northings, as calculated using the R package VAST. (6 indicators)
2. Climate
   a. First and last day of the year when the mean temperature of the Central Atlantic bluefish region is above 18°C (2 indicators)
   b. Number of days when >75% of the Central Atlantic bluefish region is above 18°C
   c. Mean proportion of the Central Atlantic bluefish region below 18°C, between 18-25.6°C, and above 25.6°C in July (3 indicators)
   d. Mean cross-shore and alongshore wind speeds in the Central Atlantic bluefish region in April and May (2 indicators)
3. Natural mortality
   a. Mako shark B/Bmsy
   b. Fall and spring condition of small, medium, and large bluefish in all biological samples (6 indicators)

Socioeconomic indicators

4. Recreational
   a. Number of directed recreational bluefish trips
   b. Proportion of directed recreational bluefish trips (relative to other species)
   c. Total recreational bluefish catch in numer of fish
   d. Total recreational bluefish landings (lbs.)
5. Commercial
   a. Average annual fuel price
   b. Average ex-vessel bluefish prices ($/lb.)
   c. Commercial bluefish landings (lbs.)
   d. Number of commercial vessels landing bluefish
   e. Total annual commercial bluefish revenue
6. Social
   a. Regional recreational fishing reliance scores (all species)
   b. Regional recreational fishing engagement scores (all species)

Indicators needing further research before development

Based on working group feedback on the indicators described above, combined with necessary modifications to indicators due to data or analysis constraints, the following indicators were not selected for development at this point in time.

Ecosystem indicators

1. Distribution
   a. Recreational catch by state: This indicator was not pursued due to uncertainty that the observed data would represent the sizes and abundances of bluefish in the region with enough accuracy to create a reliable time series. Observations of

seasonal recreational catch by state are described in the prior section, "Environmental, distribution, and cohort analyses".

   b. Recreational CPUE by state: This indicator was not pursued due to uncertainty that the observed data would represent the sizes and abundances of bluefish in the region with enough accuracy to create a reliable time series. Modeled seasonal CPUE by state are described in the prior section, "Environmental, distribution, and cohort analyses".
   c. Minimum and maximum latitude in the bottom trawl: After reviewing the NMFS bottom trawl data, we decided to pursue a modeled center of gravity in the fall NMFS bottom trawl as a distribution indicator rather than minimum and maximum latitude in the bottom trawl. This was due to concerns that the minimum and maximum latitude in the bottom trawl might reflect year-to-year differences in sampling locations and timing, rather than true changes in the distribution of the bluefish population.
   d. Assessment of Florida bluefish: This indicator was not pursued due to uncertainty that the observed data would represent the sizes and abundances of bluefish in the region with enough accuracy to create a reliable time series. Observations of bluefish in Florida are described in the prior section, "Environmental, distribution, and cohort analyses".
   e. Distribution of bluefish bycatch in other fisheries: This indicator was rejected by the working group after preliminary discussions due to lack of data.
2. Climate
   a. Number of warm core rings in March - September: At the time that this work was conducted, only annual warm core ring data was available. Annual data was not appropriate for this analysis, as the seasonal timing of warm core ring activity would be expected to affect bluefish recruitment. Additionally, there was uncertainty about whether the warm core rings might affect recruitment on a smaller regional/seasonal scale that may not be reflected in annual recruitment.
   b. Location of 29ppt isohaline in July: After assessing the EcoMon/MARMAP data, we determined that the 29ppt isohaline did not seem to affect the location or abundance of bluefish eggs, and therefore was not likely important for spawning.
   c. Location of 22°C isotherm in July: After reviewing the available data, we determined that it would be more feasible to calculate the percentage of area meeting certain temperature criteria, rather than locating the 22°C isotherm.
   d. Cumulative area-days with dissolved oxygen below 2 mg/L: This indicator was rejected by the working group after preliminary discussions due to lack of data availability.
   e. Amount of winter juvenile habitat with a minimum temperature above 12°C: This indicator was rejected by the working group after preliminary discussions due to lack of knowledge of the spatial distribution of overwintering juvenile bluefish.
3. Natural mortality
   a. Large predators other than mako shark: Lack of data prevented the development of time series of any large predators other than shortfin mako shark. Instead, we summarized available information in the background section.

b. Forage fish index: This indicator was explored in its own working paper (Working Paper 4, Gaichas et al. 2022) due to the complexity of the required calculations.

Socioeconomic indicators

1. Recreational
    a. U.S. Gross Domestic Product (GDP) and national U.S. income: On a first approximation, both GDP and national income would generally be expected to have a positive relationship with recreational activities, such that, as income/GDP increases, leisure activities would also be expected to increase. However, this positive relationship does not consider subsistence catch. In the case of subsistence fishing, we would expect to see an inverse relationship between income/GDP and subsistence activities (as income/GDP decreases, subsistence fishing increases). Premilmany assessments on these relationships have been conducted within the NEFSC Social Sciences Branch and results suggest there are mixed relationships between income/GDP based on the fishing mode. Given these mixed results, using these variables as indicators does not have a straightforward interpretation and may be misleading if taken at face value. Further analysis would be needed to develop an appropriate indicator.
    b. Bait and tackle retail: There are limited bait and tackle retail data sources that are accessible and provide adequate data. This creates challenges for analysts to use and convert bait and tackle retail information into a streamlined indicator. In addition, there may be better indicators that are more straightforward/ interpretable and more precisely describe bluefish recreational patterns (i.e., effort and bluefish trips).
    c. Nominal catch per unit effort (CPUE): There are multiple challenges to assessing CPUE from a socioeconomic standpoint. The development of recreational CPUEs require substantial attention to standardization due to the difficulty of quantifying effort over time (Working Paper 13, Drew 2022d), and the resulting CPUE may not be reflective of angler satisfaction. Additionally, the implications of developing a single indicator by averaging or otherwise combining CPUEs across states and seasons would need to be thoughtfully considered so that the resulting indicator would be informative in understanding the socioeconomics of the bluefish recreational fishery. For these reasons, a CPUE socioeconomic indicator was not developed at this time.
2. Commercial
    a. Catch per unit effort: This metric was not developed for bluefish given the low level of commercial activity relative to that of recreational activity. Vessel Trip Report data could be used to calculate landings per hour, seaday or some other standardized unit of measurement.
    b. Proportion of revenues resulting from bluefish: This metric was not developed for bluefish given the low level of commercial activity relative to that of recreational activity.
    c. Number of commercial bluefish trips: This metric was not developed for bluefish given the low level of commercial activity relative to that of recreational activity.

3. Social
    a. Local/regional quotient: The local/regional quotient is the bluefish revenue attributable to a community divided by the total revenues from all communities in the region and is presented in Alaskan ESP works such as Pacific cod, walleye pollock, and Saint Matthew Island blue king crab (Dorn et al. 2019, Armstrong et al. 2020, Barbeaux et al. 2020, Goethel et al. 2020). This indicator was not pursued for bluefish given that the recreational reliance and engagement scores may offer duplicative information. This indicator could be developed in the future if deemed necessary.
    b. Local processing capacity: Information on processing capacity is not readily available for analysts to develop a standardized indicator and may not fully capture social implications.

Methods and data sources

Ecosystem indicators

Spatial distribution indicators

Distribution indicators were calculated from the NMFS bottom trawl data, which began collecting data in 1963. NMFS bottom trawl data was queried from the Northeast Fisheries Science Center `survdat` database using the R package {survdat} (v1.0). Based on the seasonality of bluefish samples in this survey, only fall was assessed as an indicator of distribution; spring observations were inconsistent. Bluefish were classified in three size groups: small fish were up to 30.3cm, medium fish were between 30.3cm and 50.0cm, and large fish were 50.0cm or larger. The 30.3cm cutoff represents the mean size at age 1 from the empirical life history data, while the 50.0cm cutoff represents the mean size at age 3; fish ages 3 and older are fully sexually mature.

A multivariate Vector Autoregressive Spatiotemporal (VAST) model of the distributions of the three bluefish size groups from 1982 - 2019 was constructed using the R package {VAST} (v3.9.1). Years prior to 1982 were not used because temperature covariate data was not available. Years were dropped from the analysis if there were fewer than 300 total fall tows or if one or more groups had zero bluefish observations in that year. These criteria resulted in 1988, 2017, 2020, and 2021 being dropped. Spatial and spatio-temporal variability were modeled with three random fields (i.e., FieldConfig = c(3, 3, 3, 3)) to account for the three size groups. Temporal and spatio-temporal variability were not included in the model (i.e., RhoConfig = c(0, 0, 0, 0)), as this is not advised for index calculations (Thorson 2019). The log of depth was also used as a density covariate. Day of year was used as a catchability covariate to account for variable survey timing. Normalized mean sea surface temperature in September calculated from the daily OISST dataset from the Physical Sciences Laboratory and was used as a density covariate; however, the model with temperature as a covariate did not converge, and so the model with depth and day of year covariates was used for indicator creation instead. The complete VAST code can be viewed in Working Paper 3 (Tyrell 2022). Centers of gravity in units of northings (km) and eastings (km) were extracted from the model results for each size group.

Climate indicators

Six temperature-related indicators were calculated using the OISST satellite temperature dataset from the Physical Sciences Laboratory, which dates back to 1982. The spatial region considered as bluefish habitat for these analyses is shown in Figure 46. First, the spawning suitability in July was assessed by calculating the mean area above 18°C, mean proportion of the Central Atlantic bluefish region below 18°C, between 18-25.6°C, and above 25.6°C in July by year.

Next, the mean temperature was calculated by day, and the first and last days with a mean temperature above 18°C were calculated for each year. Lastly, the annual number of days with greater than 75% of the area above 18°C was calculated.

Monthly mean wind speed data was downloaded from the Physical Sciences Laboratory. This dataset has been collected since 1979. The mean wind speed in April and May was calculated by taking the spatial mean of wind speeds in April and May of each year. Wind direction was rotated 45 degrees to represent cross-shore and alongshore winds, rather than north-south and east-west winds.

Natural mortality indicators

North Atlantic shortfin mako shark B/Bmsy data was obtained from the International Commission for the Conservation of Atlantic Tunas (ICCAT). The most recent ICCAT shortfin mako shark stock assessment was conducted in 2017 and provided B/Bmsy estimates for years between 1950 and 2017. It included nine B/Bmsy estimates, which were developed from three modeling platforms and two catch scenarios. The nine B/Bmsy estimates were averaged to calculate the mako shark B/Bmsy indicator.

Bluefish condition was calculated from length and weight data, which was aggregated from multiple state and federal surveys as described in Working Paper 5 (Truesdell et al. 2022). This combined dataset contained information from 1981 to 2021. For each season, the weight-length relationship was modeled with a linear model:

$$ln(W) = a \times ln(L) + b$$

where *W* is weight, *L* is length, and *a* and *b* are constants. After fitting the constants using `stats::lm()` in R, the equation was back-transformed to determine the unlogged relationship between length and weight:

$$W = c \times L^a$$

where *W*, *L*, and *a* have the same values as above, and *c* is the constant exp(*b*). The predicted weight was determined for each bluefish in the length-weight dataset, and Fulton's Condition Factor was calculated by dividing the observed weight by the predicted weight. A condition factor under one means that the fish was skinnier than expected, while a condition factor over one means that the fish was fatter than expected. Mean annual bluefish condition in spring and fall was determined for three size groups: small fish up to 30.3cm, medium fish between 30.3cm and 50.0cm, and large fish 50.0cm or larger.

Socioeconomic indicators

Data for developing the selected socioeconomic indicators were acquired from various sources, described below. The data were retrieved to generate annual summaries for each indicator over a multidecadal time series. Data were then plotted over time and against the calculated series average and standard deviations from the mean. The time series used for the commercial indicators spans from 2000-2021, while the recreational indicator time series extends back to 1981. The difference in time series is due to data quality and data adjustments. For the commercial data, incorporating earlier time series data is expected to increase bias and decrease the overall accuracy of the reported indicators due to changes and advancement in data collection methods over the years. The use of the entire MRIP time series is possible due to the recalibration measures which control for the changes in sampling methodologies over time. Lastly, the social metrics have a different time series which is contingent on the data available for the indicators summarized.

Data downloads from MRIP

The Marine Recreational Information Program (MRIP) is run by NOAA Fisheries and conducts year-round surveys of recreational anglers to estimate total recreational catch of important marine species. MRIP uses a statistically robust method to expand these raw survey data into regional estimates of total catch, total trips, and trips directed on individual species. These expanded datasets can be downloaded from the MRIP website.

Expanded catch and trip estimates were downloaded from a data portal on the NOAA website using an R script. Here is the link that was used to download MRIP expanded catch and trip information. This data portal was linked from the public-facing MRIP page. Here is the link to the public-facing MRIP website page that linked the data portal.

MRIP also calculates the number of directed trips for each species, i.e., the number of trips targeting that species. This data was not able to be downloaded directly with an R script, but was manually downloaded from the MRIP Query Tool. Here is the link to the MRIP Query Tool that was used to download directed trip data for bluefish.

Recreational indicators

The recreational indicators calculated were: annual number of bluefish trips, annual proportion of trips targeting bluefish, annual bluefish catch (number of fish), and annual bluefish landings (pounds). All recreational indicators were calculated from data provided by MRIP (1981 - present). The annual number of bluefish trips was calculated by summing all directed bluefish trips in East Coast states (Maine to Florida, Atlantic coast only) across fishing modes and waves. All recreational trips (i.e., targeting any species) in East Coast states (Maine to Florida, Atlantic coast only) were summed across modes and waves to determine the total number of recreational trips taken each year. Bluefish recreational trips, as calculated above, were divided by the total number of recreational trips to determine the proportion of recreational trips targeting bluefish. All bluefish recreational catch in East Coast states (Maine to Florida, Atlantic coast only) were summed across modes and waves to determine the total number of bluefish caught recreationally each year. All bluefish recreational landings in East Coast states (Maine to

Florida, Atlantic coast only) were summed across modes and waves to determine the total pounds of bluefish landed recreationally taken each year.

Commercial indicators

The commercial indicators calculated were: average annual fuel price, annual bluefish landings, average annual bluefish price per pound, annual number of vessels landing bluefish, and total annual bluefish revenue. Average annual Ultra-low-sulfur number 2 diesel fuel prices were queried from the Federal Reserve Economic data. Prices are reported in 2021 constant dollars and were adjusted using the Gross Domestic Product Implicit Price Deflator from the Federal Reserve. Average annual bluefish price (dollars) per pound bluefish prices were generated using federal commercial dealer database information (CFDBS.CFDERS). Prices are reported in 2021 constant dollars and were adjusted using the Gross Domestic Product Implicit Price Deflator from the Federal Reserve. Total annual bluefish landings (pounds) from commercial activity were queried from the commercial fisheries dealer database (CFDBS.CFDERS NEFSC tables).[10] The total annual number of commercial fishing vessels that reported landing and selling one or more pounds of bluefish was retrieved from the federal commercial dealer database (CFDBS.CFDERS). The total annual revenues data, resulting from bluefish ex-vessel sales records, were retrieved from the federal commercial dealer database (CFDBS.CFDERS). Revenues are reported in 2021 constant dollars and were adjusted using the Gross Domestic Product Implicit Price Deflator from the Federal Reserve.

Social indicators

Recreational community engagement and reliance on the port level were obtained from Changhua Weng (NEFSC). The average community engagement and reliance were calculated for the North Atlantic (ME, NH, MA, RI, CT), Mid Atlantic (NY, NJ, DE, MD, VA), and South Atlantic (NC, SC, GA, FL east of 81.25°W) by taking the average of all ports in these regions. Note, community engagement and reliance were determined based on the recreational fishing of all species, not exclusively bluefish.

Analyses

If there were more than 30 years of data for an indicator, the indicator time series was tested for a significant linear trend over time using `stats::lm()` in R. If a linear trend was present, it was plotted on the indicator time series figure. If there was a suspected correlative or causative link between an indicator and the bluefish stock, `stats::cor()` and `stats::lm()` were used to test for a correlation in R.

[10] Though the NEFSC dealer database is a downstream product of the ACCSP system, values between the two sources may differ slightly due to differences in data refresh rate and differences in the implemented quality assurance and quality control algorithms.

Results and discussion

Ecosystem indicators

Spatial distribution

Spatial distribution was determined from the fall NMFS bottom trawl data. Out of all three size groups, small bluefish are found the most south and west, with the highest densities along the central Atlantic coast south of Cape Cod. Large bluefish are found the most north and east, with high densities on Georges Bank and in the New York Bight. Medium bluefish are in between, being found along the Atlantic coast, but also with hotspots near Martha's Vineyard and Georges Bank in some years. These results reflect the empirical spatial distributions shown in Figures 21-23. Analysis of bluefish distribution in the NEFSC bottom trawl shows that medium and large bluefish are shifting more northward and more eastward over time (Figure 47, 48), while the centers of gravity of small bluefish are not moving. Because juvenile bluefish utilize estuarine nursery habitats, while adult bluefish tend to be pelagic, it makes sense that small bluefish habitat has been relatively fixed over time, while medium and large bluefish are more transient. Between the period 1982 - 2019, the center of gravity of medium bluefish moved north and east at an average rate of 1.1 km/year and the center of gravity of large bluefish moved north at an average rate of 0.2 km/year and east at an average rate of 0.5 km/year (Figure 47, 48). Based on VAST maps of distribution, medium and large bluefish are moving away from the coast and towards Georges Bank (Working Paper 3 Tyrell 2022). Further research is needed to determine the environmental covariates that are associated with (and may be driving) this distributional change.

Climate influences

The first day when the mean temperature of the central Atlantic bluefish region (Figure 49) reaches 18°C has remained stable over time and did not show a linear trend (Figure 49a). The timing of the last 18°C day and the total number of days with more than 75% of the area being warmer than 18°C have both increased over time (Figure 49b,c). This may mean that the bluefish spawning season has lengthened over time. The correlation coefficients between these climate timing indicators and young-of-the-year bluefish numbers as estimated by the 2015 stock assessment were consistently between -0.2 and 0.2 (Table 7), suggesting that these indicators do not have a strong effect on bluefish recruitment; however, few young-of-year indices include sampling taken at the end of the bluefish spawning season, so additional young-of-year estimates may be needed to accurately quantify the relationship between the length of the spawning season and year class size.

The proportion of the Central Atlantic with optimal bluefish spawning temperatures between 18-25.6°C has remained consistent over time; however, the proportion of area with mean temperatures below 18°C has decreased, while the proportion of area with mean temperatures above 25.6°C has increased (Figure 50). In 2021, less than 5% of the Central Atlantic region had mean temperatures below 18°C. As sea surface temperatures continue to warm, the proportion of the Central Atlantic with optimal bluefish spawning temperatures in July may eventually decrease as more areas warm above 25.6°C and no areas are left below 18°C.

The proportion of area with mean temperatures above 25.6°C was negatively correlated with the Conn young-of-the-year index and with modeled recruitment, while the proportion of area with optimal mean temperatures was marginally positively correlated with modeled recruitment (Table 7). The proportion of area with mean temperatures below 18°C was not strongly correlated with either the Conn young-of-the-year index or with the modeled recruitment (Table 7).

The mean wind speed in April and May did not show any significant trends over time (Figure 51). Both alongshore and across-shore winds varied between positive (up shore and away from shore) and negative (down shore and inshore) values, with mean values being slightly positive. This interannual variability in wind direction could affect recruitment success, as winds that drive eggs and larvae away from shore could reduce recruitment while winds that drive eggs towards shore could increase recruitment. However, there was no correlation between winds and young-of-the-year bluefish (Table 7).

Natural mortality

Fulton's Condition Factor of large bluefish (>=50.0cm, ages 3+) showed a significant linear increase over time in both spring and fall (Figure 52, 53). Medium (30.3-50.0cm) bluefish did not show any statistically significant trends over time (Figure 52, 53). Small (<=30.3cm) bluefish showed a statistically significant decrease in spring condition over time, but recent values are within one standard deviation of the mean and nearly all years showed condition factors higher than one (Figure 52). There was no trend in fall condition of small bluefish (Figure 53). Therefore, it is unlikely that the slight change in spring condition of small bluefish over time has had a substantial impact on bluefish. Medium and large bluefish had time series low conditions in fall in 2004.

Many predators of bluefish are not well sampled, leading to uncertainty both in identifying predators of bluefish and in quantifying the abundance of predators of bluefish. Therefore, only one quantitative predation indicator is presented, the B/Bmsy of shortfin mako sharks in the North Atlantic as quantified by the ICCAT assessment. The B/Bmsy of shortfin mako has decreased over time, showing a statistically significant linear decrease, and is currently at an historical low (Fig 53). Therefore, it is unlikely that predation by shortfin mako has influenced the bluefish population in recent years. In fact, shortfin mako B/Bmsy is positively correlated with bluefish abundance (Table 8), since both populations have declined since the 1980s.

Overall, these results do not suggest that bluefish have been subject to any substantial changes in natural mortality over time.

Socioeconomic Indicators

Recreational indicators

Total recreational bluefish landings and the proportion of trips targeting bluefish both exhibit statistically significant decreasing linear trends (Figure 54). The number of bluefish caught recreationally along the Atlantic coast followed an overall decreasing trend over the past decade (Figure 54). About 62.4 million bluefish were caught in 2010 which decreased by 61% to

24.6 million fish caught in 2021. In addition, the last four years in the time series (2018-2021) have the lowest bluefish catches over the entire time series, averaging around 31.2 million fish caught per year. Catch was relatively consistent during 2015-2016, ranging from 42.1-42.5 million bluefish. Prior to 2015, catch did not fall below 50.7 million bluefish.

Total recreational bluefish trips and catch did not show a statistically significant linear trend, although recent values are at or near historical lows (Figure 54). The number of directed recreational bluefish trips off the Atlantic Coast were lowest in the last 4 years in the time series relative to the entire period (Figure 54). The number of directed trips from 2010 to 2017 ranged from 4.29-7.86 million trips, an average of 6.74 directed trips, annually. From 2018-2021, the number of directed trips ranged from 4.29-5.33 million trips, an average of 5.06 million trips, annually.

Declining recreational bluefish landings, without a corresponding trend in total recreational catch, likely reflects the shift to catch-and-release fishing. Overall, recent low numbers of recreational bluefish trips, proportion of trips targeting bluefish, and recreational bluefish catch and landings indicate that the recreational bluefish fishery is declining compared to historic levels. Further research is needed to determine the drivers of this decrease, which may be partly attributable to recent management measures that were implemented in response to bluefish being declared overfished in 2019. Expenditures and contributions to local economies stemming from bluefish angler activity may have also declined over this same period, although further research would be necessary to confirm this concept.

Commercial indicators

Average ex-vessel bluefish prices have been above average for the past four years, most likely due to the equally low commercial bluefish landings, which have been below the average for the past four years (Figure 55). The number of commercial vessels landing bluefish has also decreased over the past four years, which is reflected in the overall decline in bluefish revenues, despite the increase in ex-vessel price per pound (Figure 55). Fuel prices have been near to or lower than average over the past five years of the time series, but increased from 2020 to 2021 (Figure 55). Fuel prices from 2022 were not included in this analysis since the terminal year of the assessment was 2021. Fuel price was positively correlated with commercial bluefish catch (Table 9), because both fuel price and catch have decreased in recent years. Overall, the trends indicate a decreasing commercial bluefish fleet, with series low revenues, vessels and landings.

Social indicators

The recreational reliance and engagement scores show some positive trends in the past years for some regions (Figure 56, 57). Average recreational reliance scores in the Mid Atlantic and Northeast have trended upwards since 2016, with 2019 (the last year with available data) being above the time series average. In terms of the recreational engagement scores, the Northeast and Mid Atlantic had scores near the time series average in 2019. The Southeast shows somewhat different, in some cases opposite, trends, with recreational reliance scores near a time series low in 2019 and engagement scores decreasing slightly but still remaining above average from 2017-2019. Overall, the time series for all indicators for all regions were too short to assess for a statistical trend, and the majority show high fluctuations from time series extremes around 2014-2016. Overall, there may be increases in reliance for the Northeast and Mid-Atlantic and decreases in the South-Atlantic while recreational engagement shows less consistent trends for all regions.

Data gaps and future research priorities

None of the scientific surveys collecting data on bluefish were designed specifically to target bluefish. Many of these surveys therefore report low sampling success on bluefish. Our understanding of the bluefish population would be greatly improved by scientific sampling designed to target bluefish. This sampling would increase our understanding of bluefish distribution and seasonal movements, which would in turn allow us to better understand what ecosystem and fisheries changes would impact the bluefish population. Forthcoming research on warm core rings could help improve understanding of juvenile bluefish recruitment to inshore regions.

Bluefish is primarily a private-sector recreational fishery, and there is little data available that can be used to understand the drivers behind the targeting and harvesting of bluefish. Improved socioeconomics information would facilitate better understanding of the bluefish fishery and the development of more informative socioeconomics indicators.

Conclusions

Ecosystem considerations

- Center of gravity analyses showed that medium bluefish are moving north and east at an average rate of 1.1 km/year, and large bluefish are moving north at an average rate of 0.2 km/year and east at an average rate of 0.5 km/year. This distribution change may support anecdotes about large bluefish moving offshore in recent years. Further research is needed to fully understand bluefish distribution, as the 2020 and 2021 fall bottom trawl surveys did not catch enough bluefish to be included in this study.
- The spawning season may now extend later in the year compared to historical periods. Bluefish spawning has been recorded at 18-25.6°C (Norcross et al. 1974). In the greater Mid Atlantic Bight and Southern New England region, the first day when 75% or more of the sea surface reaches 18°C has remained stable over time, while the last day when 75% of the sea surface is above 18°C has occurred later in the year over time; the total number of days with 75% or more of the sea surface above 18°C has increased over time. It is unclear how these changes in spawning season may affect bluefish recruitment. There were no notable correlations between first, last, or number of days above 18°C and the Conn young-of-the-year index or modeled recruitment. However, the surveys used to characterize young-of-the-year bluefish may not document spawning that occurs in the fall.
- The amount of area in the Central Atlantic with optimal bluefish spawning temperatures (18-25.6°C) in July was positively correlated with bluefish recruitment. The amount of

area with excessively warm temperatures (>25.6°C) was negatively correlated with bluefish recruitment. Although the amount of area with optimal temperatures in July has remained consistent over time, future ocean warming may eventually decrease the proportion of the Central Atlantic with optimal bluefish spawning temperatures as more areas warm above 25.6°C and no areas are left below 18°C.

- Bluefish predators are not well sampled, but existing data suggest that bluefish are not currently experiencing higher predation risk relative to historical conditions.
- Relative condition of individual bluefish is at or above historical levels, indicating that bluefish are not more susceptible to natural mortality compared to historical conditions.
- An increasing trend in the relative condition of large bluefish may be beneficial for bluefish recruitment, as larger and fatter bluefish may produce more eggs and/or more high quality eggs; however, further research is needed to quantify the relationships between fecundity and length, weight, and age.

Socioeconomic considerations

- Despite lower catches in recent years, bluefish remains one of the top recreational fisheries on the U.S east coast in terms of total catch, and therefore likely helps support a robust recreational fishing industry.
- The recreational fishery has shifted to catch-and-release rather than catch for harvest, although management was fairly stable until the bag limit reductions in 2018. Pounds of bluefish landed recreationally has decreased over time, with landings in 2021 weighing in at less than 10% of landings in 1981. Over the same time period, the total recreational catch has not decreased significantly.
- Neither commercial nor recreational catch typically exceed catch limits. However, Acceptable Biological Catch (ABC) has generally decreased since it was implemented in 2011 due to stock status. Therefore, recent decreases in catch and landings may be attributable to management actions rather than lack of interest in the bluefish fishery.

Tables

Table 1: Summary of environmental conditions where bluefish eggs were found in federal surveys

Month	Number of tows	Number of positive tows	Total fish observed	Fish per tow	Number of years	Number of years with positive tows	Mean surface temperature of observations	Number of temperature data points	Mean surface salinity of observations	Number of salinity data points
5	1,681	2	875.96	0.52	12	2	19.90	875.96	35.33	2.54
6	996	28	1,636.39	1.64	10	4	20.44	1,636.39	31.56	551.28
7	966	132	10,321.29	10.68	11	8	21.51	10,321.29	31.04	3,016.70
8	1,183	53	3,095.61	2.62	11	8	24.41	3,095.61	32.62	32.27

Table 2: Summary of environmental conditions where bluefish larvae were found in federal surveys

Month	Number of tows	Number of positive tows	Total fish observed	Fish per tow	Number of years	Number of years with positive tows	Mean surface temperature of observations	Number of temperature data points	Mean surface salinity of observations	Number of salinity data points
1	1,789	1	2.19	0.00	26	1	NA	NA	NA	NA
4	3,266	13	260.30	0.08	44	1	NA	NA	NA	NA
5	3,477	105	11,913.09	3.43	38	11	21.91	10,285.48	31.11	10,285.48
6	3,083	218	15,961.08	5.18	34	17	22.33	9,463.08	31.03	9,919.76
7	1,430	1,010	46,984.94	32.86	21	17	23.33	5,376.52	31.71	5,376.52
8	3,011	915	18,413.01	6.12	31	27	24.46	7,522.94	31.58	7,520.73
9	2,210	96	631.47	0.29	43	19	23.79	564.12	32.19	564.12

Table 3: Summary of environmental conditions where small bluefish (<=30.3cm) were found in the NMFS bottom trawl

Month	Number of tows	Total fish observed	Fish per tow	Mean surface temperature of observations	Number of temperature data points	Mean surface salinity of observations	Number of salinity data points
2	2,381	2	0.00	13.93	2	35.16	2
3	8,746	987	0.11	11.69	980	32.86	518
4	8,252	200	0.02	17.00	198	35.08	94
5	1,803	18	0.01	18.58	18	NA	NA
6	123	18	0.15	19.88	18	NA	NA
7	959	840	0.88	26.39	724	NA	NA
8	1,366	1,418	1.04	23.96	1,345	NA	NA
9	7,066	62,129	8.79	21.48	50,962	30.87	25,825
10	8,974	15,643	1.74	18.79	12,862	30.80	3,667
11	3,512	787	0.22	18.42	786	31.87	2
12	243	6	0.02	14.42	6	NA	NA

Table 4: Summary of environmental conditions where medium bluefish (30.3-50.0cm) were found in the NMFS bottom trawl

Month	Number of tows	Total fish observed	Fish per tow	Mean surface temperature of observations	Number of temperature data points	Mean surface salinity of observations	Number of salinity data points
2	2,381	86	0.04	10.27	79	33.91	78
3	8,746	642	0.07	11.66	493	34.36	386
4	8,252	76	0.01	8.45	75	33.69	75
5	1,803	1	0.00	8.38	1	32.74	1
7	959	23	0.02	25.93	21	NA	NA
8	1,366	34	0.02	22.20	28	NA	NA
9	7,066	2,728	0.39	21.45	2,364	31.09	1,594
10	8,974	836	0.09	18.10	711	31.73	206
11	3,512	76	0.02	18.90	76	NA	NA

Table 5: Summary of environmental conditions where large bluefish (>=50.0cm) were found in the NMFS bottom trawl

Month	Number of tows	Total fish observed	Fish per tow	Mean surface temperature of observations	Number of temperature data points	Mean surface salinity of observations	Number of salinity data points
2	2,381	62	0.03	10.16	61	33.66	59
3	8,746	264	0.03	11.26	184	34.61	137
4	8,252	29	0.00	10.34	27	33.83	23
5	1,803	2	0.00	18.75	2	NA	NA
6	123	1	0.01	21.50	1	NA	NA
7	959	59	0.06	17.64	58	NA	NA
8	1,366	70	0.05	17.24	70	NA	NA
9	7,066	908	0.13	18.75	703	31.85	496
10	8,974	1,733	0.19	15.61	1,507	32.19	718
11	3,512	66	0.02	15.40	62	NA	NA

Table 6: Indicator scoring rubric

Criterion	Definition of a high (good) score	Definition of a medium score	Definition of a low (bad) score
Interpretability	An abstract concept that requires detailed explanation; a general audience is not familiar with the indicator.	The indicator represents a familiar concept, but might require explanation to fully understand its utility in the specific context.	An intuitive concept; the general audience has heard of the indicator and seen related data before.
Theoretical basis	The literature shows that the indicator has a weak or hard to detect response to the underlying pressure/ mechanism.	There is no existing literature information on the indicator, but literature sources support the inclusion of a similar indicator, or show that the same indicator affects a similar species; or, there may be conflicting reports in the literature. Alternatively/ additionally, the indicator may reflect multiple underlying mechanisms, which makes interpretation of the indicator more difficult (i.e., there are multiple interpretations of indicator change).	Multiple literature sources support the inclusion of this indicator. The indicator has a high or well-defined response to an underlying pressure or mechanism. The indicator is a clear reflection of an identifiable mechanistic process (i.e., indicator change has a single/streamlined interpretation).
Effort	The indicator already exists, or can be easily created from existing data.	The indicator could be created from a more detailed analysis of one or more existing data sources.	The indicator would require extensive calculations, or the collection of new data.
Data quality	The data may be inaccurate or imprecise. Data may be missing or cover a sparse spatial or temporal scale. The data is not sufficient for passing peer review.	No major red flags in data.	The data have been collected with peer-reviewed methods and are expected to be accurate and/or precise enough for their purpose. There are no concerns about spatial or temporal data coverage.

Table 7: Ecosystem indicator correlations with young-of-the-year bluefish

Correlation coefficients between the named indicators and four metrics of young-of-the-year (age 0) bluefish.

Category	Indicator	Conn Index	Conn Index per SSB	Modeled recruitment (2019)	Modeled recruits per SSB (2019)
Climate	First day of the year when the mean temperature of the central Atlantic region is warmer than 18C	Correlation coefficient: 0.117 p-value: 0.472	Correlation coefficient: 0.1 p-value: 0.573	Correlation coefficient: -0.018 p-value: 0.922	Correlation coefficient: 0.012 p-value: 0.947
Climate	Last day of the year when the mean temperature of the central Atlantic region is warmer than 18C	Correlation coefficient: -0.179 p-value: 0.269	Correlation coefficient: -0.152 p-value: 0.391	Correlation coefficient: -0.066 p-value: 0.711	Correlation coefficient: -0.12 p-value: 0.5
Climate	Number of days when at least 75% of the central Atlantic region is warmer than 18C	Correlation coefficient: -0.187 p-value: 0.248	Correlation coefficient: -0.094 p-value: 0.599	Correlation coefficient: 0.021 p-value: 0.906	Correlation coefficient: -0.015 p-value: 0.934
Climate	Proportion of the central Atlantic colder than 18C in July	Correlation coefficient: 0.182 p-value: 0.26	Correlation coefficient: 0.115 p-value: 0.517	Correlation coefficient: 0.037 p-value: 0.834	Correlation coefficient: 0.046 p-value: 0.794
Climate	Proportion of the central Atlantic between 18-25.6C in July	Correlation coefficient: 0.193 p-value: 0.232	Correlation coefficient: 0.261 p-value: 0.136	Correlation coefficient: 0.333 p-value: 0.054	Correlation coefficient: 0.334 p-value: 0.053
Climate	Proportion of the central Atlantic warmer than 25.6C in July	Correlation coefficient: -0.286 p-value: 0.074	Correlation coefficient: -0.324 p-value: 0.062	**Correlation coefficient: -0.344 p-value: 0.046**	**Correlation coefficient: -0.351 p-value: 0.042**
Climate	Mean crossshore wind in the central Atlantic in April and May	Correlation coefficient: 0.088 p-value: 0.582	Correlation coefficient: -0.038 p-value: 0.831	Correlation coefficient: 0.123 p-value: 0.489	Correlation coefficient: 0.09 p-value: 0.614
Climate	Mean alongshore wind in the central Atlantic in April and May	Correlation coefficient: -0.071 p-value: 0.657	Correlation coefficient: -0.193 p-value: 0.274	Correlation coefficient: -0.053 p-value: 0.768	Correlation coefficient: -0.053 p-value: 0.766
Natural mortality	Spring condition of small (<=30.3cm) bluefish	Correlation coefficient: 0.213 p-value: 0.218	Correlation coefficient: 0.194 p-value: 0.288	Correlation coefficient: 0.123 p-value: 0.501	Correlation coefficient: 0.085 p-value: 0.642
Natural mortality	Spring condition of medium (30.3-50.0cm) bluefish	Correlation coefficient: 0.335 p-value: 0.042	Correlation coefficient: 0.182 p-value: 0.303	Correlation coefficient: 0.005 p-value: 0.976	Correlation coefficient: -0.139 p-value: 0.433

Category	Indicator	Conn Index	Conn Index per SSB	Modeled recruitment (2019)	Modeled recruits per SSB (2019)
Natural mortality	Spring condition of large (>=50.0cm) bluefish	Correlation coefficient: -0.198 p-value: 0.278	Correlation coefficient: 0.209 p-value: 0.317	Correlation coefficient: -0.086 p-value: 0.682	Correlation coefficient: 0.187 p-value: 0.37
Natural mortality	Fall condition of small (<=30.3cm) bluefish	Correlation coefficient: 0.219 p-value: 0.192	Correlation coefficient: 0.255 p-value: 0.146	Correlation coefficient: 0.108 p-value: 0.545	Correlation coefficient: 0.146 p-value: 0.411
Natural mortality	Fall condition of medium (30.3-50.0cm) bluefish	Correlation coefficient: 0.171 p-value: 0.312	Correlation coefficient: 0.074 p-value: 0.679	Correlation coefficient: 0.254 p-value: 0.147	Correlation coefficient: 0.113 p-value: 0.526
Natural mortality	Fall condition of large (>=50.0cm) bluefish	Correlation coefficient: 0.134 p-value: 0.473	Correlation coefficient: 0.337 p-value: 0.08	Correlation coefficient: 0.004 p-value: 0.983	Correlation coefficient: 0.259 p-value: 0.183

Table 8: Ecosystem indicator correlations with spawning stock biomass

Correlation coefficients between the named indicators and biomass from the 2019 assessment model.

Category	Indicator	Modeled SSB (2019)
Natural mortality	Spring condition of small (<=30.3cm) bluefish	Correlation coefficient: 0.127 p-value: 0.487
Natural mortality	Spring condition of medium (30.3-50.0cm) bluefish	Correlation coefficient: 0.275 p-value: 0.116
Natural mortality	Spring condition of large (>=50.0cm) bluefish	Correlation coefficient: -0.351 p-value: 0.086
Natural mortality	Fall condition of small (<=30.3cm) bluefish	Correlation coefficient: 0.017 p-value: 0.924
Natural mortality	Fall condition of medium (30.3-50.0cm) bluefish	Correlation coefficient: 0.234 p-value: 0.183
Natural mortality	Fall condition of large (>=50.0cm) bluefish	Correlation coefficient: -0.307 p-value: 0.111
Natural mortality	Shortfin mako shark B/Bmsy in the North Atlantic	**Correlation coefficient: 0.465** **p-value: 0.008**

Table 9: Socioeconomic indicator correlations with catch

Correlation coefficients between the named indicators and recreational catch and commercial landings.

Category	Indicator	Recreational catch (n)	Commercial landings (lbs)
Commercial	Average price of diesel fuel (real dollars/gallon)	**Correlation coefficient: 0.616** **p-value: 0.014**	**Correlation coefficient: 0.524** **p-value: 0.045**

Figures

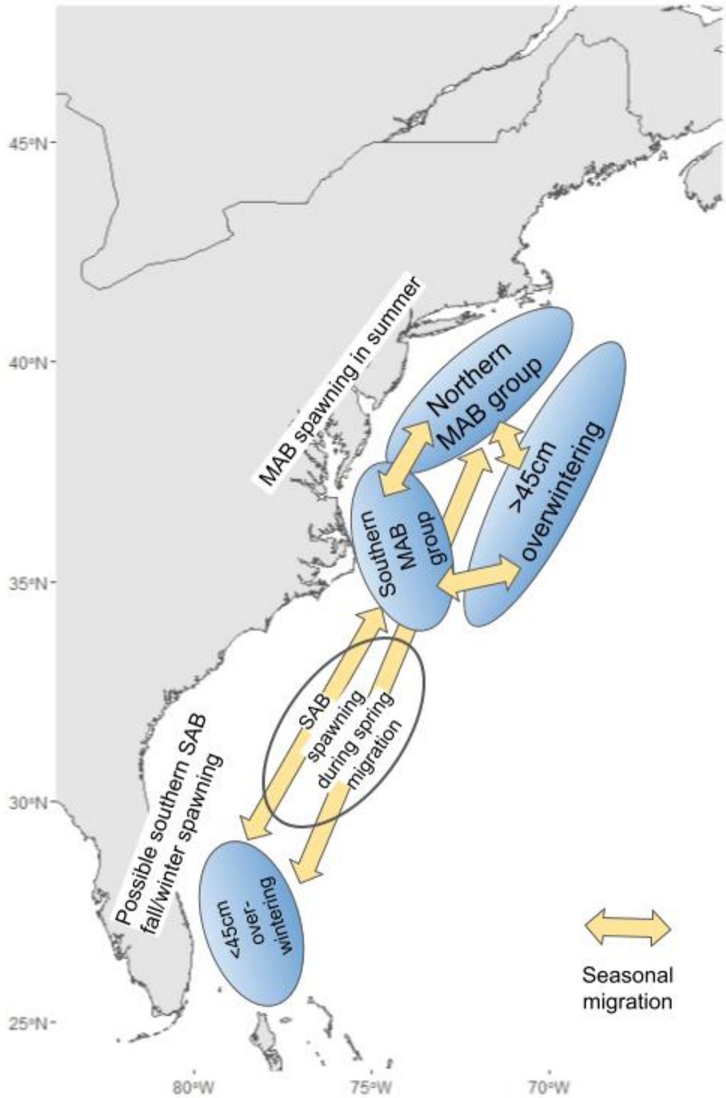


Figure 1. Conceptual model of bluefish seasonal migrations.

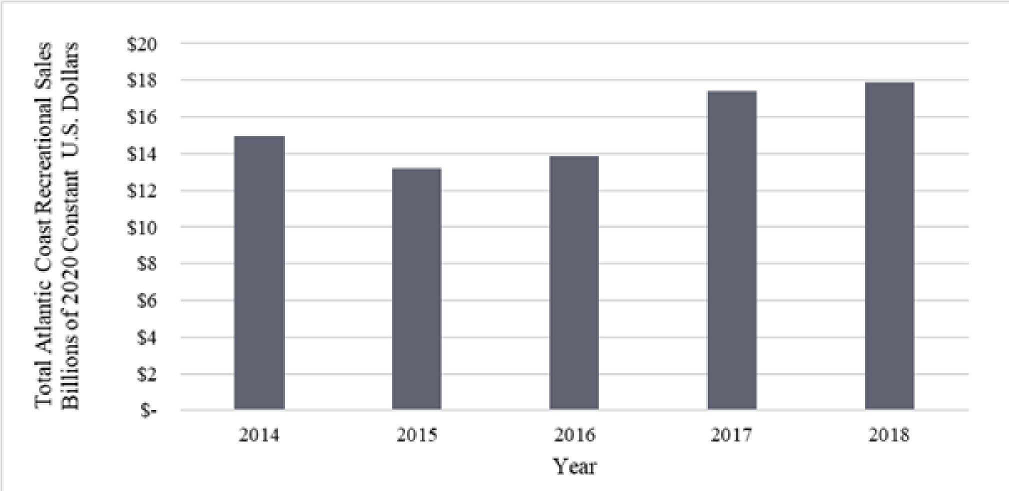


Figure 2. Total annual recreational sales from Atlantic coastal states over 2014-2018 in billions of 2020 constant U.S. Dollars. Data obtained from the Fisheries Economics of the United States Reports (2014-2018). Values were adjusted using the Gross Domestic Product Implicit Price Deflator.

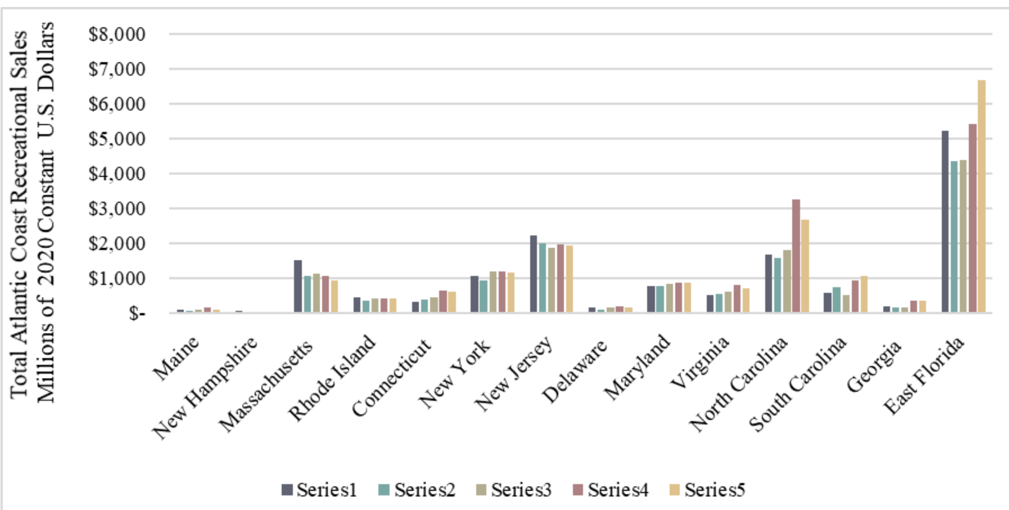


Figure 3. Total annual recreational sales by Atlantic Coastal state from 2014-2018 in millions of 2020 constant U.S. Dollars. Data obtained from the Fisheries Economics of the United States. Values were adjusted using the Gross Domestic Product Implicit Price Deflator.

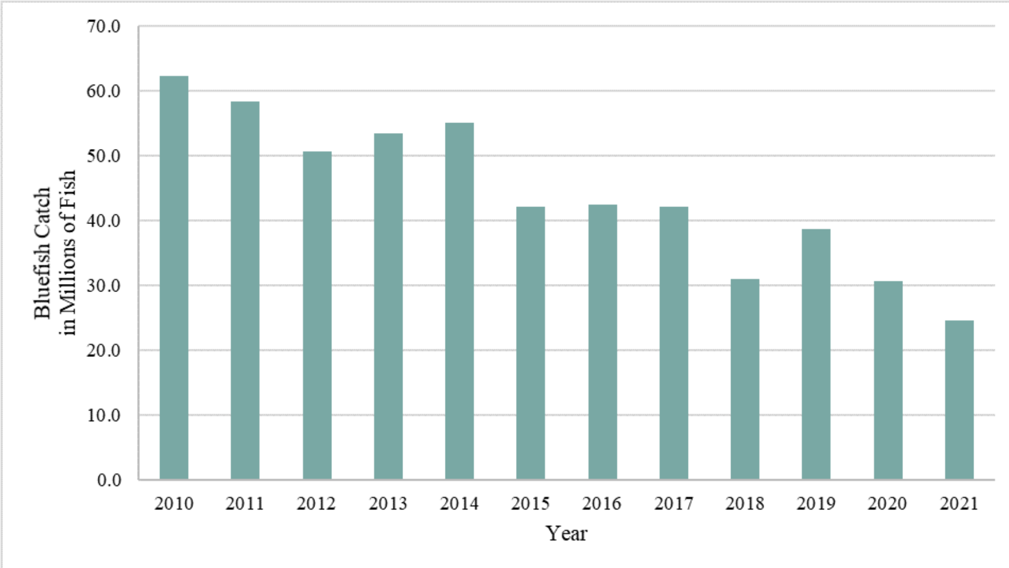


Figure 4. Recreational bluefish catch from Atlantic Coastal states over 2010-2021. Data acquired from the Marine Recreational Information Program (MRIP) query tool in January 2022.

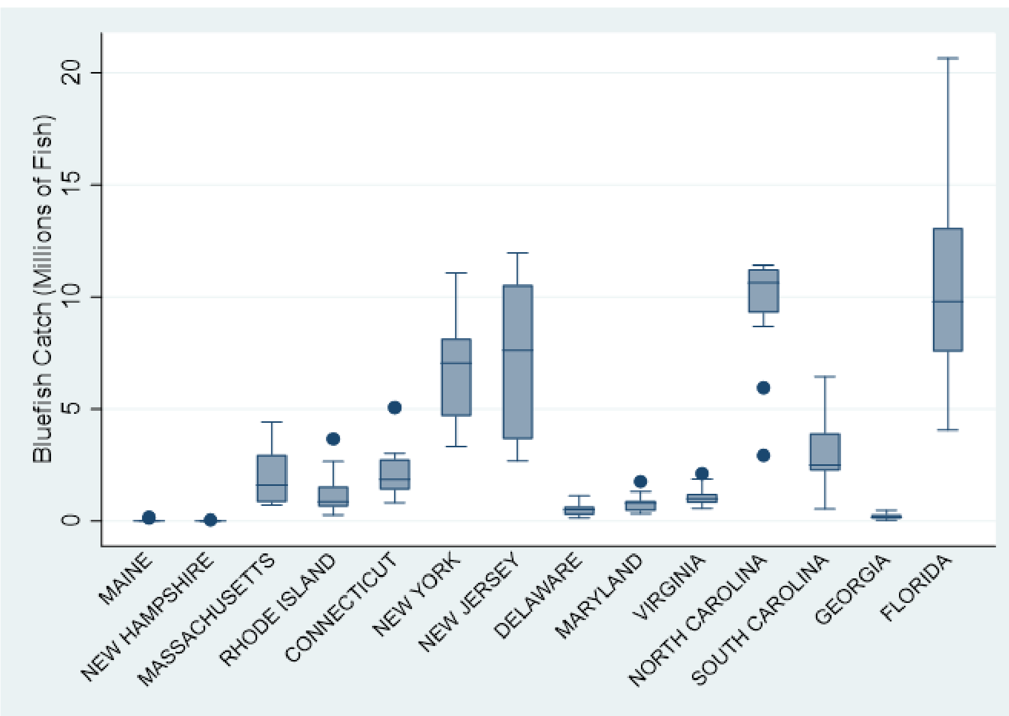


Figure 5. Recreational bluefish catch box plots from 2010-2021 by Atlantic coastal states. Data retrieved from the Marine Recreational Information Program (MRIP) query tool in January 2022.

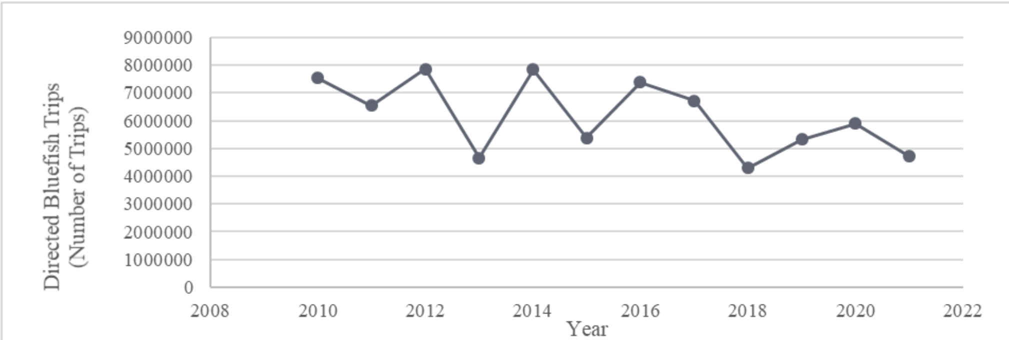


Figure 6. Number of directed recreational bluefish trips from Atlantic coastal states (2010-2021). Data retrieved from the Marine Recreational Information Program (MRIP) query tool in January 2022.

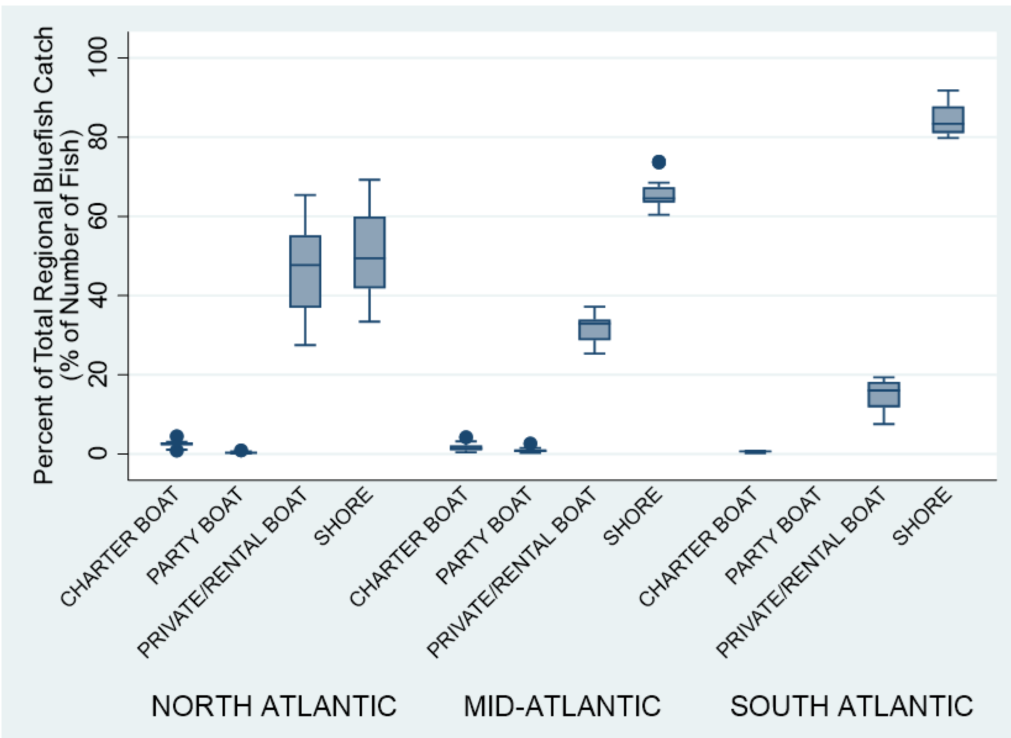


Figure 7. Proportion of regional recreational bluefish catch in number of fish by fishing mode (2010-2021). Data retrieved from the Marine Recreational Information Program (MRIP) query tool in January 2022.

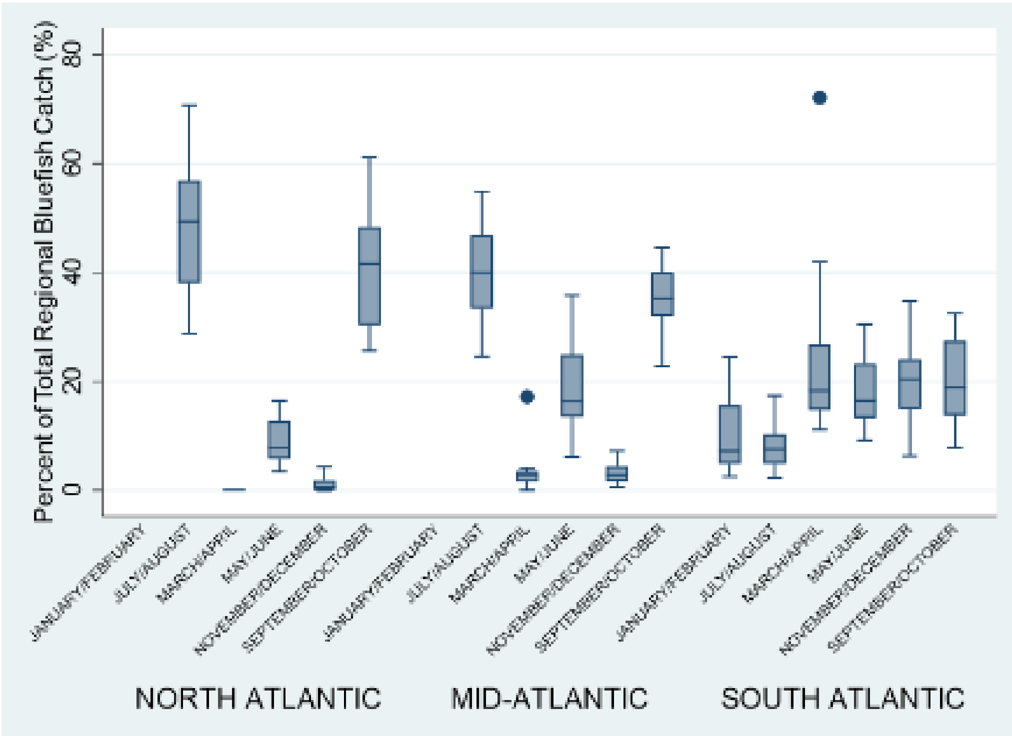


Figure 8. Proportion of total recreational bluefish catch by month grouping and region (2010-2021). Data retrieved from the Marine Recreational Information Program (MRIP) query tool in January 2022

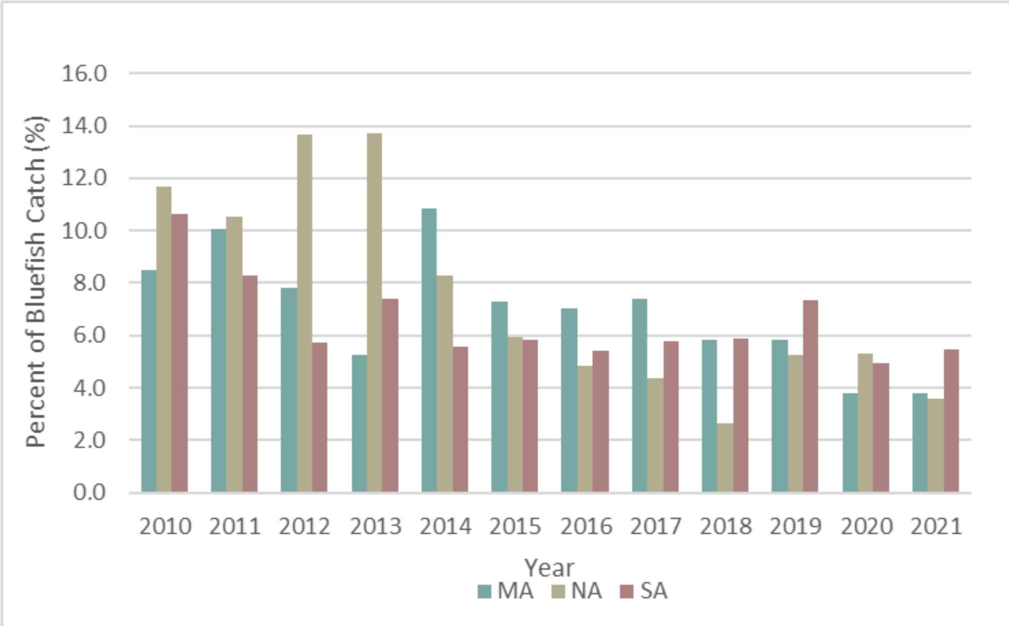


Figure 9. Recreational bluefish catch as a percent of total recreational catch by region over 2010-2021. Data retrieved from the Marine Recreational Information Program (MRIP) query tool in January 2022.

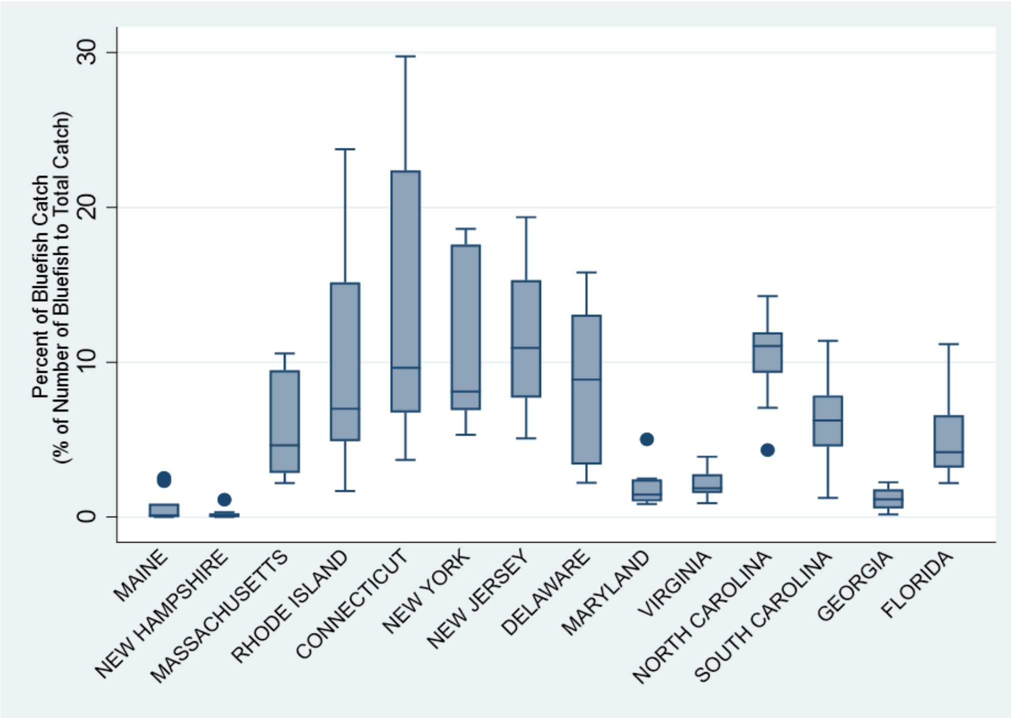


Figure 10. Box plots of recreational bluefish catch as a percent of total recreational catch by sate over 2010-2021. Data source: Data retrieved from the Marine Recreational Information Program (MRIP) query tool in January 2022. Conneticut has the hightes percent of bluefish catch relative to other species and New Hampshire the lowest.

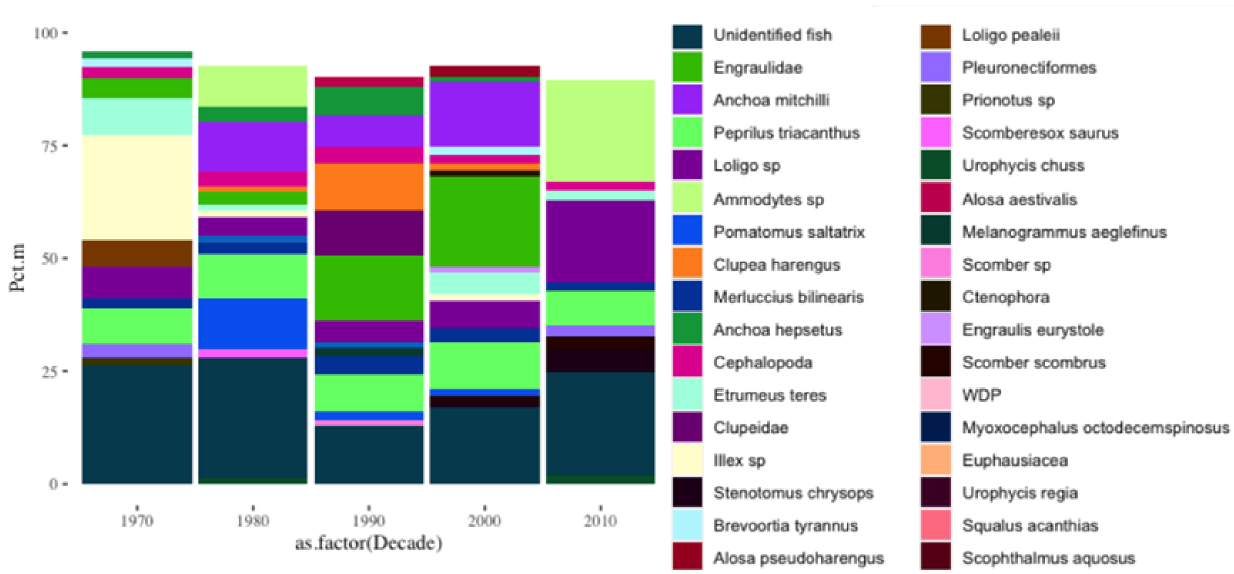


Figure 11. Bluefish diet by decade (all regions and bluefish sizes) from the Northeast Fisheries Science Center (NEFSC) bottom trawl survey, 1973-2020.

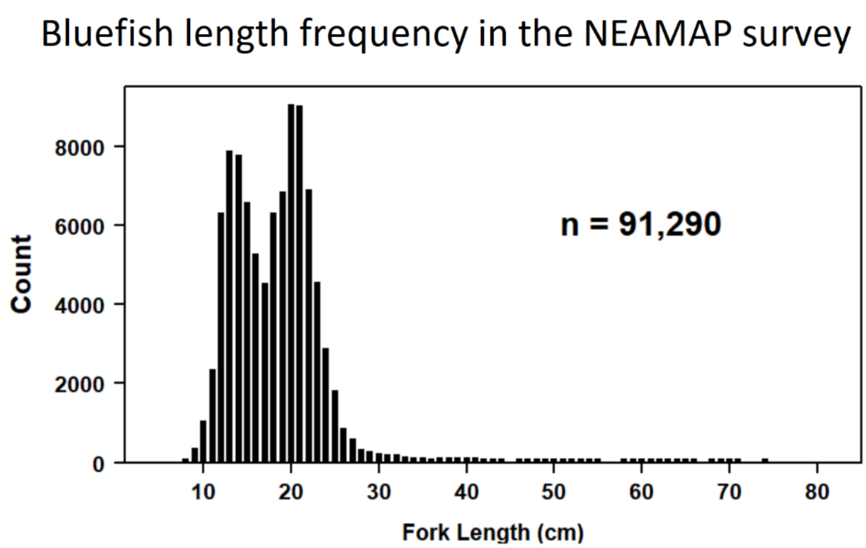


Figure 12. Length frequency of bluefish collected by the NEAMAP survey, 2007-2020. A subsample of these fish, across the full length range, was evaluated for diet.

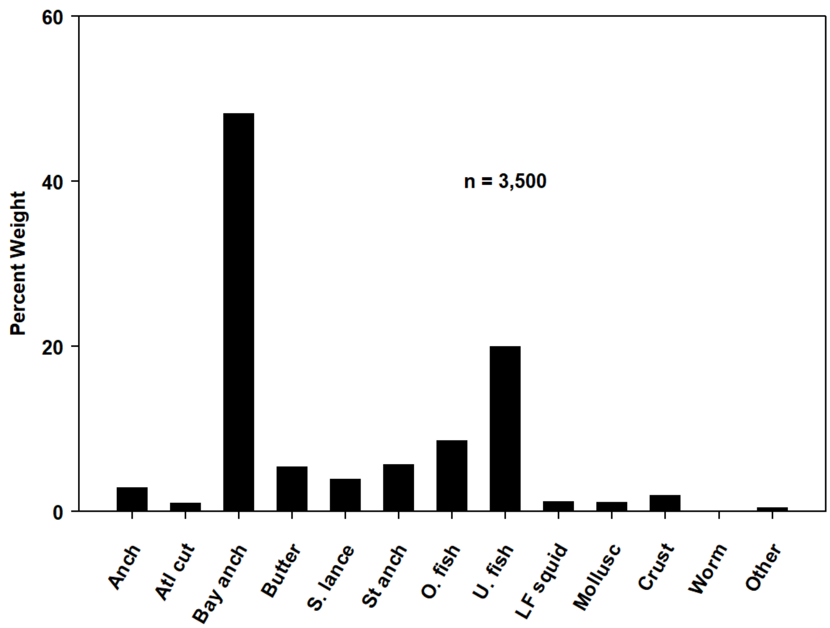


Figure 13. Prey species encountered in the stomachs of bluefish sampled by the NEAMAP survey, 2007-2021.

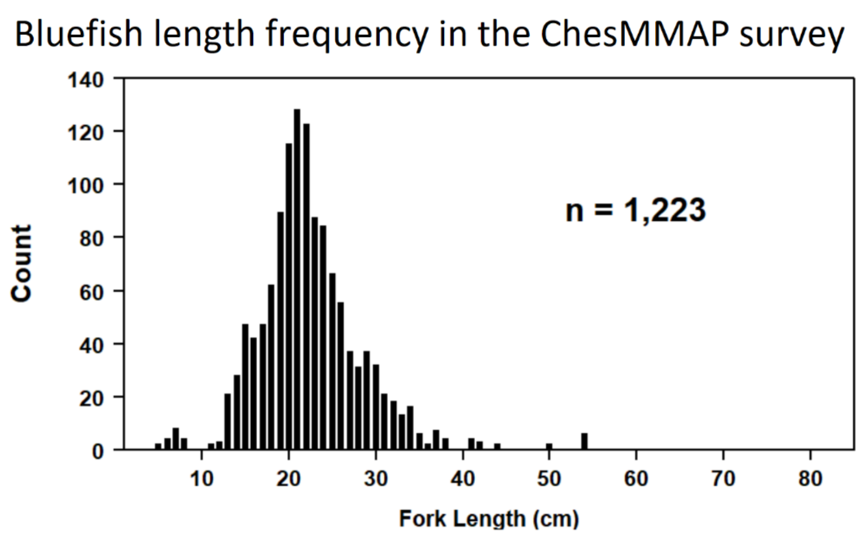


Figure 14. Length frequency of bluefish collected by the ChesMMAP survey, 2002-2020. A subsample of these fish, across the full length range, was evaluated for diet.

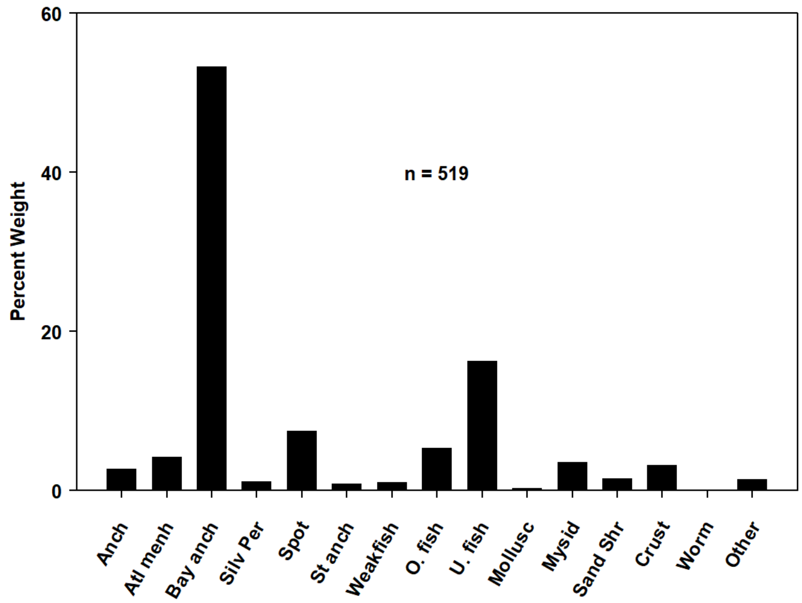


Figure 15. Prey species encountered in the stomachs of bluefish sampled by the ChesMMAP survey, 2002-2021.

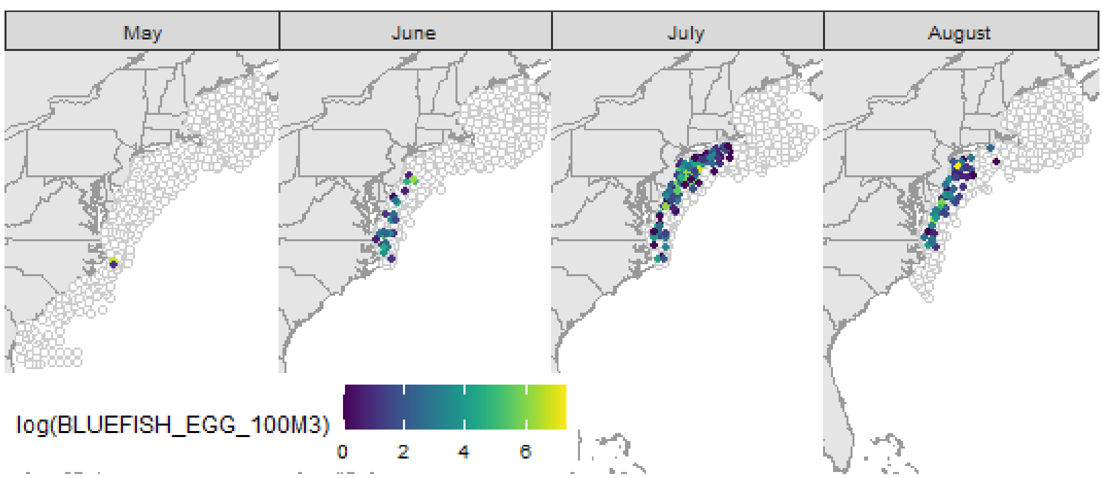


Figure 16. Map of bluefish egg distribution in the Northwest Atlantic, as collected in the Marine Resources Monitoring, Assessment and Prediction (MARMAP) program (1977-1987) and inthe Ecosystem Monitoring (EcoMon) program (1993 only). No eggs were collected in January through April or September through December.

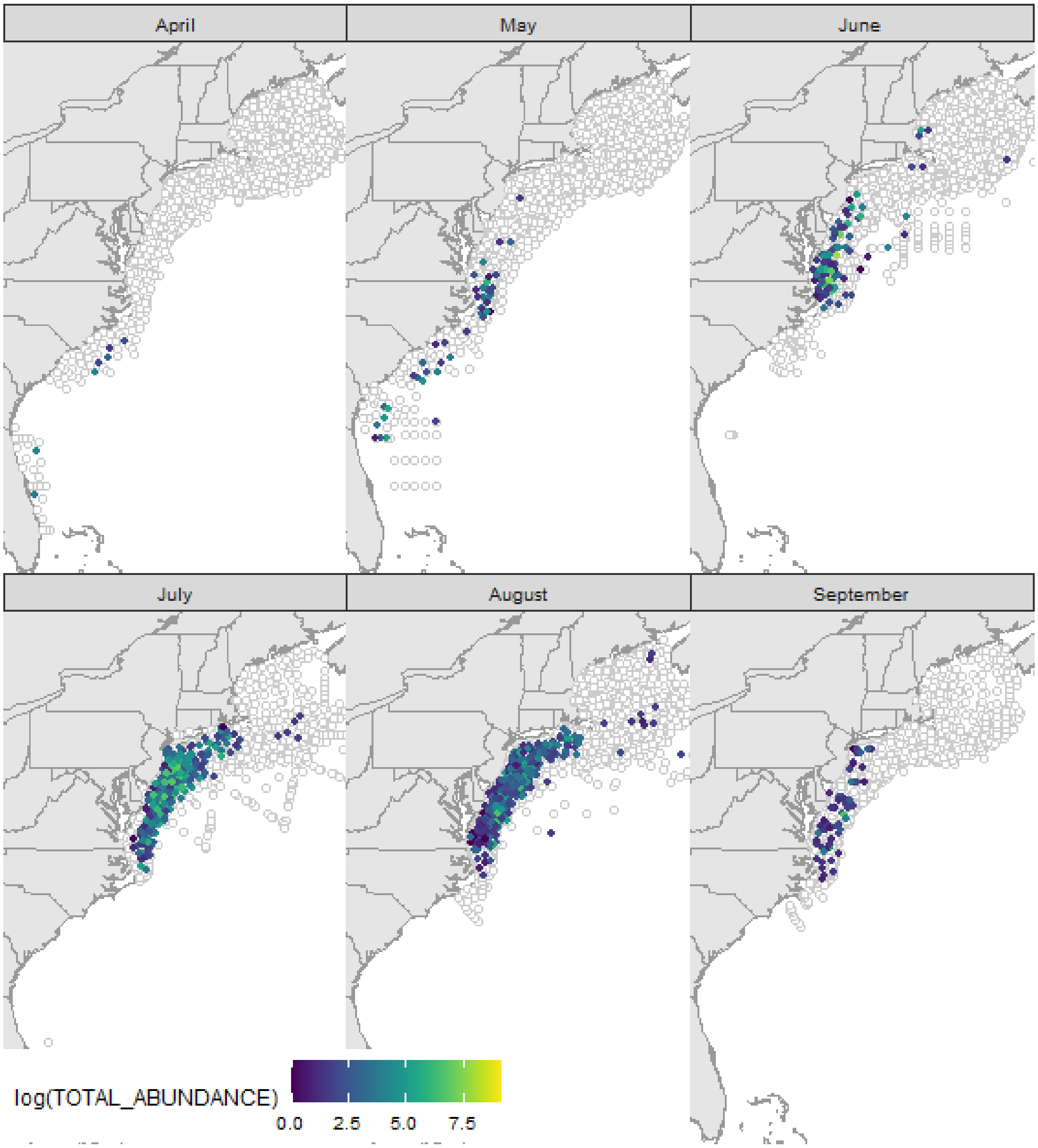


Figure 17. Map of bluefish larvae distribution in the Northwest Atlantic, as collected in the Herring and Sand Lance Program (1988-1994), Georges Bank Global Ocean Ecosystems Dynamics (1995-1999), MARMAP (1977-1987), and EcoMon (1992 – present). No larvae were collected in February or March, or October through December. There was one positive tow in January (not shown).

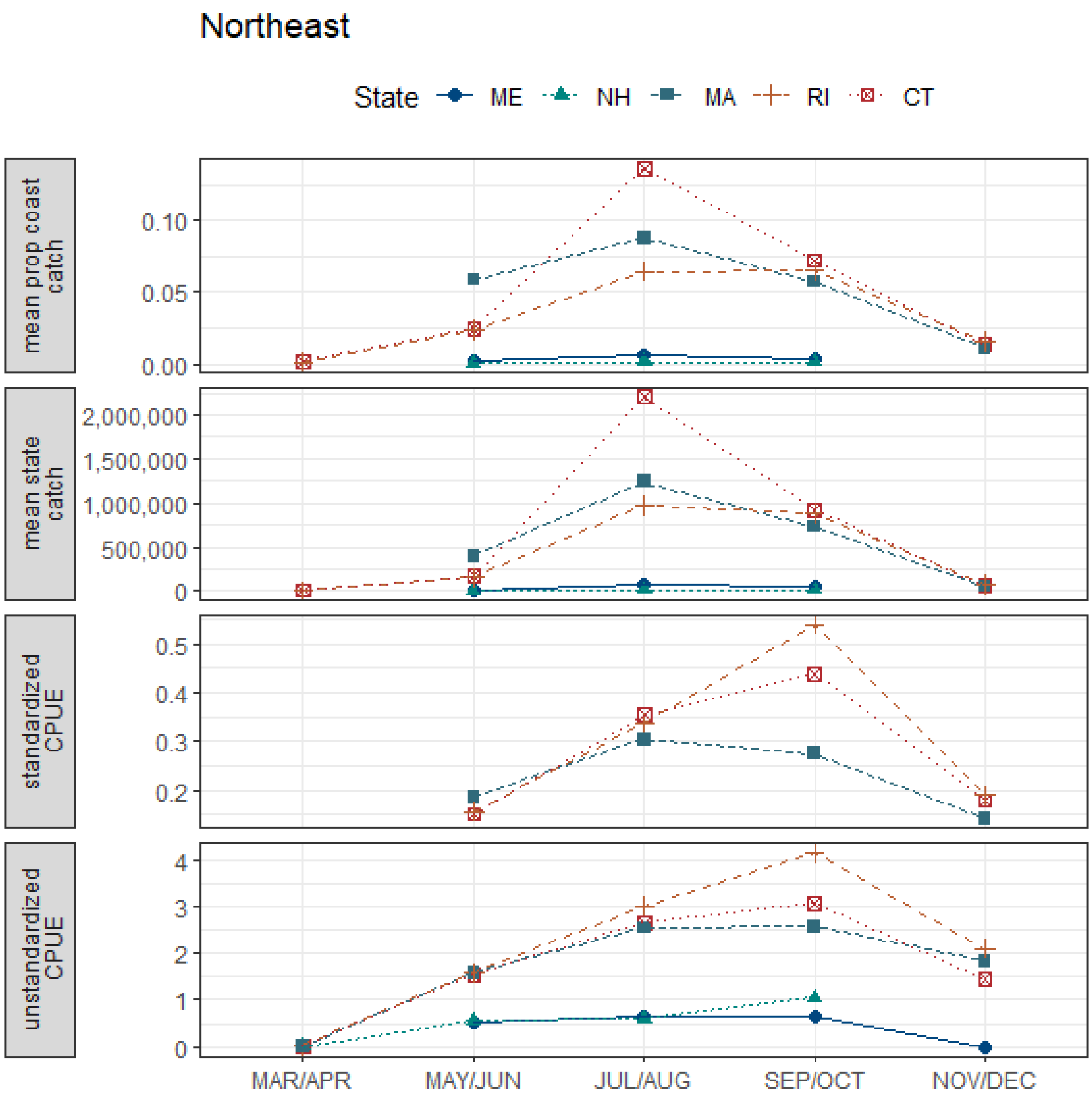


Figure 18. Mean proportion of coastwide catch, mean state catch (lbs), standardized CPUE, and unstandardized CPUE for Northeast states in March through December.

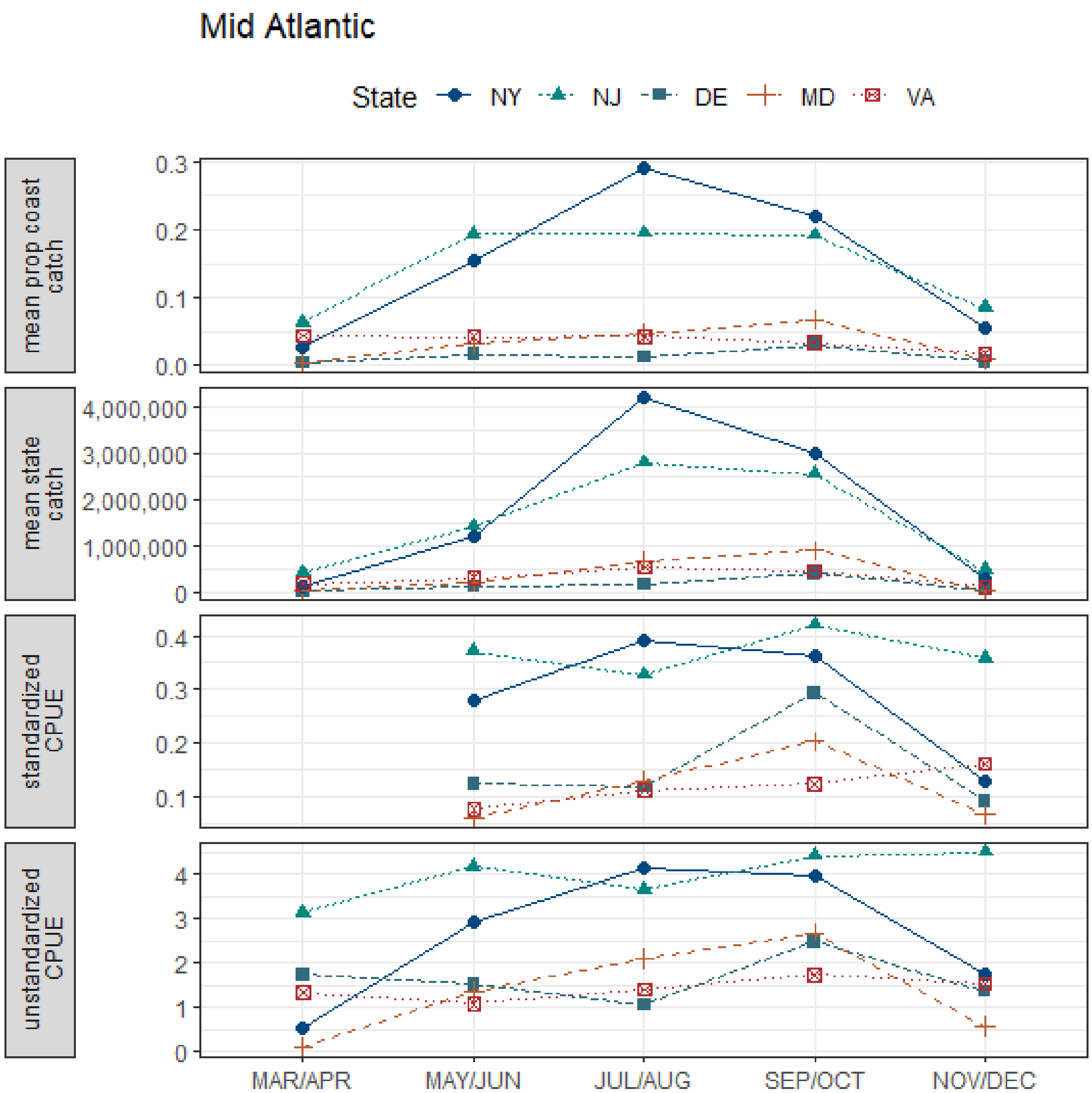


Figure 19. Mean proportion of coastwide catch, mean state catch (lbs), standardized CPUE, and unstandardized CPUE for Mid Atlantic states in March through December.

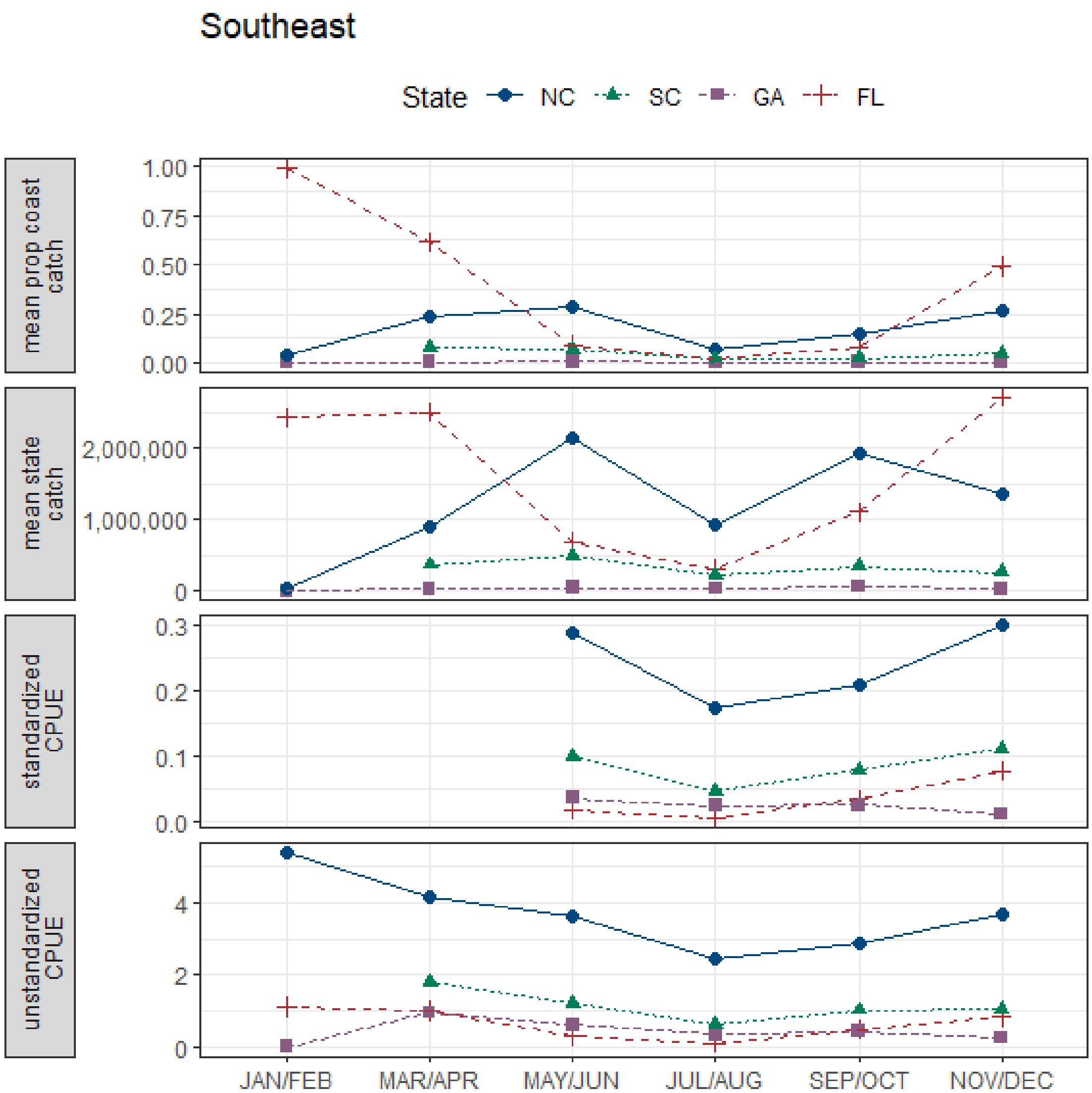


Figure 20. Mean proportion of coastwide catch, mean state catch (lbs), standardized CPUE, and unstandardized CPUE for Southeast states in January through December.

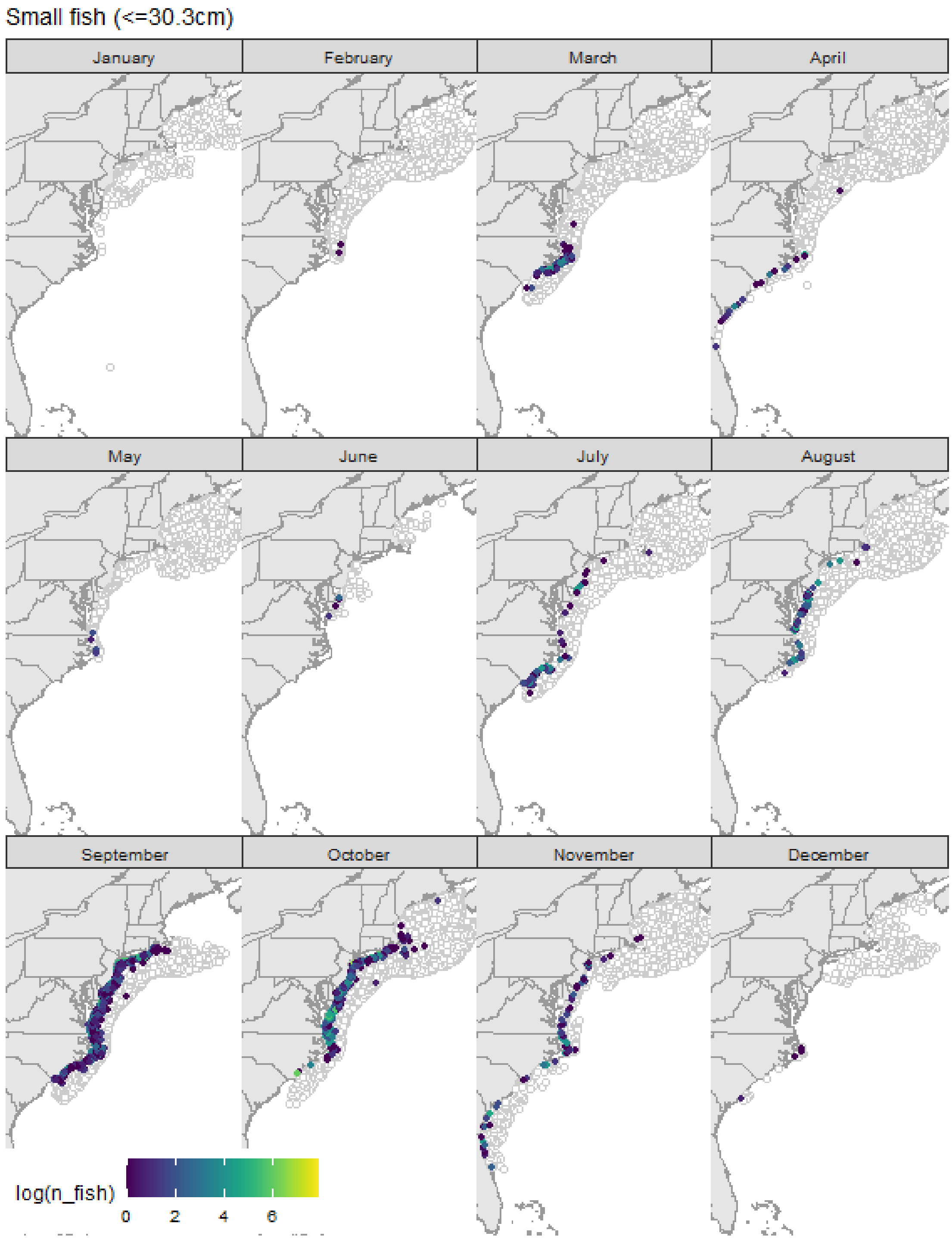


Figure 21. Map of small (<=30.3cm) bluefish distribution in the Northwest Atlantic, as collected in the NMFS bottom trawl survey, which has sampled most years since 1963.

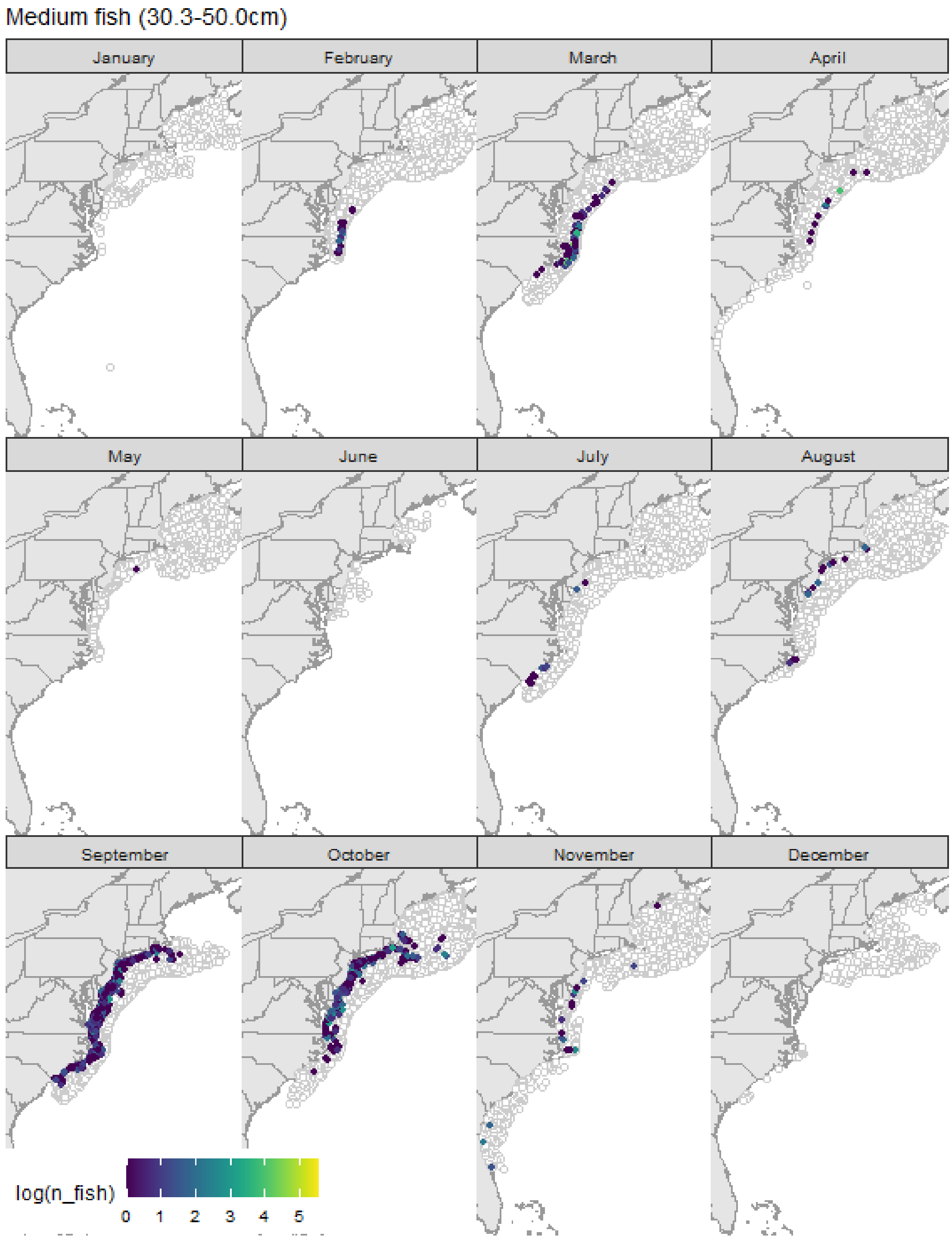


Figure 22. Map of medium (30.3-50.0cm) bluefish distribution in the Northwest Atlantic, as collected in the NMFS bottom trawl survey, which has sampled most years since 1963.

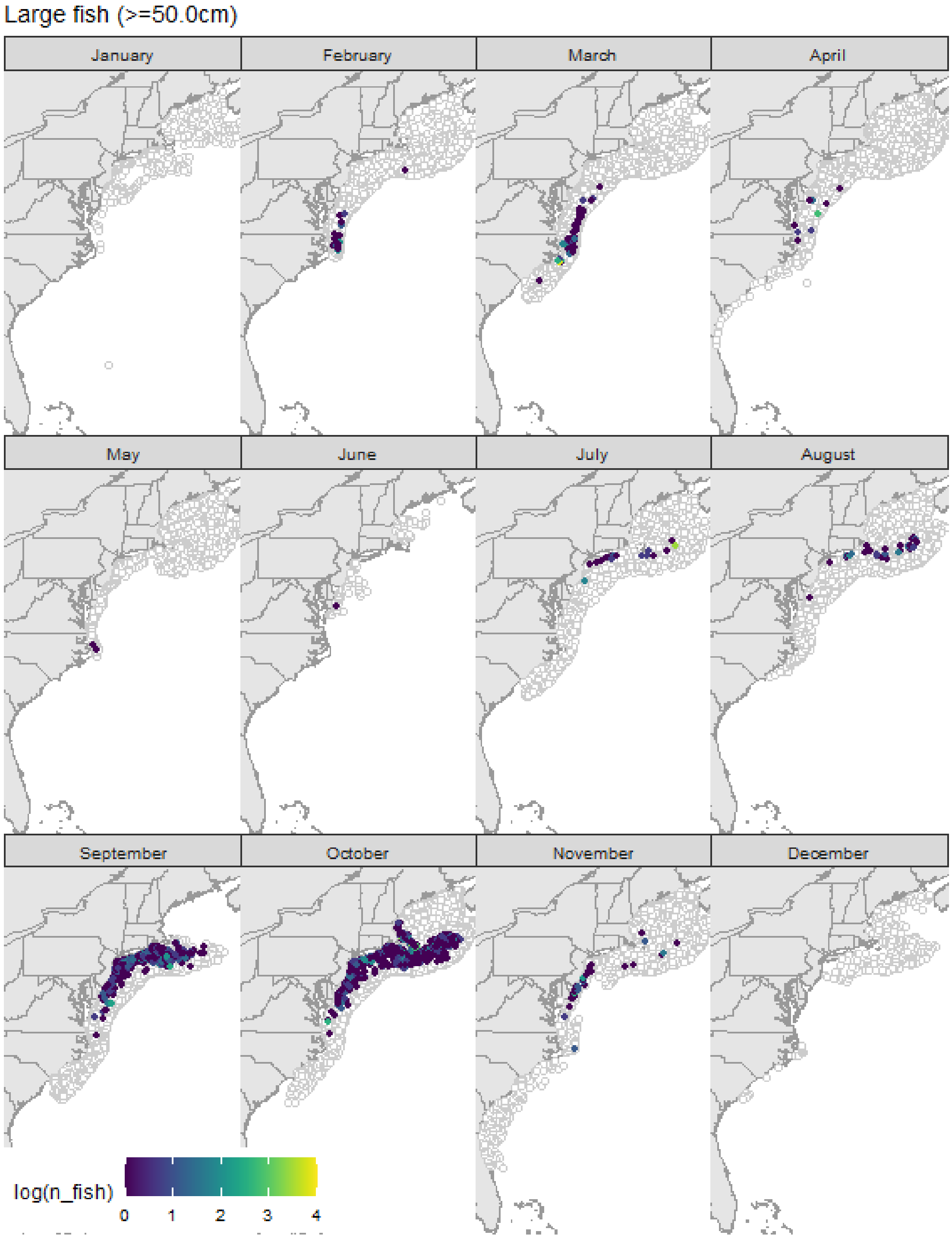


Figure 23. Map of large (>50.0cm) bluefish distribution in the Northwest Atlantic, as collected in the NMFS bottom trawl survey, which has sampled most years since 1963.

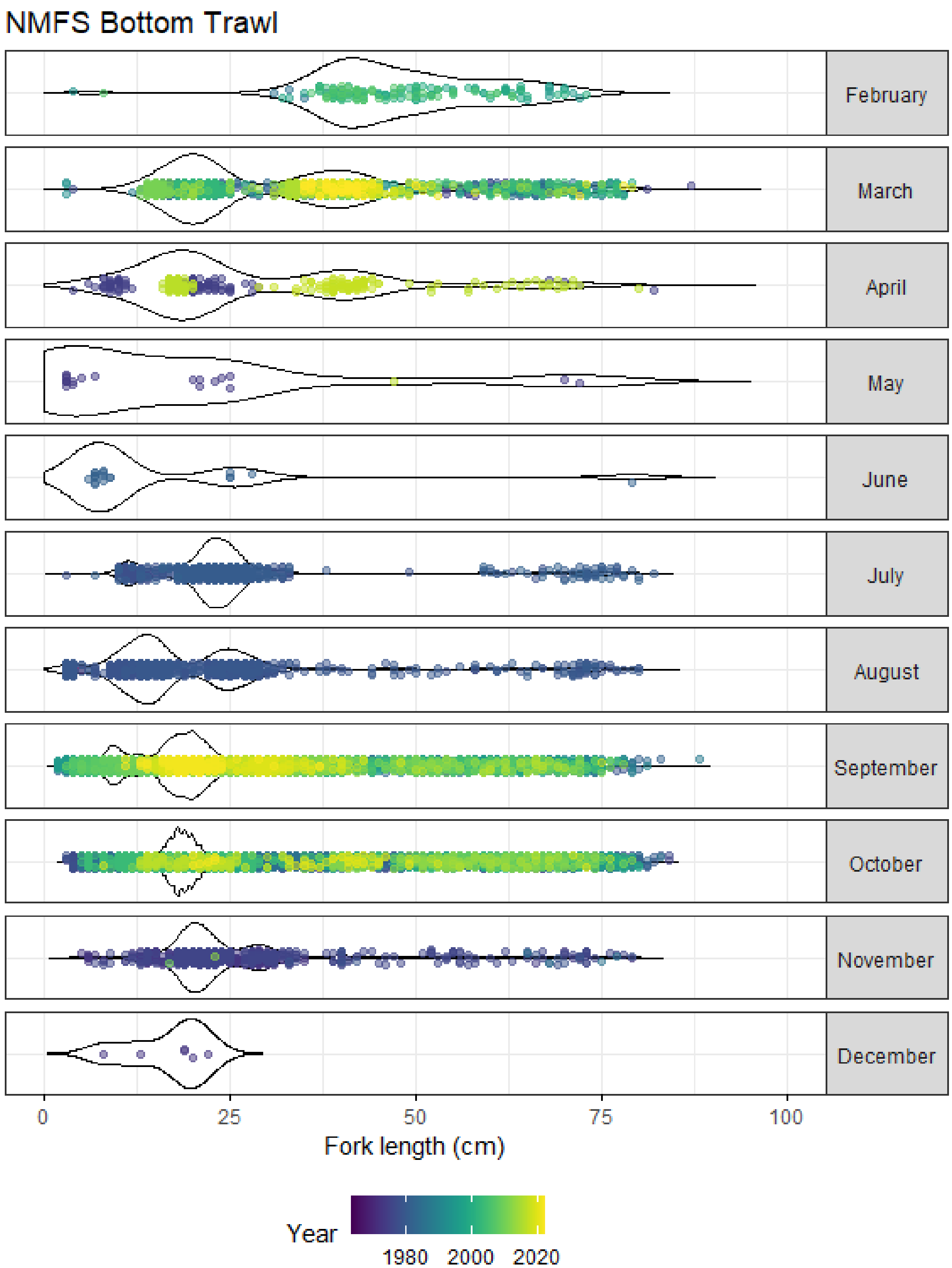


Figure 24. Bluefish length distributions in all NEFSC NMFS bottom trawl samples.

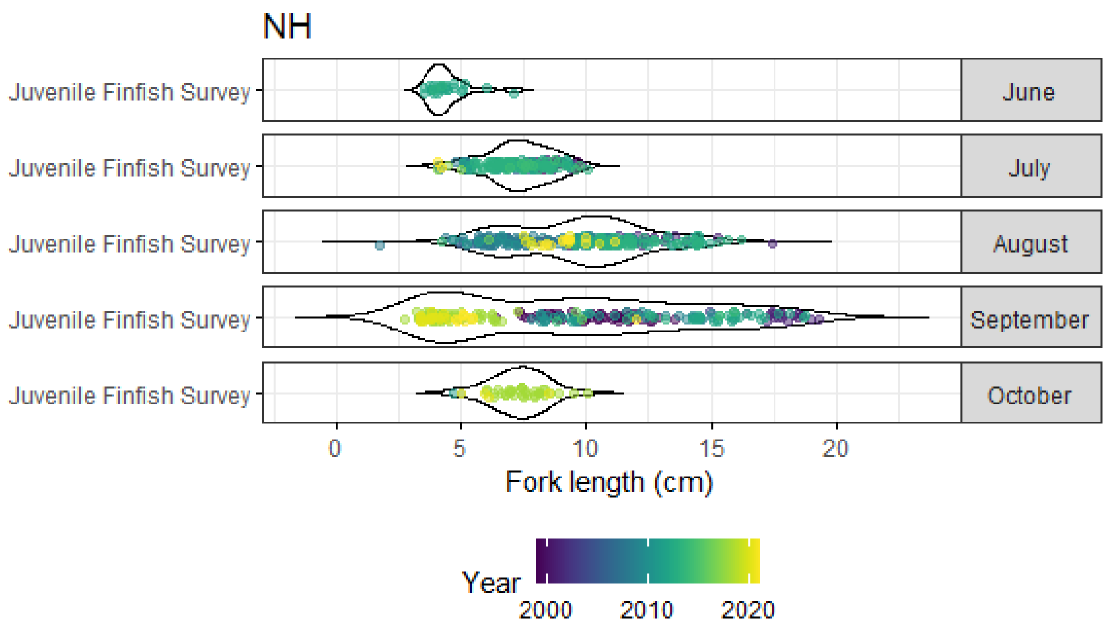


Figure 25. Bluefish length distributions in the New Hampshire Juvenile Finfish Survey.

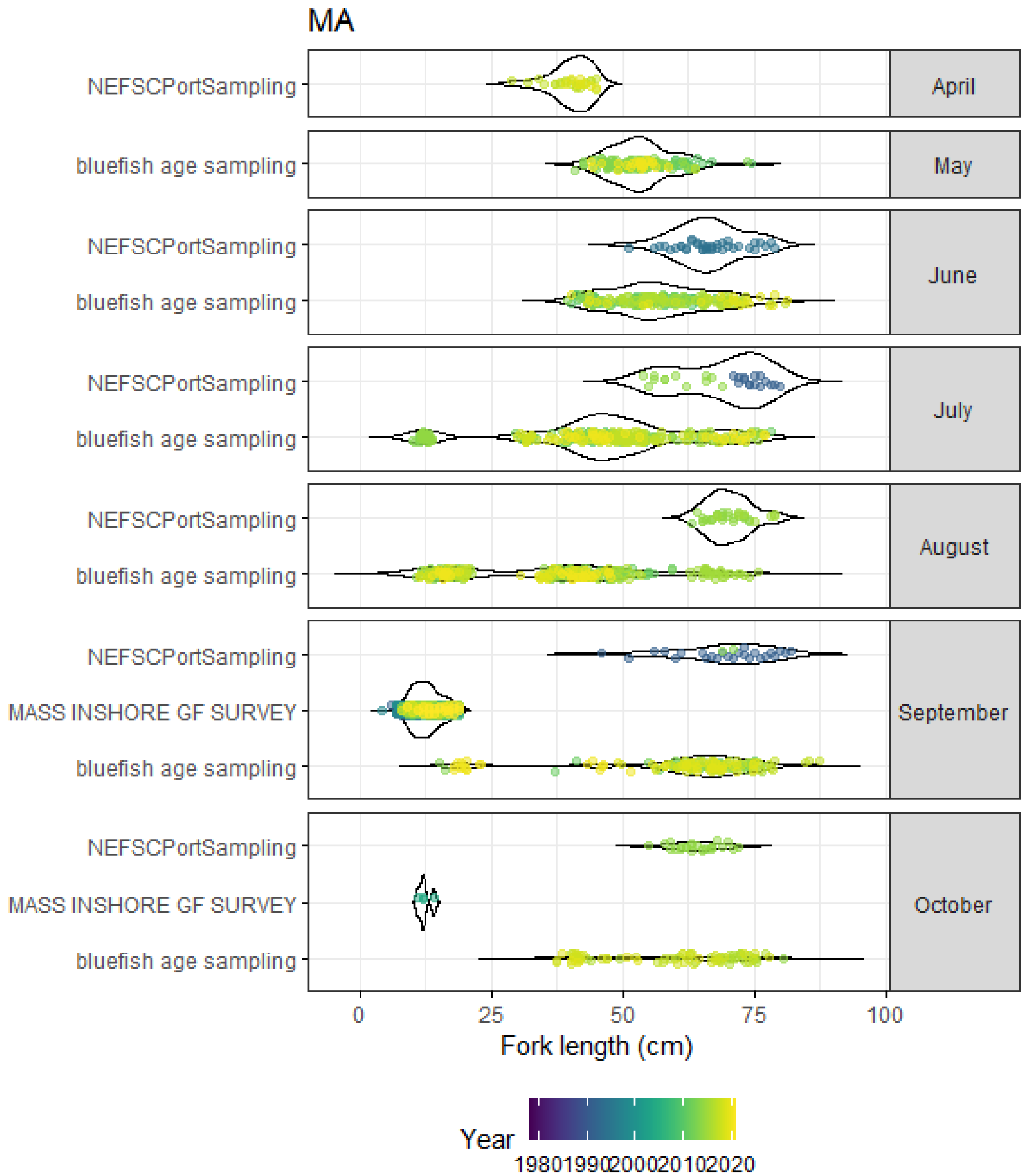


Figure 26. Bluefish length distributions in Massachusetts-based surveys and samples.

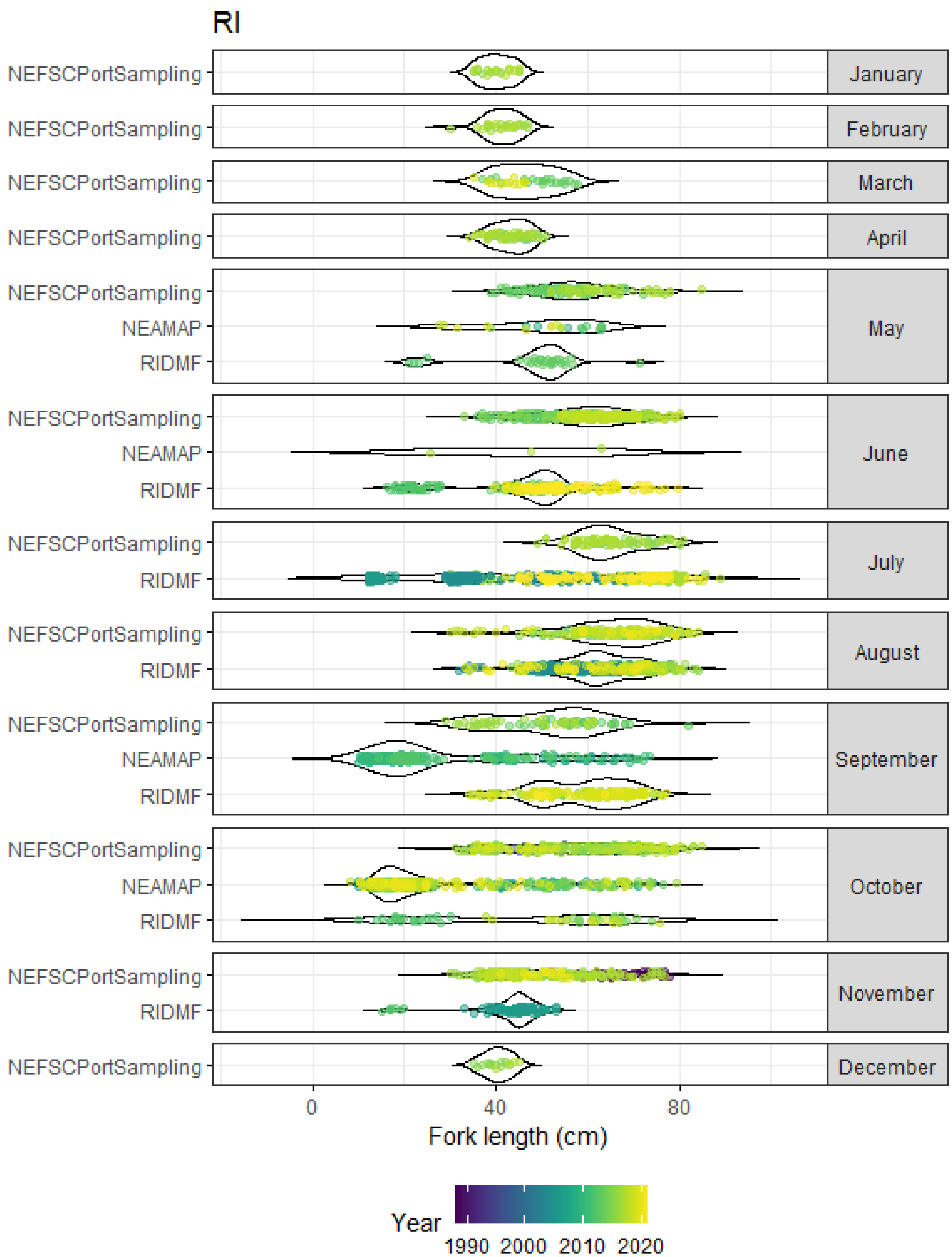


Figure 27. Bluefish length distributions in Rhode Island-based surveys and samples.

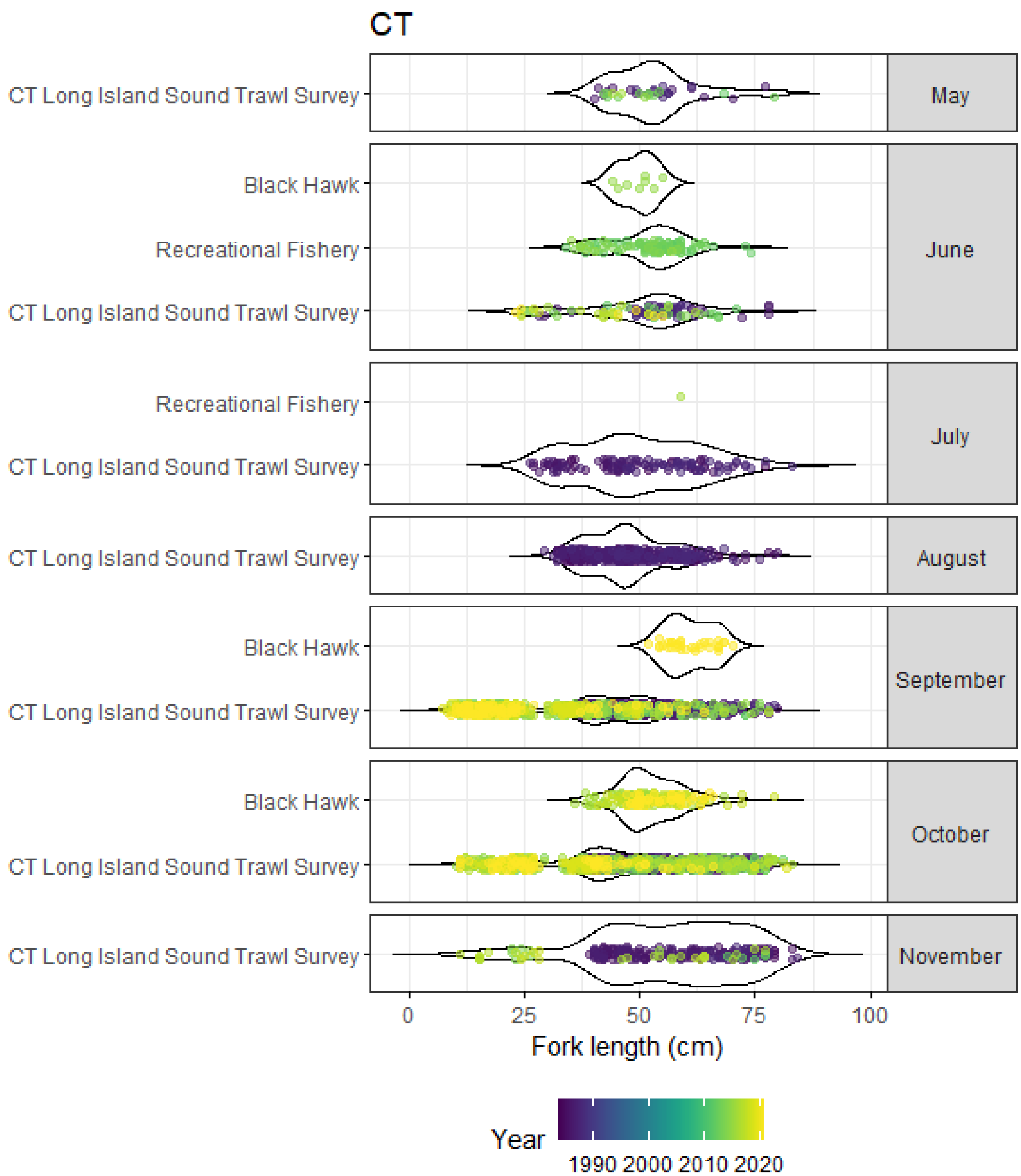


Figure 28. Bluefish length distributions in Connecticut-based surveys and samples.

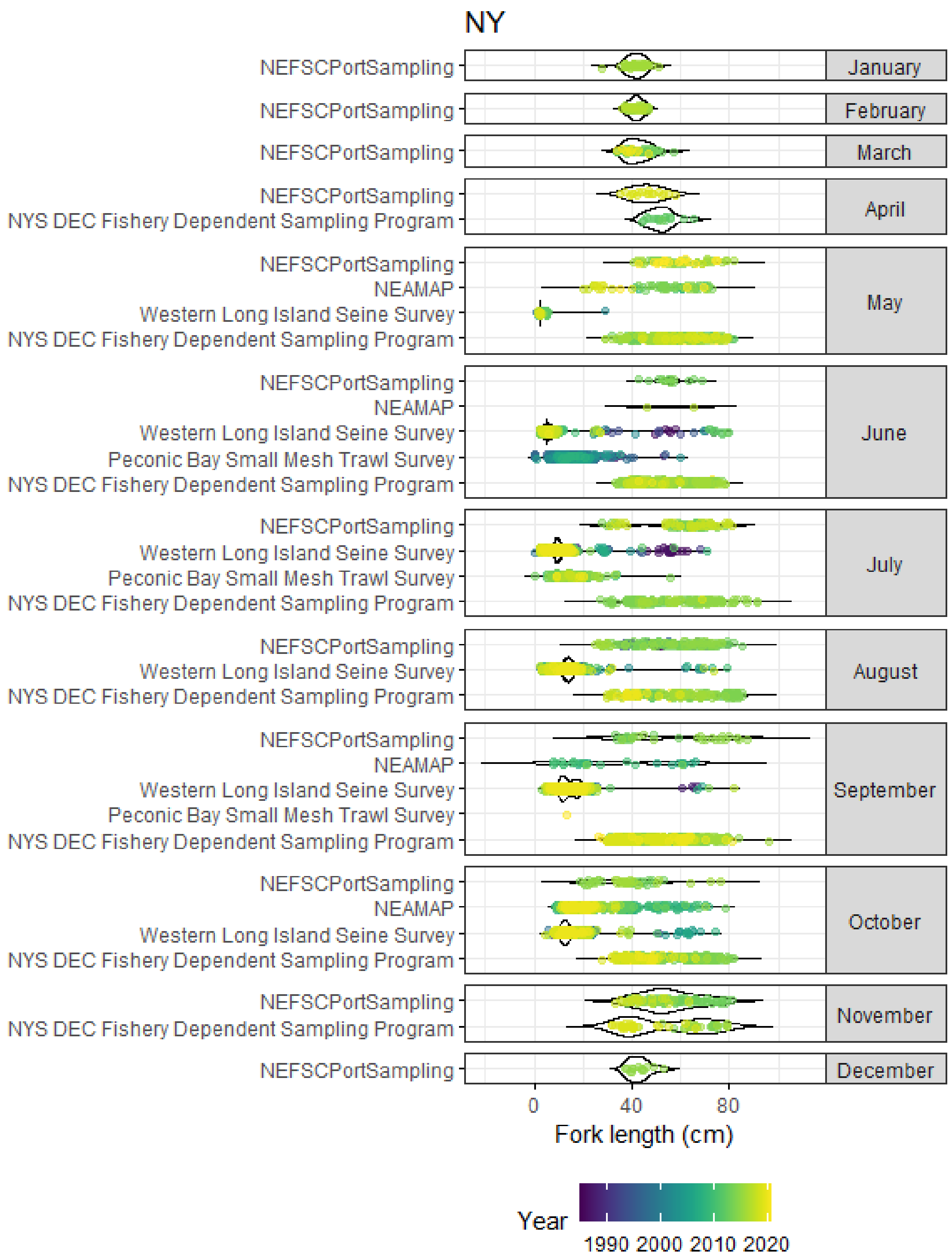


Figure 29. Bluefish length distributions in New York-based surveys and samples.

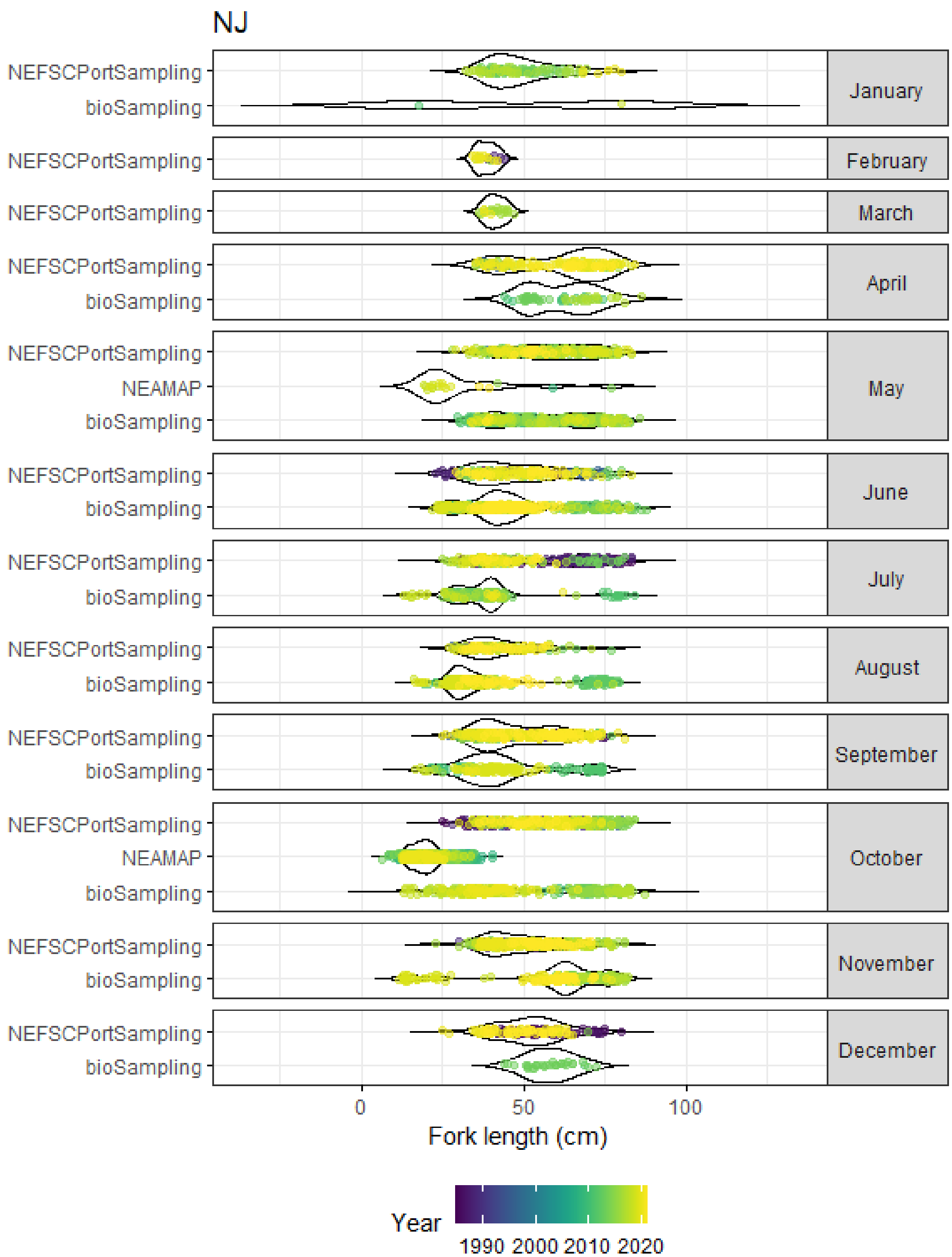


Figure 30. Bluefish length distributions in New Jersey-based surveys and samples.

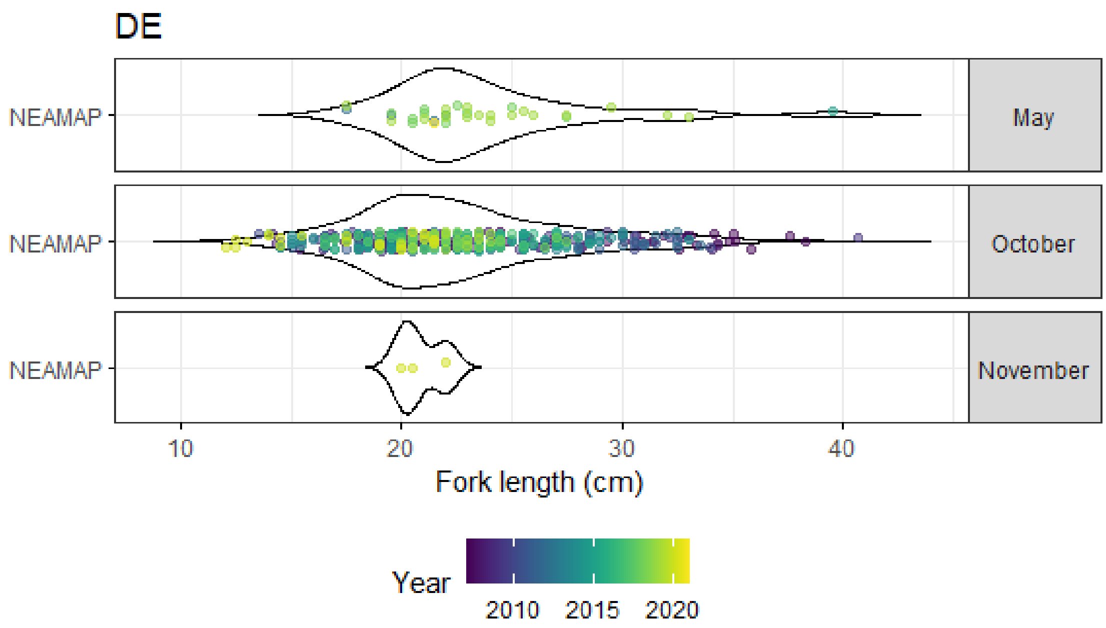


Figure 31. Bluefish length distributions in NEAMAP survey samples taken in Delaware.

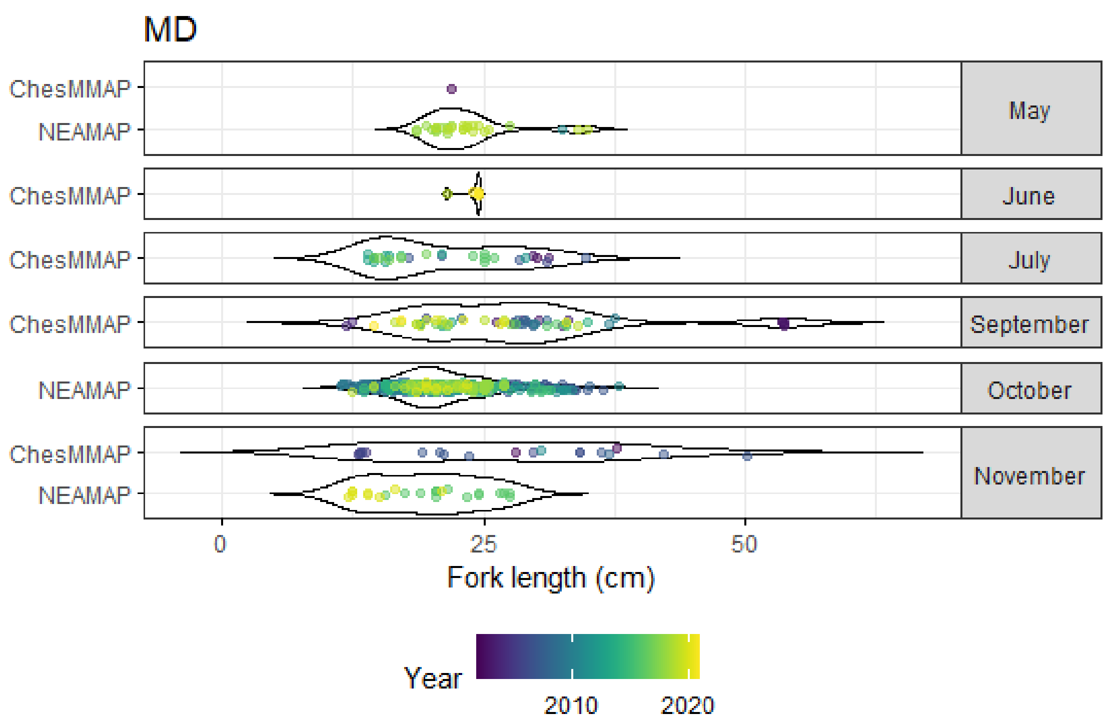


Figure 32. Bluefish length distributions in Maryland-based surveys and samples.

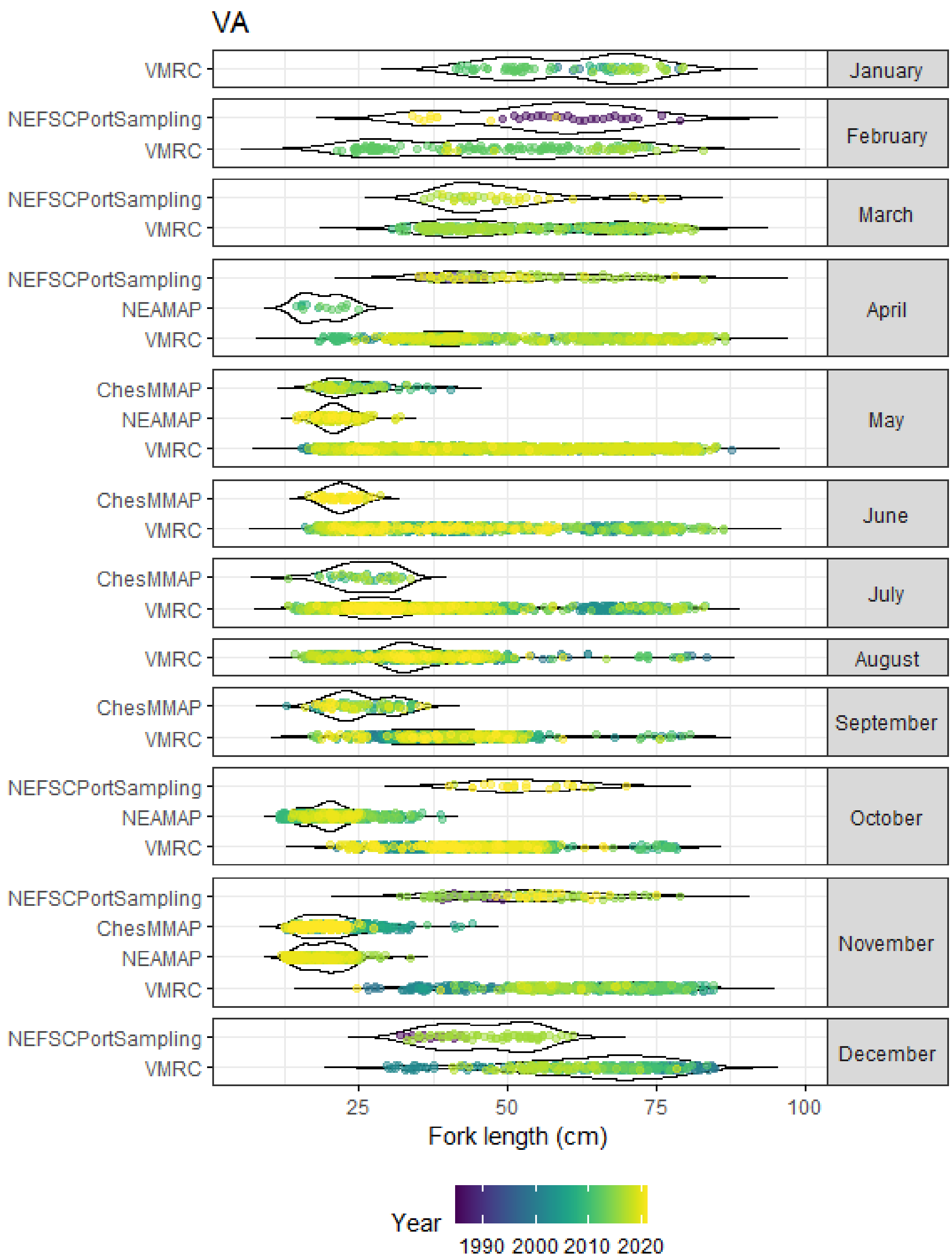


Figure 33. Bluefish length distributions in Virginia-based surveys and samples.

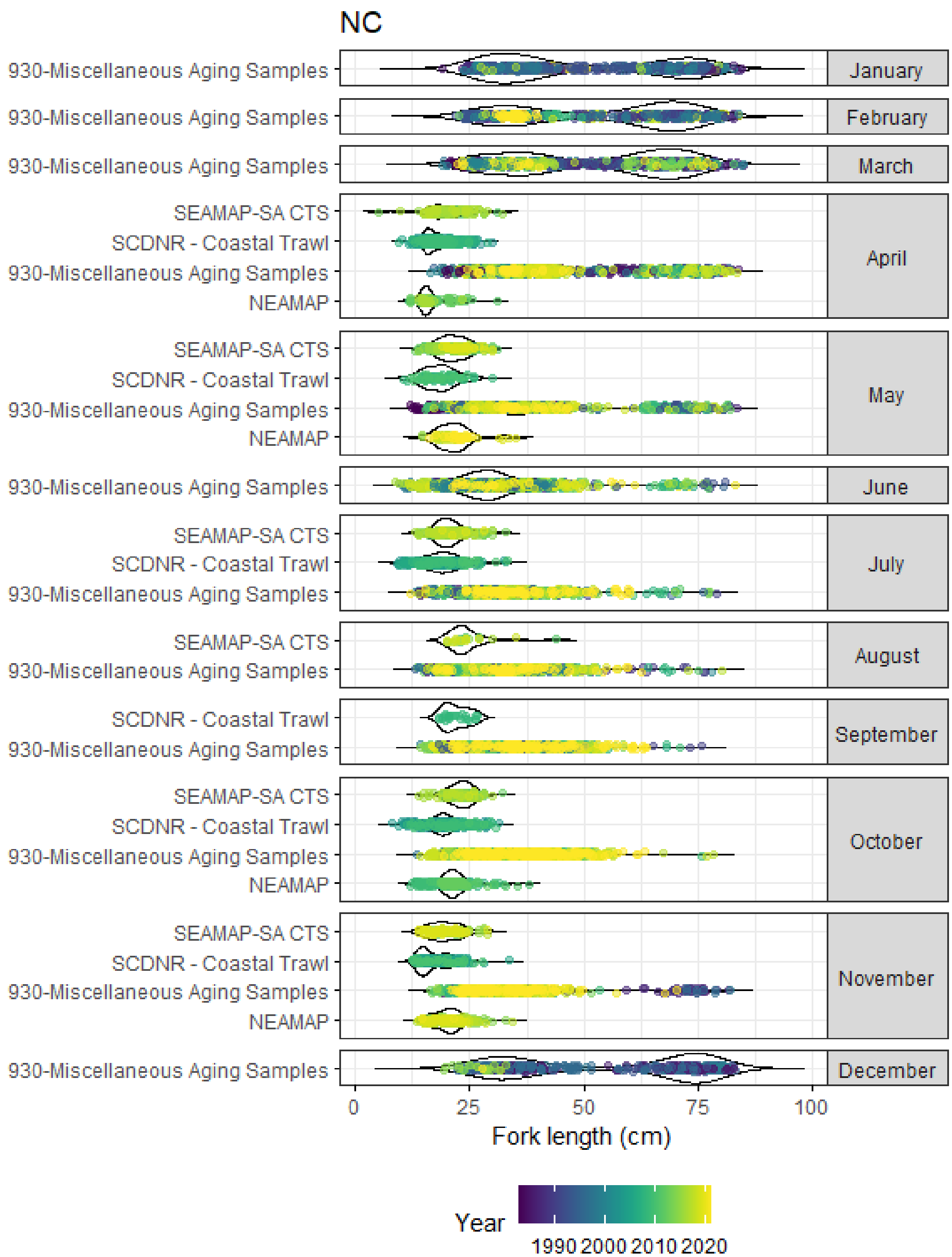


Figure 34. Bluefish length distributions in North Carolina-based surveys and samples.

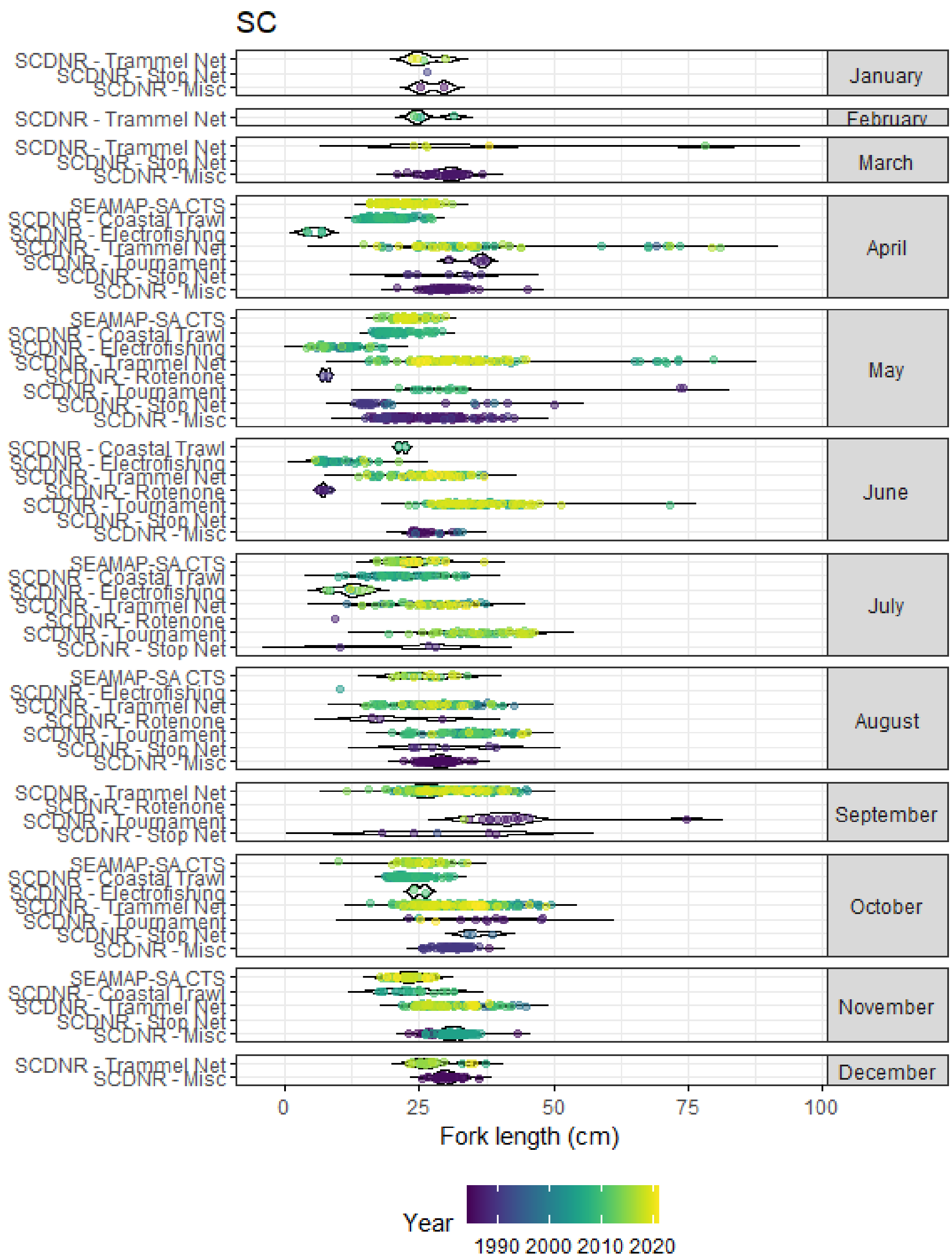


Figure 35. Bluefish length distributions in South Carolina-based surveys and samples.

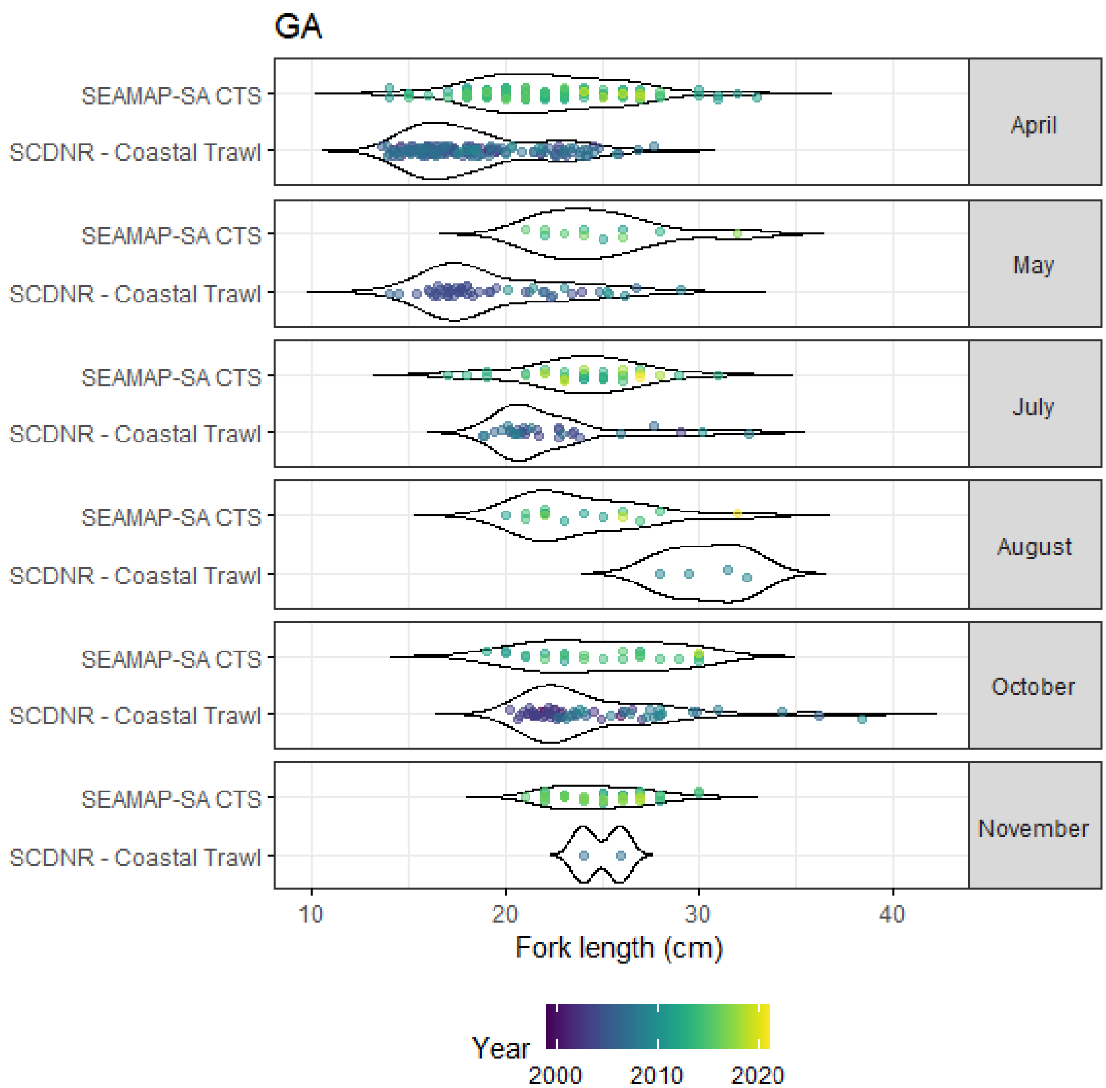


Figure 36. Bluefish length distributions in Georgia-based surveys and samples.

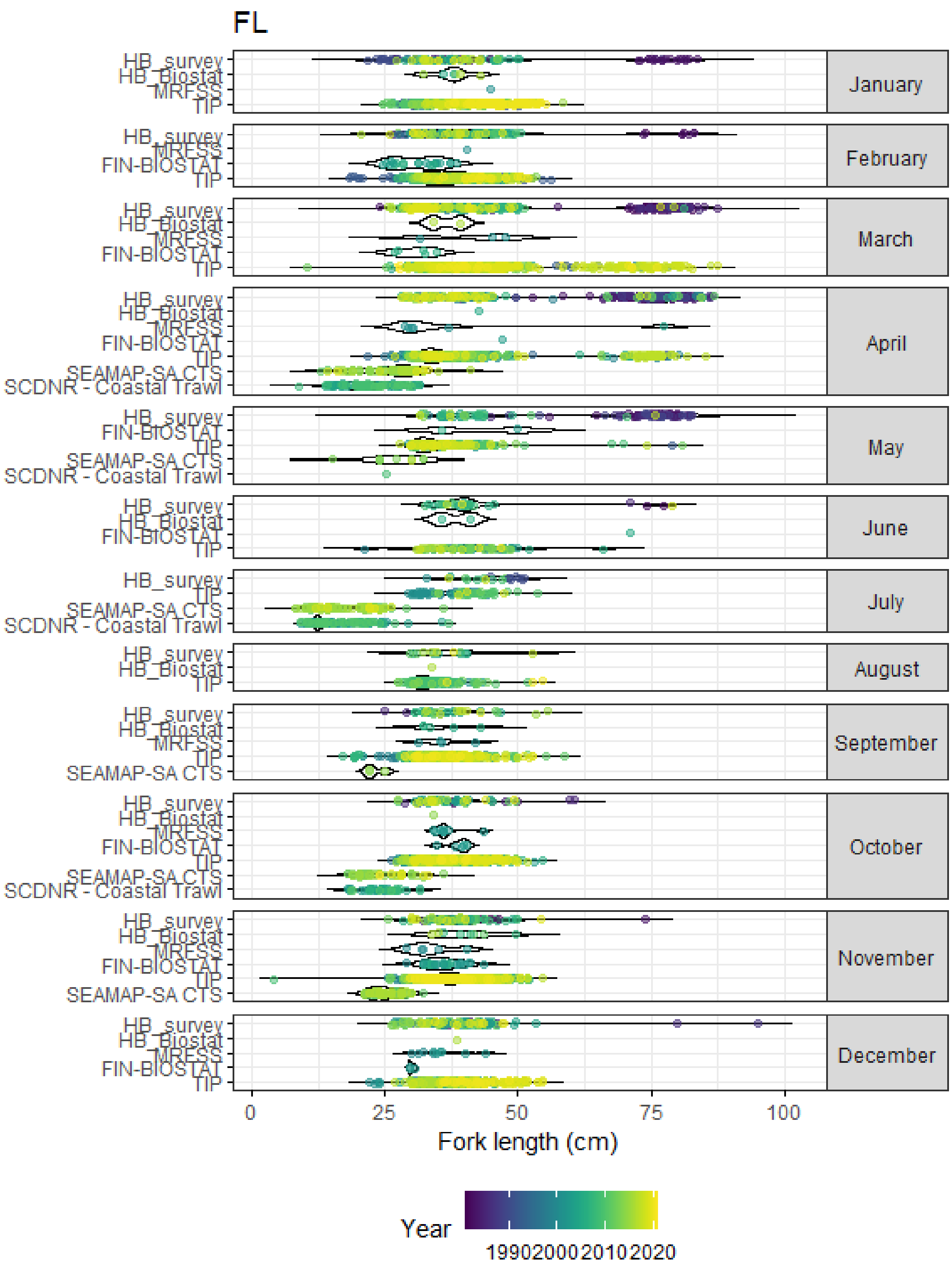


Figure 37. Bluefish length distributions in Florida-based surveys and samples.

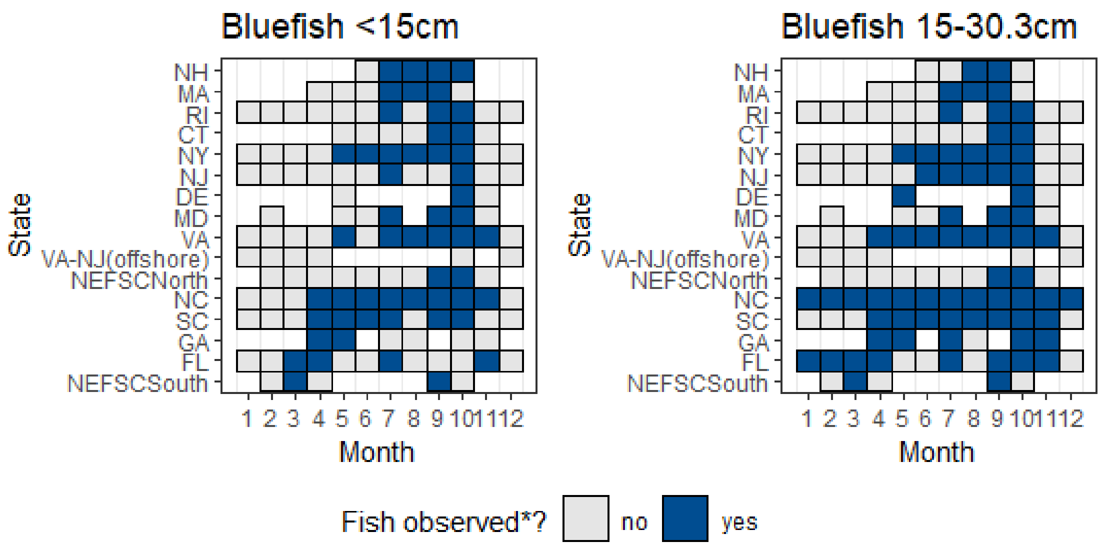


Figure 38. Summary of months when bluefish <15cm and between 15-30.3cm have been found in all coastal Atlantic states and in federal surveys. (*) Bluefish are marked as observed if the month had more than 20 fish observed over 3 or more years.

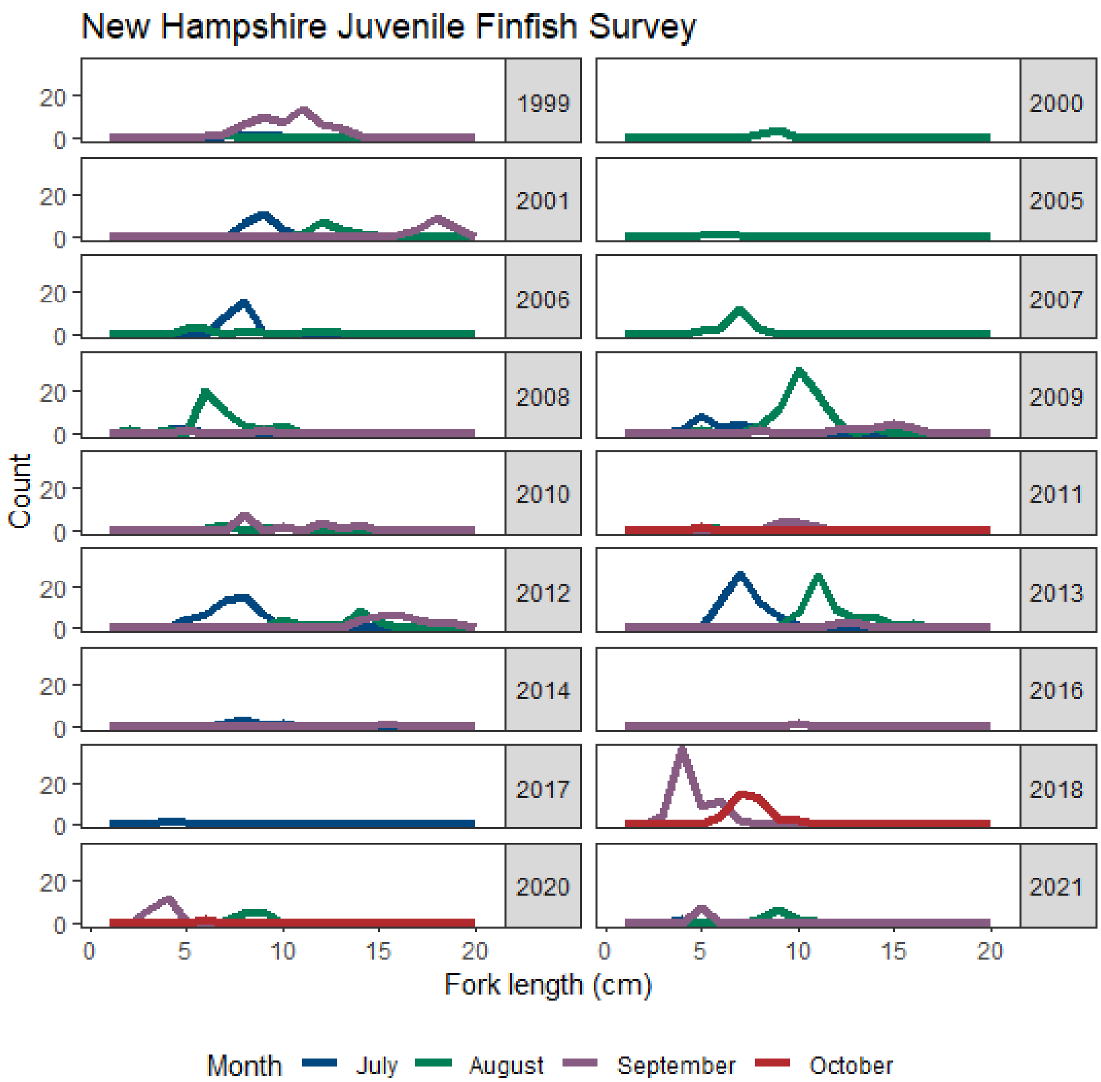


Figure 39. Length distributions of bluefish under 30.3cm by month in the New Hampshire Juvenile Finfish Survey.

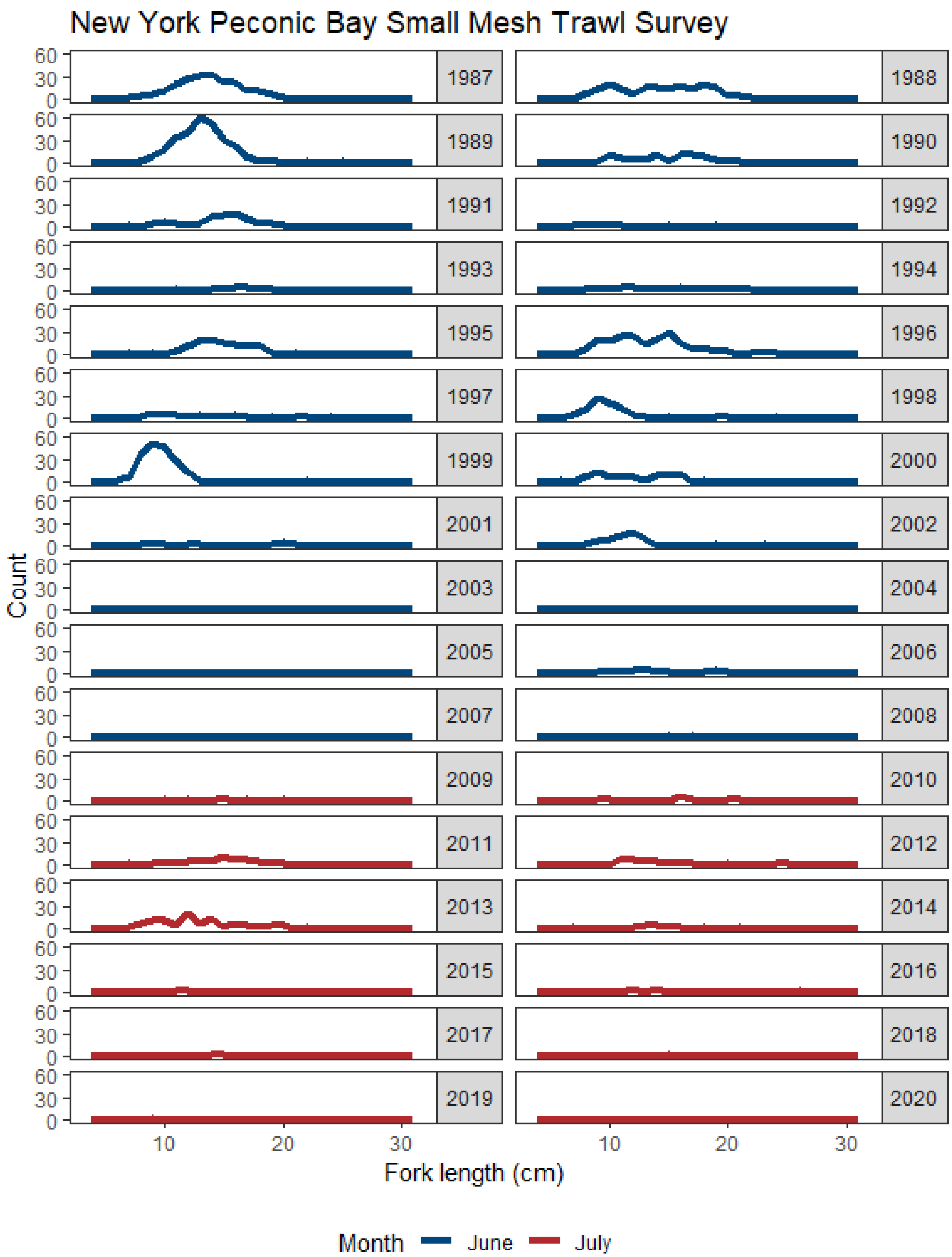


Figure 40. Length distributions of bluefish under 30.3cm by month in the New York Peconic Bay Small Mesh Survey. Bimodal cohort length peaks are visible in several years, including 1993, 2001, and 2007.

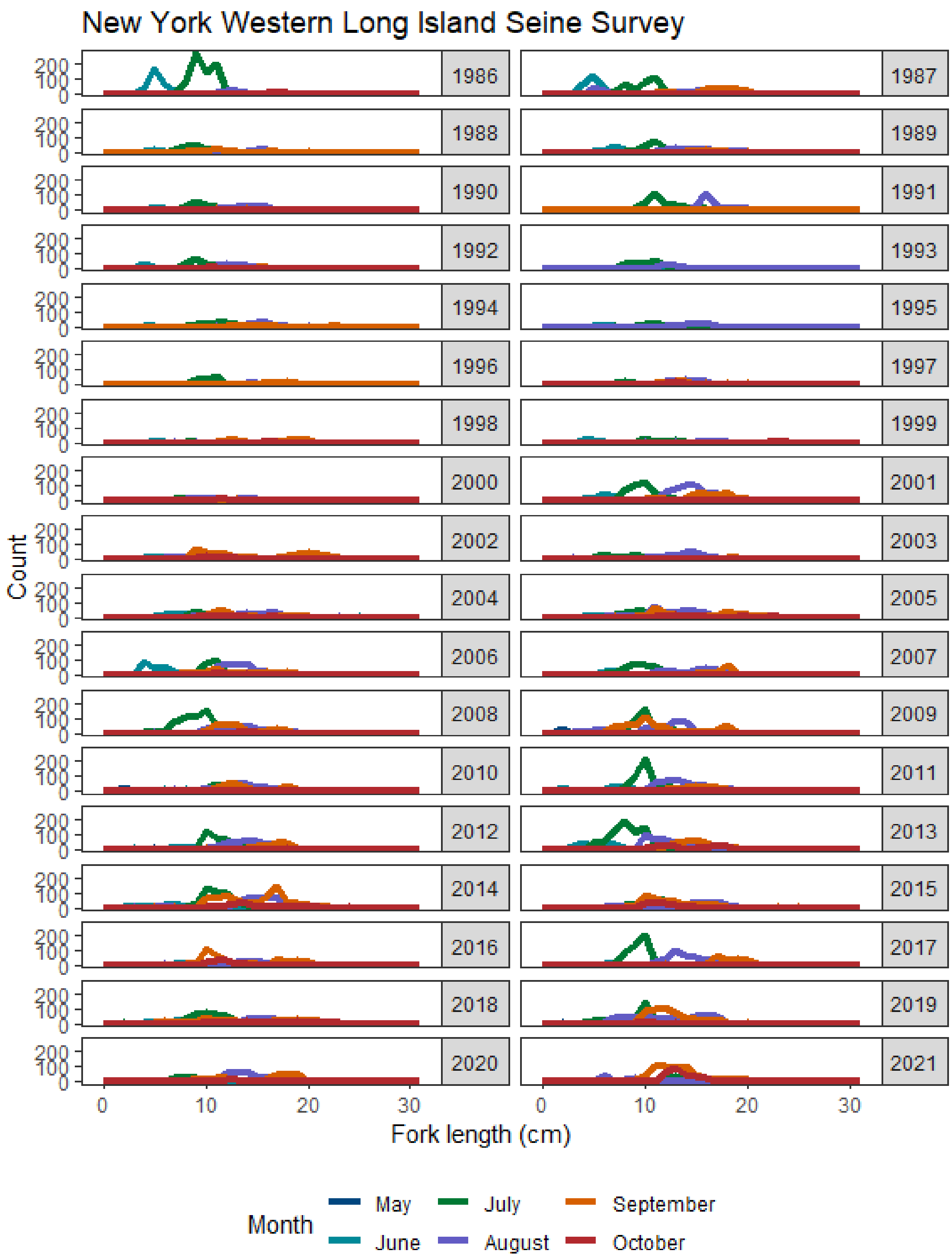


Figure 41. Length distributions of bluefish under 30.3cm by month in the New York Western Long Island Seine Survey. Bimodal cohort length peaks are visible in several years, including 1998, 2002, and 2016.

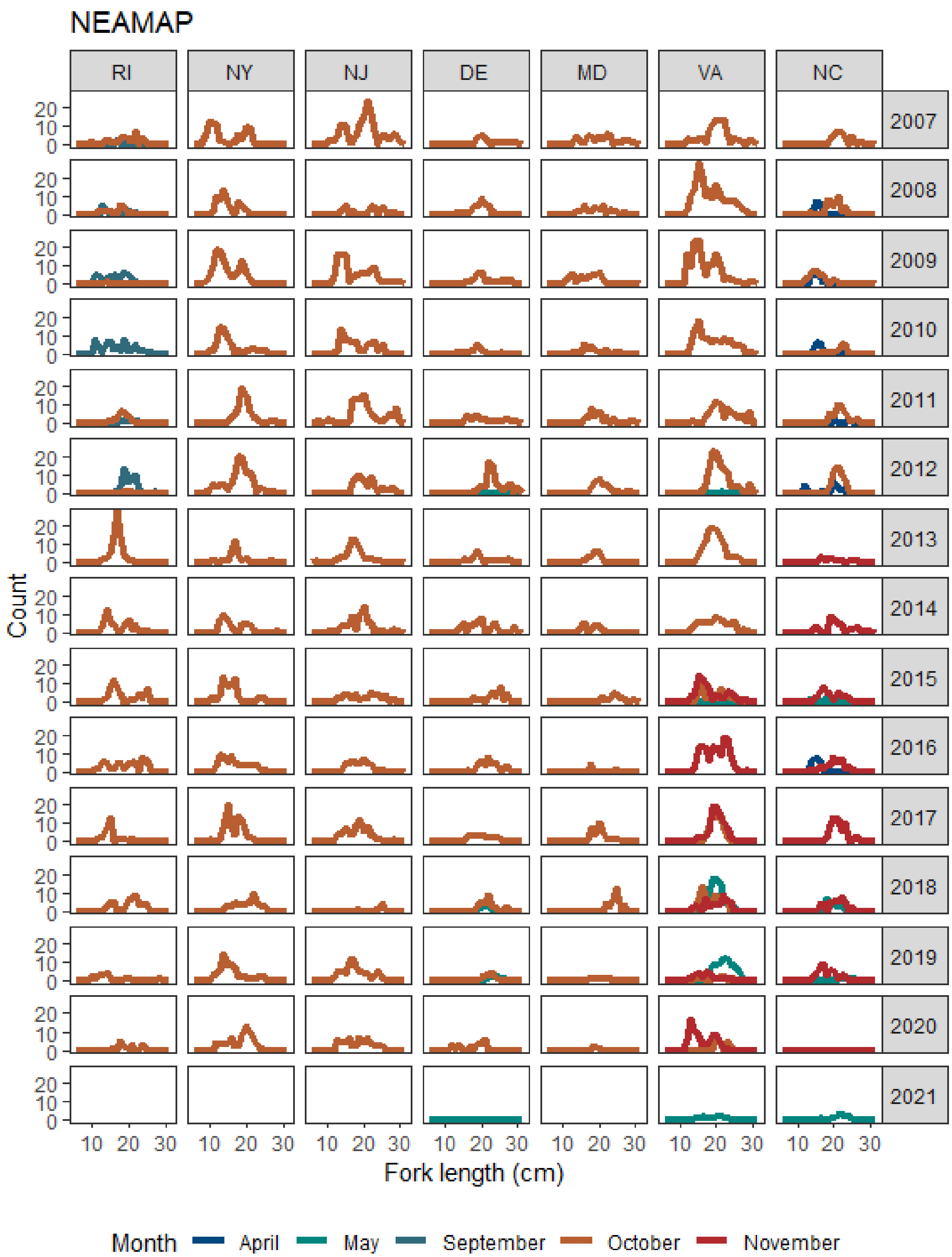


Figure 42. Length distributions of bluefish under 30.3cm by month in the NEAMAP survey. Bimodal cohort length peaks are visible in several years in some states.

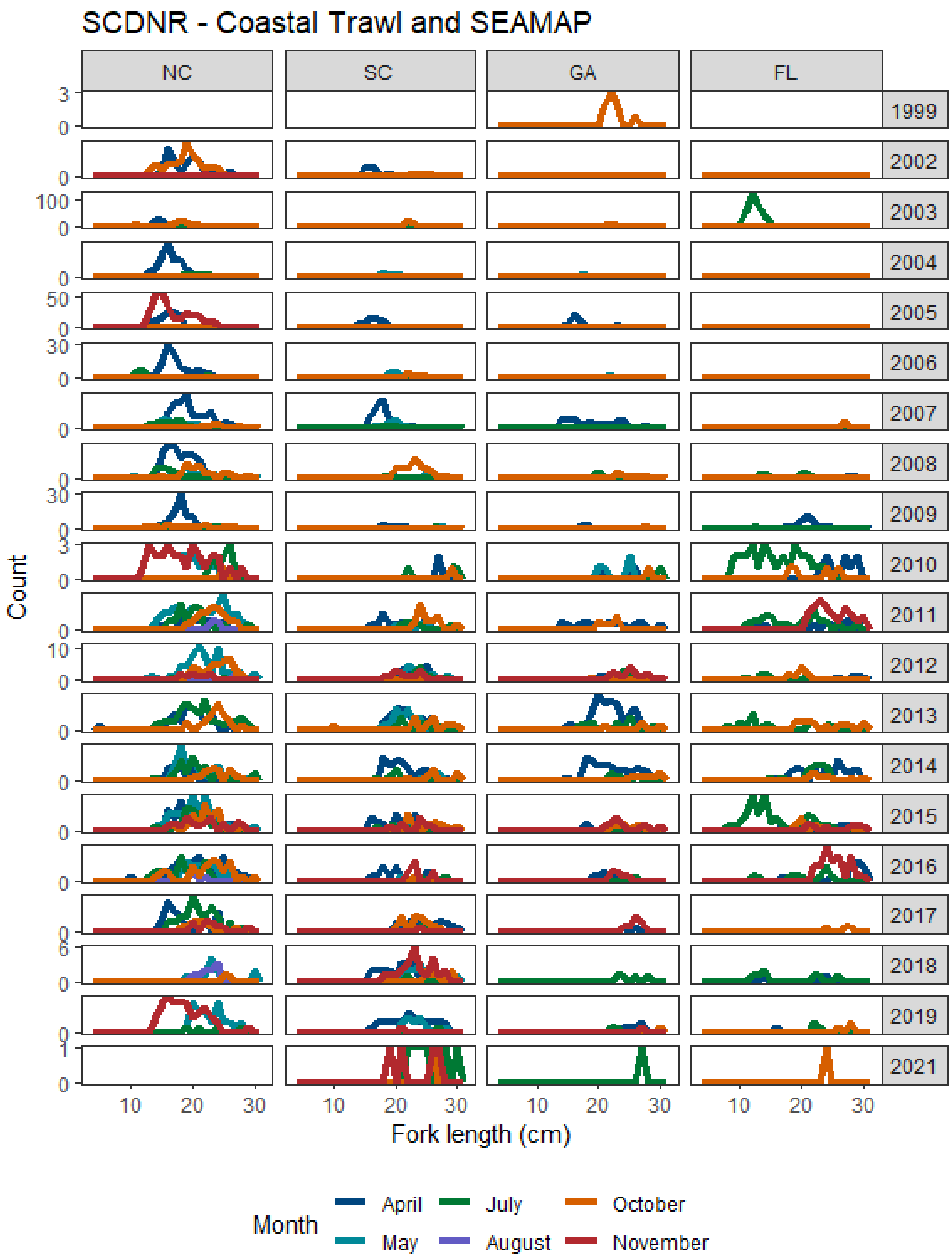
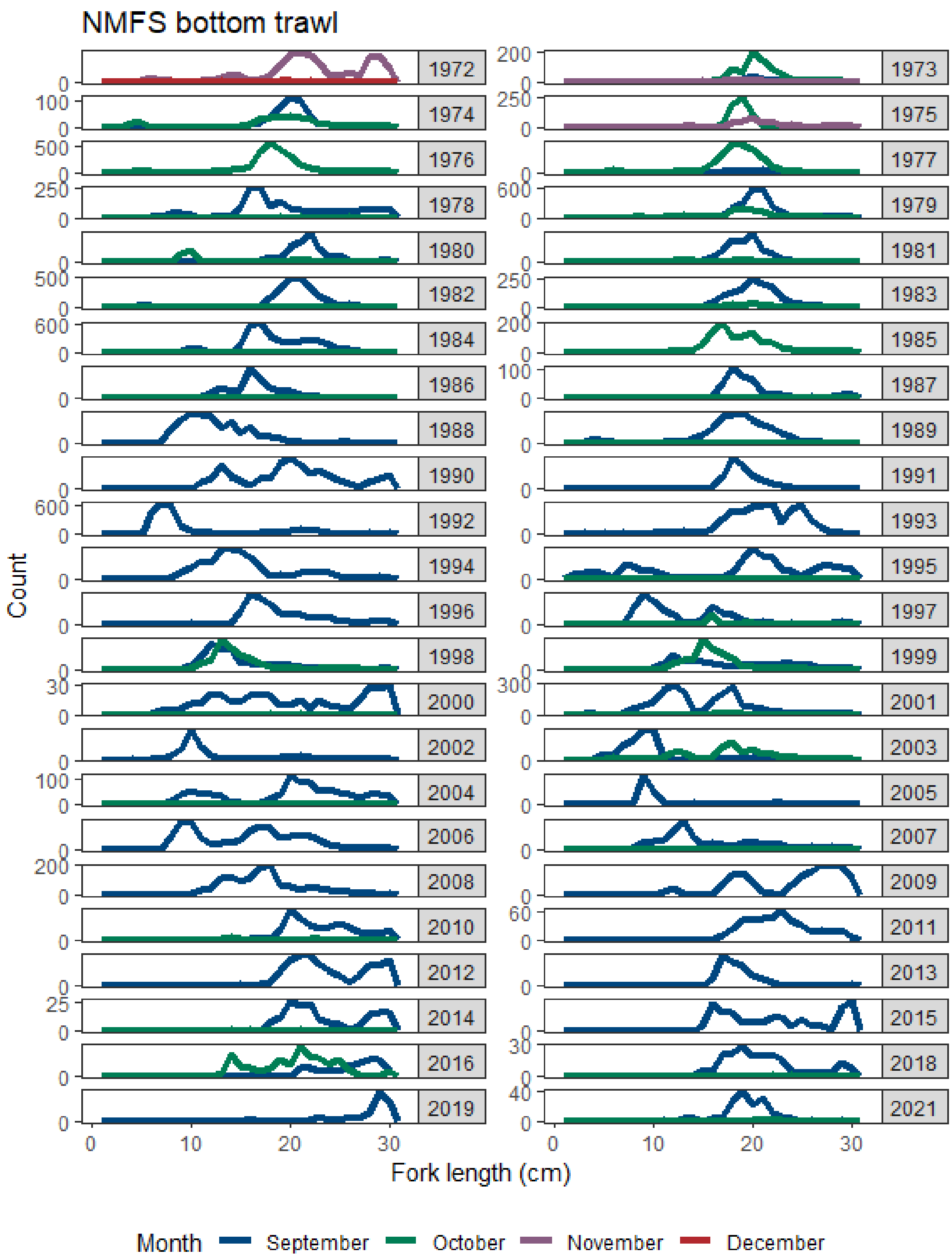


Figure 43. Length distributions of bluefish under 30.3cm by month in the South Carolina DNR Coastal Trawl (1999-2010) and SEAMAP (2011-2021) samples. Bimodal cohort length peaks are visible in North Carolina in April 2002 and November 2005.



NMFS bottom trawl
Count
Fork length (cm)
Month
September
October
November
December

Figure 44. Length distributions of bluefish under 30.3cm by month in the NMFS bottom trawl fall survey. Bimodal cohort length peaks are visible in several years, including 1990, 1995, 2001, and 2006. Note, after 2008, inshore strata were no longer sampled in the NMFS survey, and were instead sampled in the NEAMAP survey.

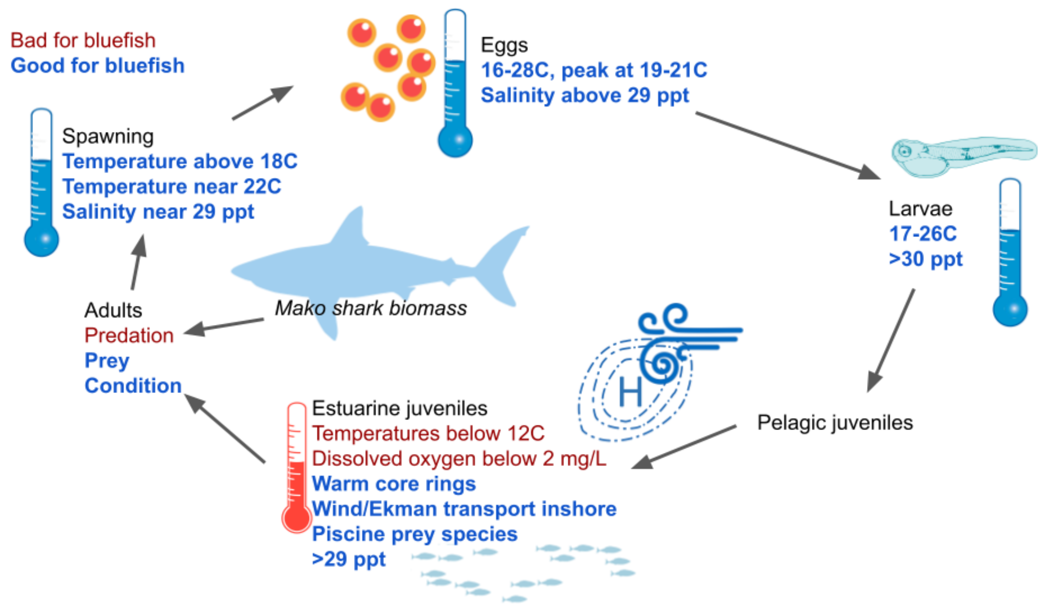


Figure 45. Life history conceptual model of bluefish.

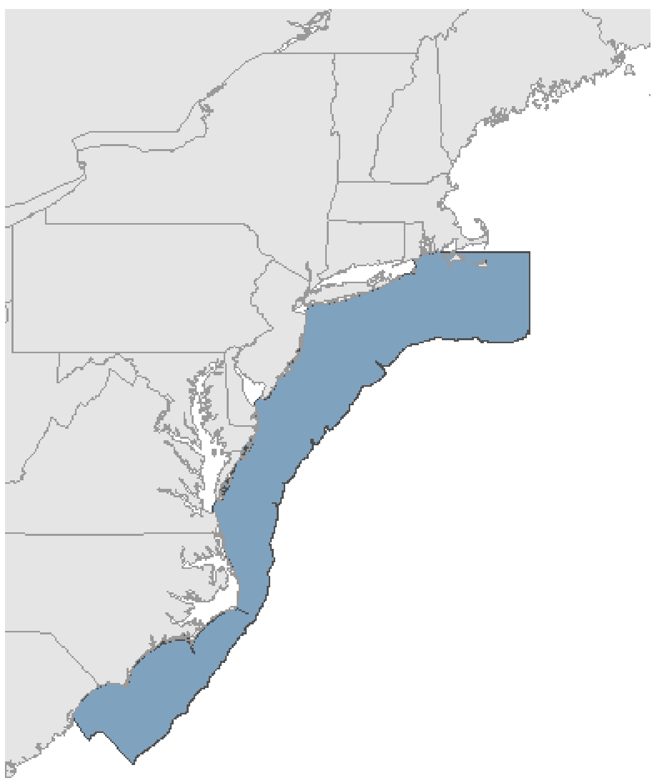


Figure 46. Map of the Central Atlantic region used in calculating spatially averaged indicators.

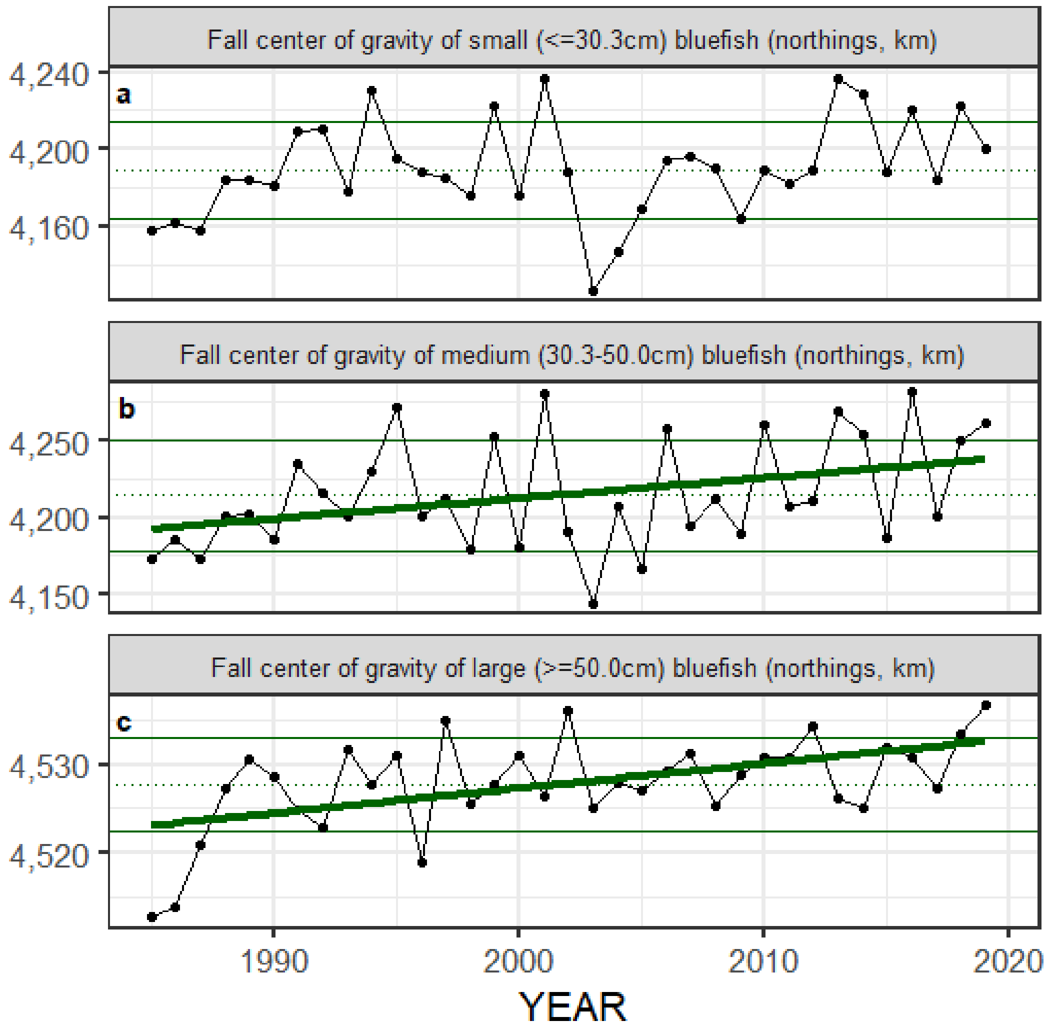


Figure 47. Selected ecosystem indicators of bluefish distribution with time series ranging from 1982 - 2019: (a) center of gravity (northings, km) of small (<=30.3cm), (b) medium (30.3-50.0cm), and (c) large (>=50.0cm) bluefish as modeled by VAST. Upper and lower solid green horizontal lines are plus and minus one standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. The slope of the medium bluefish trend is 1.1 km/year, and the slope of the large bluefish trend is 0.2 km/year. (Note, figure shows years 1985 – 2019.)

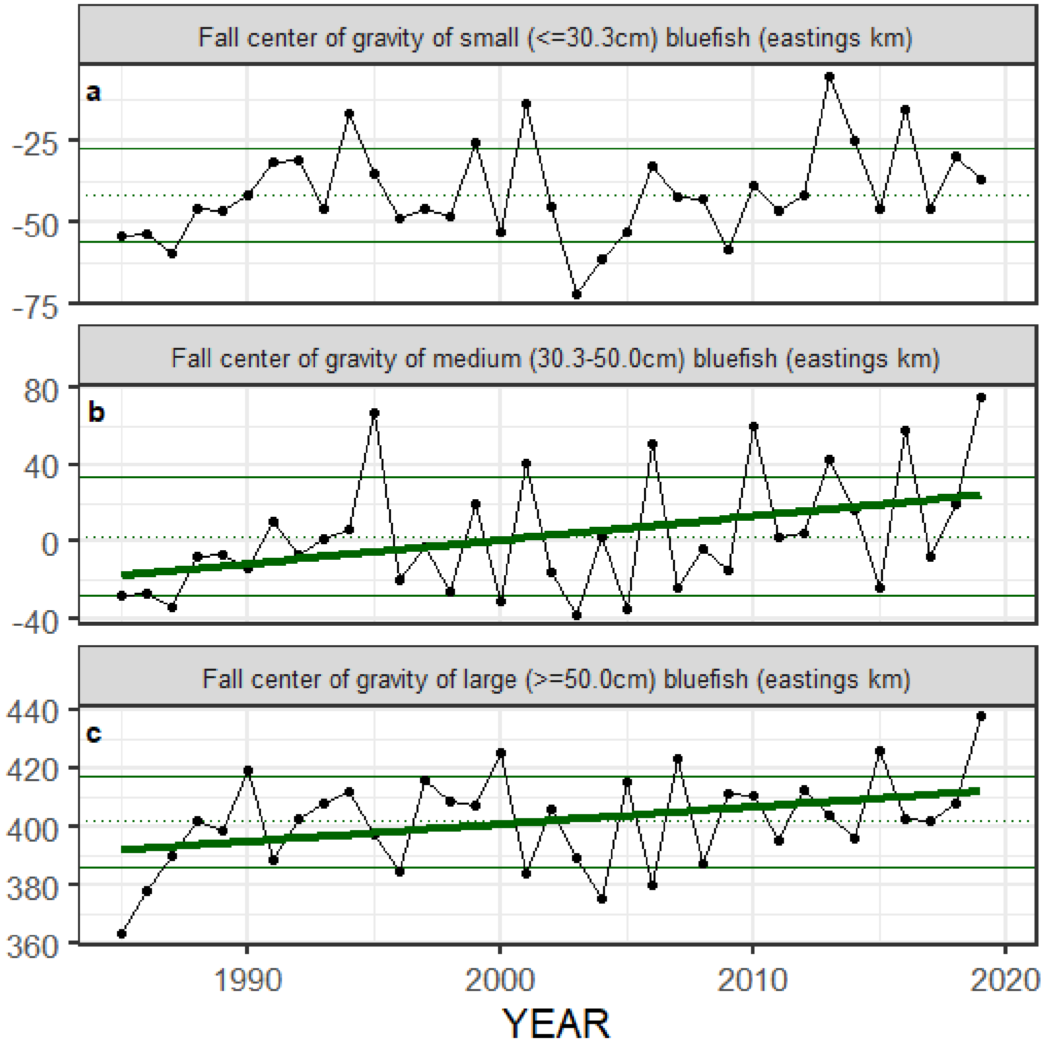


Figure 48. Selected ecosystem indicators of distribution for bluefish with time series ranging from 1982 - 2019: (a) center of gravity (eastings, km) of small (<=30.3cm), (b) medium (30.3-50.0cm), and (c) large (>=50.0cm) bluefish as modeled by VAST. Upper and lower solid green horizontal lines are plus and minus one standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. The slope of the medium bluefish trend is 1.1 km/year, and the slope of the large bluefish trend is 0.5 km/year. (Note, figure shows years 1985 – 2019.)

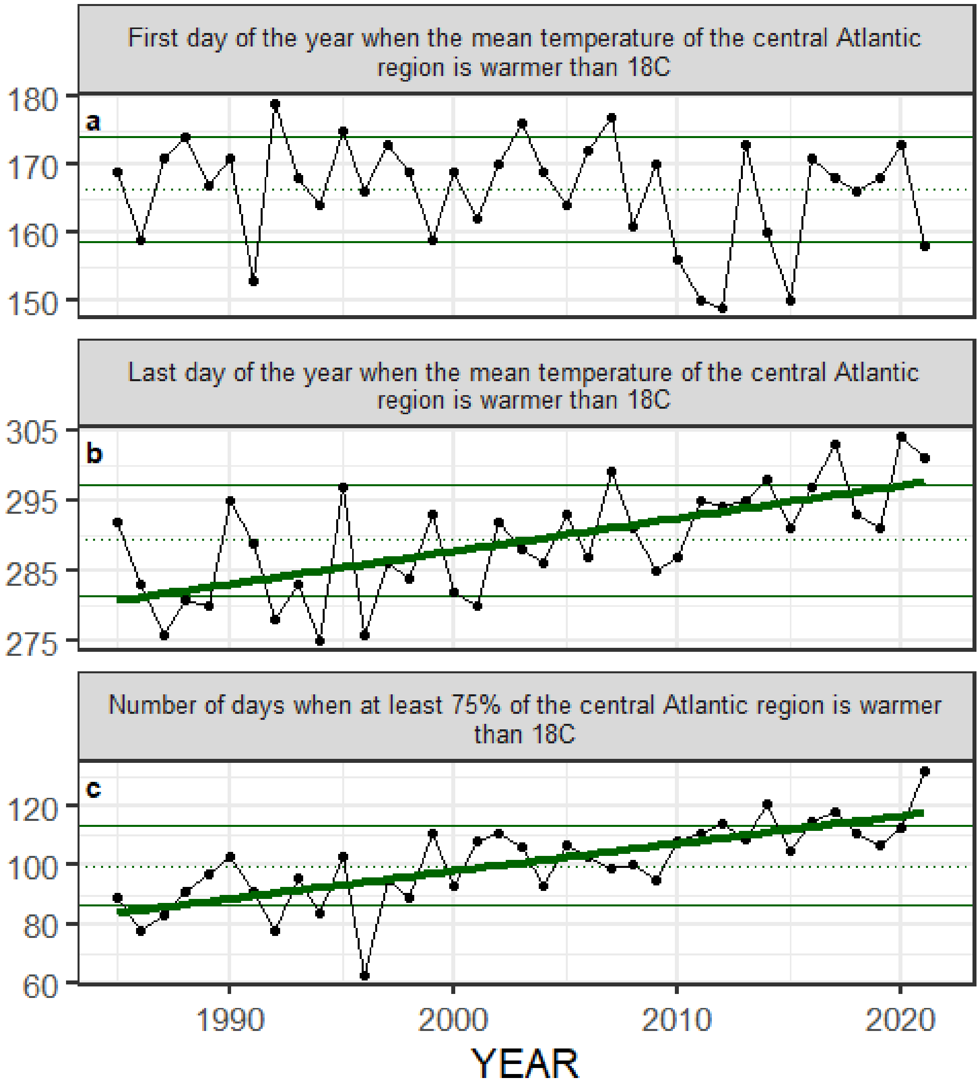


Figure 49. Selected ecosystem climate indicators for bluefish with time series ranging from 1982 - 2021: (a) first day of the year when the mean temperature of the central Atlantic region is warmer than 18C, (b) last day of the year when the mean temperature of the central Atlantic is warmer than 18C, and (c) number of days when at least 75% of the central Atlantic region is warmer than 18C. Upper and lower solid green horizontal lines are plus and minus one standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. (Note, figure shows years 1985 – 2021.)

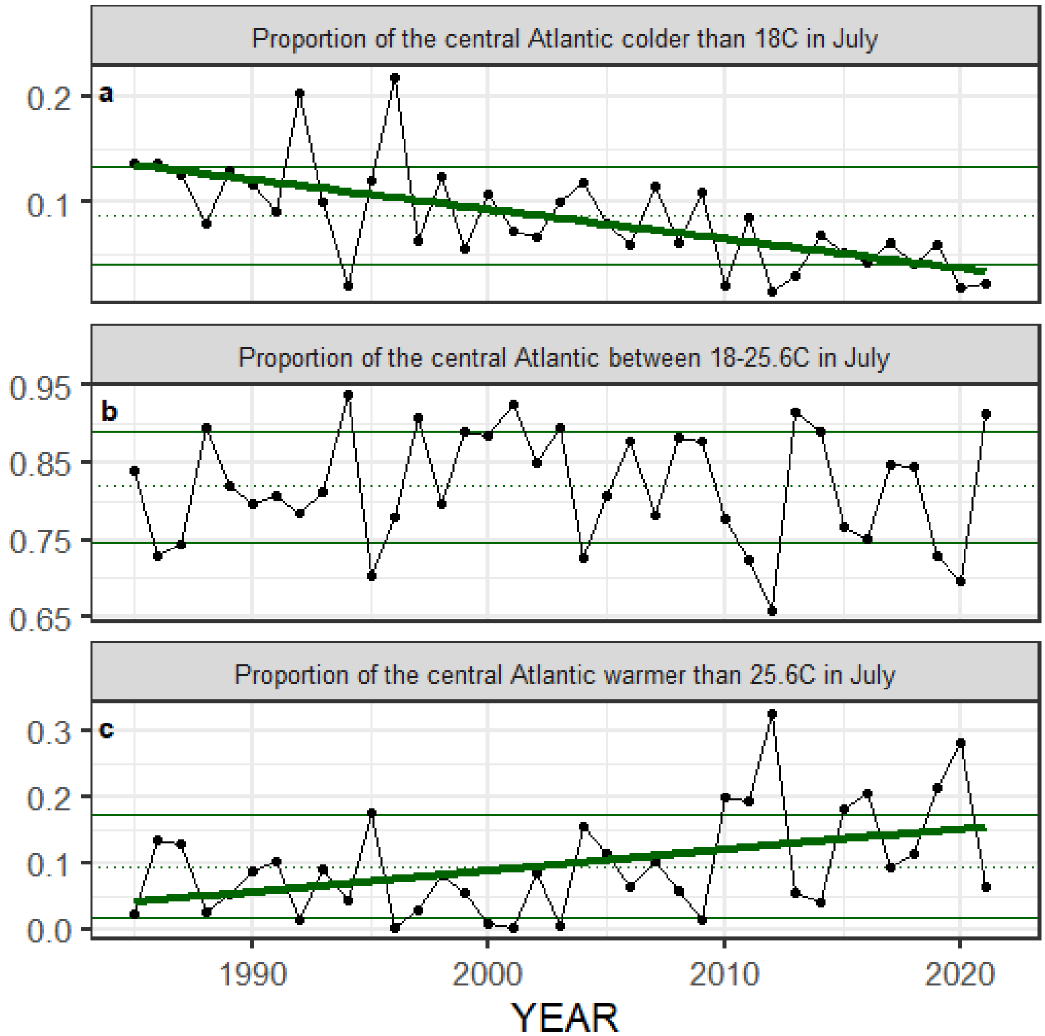


Figure 50. Selected ecosystem climate indicators for bluefish with time series ranging from 1982 - 2021: (a) proportion of the central Atlantic colder than 18C in July, (b) proportion of the central Atlantic between 18-25.6C in July, and (c) proportion of the central Atlantic warmer than 15.6C in July. Upper and lower solid green horizontal lines are plus and minus one standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. (Note, figure shows years 1985 – 2021.)

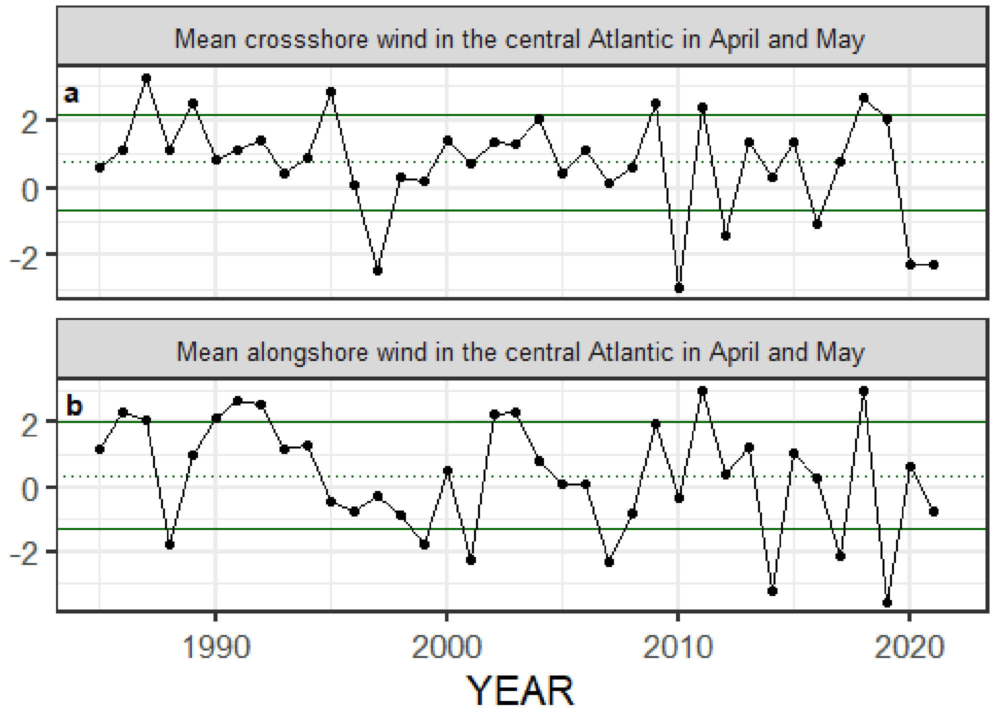


Figure 51. Selected ecosystem climate indicators for bluefish with time series ranging from 1979 - present: (a) mean crossshore wind in the central Atlantic in April and May, and (b) mean alongshore wind in the central Atlantic in April and May. Upper and lower solid green horizontal lines are plus and minus one standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. (Note, figure shows years 1985 – 2021.)

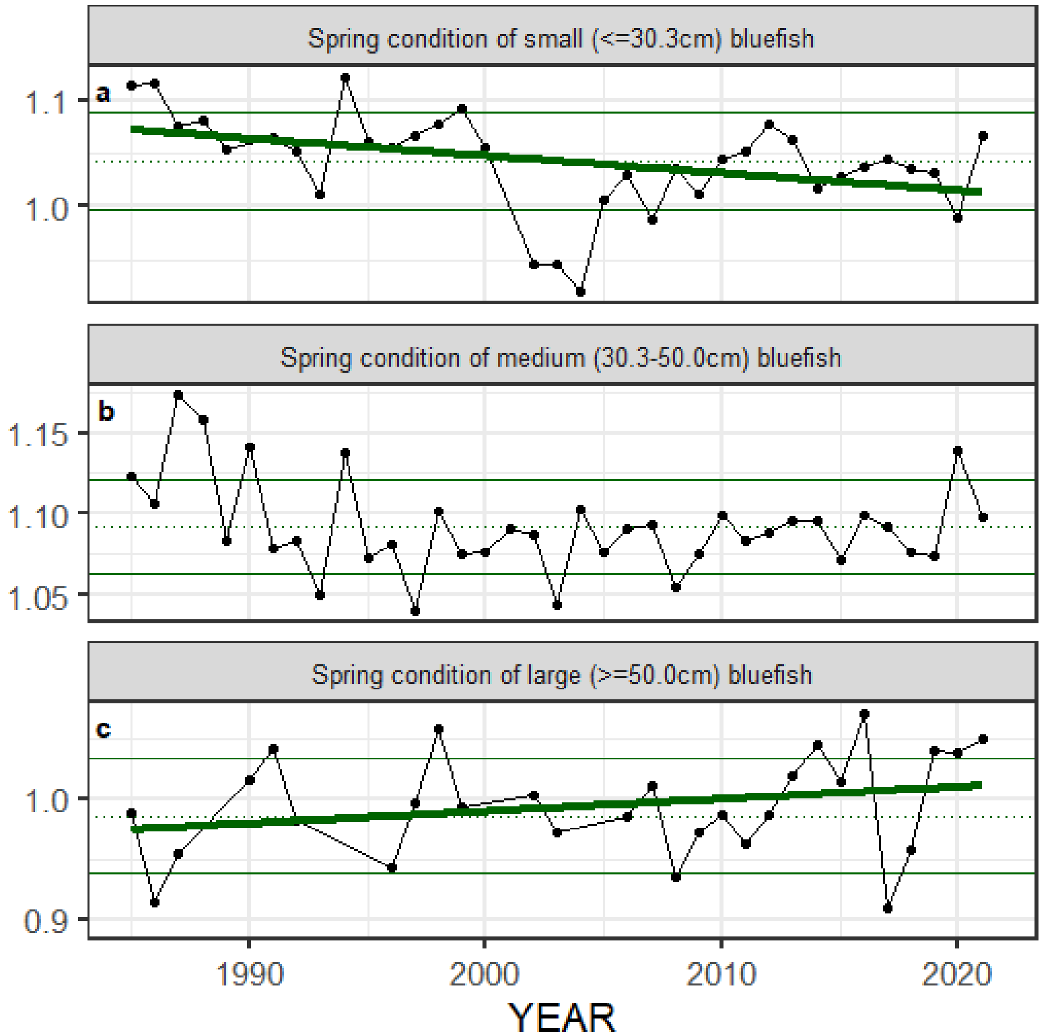


Figure 52. Selected ecosystem indicators of natural mortality for bluefish with time series ranging from 1981 - 2021: (a) spring condition of large (>=50.0cm) bluefish, (b) fall condition of large (>=50.0cm) bluefish, (c) spring condition of medium (30.3-50.0cm) bluefish, and (d) fall condition of medium (30.3-50.0cm) bluefish. Upper and lower solid green horizontal lines are plus and minus one standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. (Note, figure shows years 1985 – 2021.)

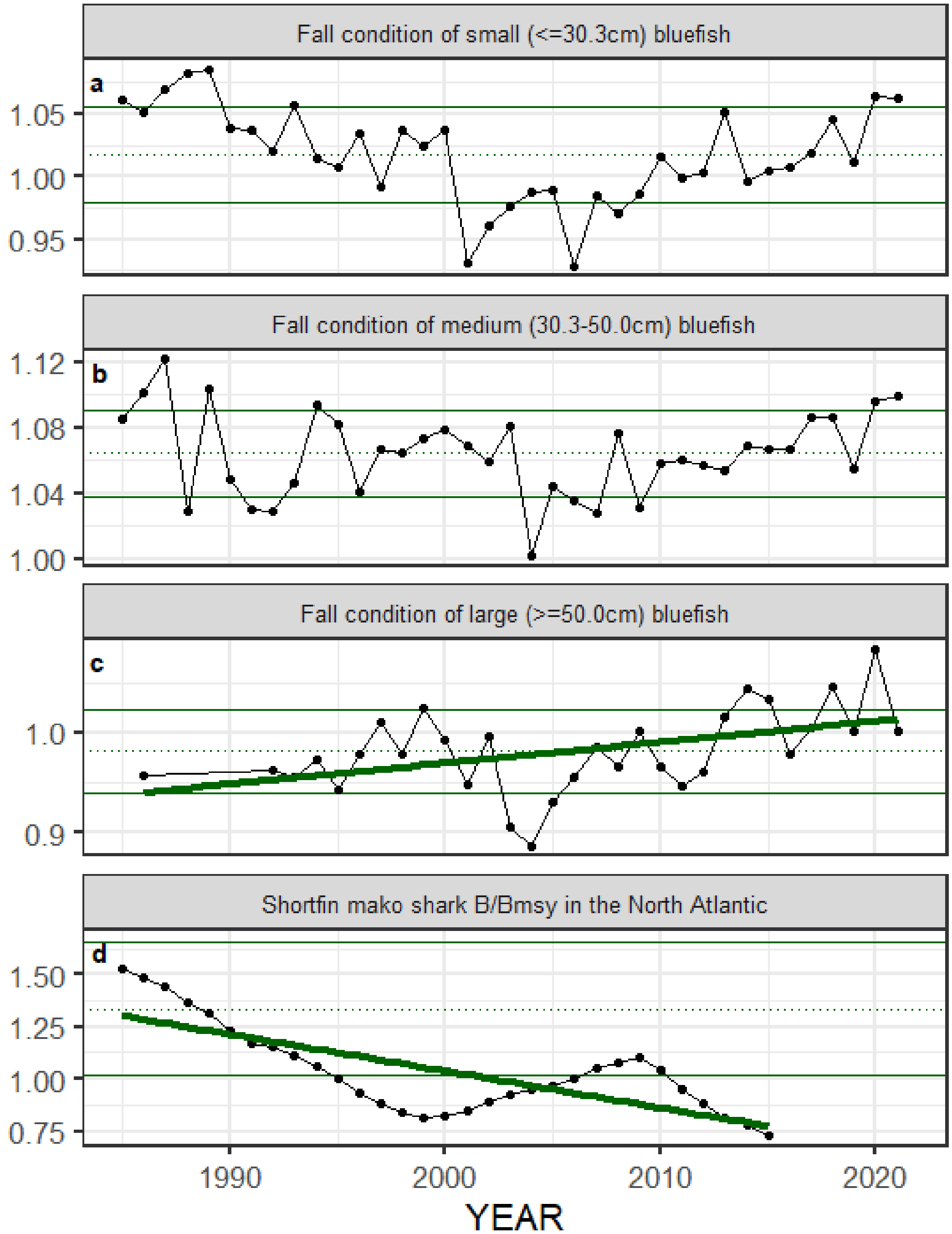


Figure 53. Selected ecosystem indicators of natural mortality for bluefish with time series ranging from 1981 – 2021 and 1950 -- 2015: (a) spring condition of small (<=30.3cm) bluefish, (b) fall condition of small (<=30.3cm) bluefish, and (c) shortfin mako shark B/Bmsy in the North Atlantic. Upper and lower solid green horizontal lines are plus and minus one standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. (Note, figure shows years 1985 – 2021.)

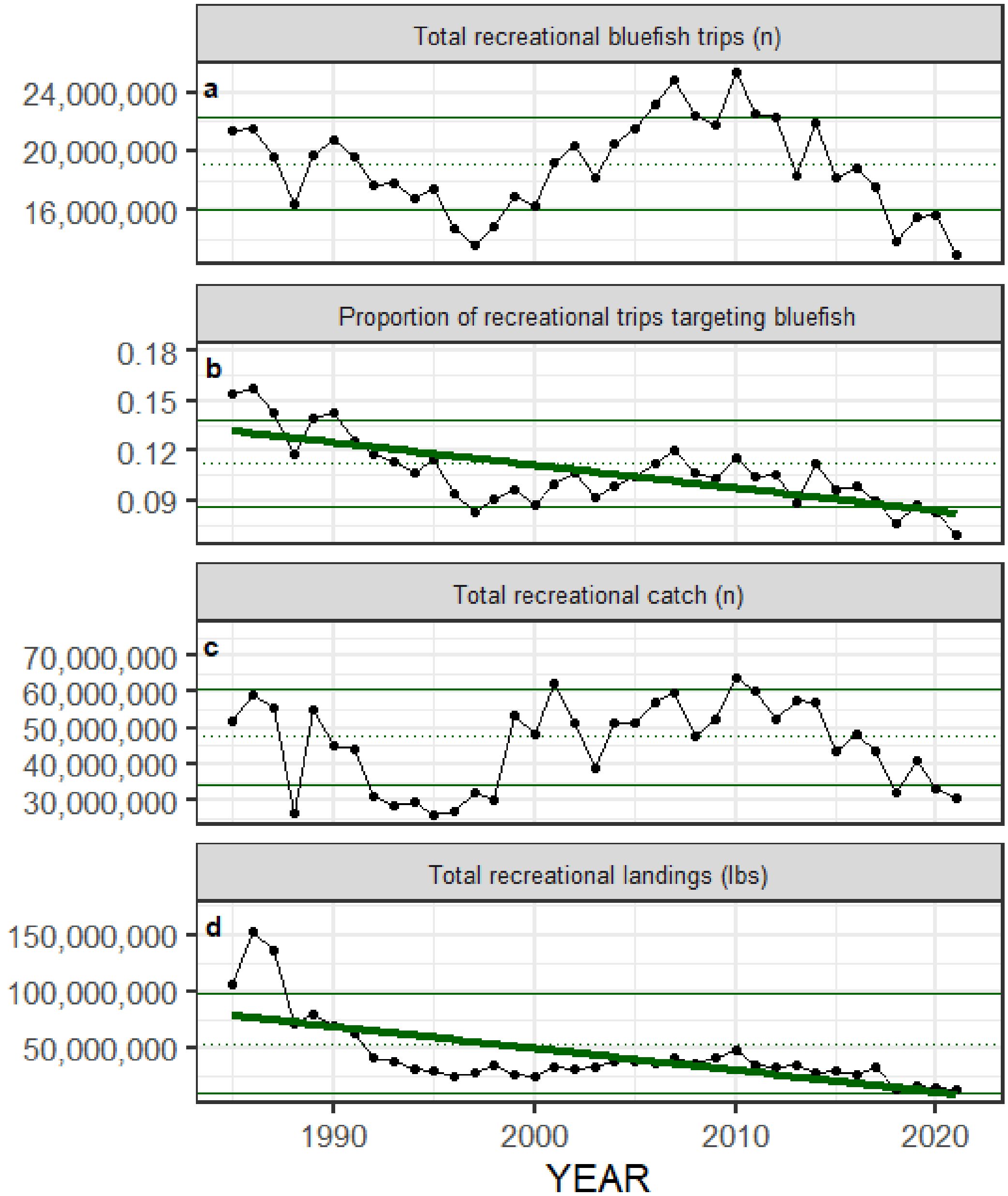


Figure 54. Selected socioeconomic recreational indicators for bluefish with time series ranging from 1985 - 2021: (a) number of directed recreational bluefish trips from, (b) proportion of directed recreational bluefish trips relative to other directed trip, (c) total recreational bluefish catch in number of fish, (d) total recreational bluefish landings (lbs). Upper and lower solid green horizontal lines are plus and minus one standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. (Note, figure shows years 1985 – 2021.)


Commercial vessels landing bluefish (n)
a
900
800
700
600
500
Total commercial bluefish landings (lbs)
b
8,000,000
6,000,000
4,000,000
2,000,000
Average price of bluefish (real dollars/lb)
c
1.0
0.8
0.6
Total bluefish revenue (real dollars)
d
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
Average price of diesel fuel (real dollars/gallon)
e
3.5
3.0
2.5
2.0
1.5
2000
2005
2010
2015
2020
YEAR

Figure 55. Selected socioeconomic commercial indicators for bluefish with time series ranging from 2000 - 2021: (a) number of commercial vessels landing bluefish, (b) commercial bluefish landings (lbs.), (c) ex-vessel bluefish prices (2021 constant U.S. dollars per lb), (d) total annual commercial bluefish revenue in 2021 constant U.S. dollars, and (e) average annual ultra-low-sulfur number 2 diesel fuel prices (2021 constant U.S. dollars) from 2007-2021. Upper and lower solid green horizontal lines are plus and minus one standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

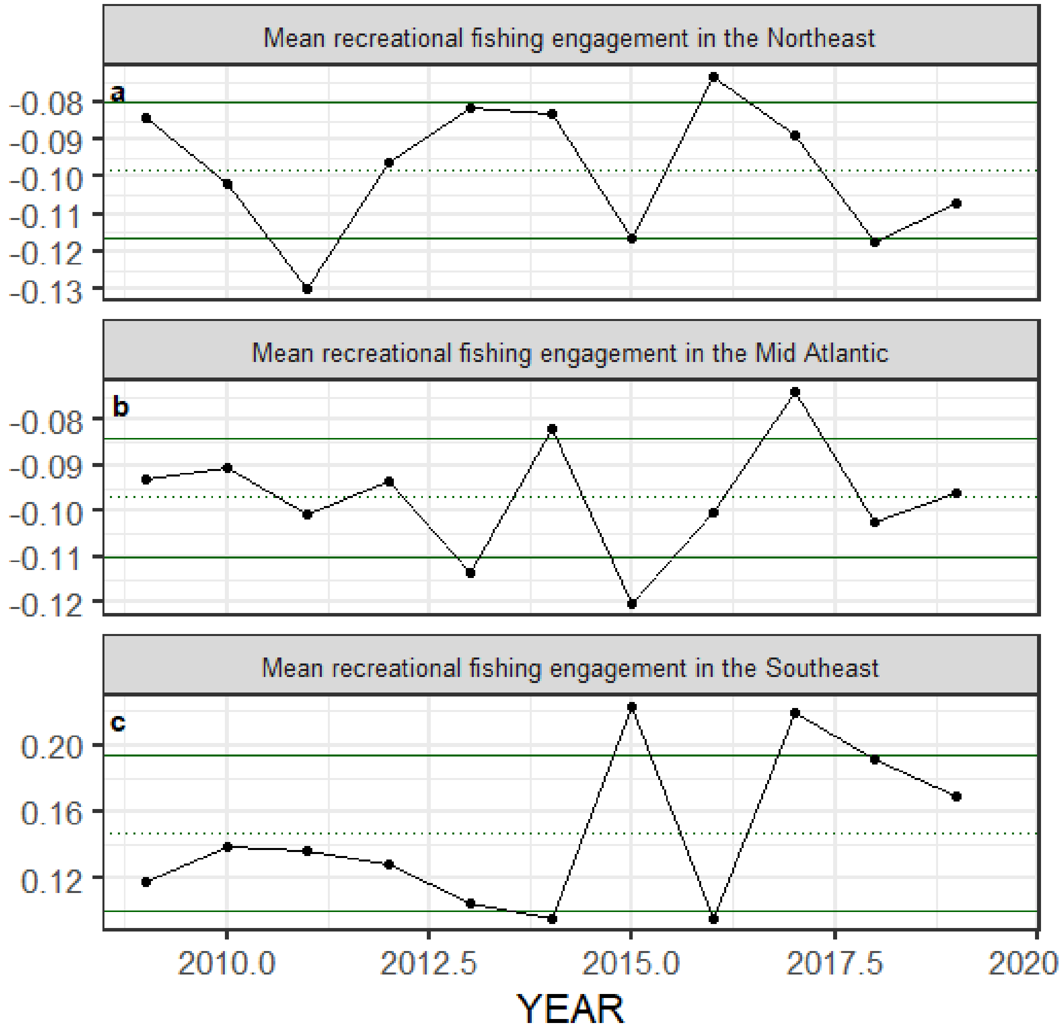


Figure 56. Selected socioeconomic community indicators for bluefish with time series ranging from 2009-2019: (a) average annual recreational engagement scores for the Northeast region, (b) average annual recreational engagement scores for the Mid-Atlantic region, and (c) average annual recreational engagement scores for the Southeast region. Upper and lower solid green horizontal lines are plus and minus one standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

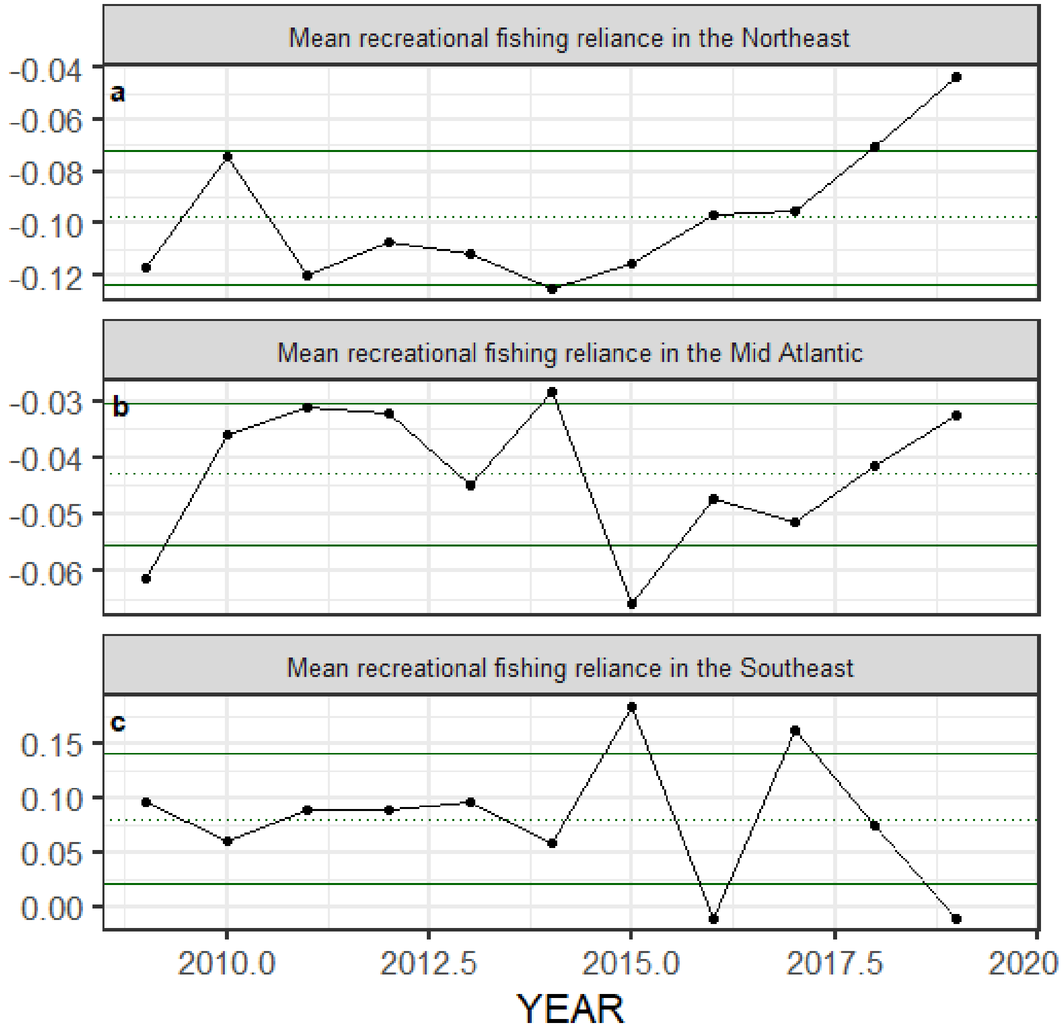


Figure 57. Selected socioeconomic community indicators for bluefish with time series ranging from 2009-2019: (a) average annual recreational reliance scores for the Northeast region, (b) average annual recreational reliance scores for the Mid-Atlantic region, and (c) average annual recreational reliance scores for the Southeast region. Upper and lower solid green horizontal lines are plus and minus one standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

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Appendix 1. Bluefish and Recreational Demand Models: A General Overview

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Recreational demand models (RDMs), in the context of recreational fisheries, estimate the demand for fishing activity expected to occur under specific fishery conditions. These estimates, in turn, can be used to calculate expected levels of recreational harvest and discards. Additionally, the demand parameters underlying RDMs allow for estimation of consumer welfare or the monetary value of angler satisfaction derived from the fishery. These outputs provide a basis for comparing expected economic benefits with biological costs of proposed regulations. Significant progress has been made in the development and use of RDMs in Northeast and Mid-Atlantic recreational fisheries management. Over the past five years, RDMs have been developed for summer flounder (Carr-Harris 2022; Holzer and McConnell 2017), striped bass (Carr-Harris and Steinback 2020), and recreational Gulf of Maine cod and haddock (Lee et al. 2017), the latter of which has been used for tactical management advice since 2014. Most recently, as a component of the Summer Flounder Management Strategy Evaluation (MSE), Carr-Harris (2022) developed a RDM for summer flounder that links changes in stock abundances and regulations to expected recreational fishing mortality and consumer welfare. Carr-Harris's research provides insight into integrating angler behavior into the policymaking process.

Recreational demand models rely on underlying parameters that identify the utility anglers receive from various attributes of a recreational fishing trip. In a recreational fisheries context, attributes of interest are typically the number of fish harvested and released as these are key factors influencing anglers' fishing decisions and are indirectly affected by managers through changes in regulations. One approach to estimating parameters of the utility function are stated preference methods, which rely on responses to survey questionnaires. A popular form of stated preference methods for non-market valuation are choice experiments (CEs). CEs elicit preferences through respondents' choices of their most-preferred multi-attribute option out of two-or more options. For the summer flounder MSE, data from a 2010 choice experiment were used in parameterizing the 2022 recreational demand model. In the 2010 choice experiment, respondents were presented with four trip options that varied in the number of fish caught and kept, the size limit, the cost of the trip, as well as the type of fish caught/kept (summer flounder, bluefish, striped bass, scup, black sea bass, and weakfish). The survey choice sets were tailored by sub-region to reflect differences in species availability. The results of the ensuing choice experiment models identified the value to anglers of keeping and releasing various fish species across the study region.

Another approach for estimating utility parameters is through revealed preference, travel cost methods such as those employed in Hicks and Schnier (2020). Unlike stated preference methods, travel cost methods rely on observational data, which in the case of Hicks and Schnier (2020), were derived from the Marine Recreational Information Program (MRIP) intercept survey. Hicks and Schnier (2020) created choice sets containing a species group, a fishing mode, and a fishing site. Each fishing site varied in average catch and release metrics by species, wave, and county, as well as the estimated travel cost of visiting the site from the anglers’ home county. With this information, the authors estimated the non-market value or harvesting and releasing fish by species.

Both stated and revealed preference methods allow for estimation of angler trip-taking behavior and angler welfare conditional on regulations and stock conditions. However, there are theoretical and practical tradeoffs that should be carefully considered when choosing which approach to pursue. When determining which method to employ, stated preference models may be viewed as the most desirable given that the survey design can be tailored to answer specific research questions. That being said, survey generation and dissemination is costly and time intensive. Furthermore, participation in voluntary surveys is far from guaranteed and can cause issues with data usage if response rates are low. Utilizing existing data through revealed preference techniques can be a cost-effective method for generating utility parameters; however, obtaining a robust pre-existing dataset which is suitable to answer specific research questions may be difficult. Stated and revealed preference models offer a unique set of benefits and challenges and the selection of either method ultimately depends on the research questions posed.

As mentioned previously, estimating angler utility parameters allows for subsequent development of RDMs that can predict how angler effort, angler welfare, and recreational fishing mortality responds to changes in regulations and stock abundances. For example, Carr-Harris used an RDM to make out-of-sample predictions of total summer flounder harvest and catch and compared the predictions to MRIP estimates. Predicted total catch and harvest were within the MRIP 95% confidence interval for all out-of-sample prediction years, bolstering confidence in the model’s predictive ability.

In summary, recreational demand models can inform managers of the likely economic and biological implications of alternative regulatory and stock conditions. These models are unique in that they consider changes in recreational effort, which are often overlooked in the policymaking process. Given the large role recreational effort plays in the bluefish fishery, efforts in developing recreational demand models should be prioritized.

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