Review and analysis of Atlantic herring (*Clupea harengus*) spawning on Georges Bank

2019 Discussion Document for the New England Fishery Management Council

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New England Fishery Management Council

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List of Acronyms

ASM – At Sea Monitoring

ASMFC – Atlantic States Marine Fisheries Commission

DFO – Department of Fisheries and Oceans (Canada)

DMF – Division of Marine Fisheries (Massachusetts)

DMR – Department of Marine Resources (Maine)

EFH – Essential Fish Habitat

EGOM – Eastern Gulf of Maine

EU – European Union

FMP – Fishery Management Plan

FSB – Fisheries Sampling Branch

GB – Georges Bank

GMRI – Gulf of Maine Research Institute

GOM – Gulf of Maine

GS – Great South Channel

GSI – Gonadal Somatic Index

ICES – International Council for the Exploration of the Sea

ICNAF – International Commission for the Northwest Atlantic Fisheries

LEC – Law Enforcement Committee

NAFO – Northwest Atlantic Fisheries Organization

NEFMC – New England Fisheries Management Council

NEFOP – Northeast Fisheries Observer Program

NEFSC – Northeast Fisheries Science Center

NEP – Northeast Peak

NF – Northern Flank

NMFS – National Marine Fisheries Service

OHA2 – Omnibus Habitat Amendment 2 (NEFMC)

PPI – Predation Pressure Index

SST – Sea Surface Temperature

TAC – Total Allowable Catch

VMS – Vessel Monitoring System

WGB – Western Georges Bank

I. Executive Summary

This document contains an analysis of Atlantic herring spawning on Georges Bank and provides an overview of management decisions leading to spawning protections in the nearby Gulf of Maine. It also includes a review of spawning protection strategies used in other parts of the north Atlantic. The purpose of this review is to provide up-to-date information on Georges Bank spawning dynamics (location and timing) and spawning protection strategies that may be considered by the New England Fishery Management Council (NEFMC) in future management actions regarding herring spawning protection on Georges Bank.

The bulk of this review involves new analyses of existing datasets, most of which have not been considered together in the context of herring spawning. The existing data sets considered here include: portside monitoring data, trawl survey data, and ichthyoplankton data (larvae). We also considered diet data from the National Marine Fisheries Service's (NMFS) Food Habits database and at-sea observer data. Finally, industry members were consulted for their input.

The portside monitoring data came from two sources (the Maine Department of Marine Resources, DMR and the Massachusetts Division of Marine Fisheries, DMF). This data covered the period 1971 – 2018 and included data on location, date, maturity stage and gonadal somatic index (GSI, used in the Gulf of Maine to determine timing of spawning closures). Trawl survey data came from the Northeast Fisheries Science Center's (NEFSC) trawl survey database and covered the period 1987 – 2018. Trawl survey data considered for this review included location, date, and maturity stage. Larval data came from the NEFSC ichthyoplankton surveys (1971 – 2017) and spawning locations were inferred from the distribution of early stage (< 9 mm) herring larvae.

Where possible, data/information sources were used to map the distribution of spawning herring and these were compared to existing/historical maps of herring spawning areas, as well as egg essential fish habitat. Maps from all data/information sources were then overlain to examine areas of overlap in a manner that has been used before to determine 'consensus' cod (*Gadus morhua*) spawning locations on Georges Bank (DeCelles et al 2017). This was done for the full range of years represented by each dataset as well as by decade. Resulting consensus herring spawning areas, one near the Great South Channel and the other on the Northern Flank of Georges Bank, were then compared to herring fishing effort. The analysis suggests that most of the herring fishing effort takes place outside of consensus spawning areas with the exception of some fishing effort in the eastern spawning area (Northern Flank) in some decades. For the portside monitoring data, GSI data taken throughout the year since the early 1990s allowed for an examination of seasonal trends in spawning across Georges Bank and areas further south. This analysis showed that spawning takes place primarily in September and October and has no directional trend among years or areas. This document ends with a consideration of how consensus herring spawning areas may overlap with other fishing activities (herring and non-herring) and how spawning may be affected by non-fishing drivers such as climate change and predators. The NEFMC Atlantic Herring Plan Development Team was consulted during development of these analyses and the PDT drafted research priorities for future survey work on this topic.

1. Background

1.1. Purpose and Structure of Review

In 2019 the New England Fishery Management Council (NEFMC) committed resources to develop a discussion document that would review historical and current scientific research and other relevant information about offshore spawning of Atlantic herring. The intent of this discussion document is to summarize all pertinent information in one place to support future Council deliberations about potential management measures to protect spawning of Atlantic herring on Georges Bank and Nantucket Shoals.

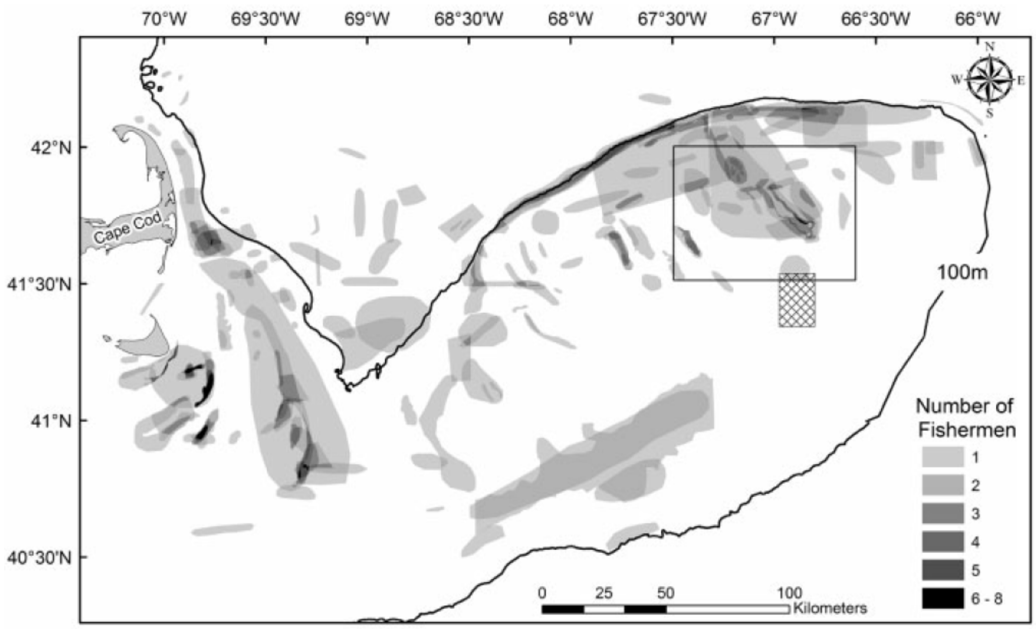
The Gulf of Maine Research Institute (GMRI) was awarded a contract to carry out this review of herring spawning on Georges Bank. In addition to reviewing and reproducing (from previous council documents) existing information on herring biology and spawning on Georges Bank and reviewing spawning protections in other locations (contained in sections 1.2 – 1.4), the bulk of this document is focused on examining sources of data that can be used to newly infer spawning timing and location on Georges Bank. This included analyses of larval distributions from NEFSC ichthyoplankton surveys (EcoMon; 1971 – 2017), and distributions of spawning stage (mature) herring from portside monitoring programs (DMR and DMF; 1971 – 2018) and trawl surveys (NEFSC spring and fall bottom trawl surveys; 1987 - 2018). Additional information included data from the NEFSC Food Habits Database as well as input from fishing industry members. Table 1.1 is a summary of data sets used in this analysis.

Table 1.1.1. Summary of time span of various data sources used in this review as well as data type and samples sizes.

	1970s									1980s										1990s										2000s											2010s							
Data Source	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
ME DMR portside monitoring	**17,529 (from 583 trips)** - location, date, maturity stage, GSI (Areas 1B, 2 and 3 only)																																															
Mass DMF portside monitoring																												**2,725** - location, date, maturity stage, GSI																				
Trawl surveys																	**46,242** - location, date, maturity stage (focus on fall survey)																															
Larval surveys	**6,446** tows with herring larvae - location, date, size (2,371 samples with larvae < 9mm)																																															
Food Habits Database			**>650,000** stomachs - location, date, presence of herring eggs (113 positive for herring eggs)																																													

The approach used for identifying herring spawning areas in this document was modified from DeCelles et al (2017) who examined Atlantic cod (*Gadus morhua*) spawning on Georges Bank using a 'consensus' approach (Figure 1.1.1). This involved interviewing fishermen and asking them to identify cod spawning locations. Each of these was mapped and areas of overlap were determined. The resultant 'consensus' areas, where three or more sources agreed, were given greater weight in the final representation of cod spawning. A similar method was used here. However, in our case, maps were derived from various data sources described above and groundtruthed with input from members of the mid-water trawl fishery.

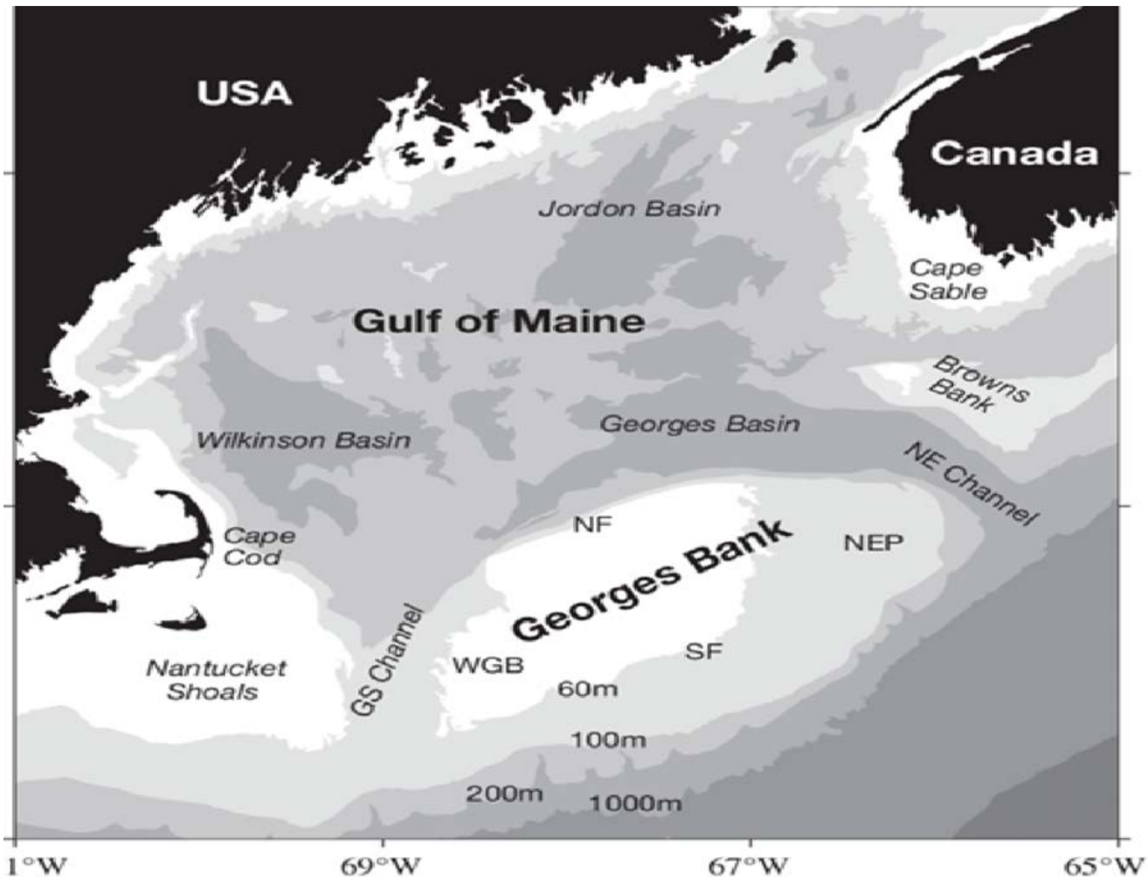
Figure 1.1.1. From DeCelles et al (2017). "Cod spawning grounds that were identified by fishermen. Each polygon represents a spawning ground that was identified by a single fisherman. The shading is used to identify areas where there is overlap in the spawning locations reported by multiple fishermen. The rectangle outlined in black depicts the "Winter Fishing Grounds" that were described by Goode (1884) and Rich (1929). The hashed rectangle represents the cod spawning grounds that were reported by Bigelow and Schroeder (1953)."



This document first outlines the results from each data source independently in section 2. Spatial patterns are explored using interpolation and density mapping techniques where the distribution of spawning adult herring or larvae can be visualized. Section 2 also contains an analysis of the seasonal trends in GSI values from portside monitoring data.

Section 3 of this document collates all of the maps generated from consideration of the different data sets. A consensus approach similar to that of DeCelles et al (2017) is used to look for areas of overlap between the different data sets. Consensus areas are then compared to herring fishing effort distribution to examine potential areas of overlap in section 4 which also considers previous, current and planned management boundaries that may overlap herring spawning. Consensus herring spawning areas are also compared to the footprint of other fisheries in section 5 which also considers potential threats to spawning from other sources including climate change and predators. Finally, future research recommendation from the herring Plan Development Team are included in section 6. Throughout the document, a number of different areas throughout the Georges Bank region are referred to. These areas are shown in Figure 1.1.2.

Figure 1.1.2. Map of Gulf of Maine and Georges Bank showing place names referred to in this document: Nantucket Shoals, Great South Channel (GS Channel), Western Georges Bank (WGB), Northern Flank (NF), and Northeast Peak (NEP). From Lough et al. (2006).



1.2. Herring Spawning Biology

Herring spawning biology is described in Amendment 8 to the Atlantic Herring Fishery Management Plan (NEFMC 2019). The description is reproduced here (in italics).

> *While Atlantic herring reproduce in the same general season each year, the onset, peak and duration of spawning may vary by several weeks annually (Winters & Wheeler 1996) due to changing oceanographic conditions (e.g., temperature, plankton availability, etc.). Atlantic herring are believed to return to natal spawning grounds (Map 9) throughout their lifetime to spawn (NEFMC 2006; Ridgeway 1975; Sinderman & Iiles 1985).*
>
> *Spawning occurs at specific locations in the Gulf of Maine in depths of 20-50 m (about 60-160 feet), on coastal banks such as Jeffreys Ledge and Stellwagen Bank located 8-40 km offshore, along the eastern Maine coast between the U.S.-Canada border and at other locations along the western Gulf of Maine (Figure 1.2.1). Some spawning sites are used repeatedly, sometimes more than once a year (NEFMC 2006; Stevenson 1989). Jeffreys Ledge*

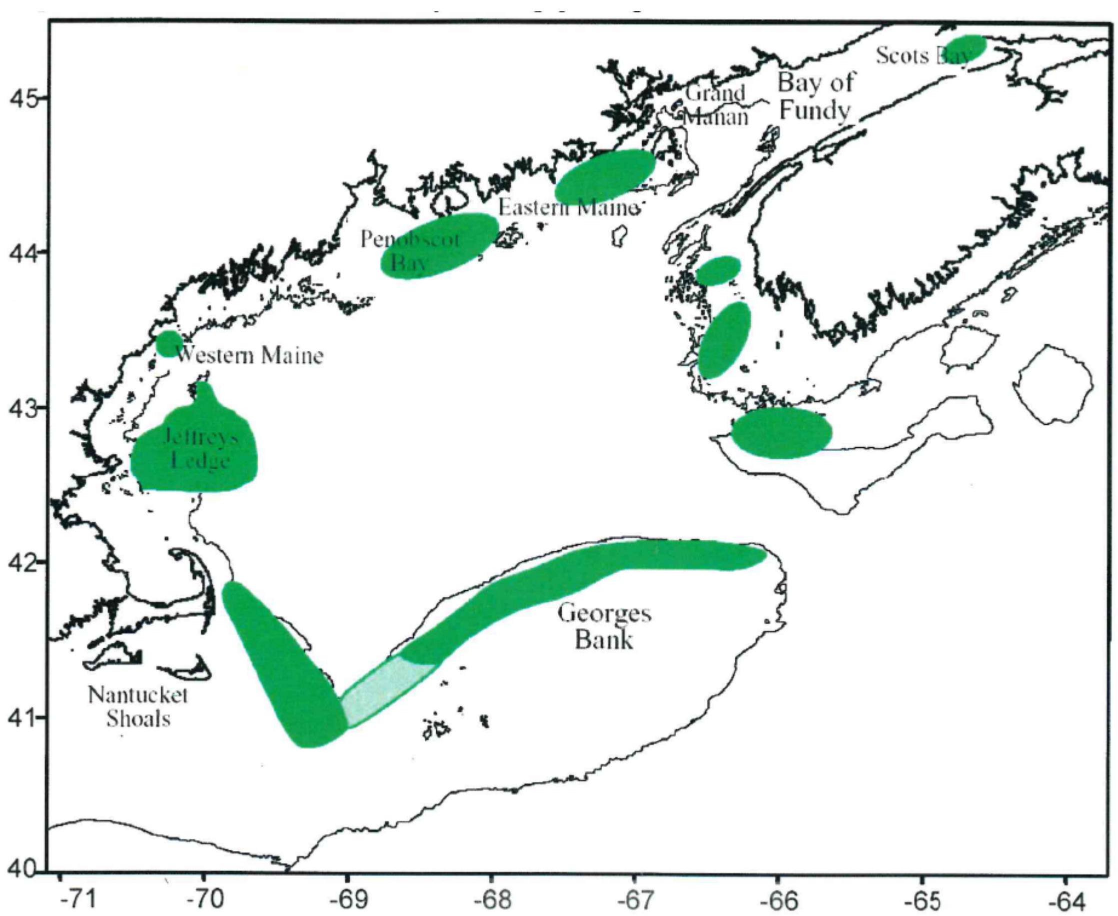
may be the most important spawning ground in the Gulf of Maine based on the number of spawning and near-spawning adults found there (Boyar et al. 1973). Figure 1.2.1 summarizes the general locations of major herring spawning areas in the GOM and GB.

Herring also spawn on Nantucket Shoals and Georges Bank, but not further south. In Canada, spawning occurs south of Grand Manan Island (in the entrance of the Bay of Fundy) and on various banks and shoals south of Nova Scotia (Figure 1.2.1). Spawning occurs in the summer and fall, starting earlier along the eastern Maine coast and southwest Nova Scotia (August-September) than in the southwestern Gulf of Maine (early to mid-October in the Jeffreys Ledge area and as late as November-December on Georges Bank; NEFMC 2006; Reid et al. 1999). Eggs are laid in layers and form mats as thick as 4-5 cm. Herring in the Gulf of Maine region usually reproduce at relatively high temperatures (10-15°C) and at high salinities (NEFMC 2006). Herring do not spawn in brackish water.

Atlantic herring spawn on the bottom in discrete locations by depositing adhesive eggs that stick to any stable bottom substrate, including lobster pots and anchor lines. Eggs are laid in layers and form mats or carpets. In the Gulf of Maine, egg mats as thick as 4-5 cm have been observed in discrete egg beds that have varied in size from 0.3-1.4 km2 . One very large egg bed surveyed on Georges Bank in 1964 covered an area of about 65 km^2 *(Noskov & Zinkevich 1967).*

Atlantic herring are synchronous spawners, producing eggs once annually upon reaching maturity. Depending on their size and age, female herring can produce 55,000-210,000 eggs (Kelly & Stevenson 1983). Once they are laid on the bottom, herring eggs are preyed upon by a number of fish species, including cod, haddock, red hake, sand lance, winter flounder, smelt, tomcod, cunner, pollock, sculpins, skates, mackerel and even herring themselves (Munroe 2002; NEFMC 2006). Egg predation and adverse environmental conditions often result in high egg mortalities.

Figure 1.2.1. Generalized view of the current major herring spawning areas in the GOM and on GB (from Overholtz et al. 2004).



1.3. Spawning Closures as a Fisheries Management Tool

Spawning closures are used throughout the world to protect this vulnerable stage of a fish's life-cycle. Spawning closures may be designed to account for the fact that spawning may make fish more susceptible to overfishing since fish are highly aggregated during this time. In this sense, spawning closures may be considered as an effort control measure. Alternatively, fishing may disrupt spawning behavior (e.g., formation of schools) that may lead to missed spawning potential, which could ultimately affect recruitment. Finally, spawning closures may be designed to protect habitat over which fish may spawn. This is particularly important for fish that deposit eggs over specific habitats including certain bottom types and structures (e.g., macroalgae). Additionally, spawning closures may be designed in a network fashion to avoid overexploitation of specific spawning components. van Overzee and Rijnsdorp (2015) provided a review of the various goals and benefits of spawning closures for a range of species and considered a semi-quantitative assessment of the potential for disruption to spawning by fishing for different aspects of spawning: aggregation during spawning, spawning behavior complexity, and spawning habitat. Different species were more or less vulnerable for different aspects. For example, bivalves have a low vulnerability across all aspects of spawning as considered by van Overzee and Rijnsdorp (2015); they do not form spawning aggregations, they broadcast their spawn with no courtship behavior and their spawning habitat is pelagic. Herring, on the other hand, were scored intermediate for their vulnerability to fishing during aggregation and during the act of spawning since they do form spawning aggregations and they do have some level of courtship behavior that can be disrupted. Herring were scored high in their vulnerability to fishing effects with respect to habitat since their eggs are attached and aggregated on the bottom, thus making them vulnerable to various bottom tending gears. In terms of the assessment of van Overzee and Rijnsdorp (2015), herring were among the most vulnerable species considered to fishing effects during all aspects of spawning and would therefore be expected to benefit from some sort or range of spawning protection(s).

1.4. History of Spawning Closures in the Gulf of Maine

Perhaps the most relevant example of spawning protections being implemented for Atlantic herring comes from the Gulf of Maine. The discussion document from Appendix VIII to Amendment 5 to the Atlantic herring Fishery Management Plan (FMP, NEFMC 2013) outlines the timeline of implementation of spawning closures in the Gulf of Maine (up until 2013) and is reproduced below (in italics).

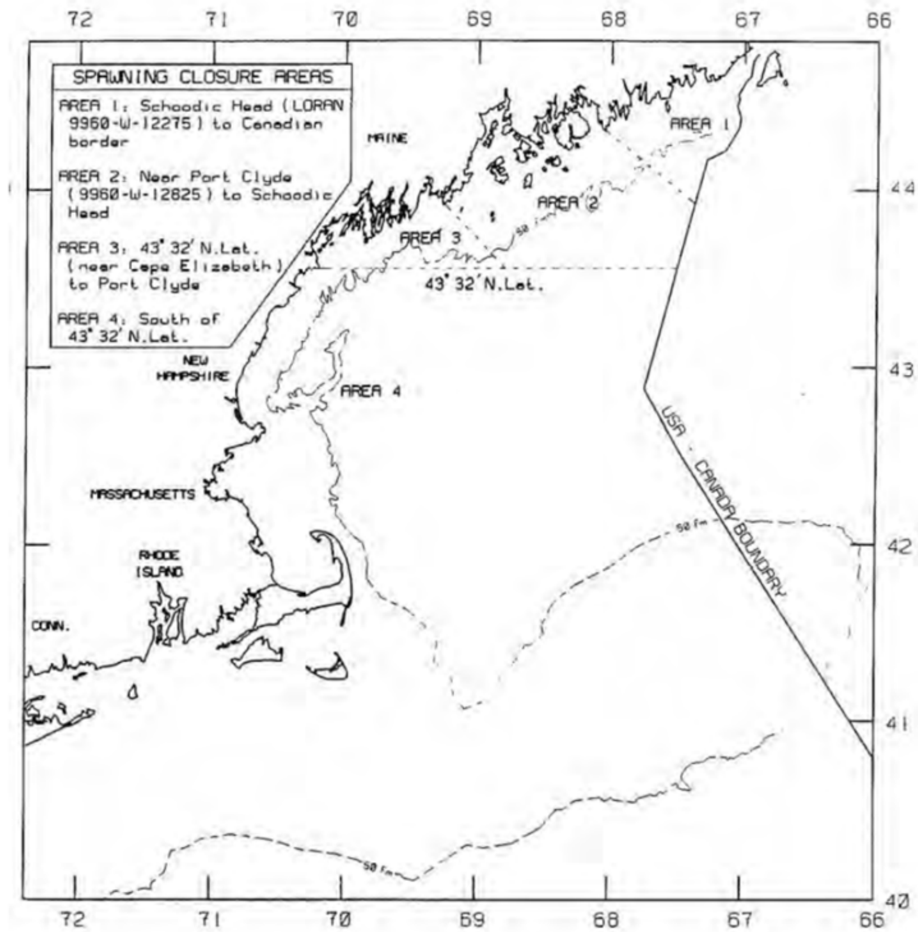
The Atlantic States Marine Fisheries Commission (ASMFC) began formal spawning closures in 1994 as part of the 1993 Atlantic Herring Fishery Management Plan (FMP). These spawning closures were a continuation of an agreement among Maine, New Hampshire, Massachusetts, and Rhode Island, who had adopted a series of spawning closures in November 1983 as part of their Interstate Herring Management Plan. The 1993 FMP included spawning protection for the entire range of Atlantic herring, including offshore areas such as Georges Bank. Foreign fishing from the late-1960s to the mid-1970s had depleted the offshore stock. Consequently, there were few spawning females in offshore areas. States sought to protect the new abundance of offshore spawning females when the population rebounded in the late 1980s and included offshore spawning restrictions.

The goals of the ASMFC FMP relating to the spawning closures were "to maintain the U.S. northwest Atlantic sea herring resource at or above 20% of its maximum spawning potential for optimal utilization while reducing the risk of stock collapse" and "to provide adequate protection for spawning herring and prevent damage to herring egg beds".

The 1993 ASMFC FMP required states to monitor the spawning closures by sampling commercial catch just prior to the automatic closure dates. Closures were delayed for one week if the average gonad somatic index (GSI) of mature females (International Convention for the Northwest Atlantic Fisheries [ICNAF] gonadal stages III – V) was below the threshold value for either size class (18% for fish ≥ 28 cm total length and 10% for fish between 24 and 28 cm total length). Additional one week delays were implemented if sampling indicated that at least one size class had not yet reached the threshold value. The FMP allowed some landing of spawning fish (tolerances). Tolerances varied between closure areas with a 25% spawn allowance by number in the eastern, central, and western Maine spawning areas and a 5% or

1,000 pound (whichever is greater) spawn allowance in New Hampshire and Massachusetts. Vessels were prohibited from fishing for, possessing, or landing any Atlantic herring containing spawn in all other areas. Spawning closures boundaries are shown in Figure 1.4.1 and language specific to the 1993 ASMFC FMP follows:

Figure 1.4.1. *Spawning closure areas from 1993 Atlantic Herring Fishery Management Plan.* Note that figure is renumbered from original document.



From Section 6.2.3 Spawning Closures of 1993 ASMFC FMP:

1. *A four week closure in eastern Maine beginning August 15 (unless samples of the commercial catch taken prior to the closure date indicate that females are delayed in reaching full maturity) during which time it is unlawful to fish for or take herring containing spawn (milt or roe) when they make up more than 25% by number of any load.*
2. *A four week closure in two additional areas in central and western Maine beginning September 1 subject to the same monitoring or maturity and 25% tolerance exceptions.*
3. *A three week closure beginning October 1 for the area south of 43˚ 32'N (Cape Elizabeth) that is not subject to any tolerance exceptions. The closure date in this area*

is subject, however, to successive one week delays if sampling indicates that spawning will be delayed (identical to provisions which apply in the three areas north of 43 ˚ 32' N). This closure is enforced jointly by the four states which are party to the Interstate Herring Management Plan.

- *Area 1 (eastern Maine) : area northeast of Loran C 9960-W-12275 (Schoodic Point) to the U.S.-Canadian border.*
- *Area 2 (central Maine) : area east (or north) of Loran C 9960-W-12825 (Small Point) to Loran C 9960-W-12275 and north of 43˚ 32' N. Amendment 5 Volume II Appendix VIII Discussion Document: Spawning Atlantic Herring 4*
- *Area 3 (western Maine) : area bounded by 43˚ 32' N (Cape Elisabeth) on the south and by Loran C 9960-W-12825 on the east (or north).*
- *Area 4 : area south of 43˚ 32' N, including state and federal waters adjacent to Maine, New Hampshire and Massachusetts and the southern New England area.*

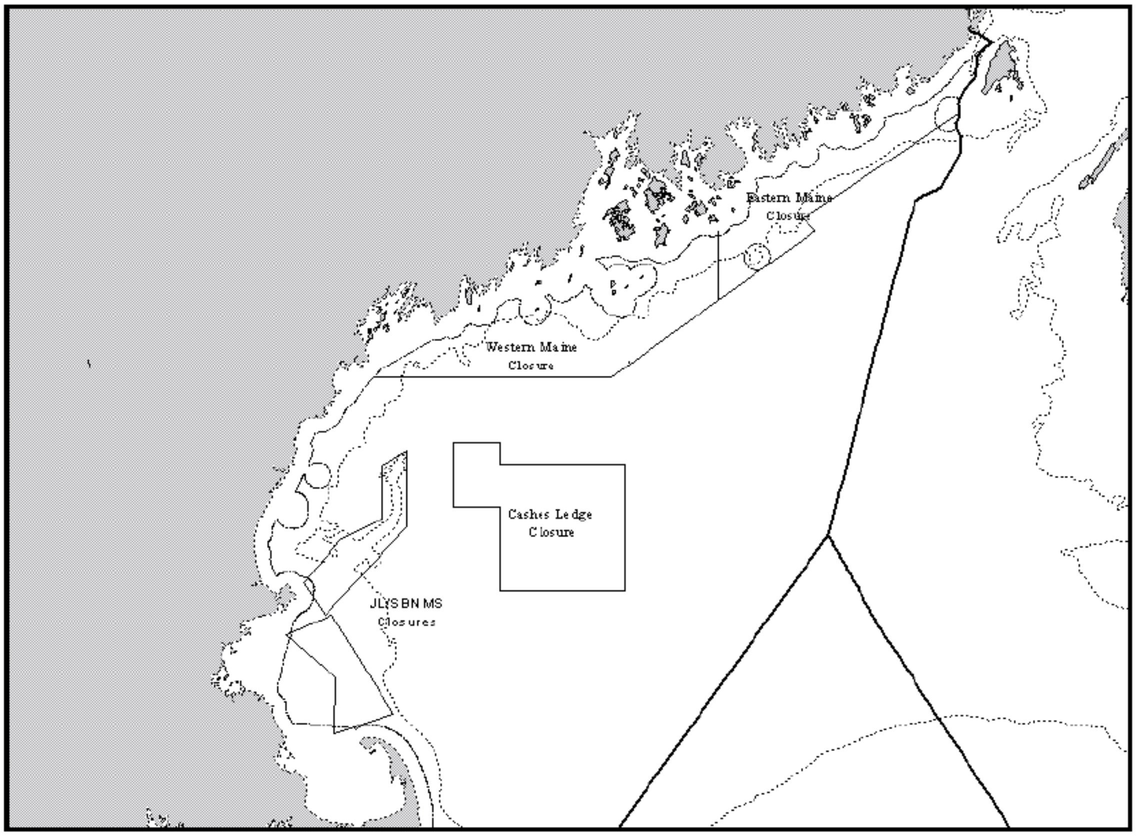
The New England Fishery Management Council (NEFMC) first proposed spawning area closures as a part of its Atlantic Herring FMP in 1998. The measures were intended to be adjusted through framework actions which could be initiated when additional information on the timing and locations of spawning became available. Additional closures were also a possibility through a framework action, particularly in the lesser known offshore areas. The proposed closures in the 1998 NEFMC FMP were considered necessary to ensure adequate protection of the herring resource. Herring fat content is at its peak during spawning, making them more economically valuable for human consumption, while concentrated spawning aggregations make herring susceptible to harvesting.

In addition, spawning behavior of the uncaught herring was believed to be influenced by harvesting operations. At the time that the spawning closures were being considered, it was believed that protection of individual spawning populations would ensure successful recruitment across the entire stock complex. It was also believed that removal of fishing pressure during spawning would relieve the aforementioned stresses while also making it easier to accurately assess the extent and size of the spawning populations, as they would not be disturbed by fishing pressure. The closures proposed by the NEFMC are shown in Figure 1.4.2. These areas were modified from the spawning closures implemented by the ASMFC 1993 Atlantic Herring FMP. Language specific to the proposed NEFMC FMP follows. The spawning closure dates in Management Area 1 were defined as:

- *Eastern Maine August 15 – September 11*
- *Western Maine September 1 – September 28*
- *Jeffreys Ledge/Stellwagen Bank September 15 – October 12*
- *Cashes Ledge August 1 – September 25*

The spawning closure dates proposed were fixed. In an area closed to protect spawning, fishing for, harvesting, or possessing herring would not be allowed except for the following exception: vessels will be allowed to catch and possess up to 2,000 pounds of herring per trip. The amount of herring landed from a closed spawning area by one vessel in a day could not *exceed 2,000 pounds (this prohibits a vessel from making multiple trips in one day to exceed the 2,000 pound trip limit).*

Figure 1.4.2. *Herring Management Area 1 spawning closures (with approximate territorial sea boundary shown) proposed in the 1998 NEFMC Atlantic Herring FMP.* Note that figure is renumbered from original document. From south to north, Stellwagen Bank National Marine Sanctuary Closure, Jeffreys Ledge Closure, Cashes Ledge Closure, Western Maine Closure, Eastern Maine Closure.



Management Areas 2 and 3 were not considered for closures in the proposed measures of the NEFMC FMP because the offshore herring resource was considered robust and there was interest in developing the offshore fishery.

The proposed NEFMC closures in federal waters were also intended to complement the efforts of the ASMFC Amendment 1 (1999) measures (see below). The tolerance measures enacted by ASMFC allowed for some landing of spawn fish but enforcement was limited to landing regulations implemented by the individual States within ASMFC. The NEFMC developed its proposed measures out of concern that some states did not have the resources to implement and enforce the measures, which would have negated the spawning protection. The NEFMC's intention was to augment the efforts of the ASMFC by preventing the catch of spawn herring in federal waters.

In the proposed NEFMC FMP, the spawning area closures were predicted to increase cost and decrease revenue for the herring industry. Effort would have been shifted to where and when herring would be less aggregated and contain less fat. It was projected that one-third of the landings of the year prior to the proposed measures (1997) would have been closed to fishing in subsequent years as a result of the proposed action. This analysis was based on only one year of data, however, and may not have represented average fishing. A shift in effort as a result of the measures also was not considered. However, community impacts were projected to be minimal to non-existent because the NEFMC's proposed closures were smaller than those in the Amendment 5 Volume II Appendix VIII Discussion Document: Spawning Atlantic Herring 6 ASMFC's 1993 plan, and other open areas closer to shore were made available for fishing to the potentially affected boats.

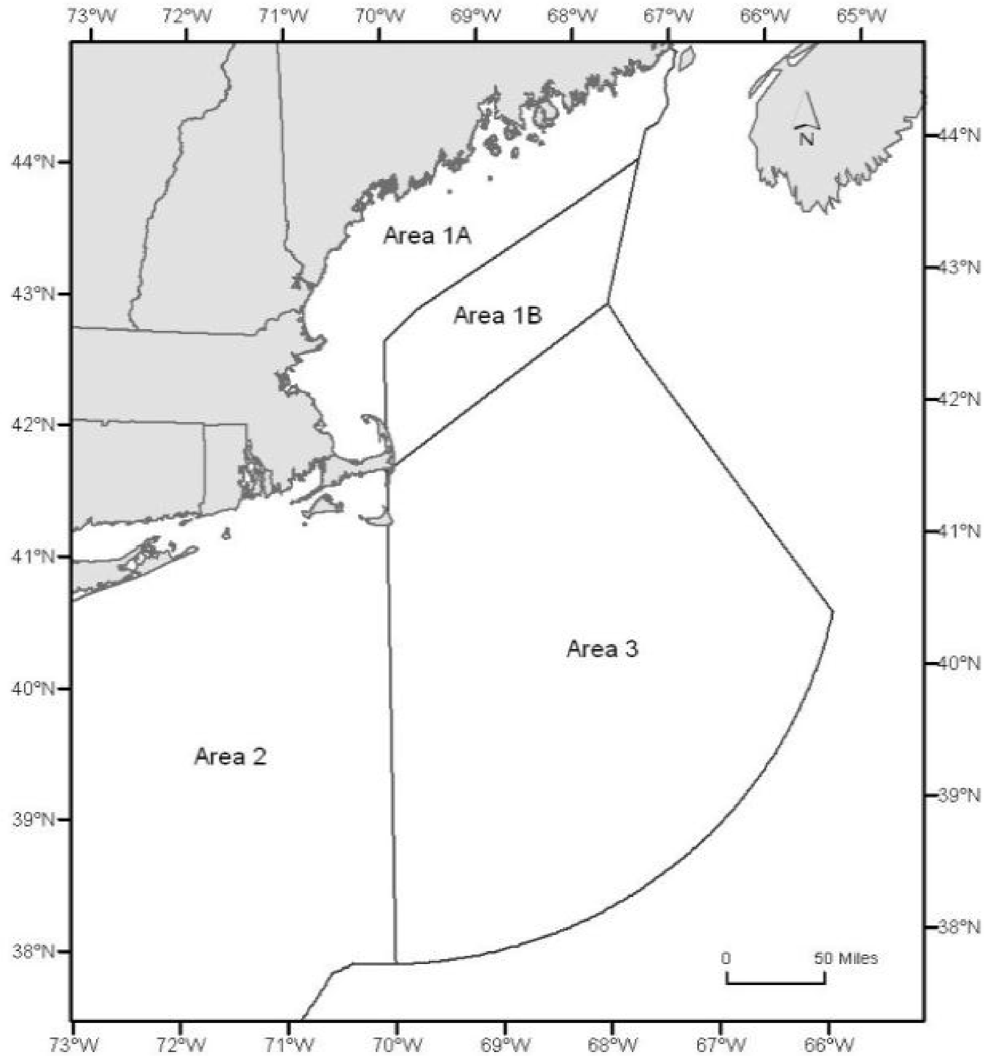
On October 27, 1999, the NEFMC received notification that the National Marine Fisheries Service (NMFS) Regional Administrator rejected the measures that would have created spawning area closures:

"I disapproved the spawning area closures because it was not demonstrated that the costs of imposing the closures outweigh the benefits, and the measure appears to be inconsistent with National Standard 7 in that conservation benefits are uncertain. The measure also appears to contravene the M-SFCMA, Sec. 303 (a)(1)(A). Further, the spawning closures would not apply to mobile, bottom-tending vessels, just to purse seiners and mid-water trawlers. Such fishing gear may also disturb spawning herring. Also, the Northeast Region Office of Law Enforcement stated that spawning area closures that allow the possession of herring on board pose enforcement problems. In consideration of the aforementioned and of concerns raised by commenters, and given the uncertainty of conservation benefits to be realized, a spawning closure at this time does not appear to be a necessary and appropriate conservation and management measure."

The ASMFC developed Addendum I as a result of NMFS disapproval to readdress the spawning measures that had been defined in ASMFC Amendment 1 (see following).

Amendment 1 (1999) to the ASMFC Atlantic Herring FMP replaced all previous ASMFC Atlantic herring measures including spawning closures. The goal of the new spawning measures was to protect distinct spawning units that are especially susceptible to fishing when they aggregate for spawning. The new spawning measures applied only to state waters within Management Area 1A (Figure 1.4.3) and did not include any measures to protect spawning fish in offshore areas such as Georges Bank. From August 1 through October 31, vessels were prohibited from taking, landing, or possessing more than 20% (by number) "spawn" herring containing roe or milt from state waters within Management Area 1A. Amendment 1 (1999) defined spawn herring as "ICNAF gonadal stages 4, 5, & 6."

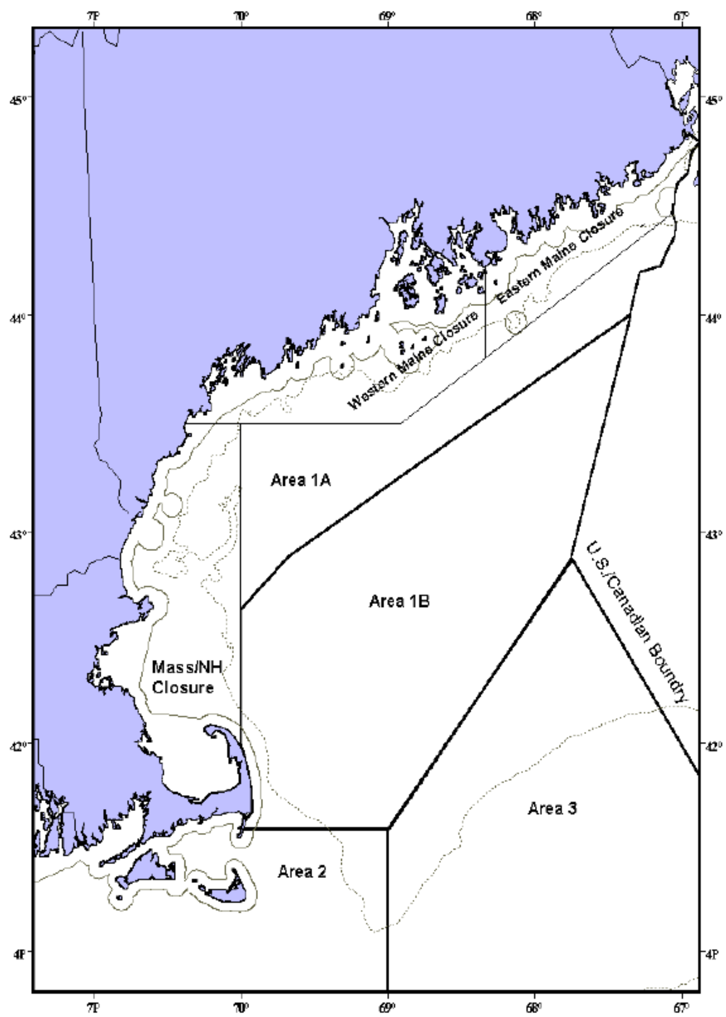
Figure 1.4.3. *Management areas under ASMFC Amendment 1.* Note that figure is renumbered from original document.



Addendum I (2000) to Amendment 1 of the ASMFC Atlantic herring FMP was developed to readdress the protection of spawning areas because NMFS rejected the NEFMC's proposed Area 1A spawning closures in federal waters (see above). Under Addendum I, three spawning management areas were created (Figure 1.4.4) – Eastern Gulf of Maine (EGOM), Western Gulf of Maine (WGOM), and Massachusetts/New Hampshire (MA/NH), all of which are in Management Area 1A. These spawning areas extended into federal waters and had distinct start dates of August 15 (EGOM), September 1 (WGOM), and September 21 (MA/NH). Closures lasted 4 weeks by default, but would be extended 2 weeks if commercial catch sampling found that 25% or more mature herring, by number, had yet to spawn. Mature or "spawn" herring were defined as Atlantic herring in ICNAF gonadal stages V & VI. The *definition remained "ICNAF gonadal stages V & VI" in all subsequent management documents.*

In 2000, members of the public, herring fishermen, and Maine Department of Marine Fisheries personnel all noted a significant take of spawn herring from the area just outside the EGOM area during the closure. Consequently, Technical Addendum 1A (2001) was created to expand the EGOM spawning area to protect spawning females inside the eastern tip of Inner Schoodic Ridge (Figure 1.4.4).

Figure 1.4.4. *Spawning closure boundaries under Technical Addendum 1A to ASMFC Amendment 1.* Note that figure is renumbered from original document.



Today [note that 'today' refers to 2013 when document was written], *ASMFC spawning regulations are specified through Amendment 2 and Technical Addendum I (2006), which continue with the three spawning areas and default dates established by Addendum 1 and Technical Addendum 1A (Figure 1.4.4). Spawning closures begin on the default start date* *unless commercial catch samples show significant amounts of spawn herring, defined as 25% or more in ICNAF gonadal stages V & VI. By default, closures last 4 weeks, at which point fishing is allowed. If a significant amount of spawn herring are found in the commercial catch samples after the closure, an additional 2 week closure is triggered. Fishermen are notified of the additional closure by the states, which use a distribution list that includes the ASMFC. The ASFMC will then place notice of the closure on their website.*

Amendment 2 contains a "zero tolerance" provision that prohibits vessels from fishing for, taking, landing, or possessing "spawn" herring (ICNAF gonadal stages V & VI) in a spawning area during a closure. Some states interpreted zero tolerance to allow fishing in a closed area as long as no spawn herring are caught. Upon review of the loose interpretation of zero tolerance, and based on input from the Atlantic Herring Law Enforcement Committee (LEC), ASMFC developed Technical Addendum I to Amendment 2 to clarify that vessels are prohibited from fishing for, taking, or possessing herring within a restricted spawning area. The LEC was concerned that tolerances are difficult to enforce while prohibiting fishing in a closed area is easily enforceable.

Vessels on non-directed herring trips are allowed an incidental catch of 2,000 pounds from a restricted spawning area as a bycatch allowance. Any herring vessel that has more than 2,000 pounds of herring onboard that were caught outside an area under a spawning closure must have all of its fishing gear stowed as it travels through the closure area. Fixed gear fishermen east of Cutler, ME, are exempt from spawning closures and are not limited to the 2,000 pound bycatch allowance.

Amendment 2 does not include spawning restrictions for any offshore areas, although enforcement is by possession, not location of fishing. Its measures are designed to protect the inshore component of the stock by moving effort to offshore areas where the total allowable catch was historically not fully harvested. Section 4.3.2 Spawning Restrictions states that "protection to the offshore spawning component would come at the expense of putting more pressure on the inshore component of the stock complex."

1.5. Current Approach for Managing Spawning Closures in the Gulf of Maine

The current approach for managing spawning closures in the Gulf of Maine is outlined in Amendment 3 to the Atlantic Herring Interstate Fishery Management Plan (ASMFC). This approach, launched in 2015, utilizes what is known as the GSI30 protocol. GSI, or gonadal somatic index (percent of gonad weight to whole body weight), is calculated for females sampled from portside monitoring programs or other fishery independent sources. Three or more samples are required to model the relationship between GSI and date. If a significant relationship exists between GSI and date, the trend can be extrapolated to forecast the date at which GSI will cross a threshold value – established as 25% in Amendment 3, but reduced to 23% in Addendum II to Amendment 3; the lower value ensures that pre-spawning fish are protected earlier in the spawning season. While previous schemes used different GSI trigger values in different length classes to determine closures, the GSI30 method standardizes GSI values to a 30 cm fish to ensure protection of the whole population (i.e., all sizes). If insufficient data exists to model the relationship between GSI and date, default closure dates are used. Default dates are derived from historical GSI samples over the last decade as well as from the literature. The following default dates were derived from spawning samples collected between 2005-2017 and using a trigger value of 23%.

- Eastern Maine – August 28
- Western Maine – September 23
- Massachusetts/New Hampshire – September 23

The duration of spawning closures was initially set at 4 weeks under Amendment 3 but raised to 6 weeks in Addendum II to Amendment 3, based on an analysis by Dean et al (2018) which showed that spawning season often exceeds 4 weeks. Amendment 3 specified the following reclosure protocol: If a significant number of spawning herring (25% or more mature herring in the sample; sample must contain at least 80 randomly sampled adult sized fish) are observed at the end of the initial closure, the closure can be extended another 2 weeks. Addendum II refined this protocol such that 'significant number of spawn herring' now means 20%. Mature herring in both case means herring in ICNAF gonadal stages V and VI. Samples should be taken in final week of the initial closure or at the end of the initial closure period.

Figure 1.5.1. Real output from GSI30 forecast method for Mass/NH Spawning Area. In this case, 4 samples were taken prior to spawning closure. The trend (black line) showed that forecast mean GSI would not reach the threshold value of 23 (blue line) before the default date (red line). In this case the closure was triggered by the default date of September 23rd.

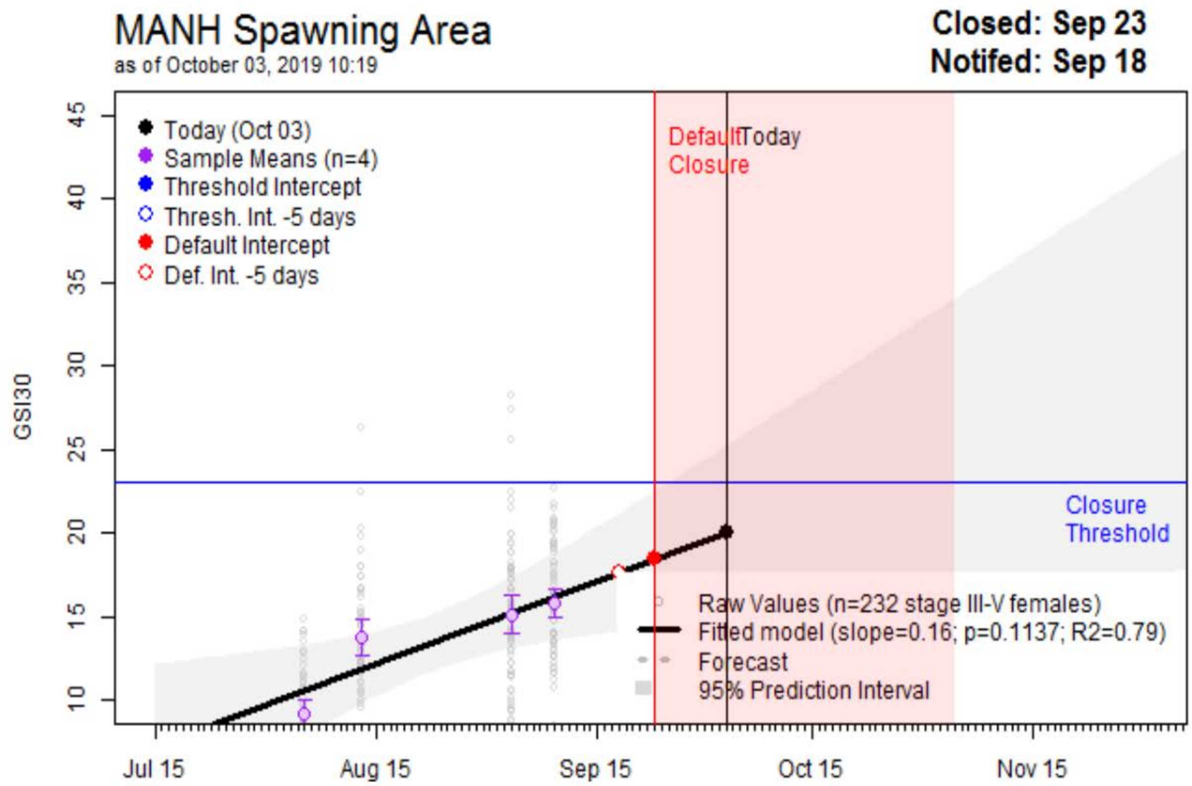
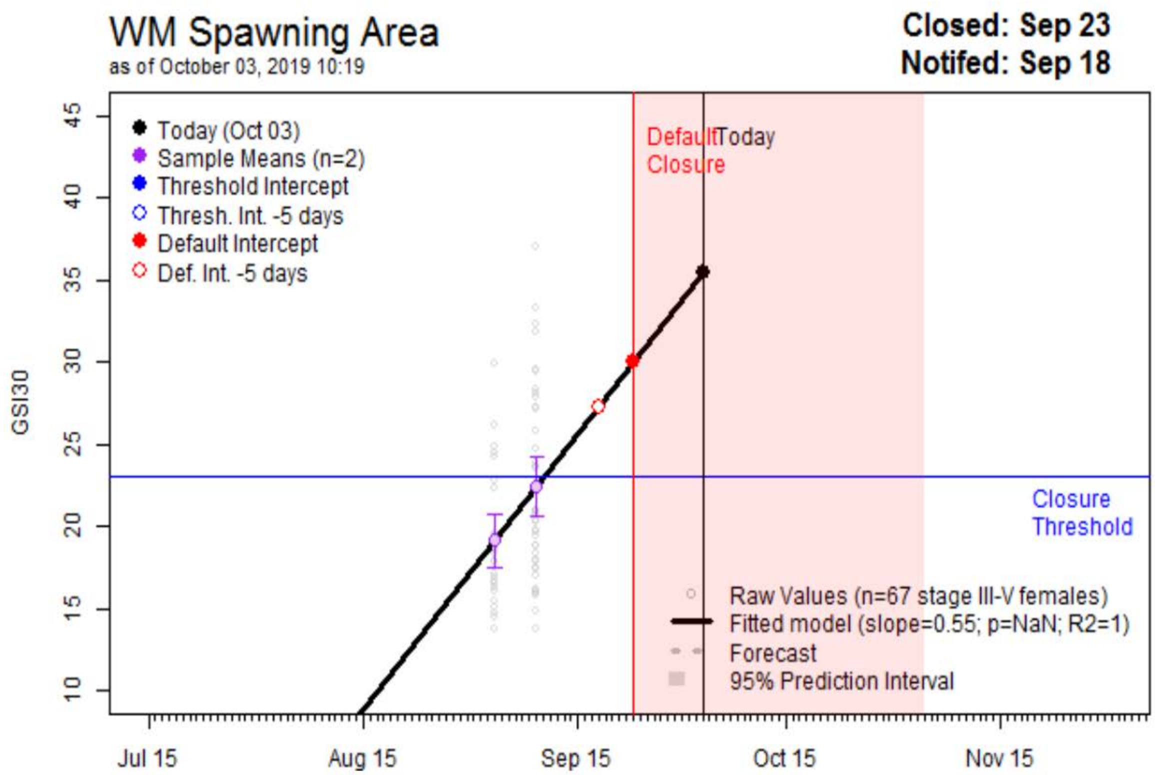


Figure 1.5.2. Real output from GSI30 forecast method for Western Maine Spawning Area. In this case, only 2 samples were taken prior to spawning closure. The trend (black line) showed that forecast mean GSI would cross the threshold value of 23 (blue line) before the default date (red line). However, since only 2 samples were taken (short of the required 3), the default date of September 23rd was used. Note that no samples were available from the Eastern Maine Spawning Area this year (2019).



1.6. Examples of Herring Spawning Protections in Other Areas of the World

An exhaustive review of management measures in other parts of the world intended to directly or indirectly protect spawning herring is beyond the scope of this document. However, some examples from different fishery management plans, with different objectives with respect to spawning protections, are provided for reference.

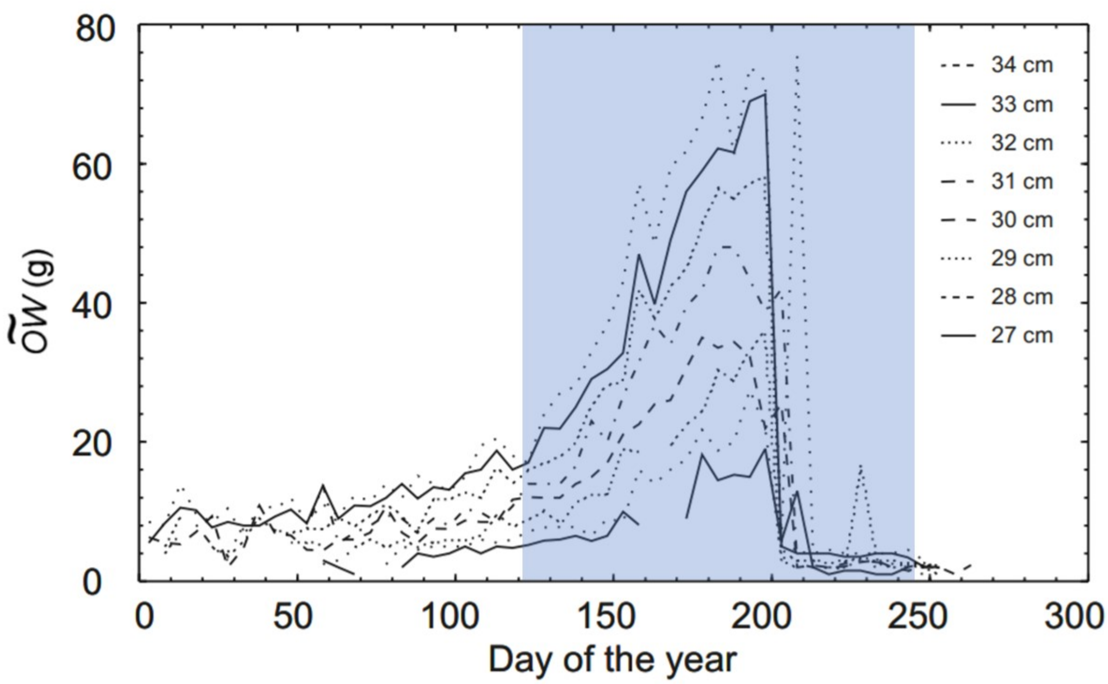
Closest to home, the management plan for herring in the southwest Nova Scotia/Bay of Fundy region includes a number of measures to reduce mortality and encourage stock growth. With respect to spawning, the main strategy is to maintain biomass of each spawning component of which there are four main grounds: Scots Bay, German Bank, Trinity Ledge and Seal Island. Fishing on spawning aggregations is part of the management plan and thus the goal of maintaining each spawning component above limit reference points is achieved via TACs informed by acoustic surveys and fishermen input. The management plan also includes a range of size limits, seasonal closures and area-based TACs all which address the strategy of maintaining biomass of each spawning component (DFO 2014).

In the Gulf of St. Lawrence, the bottom of Bay St. George (in western Newfoundland) has been identified as a major spawning area for spring spawning herring in NAFO Divisions 4R3Pn. In order to protect the spawning ground, a portion of the bottom of Bay St. George was closed to fishing for all gear types (DFO 2017). Thus, in contrast to the previous example, which was focused on maintaining reproductive capacity of herring in each management unit, the focus in western Newfoundland was on protecting habitat.

In northeastern Newfoundland (NAFO Divisions 2J3KLPs), while there are currently no explicit protections for spawning herring, an important future objective for DFO is to "work with stakeholders to ensure that migrating and spawning herring are not adversely impacted. This may necessitate additional closed areas and times."

In Iceland, a number of measures are in place to protect summer-spawning herring. Most notably, fishing is limited to the period September 1st to May 1st, outside of the spawning season (Figure 1.6.1). While not spawning protections, there are also regulations to protect juvenile herring (27 cm and smaller). In this case, a series of closures are enforced when the proportion of juveniles in the catch exceeds 25% in number (ICES 2017a).

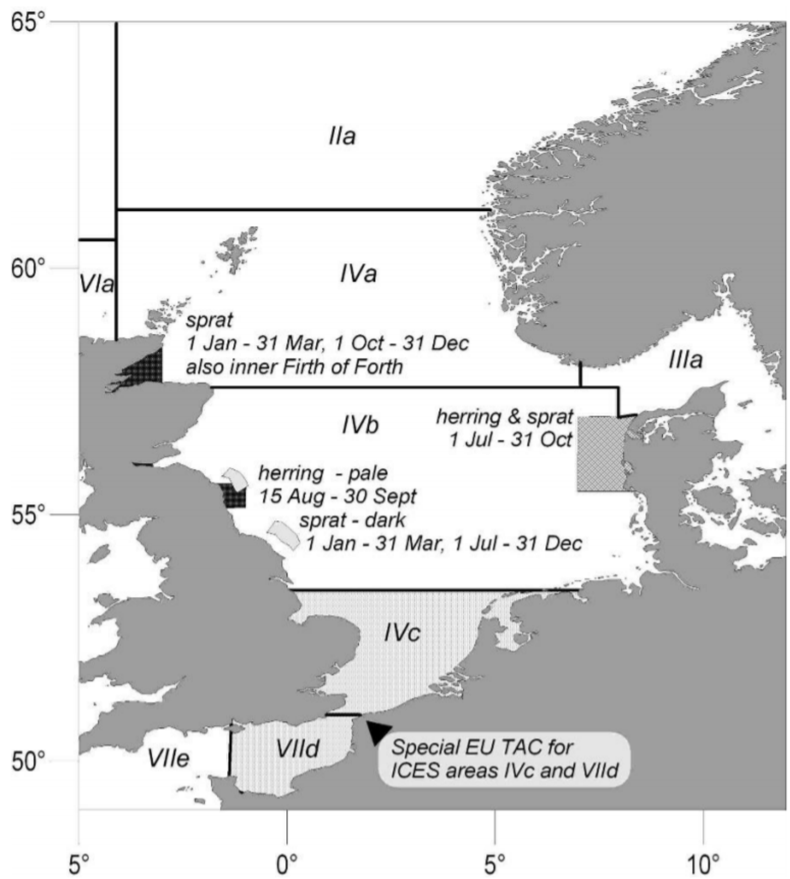
Figure 1.6.1. Time series of median ovarian weight (OW) by size class (27-34 cm) in Icelandic summer-spawning herring aggregated over period 1953-2000. Blue shading represents closed season. Modified from Óskarsson and Taggart (2009).



A series of herring spawning closures have been used around the United Kingdom over the last several decades. These are outlined and evaluated in a working document commissioned by the European Commission (STECF 2007). The general takeaway from this analysis is that spawning closures were implemented during periods of herring stock declines and heavy exploitation to limit overexploitation of herring when they are highly aggregated and when roe fisheries are most valuable. The group recommended that herring spawning closures could be lifted when stocks are healthy. They also argued that spawning closures can be an effective way of controlling fishing mortality when there is little confidence in management being able to maintain F at desired levels.

Clarke and Egan (2017) describe the role of spawning closures in the recovery of Celtic Sea herring between 2000 and 2012. The Celtic Sea herring stock collapsed first in the 1970s and again in the early 2000s. Following the first collapse, the stock was managed by TACs and with input from stakeholders, efforts to reduce fishing mortality were increased including the establishment of box closures in the 1980s that still exist. Following the second collapse, a number of actions were taken to rebuild the fishery including the closure of the 'recruit-spawner' box which varied in temporal duration each season. In concert with other management measures, including time/area allocations of TACs to shift effort away from dense spawning aggregations and the removal of a "use it or lose it" provision for license holders, the stock recovered by 2012.

Figure 1.6.2. ICES areas and areas closed to fishing on herring and sprat under EU legislation. Black areas denote three small sprat closures to protect juvenile herring. Pale areas denote two closures on the herring fisheries to protect spawning herring around the Banks spawning ground. The shaded area to the west of Denmark is closed to the juvenile herring and the sprat fishery (although there is no targeted juvenile herring fishery). Figure and caption from ICES (2017b).



There has been a history of spawning closures for North Sea autumn spawning herring in ICES subarea 4, divisions 3.a and 7.d which consists of four major spawning components. This Fishery involves Norway, Denmark, Sweden, Germany, The Netherlands, Belgium, France, UK, Faroe Islands and Ireland. Two different types of closures are used: sprat closures to protect juveniles and spawning closures to protect spawning herring (ICES 2017b). The closures with their respective closure dates are shown in Figure 1.6.2.

2. Analysis of Existing Data Sets

2.1. Larval Data

Fish larvae can be a valuable indicator of spawning locations in fish (Richardson et al. 2010), particularly for herring since eggs are demersal and not subject to dispersal. Thus, young larvae, within a short time frame of hatching, may be spatially associated with where they were spawned. Herring larval data from Georges Bank monitoring have been presented in numerous publications and assessments (e.g., 54th Northeast Regional Stock Assessment Workshop; NEFSC 2012). For this review, larval data were accessed (D. Richardson, pers. comm.) and explored from the Northeast Fisheries Science Center ichthyoplankton sampling program from 1971-2017 (see Richardson et al. 2010 for description of monitoring program). Sampling was not conducted in every region every year during sampling cruises. During some sampling trips, there were ship time limitations, inclement weather, and other unforeseen circumstances leaving gaps in sampling. For this analysis, abundance of Atlantic herring <9mm was summed for each sample with unique locations. Larvae less than 9mm length are typically 10-15 days old (Richardson et al. 2010).

Larval distribution was visualized using the 'MASS' package in R where data was plotted by 2-dimensional kernel density estimation (Venables and Ripley 2002). Most larval herring were observed in October and November. Over the entire time series, highest densities of larval herring occurred on the northeast section of Georges Bank and Nantucket Shoals (Figure 2.1.1). These two areas had high densities in the 1970s and again in the 1990s, while Nantucket Shoals and Stellwagen Bank were prominent in the 1980s (Figure 2.1.2). Smith and Morse (1993) similarly found that the full extent of larval herring contracted to only Nantucket Shoals and Stellwagen Bank after the fishery collapsed in 1976, but then expanded eastward on Georges Bank through 1990. Between 2000 and 2017 larval herring density has concentrated to the Northeast section of Georges Bank (Figure 2.1.2).

Figure 2.1.1. 2-dimensional kernel density estimates of larval herring (<9 mm) abundance per sample 1971-2017 with all sample location points overlaid. Red areas indicate higher densities. Total sample size = 2,371. 100 m isobath is shown. Points are sample locations.

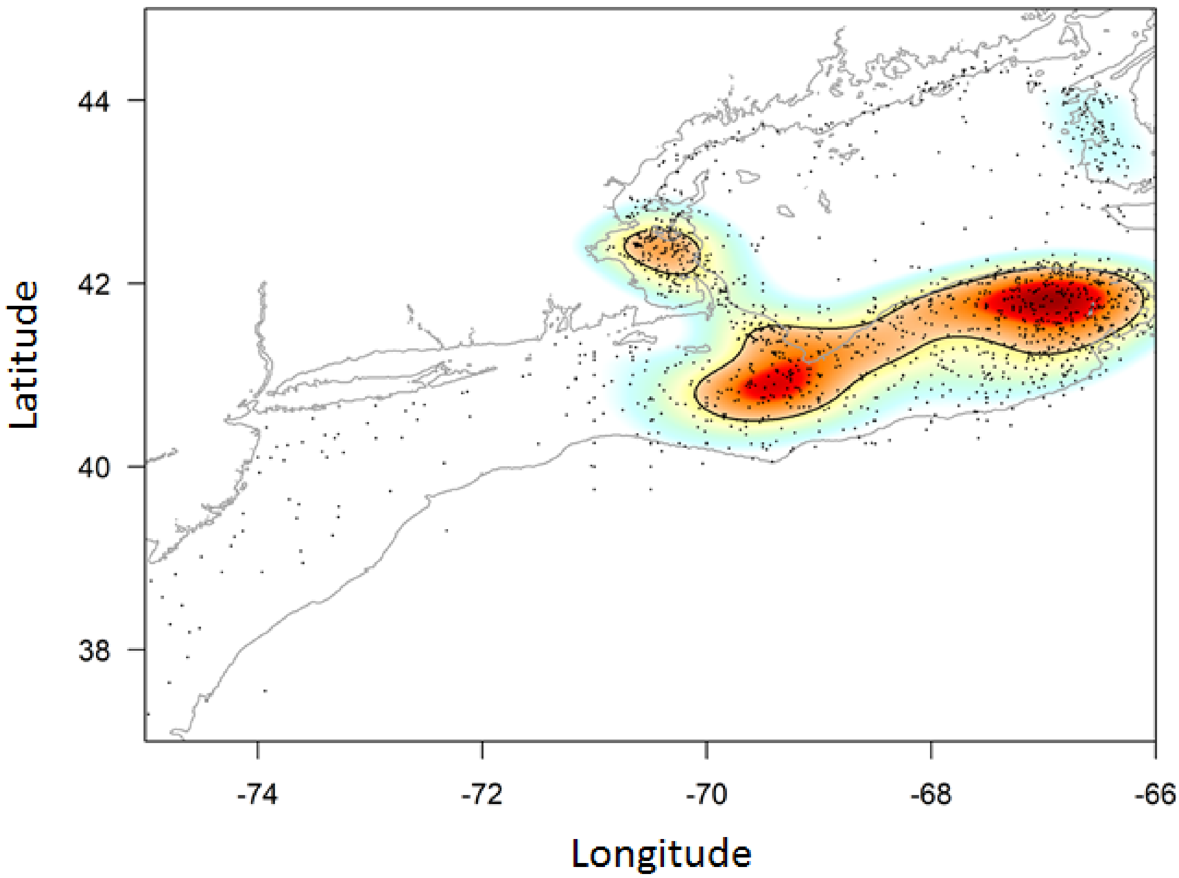
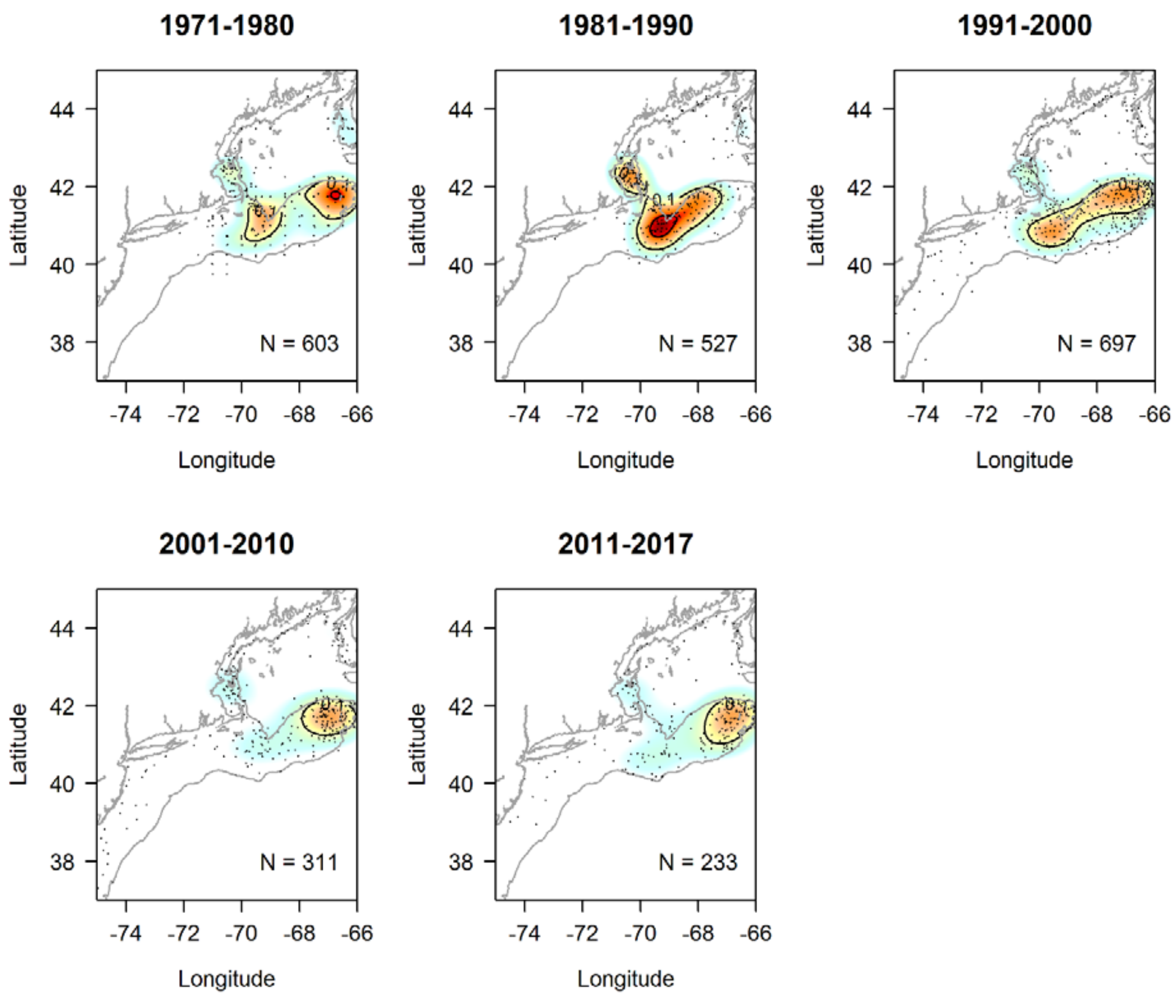


Figure 2.1.2. 2-dimensional kernel density estimates of larval herring (<9mm) per sample by decade with all sample location points overlaid. N = sample size and red areas indicate higher densities. 100 m isobath is shown. Points are sample locations.



2.2. Adult Data: DMR and Mass DMF Portside Monitoring Data (spatial patterns)

The Maine Department of Marine Resources (DMR) has administered a portside monitoring program for the US Atlantic herring fishery and has collected and processed commercial catch samples using a consistent methodology since 1971. Herring samples are collected from all commercial gear types; purse seine, single midwater trawl, pair midwater trawl, small mesh bottom trawl, and fixed gear. Two types of samples are collected, catch-at-age and spawn samples. Catch-at-age samples are collected throughout the entire range of the US fishery, year-round, including all four management areas, 1A, 1B, 2, and 3. Ports used for sample collection are from north to south: Jonesport ME, Prospect Harbor ME, Stonington ME, Rockland ME, New Harbor ME, Boothbay Harbor ME, Portland ME, Portsmouth NH, Newington NH, Seabrook NH, Gloucester MA, Fall River MA, New Bedford MA, Point Judith RI, Davisville RI, Newport RI, and Cape May NJ. Catch-at-age sampling requires n=50 randomly selected herring per gear type, per NMFS statistical area, per week. Spawn samples require n=150, adult sized herring per sample (≥23cm) during the spawn season (August – October) per week from all three spawn areas within Area 1A, only. Whole lengths, weights, age via otoliths, gender, spawn condition via staging (see Table 2.2.1) and stomach fullness, and additionally, GSI calculation for spawn samples are collected (J. Becker, Maine DMR, pers. comm.). The Massachusetts Department of Marine Fisheries (DMF) has collected additional data from 1998 – 2018 which were also included in this review.

Table 2.2.1. Maturity stages/codes used in DMR portside monitoring and NMFS trawl surveys. Rows in bold are stages of interest for this review (i.e., closest to spawning condition).

DMR	Description	NMFS	Description
1	immature	I	immature
2	starting		
3	developing	D	developing
4	maturing		
5	**mature**	**R**	**ripe**
6	**ripe/running**	**U**	**ripe/running**
7	spent	S	spent
8	resting	T	resting
		X	unknown

The DMR data set included 17,529 samples from Areas 1B, 2 and 3. Additional samples for Area 1A exist but were not included in this review. Other data included length, weight and sex. This rich data set allowed for explorations of spatial and temporal patterns in maturity and GSI, both of which can be used to infer location of spawning. In other words, spawning could be assumed to occur at or near areas with high mean GSI values or high densities of later stage maturity fish (i.e., stages 5 and 6; Table 2.2.1).

Spatial patterns using both GSI and maturity stage were examined. For GSI, the ‘MBA’ and ‘fields’ packages in R (Finley et al. 2017, Nychka et al. 2019) were used to interpolate mean GSI per sample using multilevel B-spline approximation. This was done for the entire data set (all years and sexes combined) as well as by decade and with just females (Figures 2.2.1 to 2.2.7). The progression of GSI figures is as follows. Figure 2.2.1 shows mean GSI over the sample area (Areas 1B, 2 and 3) for all years.

Overall, the highest GSI values tended to follow the northern edge of Georges Bank from Cape Cod to off of the bank near the Northern Flank. Some higher values were also associated with on the Bank (between Northern Flank and Southern Flank) but were associated with only 2 sample locations. The highest density of fishing locations was along the northern edge and was associated with relatively low GSI values. Figure 2.2.2 is the same as the previous but includes only females. The spatial pattern in GSI is similar with slightly higher mean GSI values (i.e., darker reds). Two areas in particular stand out as having higher GSI values: the Great South Channel and to the north of the Northern Flank. Figure 2.2.3 is the same as figure 2.2.1 except that instead of applying the spline to the raw data (with multiple individuals per sample), the spline was applied to summarized data per sample (i.e., mean GSI per sample). The spatial pattern was again the same as in previous figures. Since spatial patterns were relatively consistent regardless of sex or whether samples were averaged or not, the following are both sexes and for whole data set (i.e., not averaged by sample).

Figure 2.2.4 shows mean GSI over sample area by decade. Note that there was not continuous sampling between 1971 and 2018. There was a major gap in sampling between 1983 and 1995. As such data was pooled between 1971 and 2000, whereas the last two decades had relatively complete sampling and therefore were considered separately. The spatial pattern among decades/time periods was relatively consistent with previous figures. Figure 2.2.5 shows the Mass DMF data separately. This figure shows that the Mass DMF data set is relatively limited compared to the DMR data set. Finally, for the splines, figures 2.2.6 and 2.2.7 show the DMR and Mass DMF data combined for both sexes and for females alone. Given the limited size of the Mass DMF data the figures are not different than Figures 2.2.1 and 2.2.2.

Figures 2.2.8 and 2.2.9 show 2-D kernel density estimates of the distribution of ripe and ripe and running herring, respectively (maturity stages 5 and 6 or R + U; see Table 2.2.1). In this case, ripe herring are most associated with the Northern Flank for the entire data set, whereas ripe and running herring are associated with both the Great South Channel and the Northern Flank. Figure 2.2.10 shows the distribution of female herring with GSI30 values greater than or equal to 0.23 (see section 1.5 for explanation of GSI30 method and threshold values). In this case, the highest density of high GSI female herring, with values that would trigger closures in the Gulf of Maine, is at the Northern Flank.

Figures 2.2.11 to 2.2.13 show 2-D kernel density estimates of ripe + ripe/running (R + U), ripe/running only (U), and GSI30female $\geq$ 0.23 herring, respectively by decade. Densities of R + U stage herring were relatively high at both the Northern Flank and Great South Channel in all decades. Densities of U stage herring were high in both Northern Flank and Great South Channel in 1991 – 2000 and were highest in the Great South Channel in the decade 2001 – 2010. No ripe and running herring were sampled in the decade 2011 – 2018. Finally, densities of high GSI female herring (GSI30 $\geq$ 0.23) were generally highest at the Northern Flank for all decades but areas of high density also existed at the Great South Channel. Consistent with all of these depictions of spawning (Figures 2.2.1 to 2.2.13) is the relatively high importance of the Northern Flank and Great South Channel for harboring spawning condition (or near spawning condition) herring.

Figure 2.2.1. Surface spline interpolation of mean male and female GSI from DMR portside monitoring data (1971-2018). 100 m isobath is shown. Faint lines are boundaries of herring management areas (see figure 1.4.3). Points are sample locations.

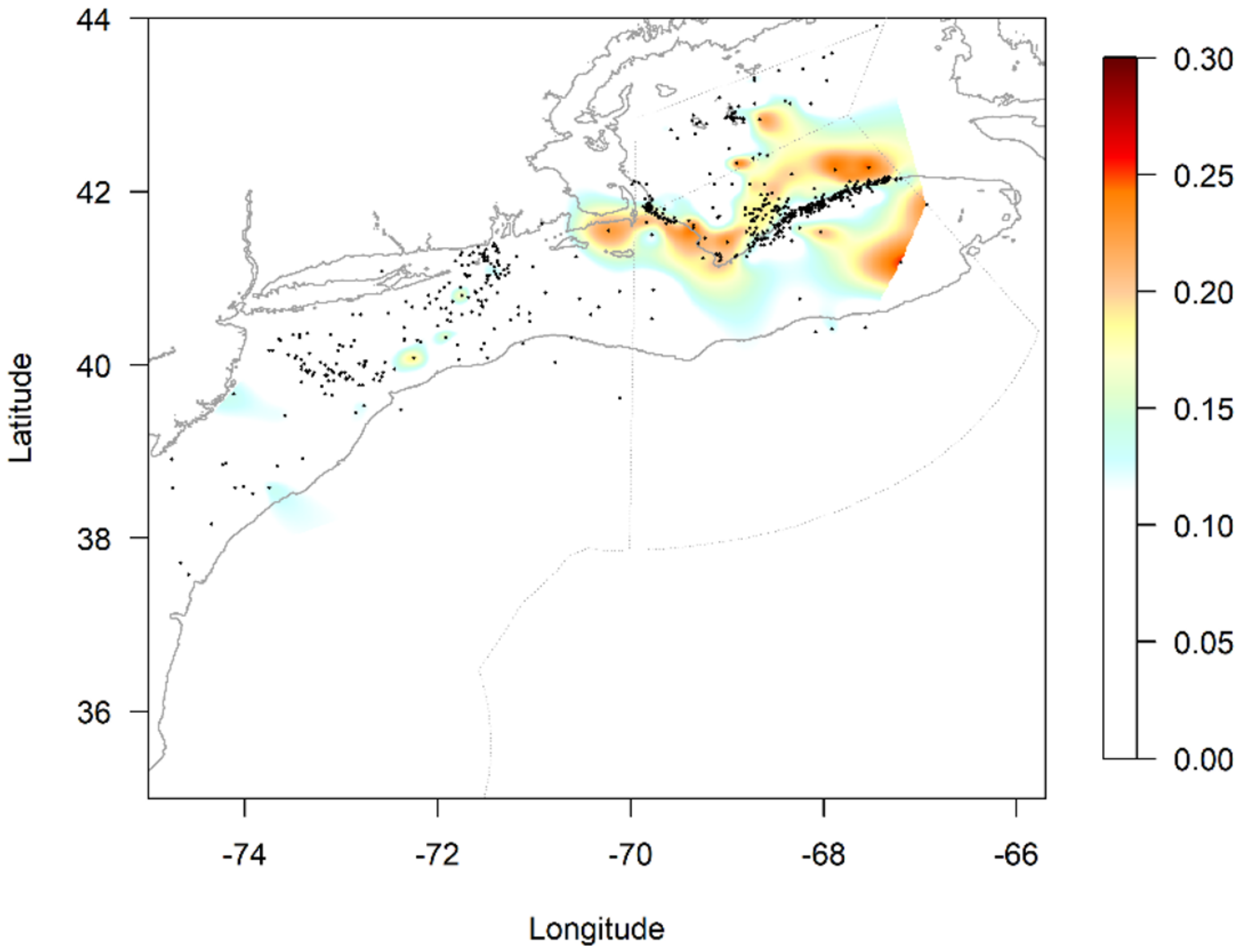


Figure 2.2.2. Surface spline interpolation of mean female GSI from DMR portside monitoring data (1971-2018). 100 m isobath is shown. Faint lines are boundaries of herring management areas (see figure 1.4.3). Points are sample locations.

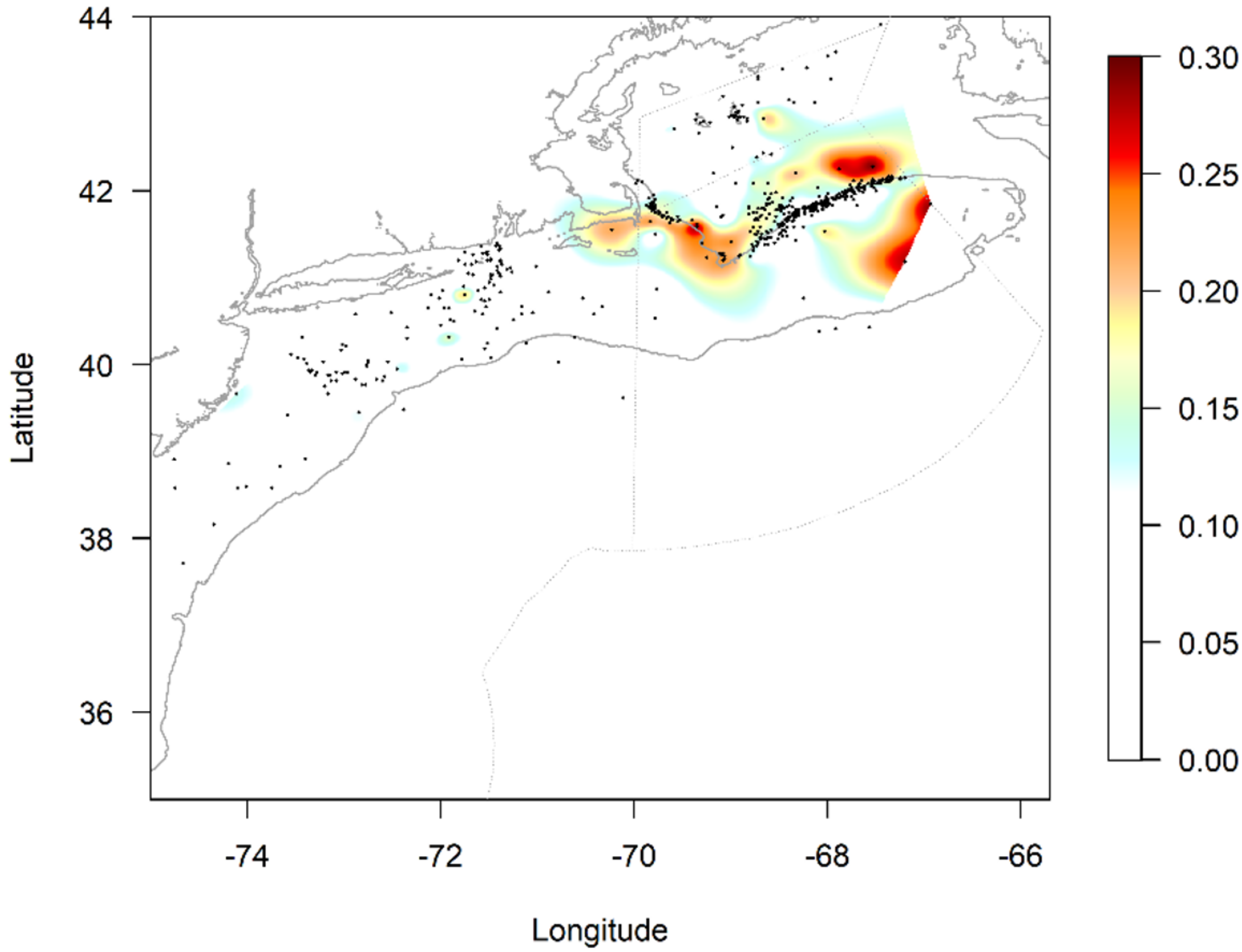


Figure 2.2.3. Surface spline interpolation of mean male and female GSI/sample from DMR portside monitoring data (1971-2018). Samples were defined as unique date/locations (i.e., values were averaged for each sample). 100 m isobath is shown. Faint lines are boundaries of herring management areas (see figure 1.4.3). Points are sample locations.

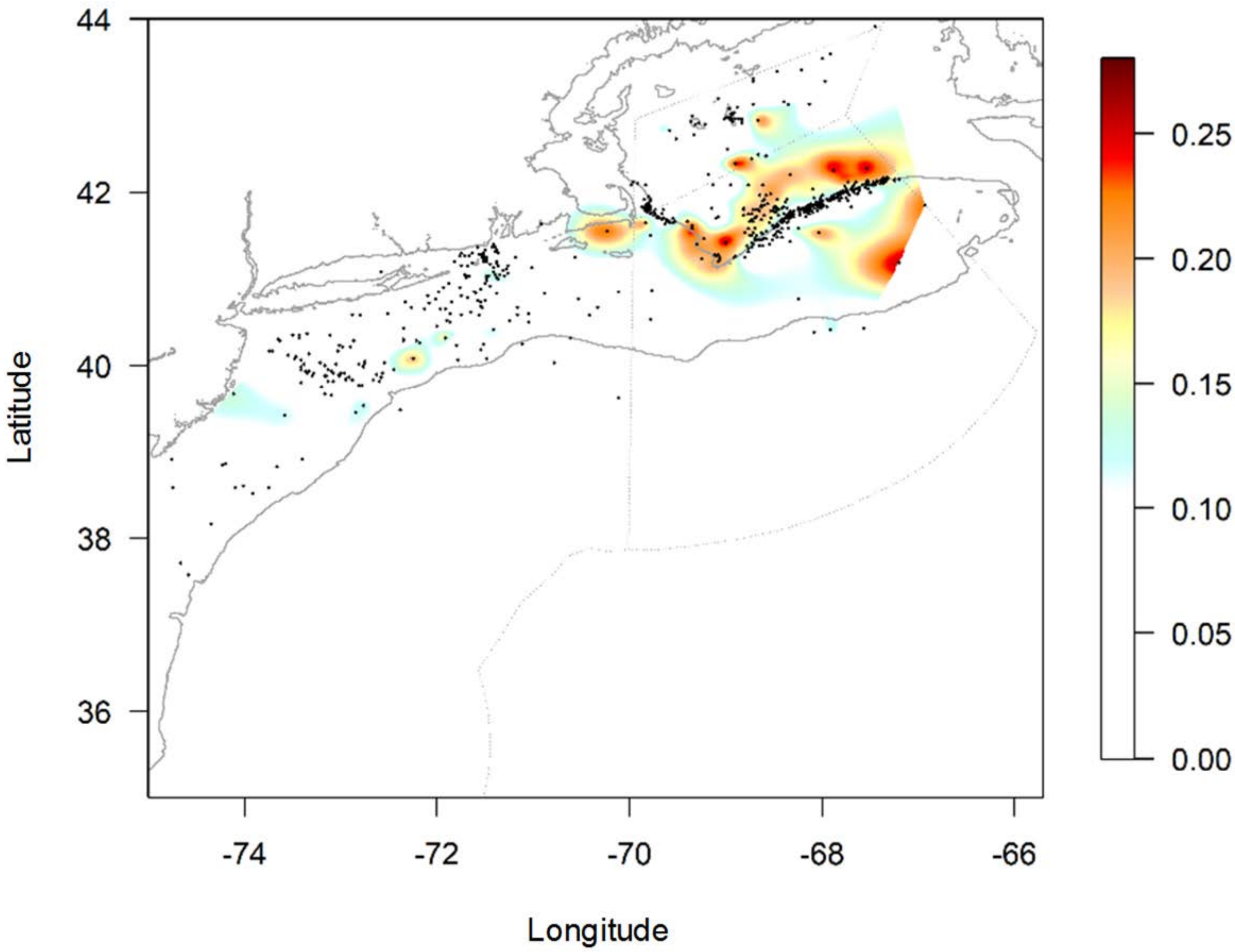


Figure 2.2.4. Surface spline interpolation of mean male and female GSI from DMR portside monitoring data by decade (1971-2018). Note that 1971 – 2001 was pooled due to data gaps. 100 m isobath is shown. Faint lines are boundaries of herring management areas (see figure 1.4.3). Points are sample locations.

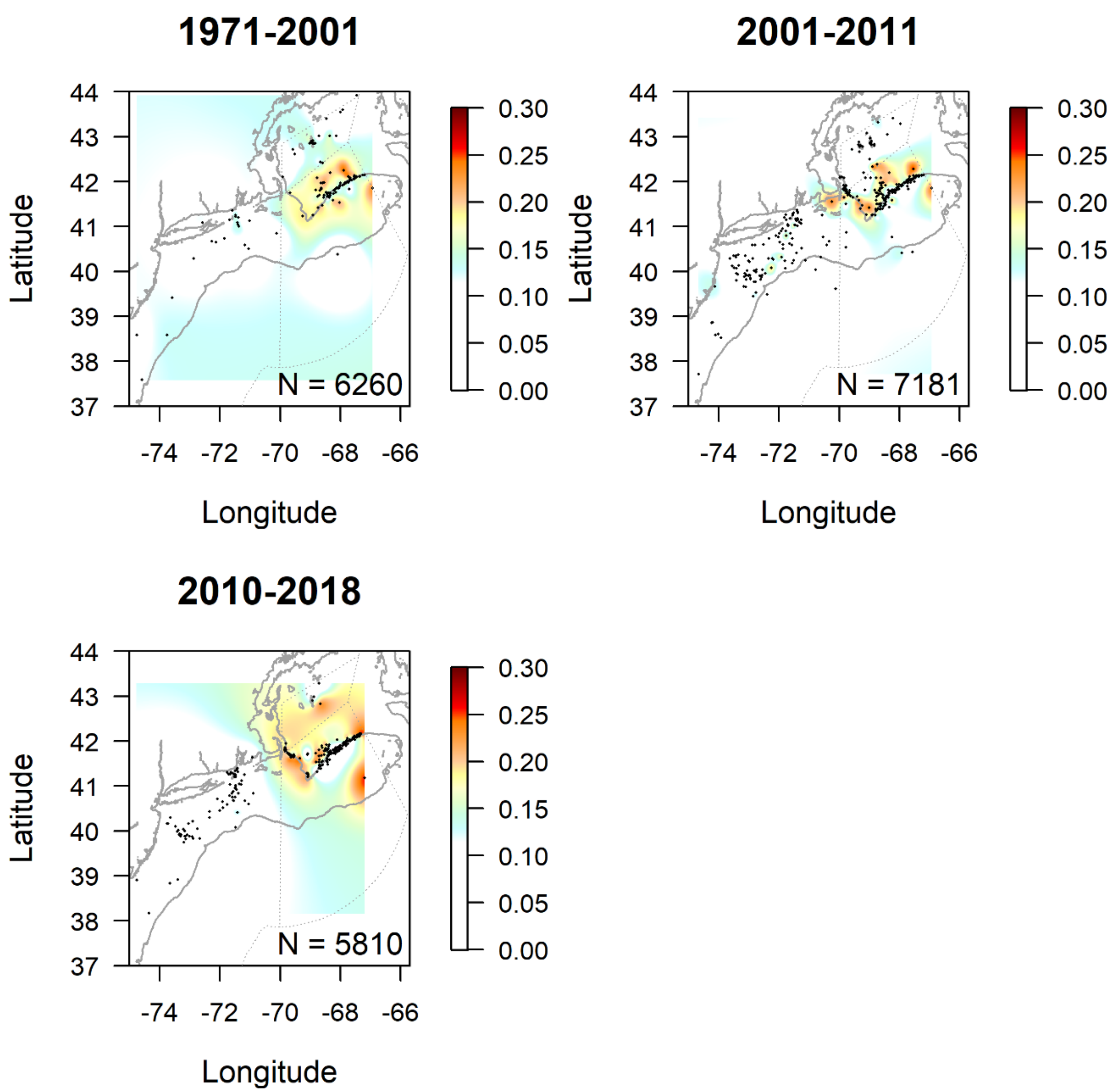


Figure 2.2.5. Surface spline interpolation of mean female GSI from Massachusetts Division of Marine Fisheries data (1998-2018); note: only female observations were available. 100 m isobath is shown. Faint lines are boundaries of herring management areas (see figure 1.4.3). Points are sample locations.

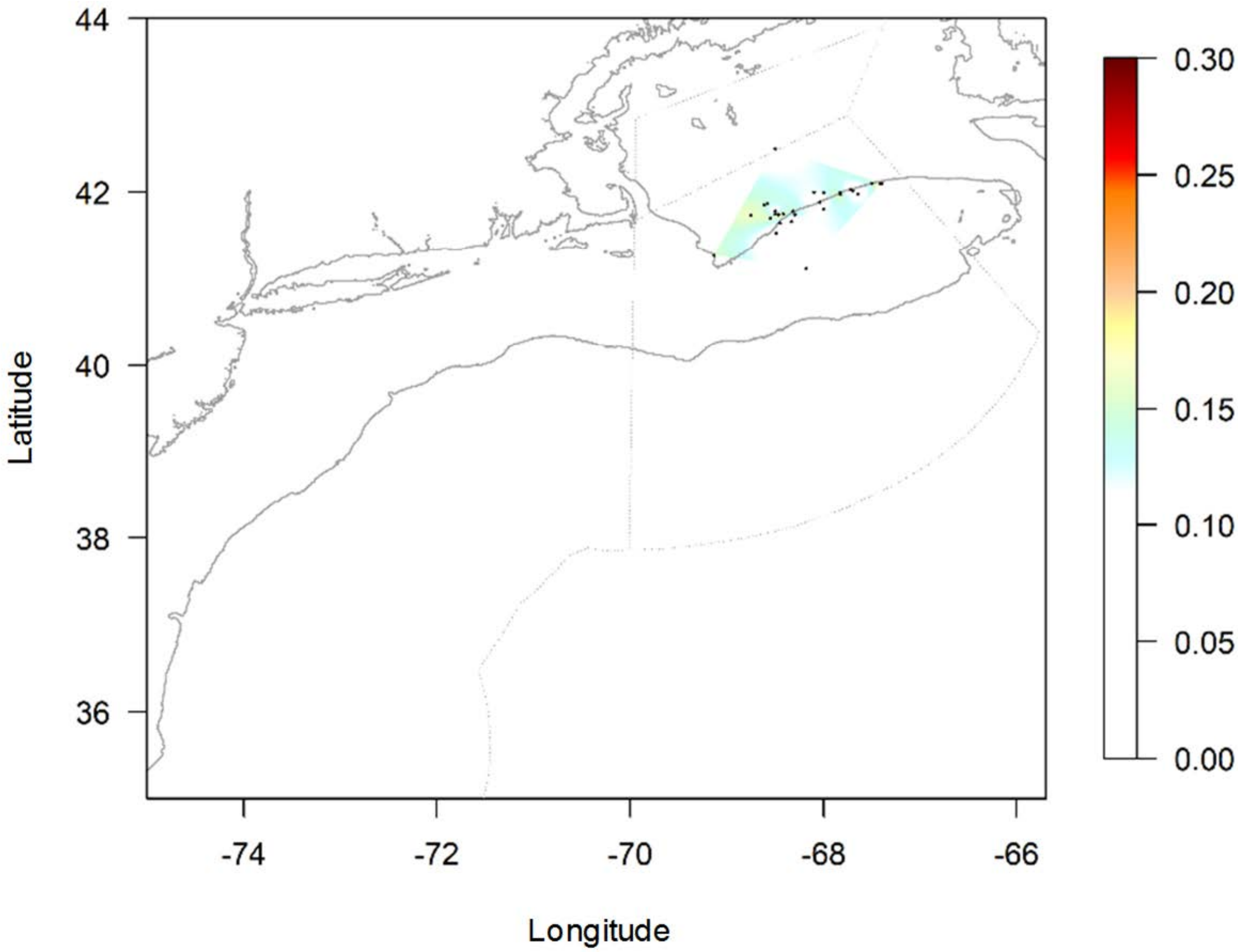


Figure 2.2.6. Surface spline interpolation of mean male and female GSI from combined DMR portside monitoring data (1971-2018) and Massachusetts DMF data (1998-2018). 100 m isobath is shown. Faint lines are boundaries of herring management areas (see figure 1.4.3). Points are sample locations.

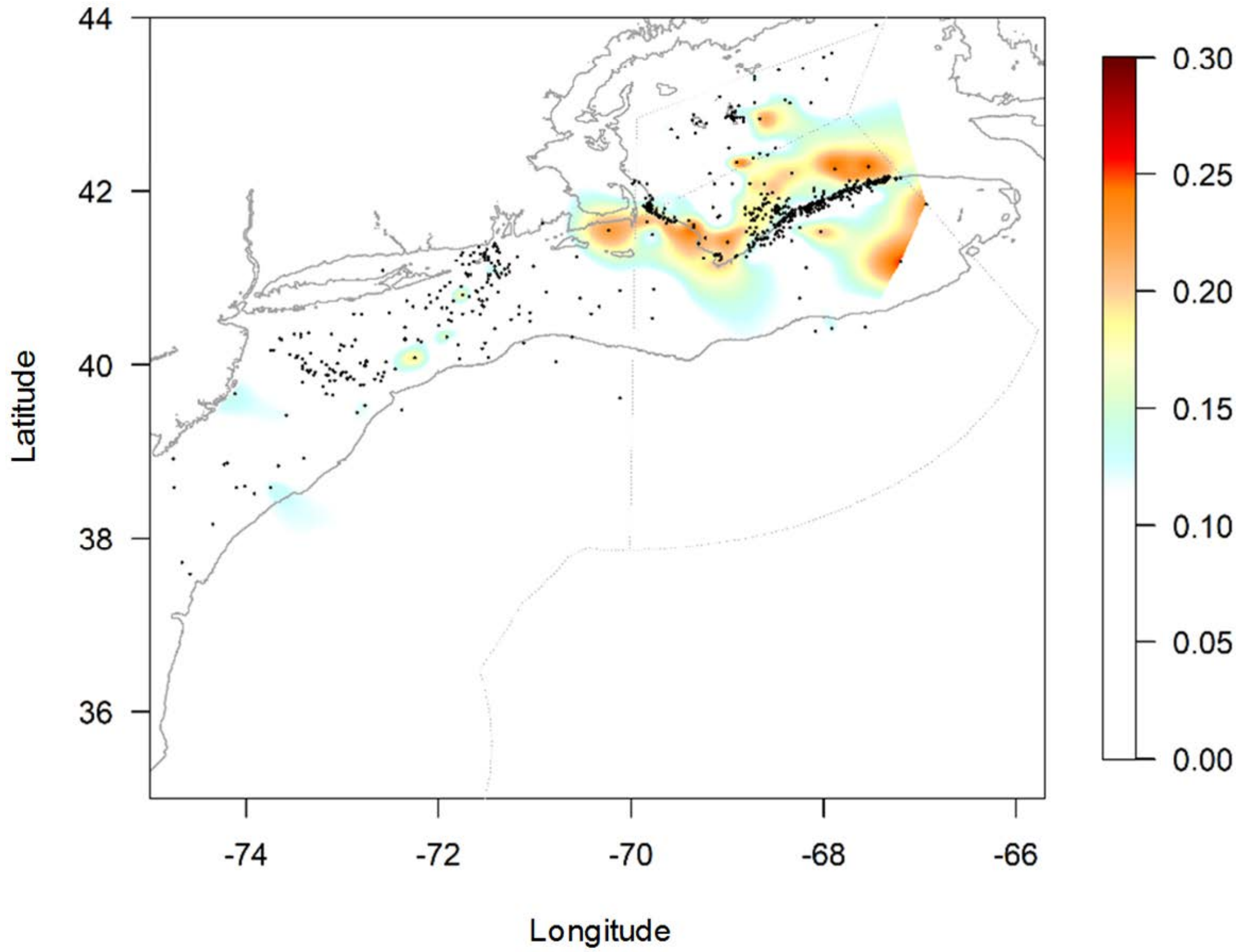


Figure 2.2.7. Surface spline interpolation of mean female GSI from combined DMR portside monitoring data (1971-2018) and Massachusetts DMF data (1998-2018). 100 m isobath is shown. Faint lines are boundaries of herring management areas (see figure 1.4.3). Points are sample locations.

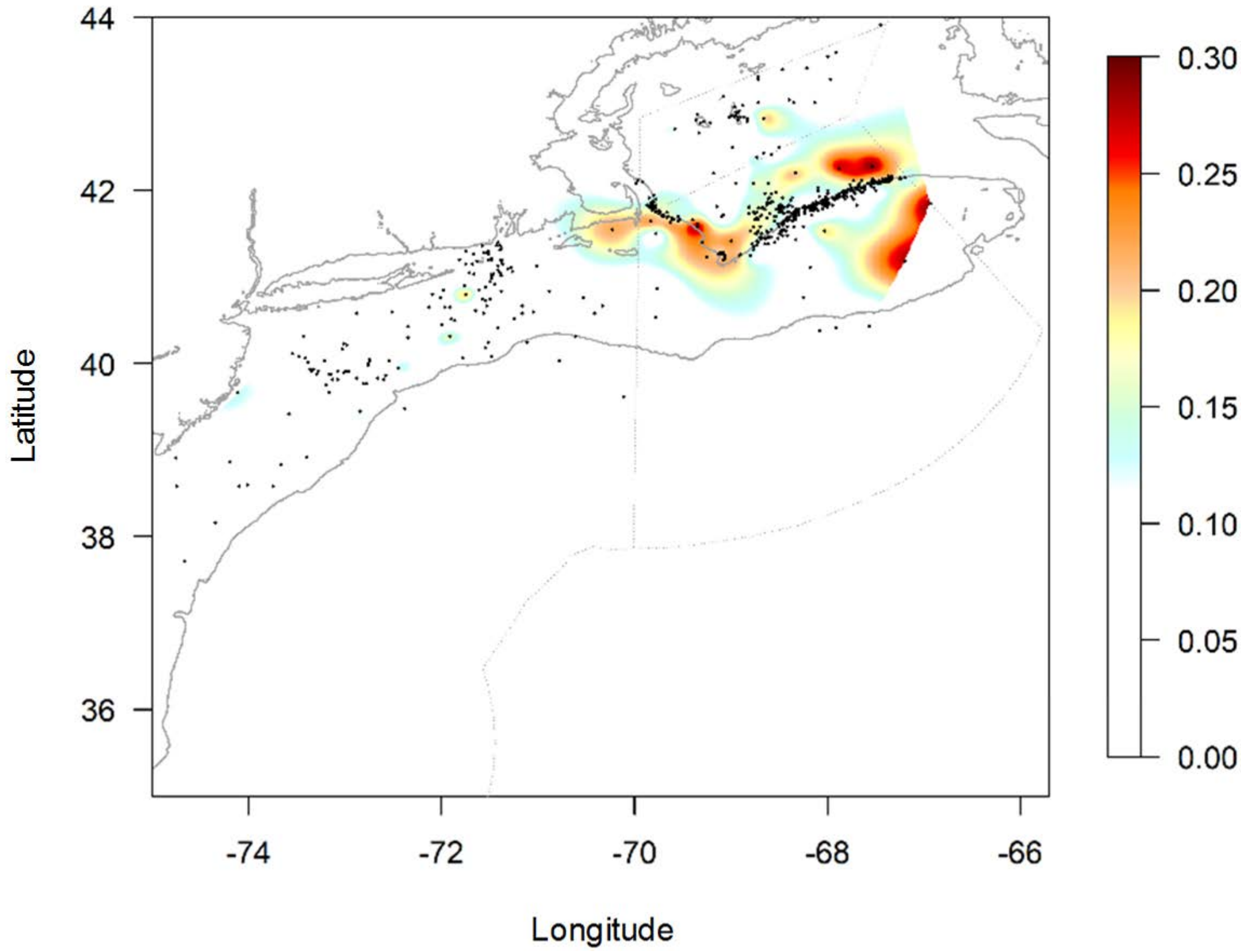


Figure 2.2.8. 2-dimensional kernel density estimates of DMR portside monitoring data (1971-2018) of male and female “ripe + ripe/running” herring. 100 m isobath is shown. Points are sample locations.

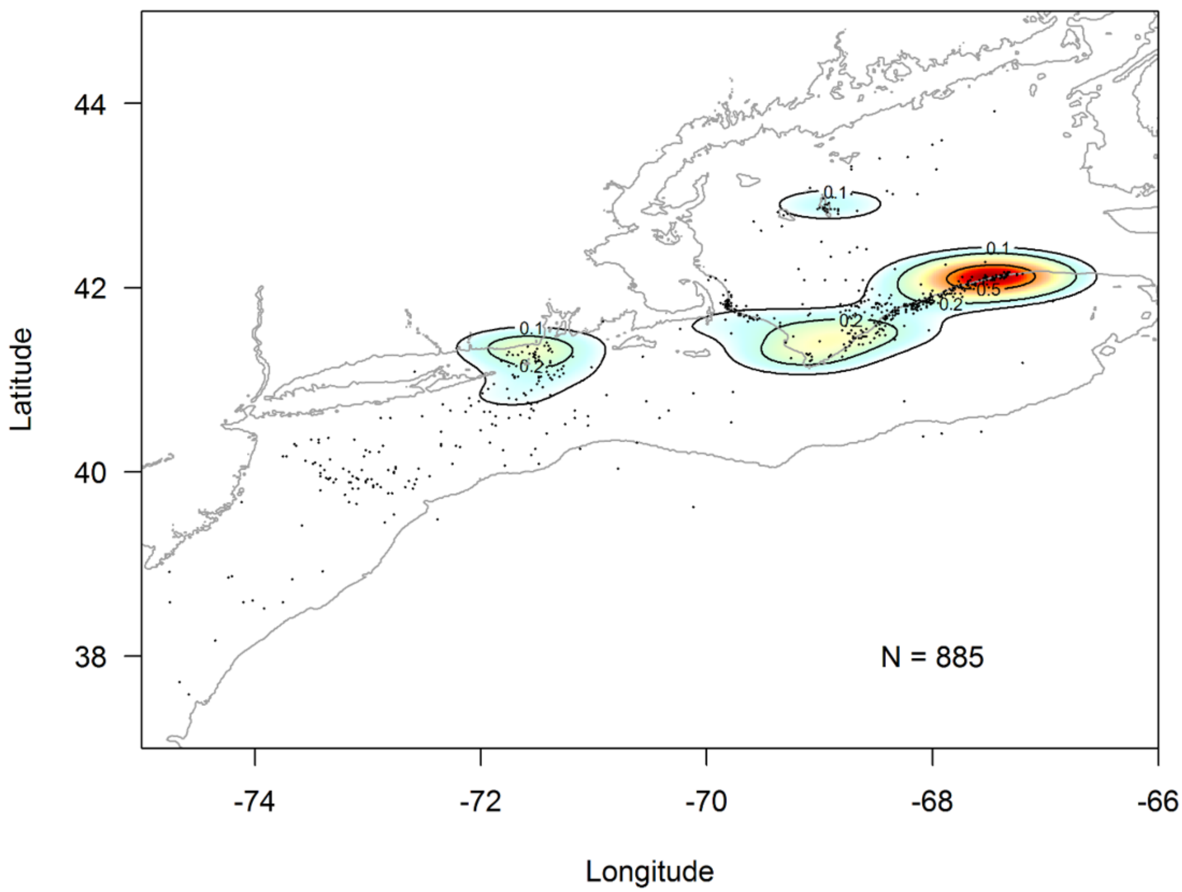


Figure 2.2.9. 2-dimensional kernel density estimates of DMR portside monitoring data (1971-2018) of male and female “ripe and running” herring. 100 m isobath is shown. Points are sample locations.

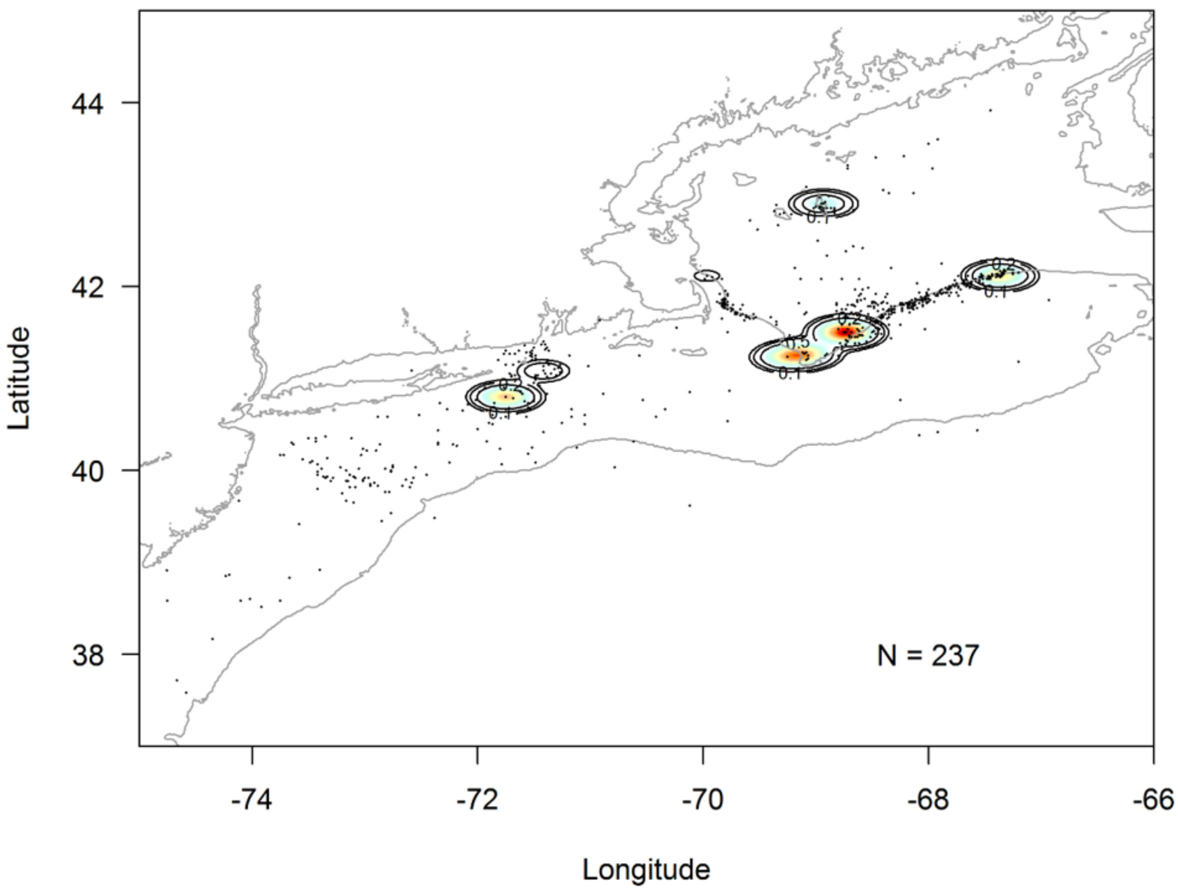


Figure 2.2.10. 2-dimensional kernel density estimates of DMR portside monitoring data (1971-2018) of female herring with GSI30 values ≥ 0.23. 100 m isobath is shown. Points are sample locations.

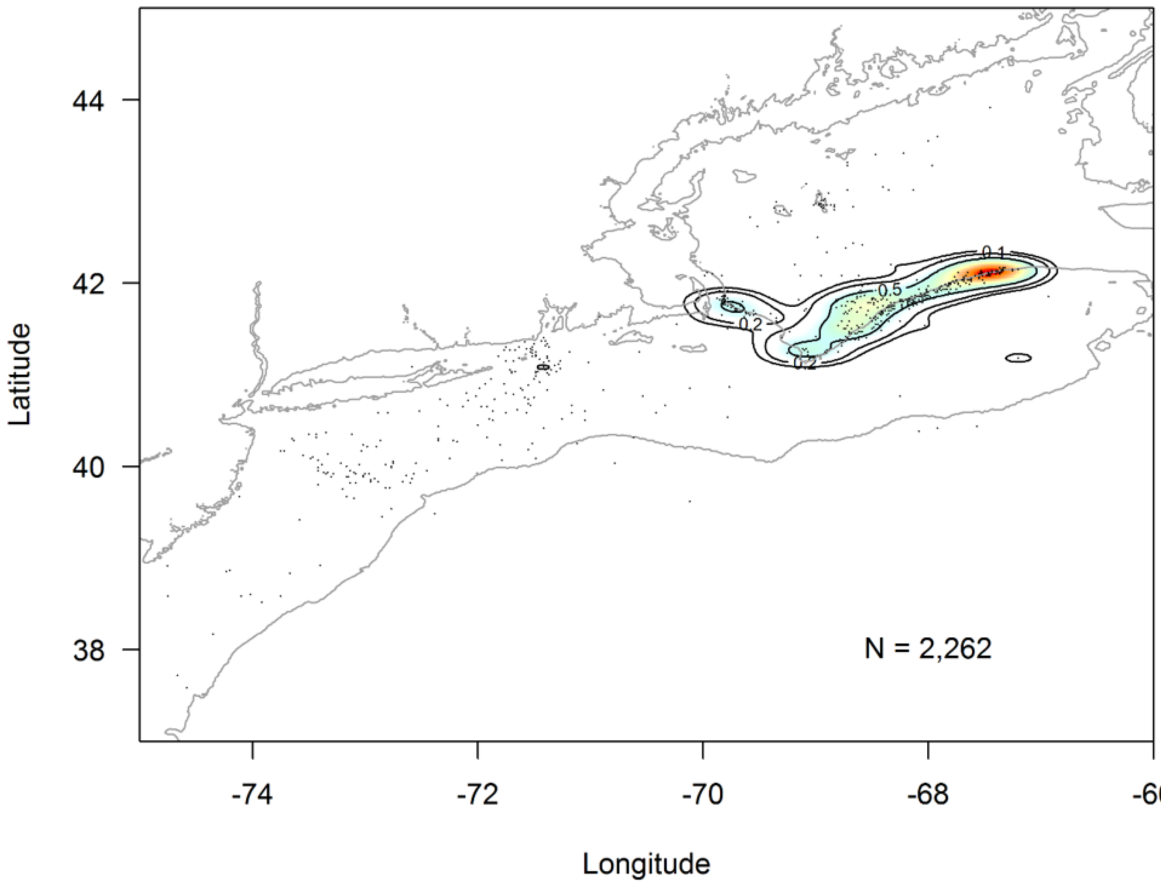


Figure 2.2.11. 2-dimensional kernel density estimates of DMR portside monitoring data by decade of male and female "ripe + ripe/running" herring. Decades began at 1991 because there were no observations of ripe + ripe/running fish prior to this. This was likely due to sampling timing during the year (see Figure 2.3.1). 100 m isobath is shown. Points are sample locations.

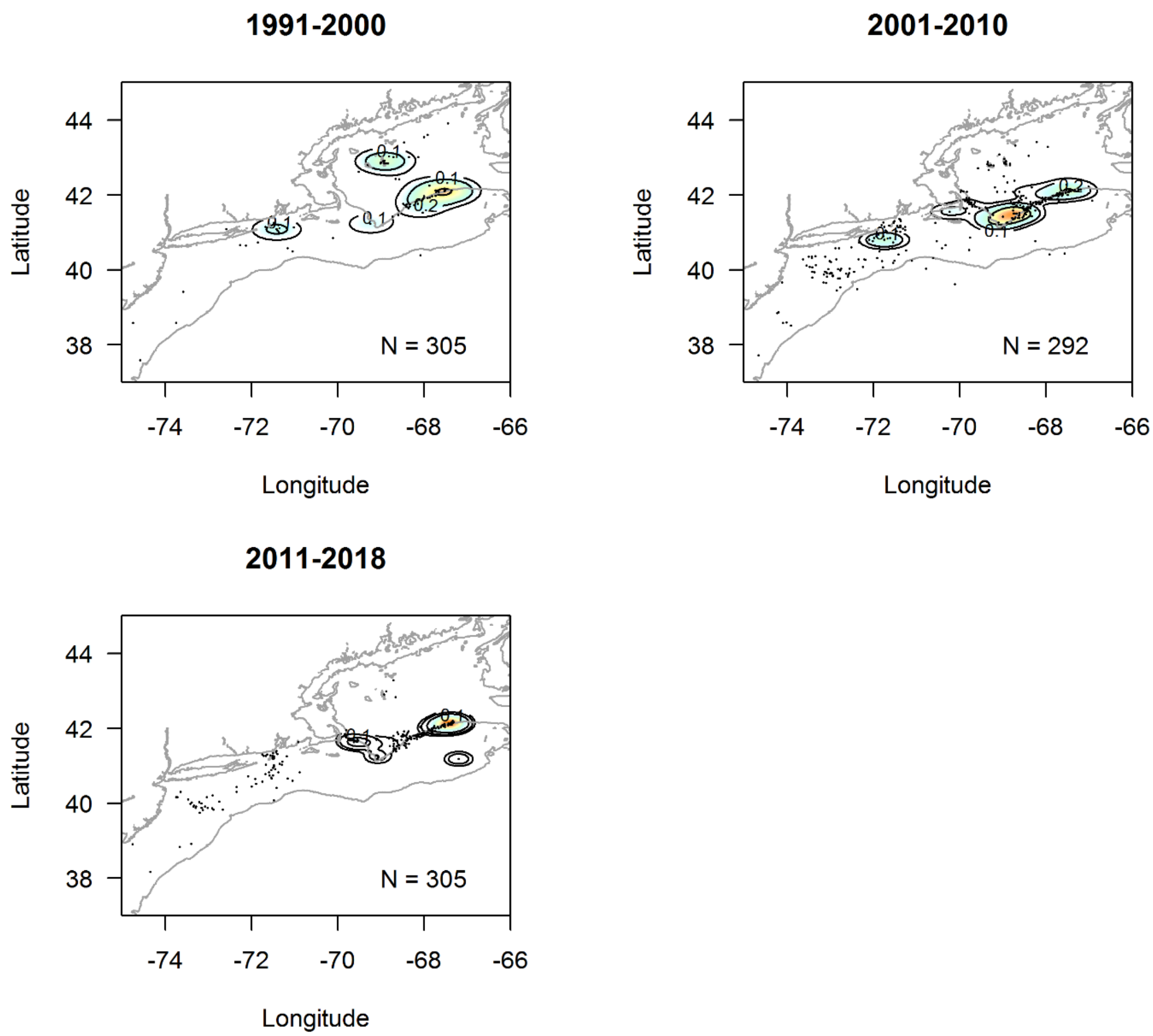


Figure 2.2.12. 2-dimensional kernel density estimates of DMR portside monitoring data by decade of male and female "ripe and running" herring. Decades cover only 1991-2010 because there were no observations of ripe and running fish outside of that time frame. 100 m isobath is shown. Points are sample locations.

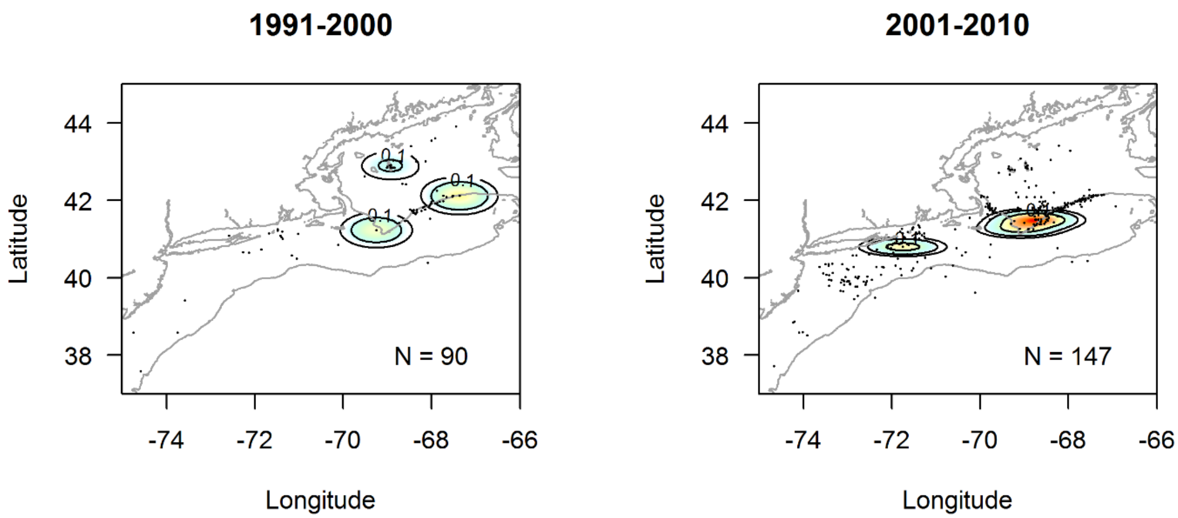
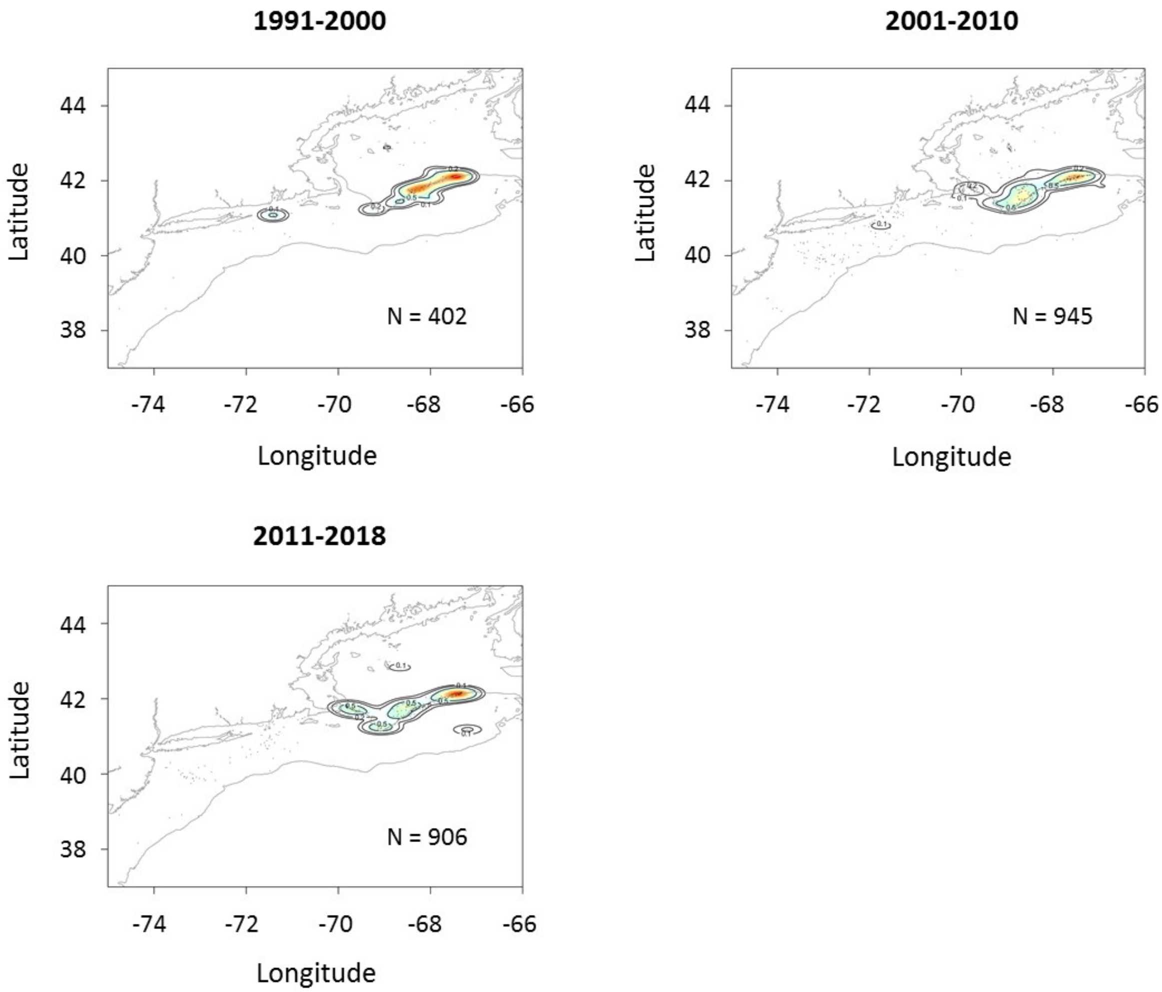


Figure 2.2.13. 2-dimensional kernel density estimates of DMR portside monitoring data by decade of female herring with GSI30 values ≥ 0.23. 100 m isobath is shown. Points are sample locations.



2.3. Adult Data: DMR Portside Monitoring Data (temporal patterns)

The DMR portside monitoring data was comprehensive enough to allow for temporal comparisons using GSI values. Here, mean GSI values were calculated by month and by year and are presented as heat maps using the ‘ggplot2’ package in R (Wickam 2016). Figure 2.3.1 shows mean GSI by month and year for the entire data set. This figure shows the temporal distribution of sampling effort. Particularly, sampling was confined to the early months (January – April) for the first half of the data set. It was not until the mid to late 90s that sampling occurred year-round.

From the 1990s on, the highest mean GSI values were in September and October. The limited sampling that took place in November suggests that spawning was completed by October, although only three years had data for November. There did appear to be some higher GSI values in March in the early half of the data set. However, these values did not approach those seen in the fall. Figures 2.3.2 and 2.3.3 show the same data separated by sex; females tended to have a more contracted period of higher GSI values than males.

Mean GSI values by month and year were also explored between different regions. The spatial analyses suggest that there are eastern and western components to spawning on Georges Bank (i.e., Northern Flank versus Great South Channel; previous section). We chose 68.7 degrees west longitude to divide eastern Georges Bank from western Georges Bank. We also considered Southern New England separately from these two. In this case, the cutoff between SNE and western Georges Bank was 70.5 degrees west longitude. There did not appear to be any difference between the timing of spawning between eastern Georges Bank western Georges Bank. Peak values for females were in September and October for both regions. Southern New England samples were clustered earlier in the year and showed no obvious sign of a spawning period; although higher GSI values in males in February and March in the 1970's may be indicative of spring spawning during this time.

Figure 2.3.1. Mean GSI by month and year for entire DMR data set (both sexes). GSI approaching 0.23 indicates fish that are spawning.

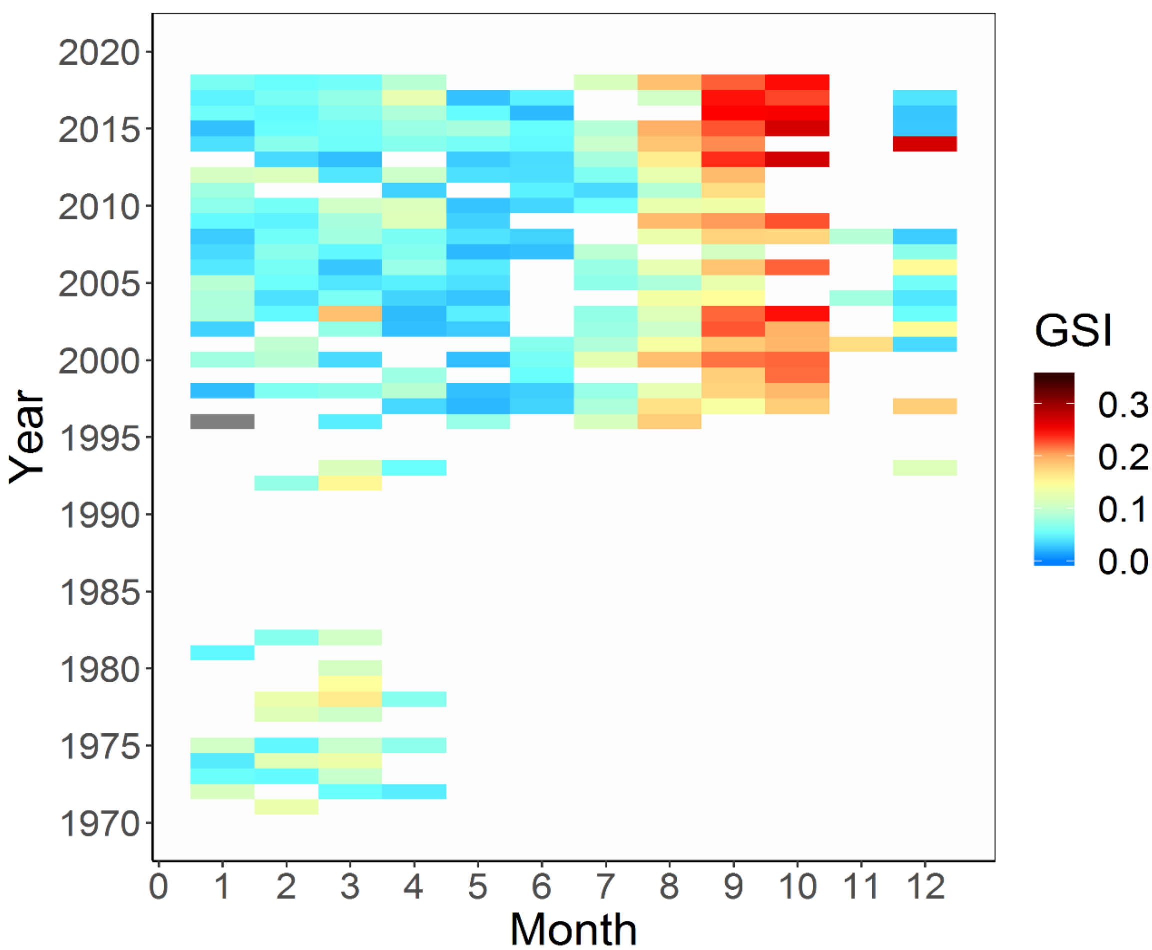


Figure 2.3.2. Mean GSI values by month and year for females. GSI approaching 0.23 indicates fish that are spawning.

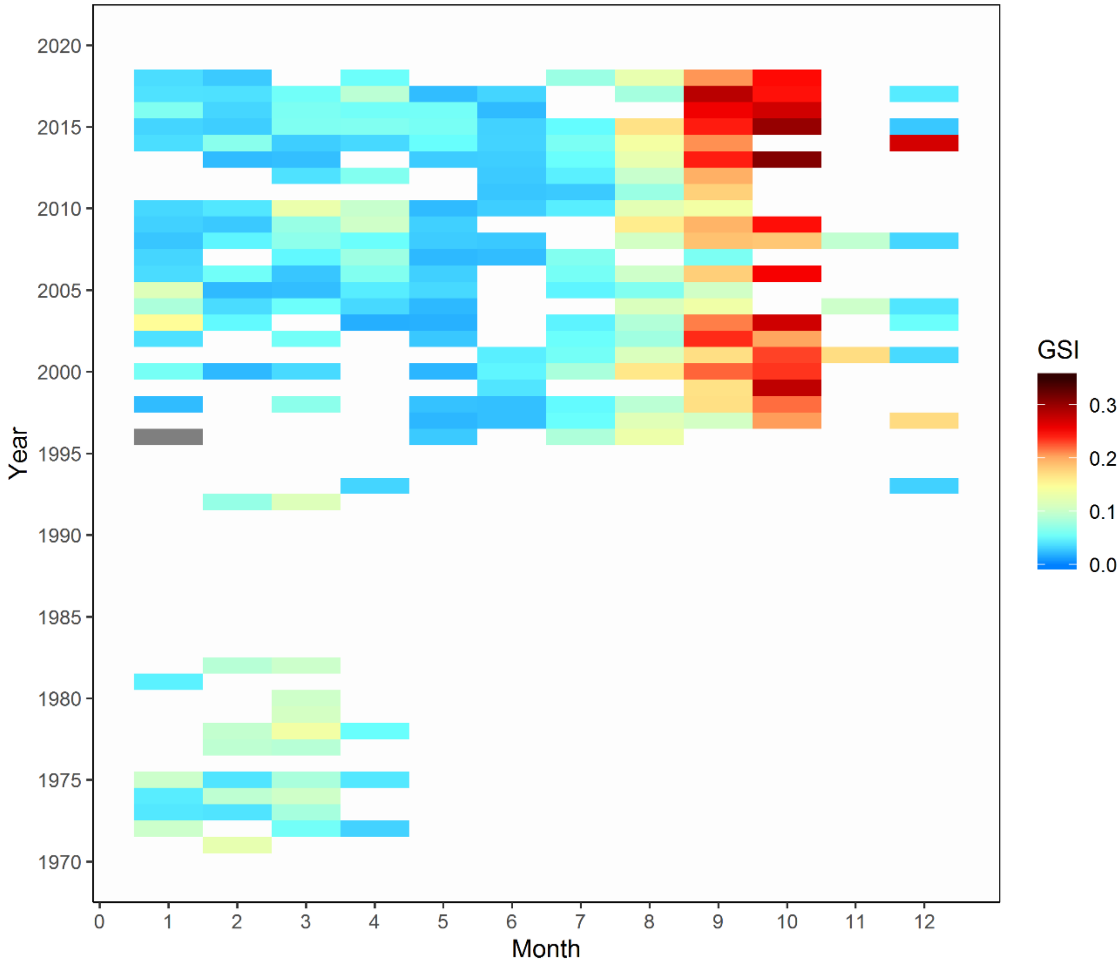


Figure 2.3.3. Mean GSI values by month and year for males. GSI approaching 0.23 indicates fish that are spawning.

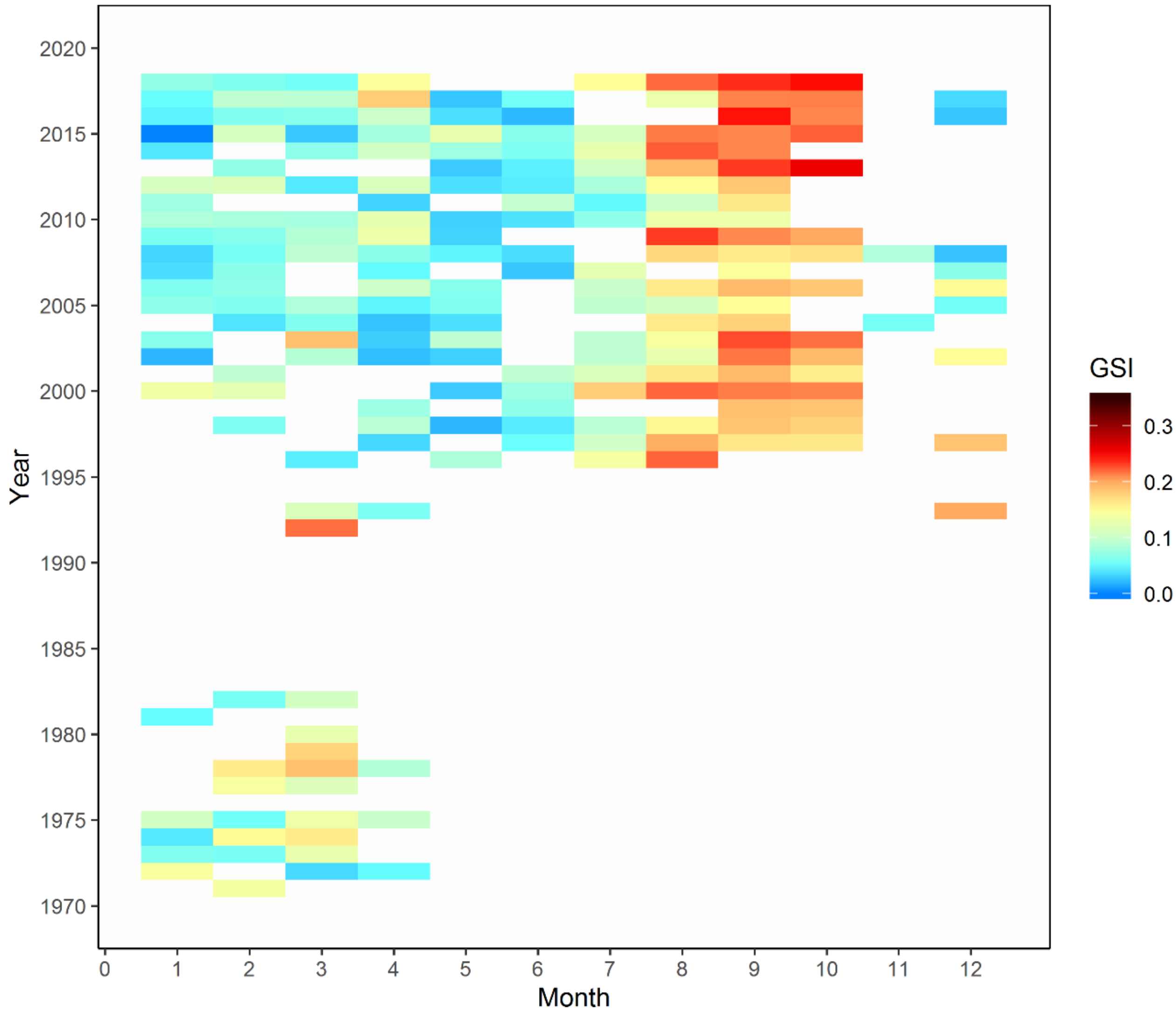


Figure 2.3.4. Same as figure 2.2.7 but with regions defined as southern New England (SNE), western Georges Bank (WGB) and Eastern Georges Bank (EGB). These regions were defined to explore spatial differences in temporal GSI patterns shown in figure 2.3.5. 100 m isobath is shown. Faint lines are boundaries of herring management areas (see figure 1.4.3). Points are sample locations.

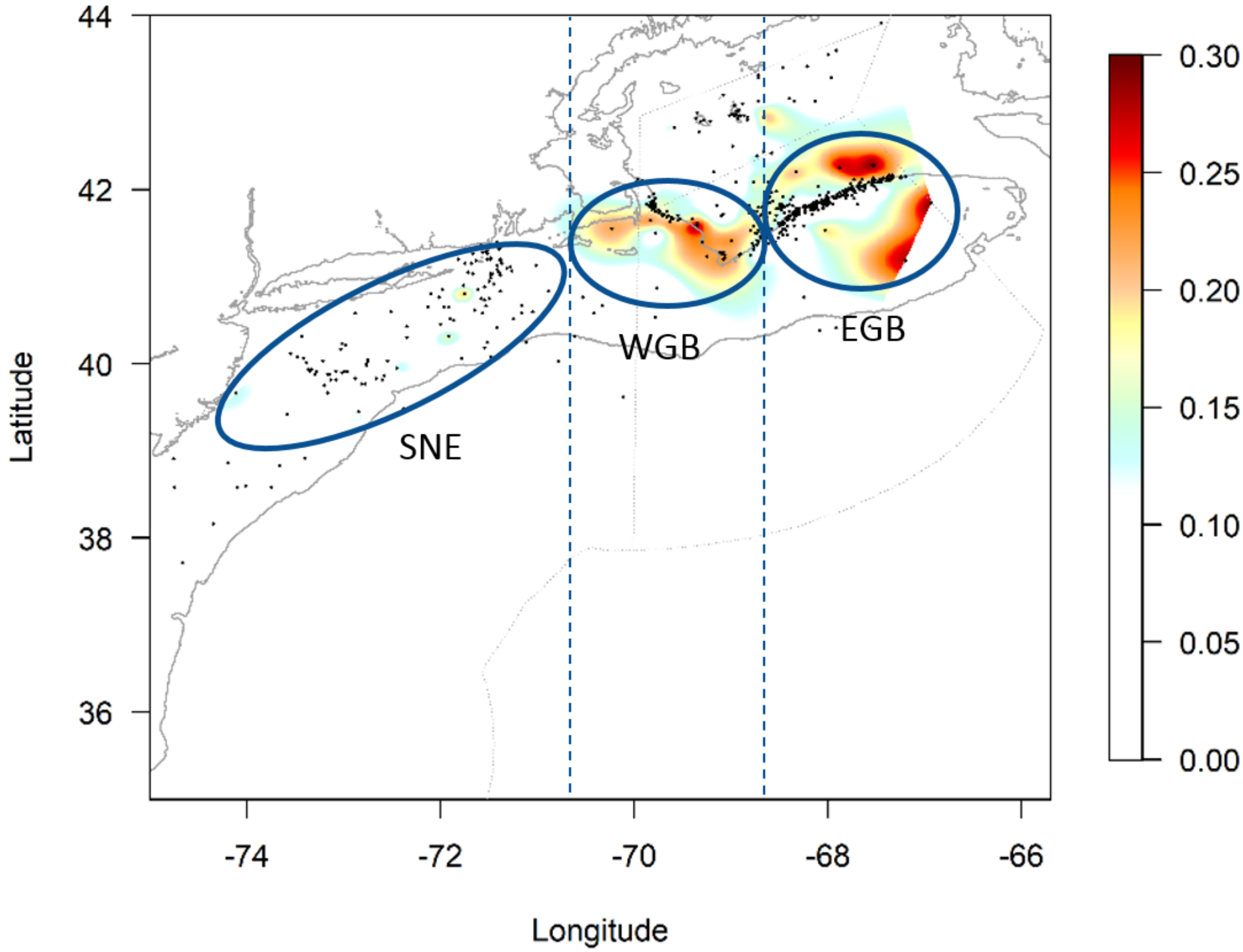
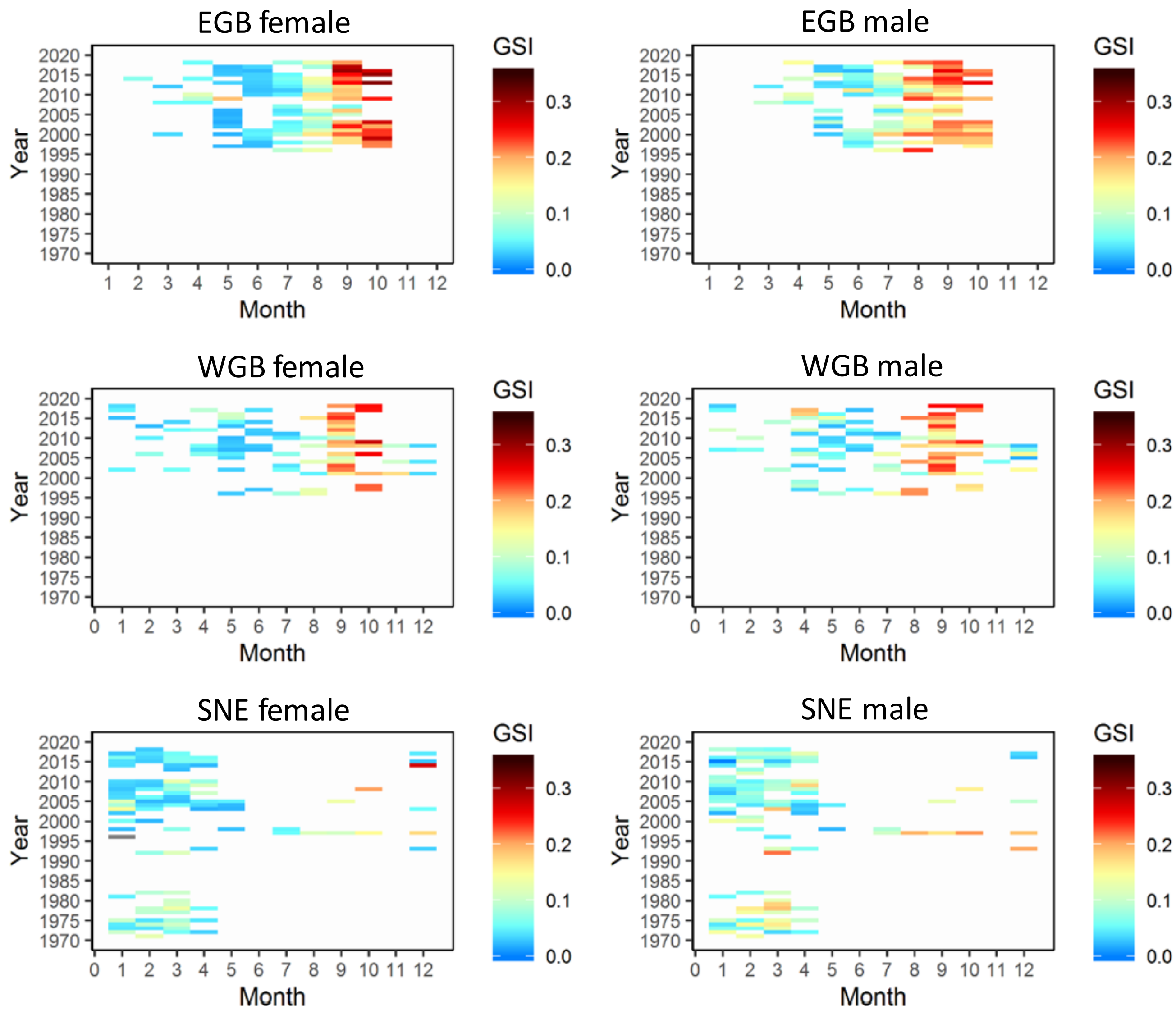


Figure 2.3.5. Mean GSI values by month and year and by location and sex. See text and figure 2.3.4 for description of locations. GSI approaching 0.23 indicates fish that are spawning.



2.4. Adult Data: Trawl Survey

Spatial and temporal patterns in maturity for herring sampled as part of biological processing during the Northeast Fisheries Science Center's spring and fall trawl surveys were examined. While the trawl surveys have been operating since the 1960's, biological sampling for herring did not begin until 1987. Thus, the sample period includes the years 1987 – 2018. During this time, a total of 46,242 (28,878 spring and 17,364 fall survey) herring were sampled for length, weight, age, sex and maturity from 6,650 trawl tows. Thus, an average of 7.0 herring were sampled per tow. Sampling intensity was higher in the spring than in the fall (8.5 versus 5.4 herring per tow). The parameter of interest for this review was maturity stage. Maturity stages were as follows: immature (I), developing (D), ripe (R), ripe and running (U), spent (S), and resting (T). See table 2.2.1 for how these codes translate to DMR codes. We considered two stages as potentially indicative of spawning locations. That is, if herring in spawning stages R or U were captured, they were inferred as being close to spawning grounds since they were in near or actual spawning condition. In reality, herring in maturity stage U would be the closest to spawning and therefore most likely to be near spawning grounds.

The location of herring in maturity stages R and U were mapped using a 2-D kernel density estimator in the package 'MASS' (Ripley et al. 2019) in R (R Core Team 2019). This was done for all samples combined by season (i.e., spring and fall separately), and for different decades (by season). In this case, 'decades' were as follows: 1987 – 1990, 1991 – 2000, 2001 – 2010, and 2011 – 2018. For eventual incorporation of spatial depictions of spawning condition herring as layers in our consensus figures (see section 3), we considered polygons containing density values of 0.2 or greater (arbitrary).

For all the fall data combined, the location of ripe and ripe/running (R + U) herring was throughout the northern edge of Georges Bank with higher densities near the Great South Channel and the Northern Flank (Figure 2.4.1). Figure 2.4.2 shows the same data over different decades. Higher densities of R and U herring were found primarily on the western side of Georges Bank in the 1980's and 1990's. The distribution of R and U herring appeared to shift to the eastern side in the 2000's and in the most recent decade there are two areas of high density in both the east and the west. Figure 2.4.3 shows just maturity stage U herring from the fall survey from all years. Two areas of high density are evident in the Great South Channel (western side) and the Northern Flank (eastern Georges). The areas of high density of U stage herring shifts from decade to decade. It was highest in the west in the 1980's and 1990's, highest in the east in the 2000's and in the most recent decade it appears to have shifted back to the west, although densities were quite low. The density of spawning herring (maturity stage U) from the spring trawl survey are shown in Figure 2.4.5. Only 9 of 28,878 samples were in maturity stage U confirming that spawning does not take place on Georges Bank in the spring. Similarly, only 179 herring were in maturity stage R in the spring (all years combined; not plotted).

Figure 2.4.1. 2-dimensional kernel density estimates of ripe (mat stage R) and ripe/running (mat stage U) herring from fall trawl survey. Sample size is indicated; smaller number for samples in mat stage R + U and larger number for total sample size. 100 m isobath is shown. Points are sample (tow) locations.

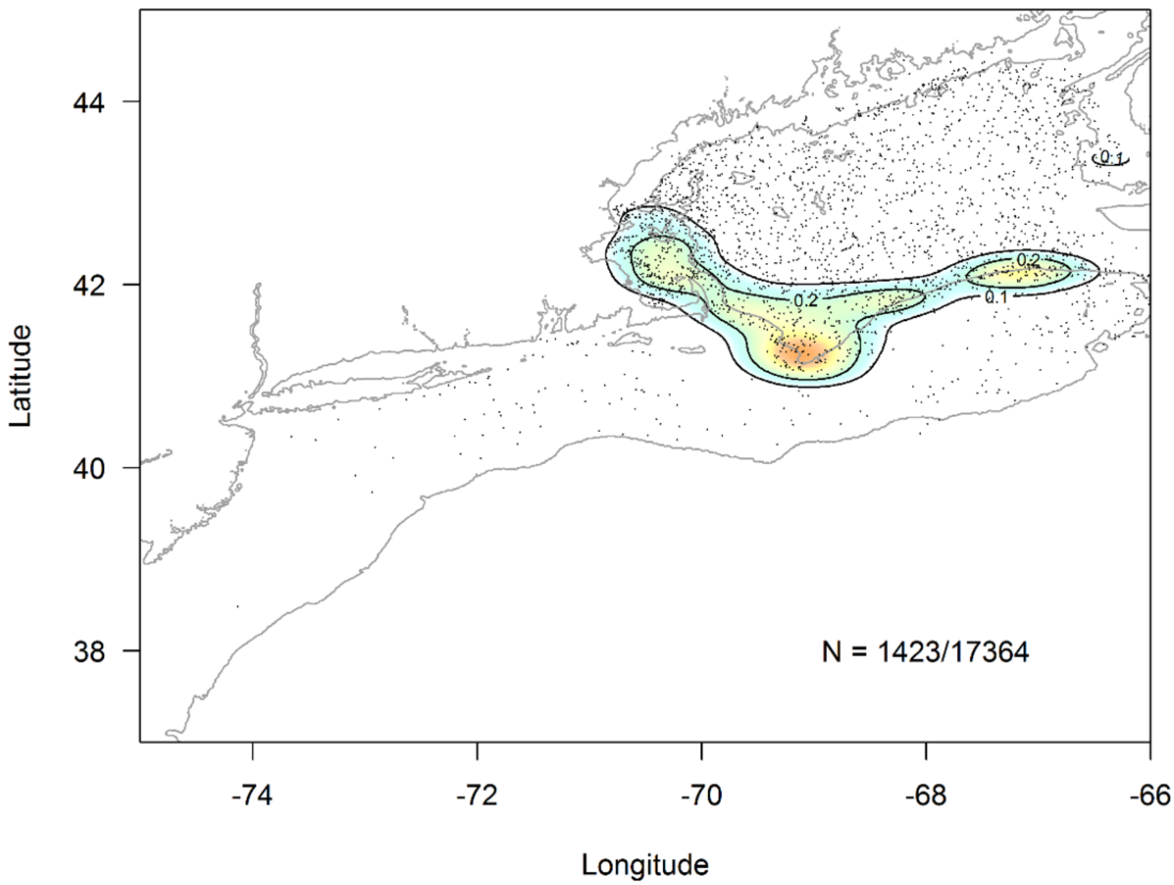


Figure 2.4.2. 2-dimensional kernel density estimates of ripe (mat stage R) and ripe/running (mat stage U) herring from fall trawl survey by decade. Sample size is indicated; smaller number for samples in mat stage R + U and larger number for total sample size by decade. 100 m isobath is shown. Points are sample (tow) locations.

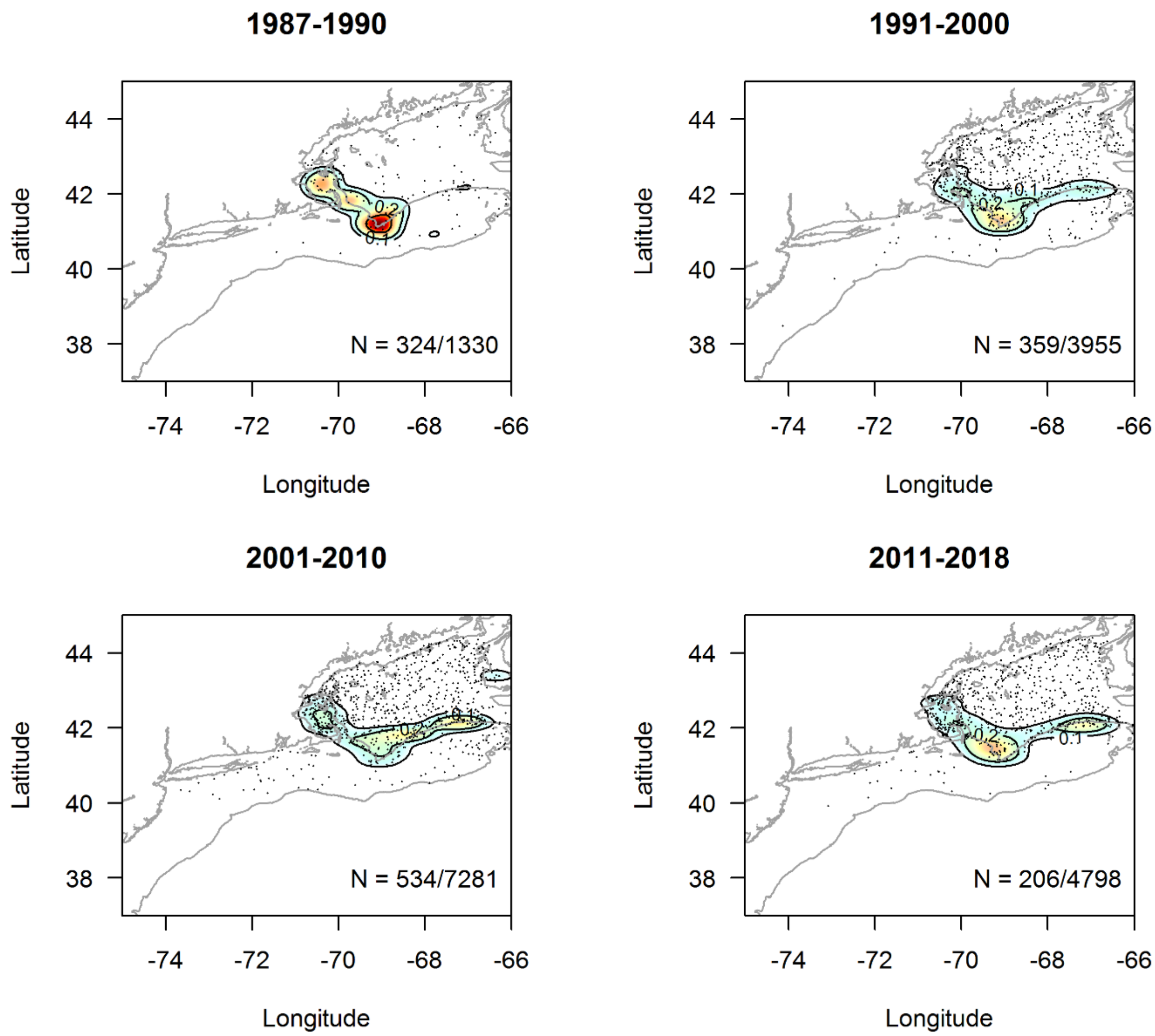


Figure 2.4.3. 2-dimensional kernel density estimates of ripe/running (mat stage U) herring from fall trawl survey. Sample size is indicated; smaller number for samples in mat stage U and larger number for total sample size. 100 m isobath is shown. Points are sample (tow) locations.

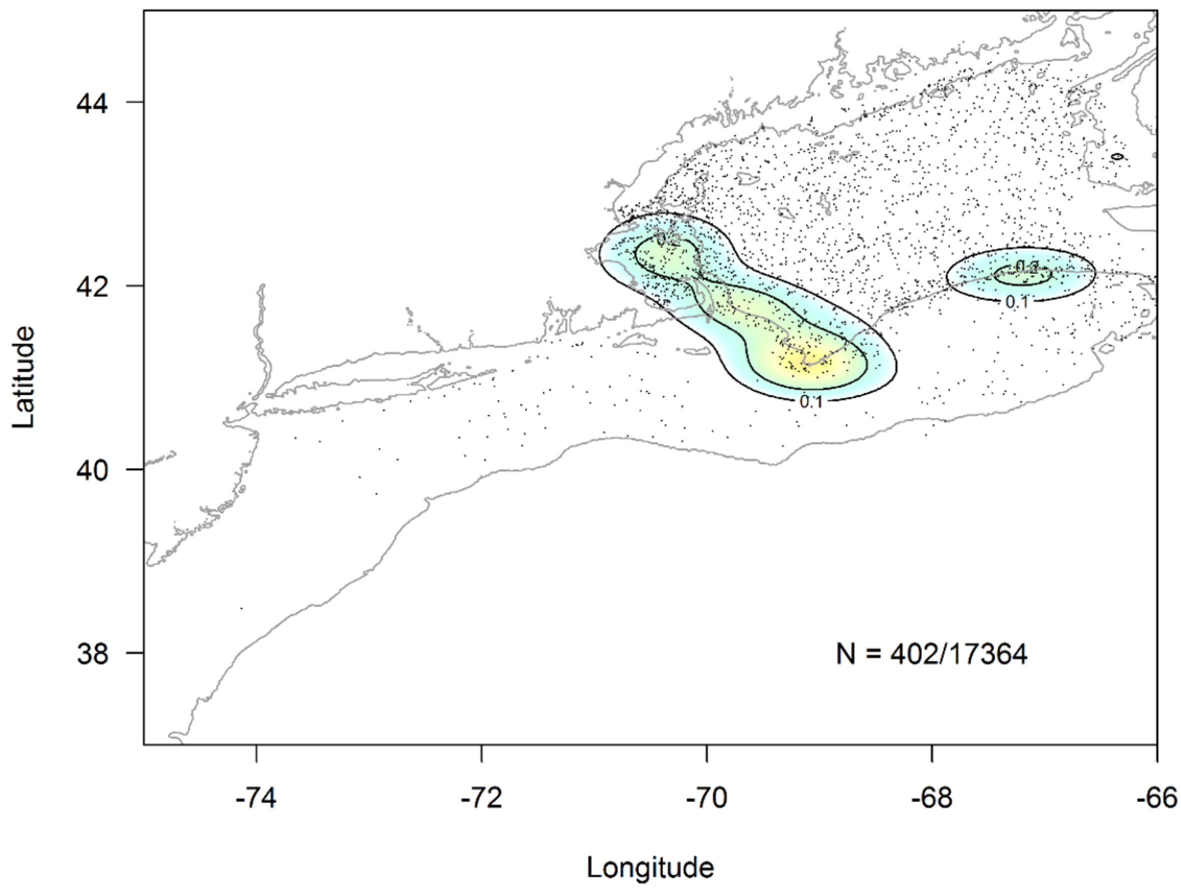


Figure 2.4.4. 2-dimensional kernel density estimates of ripe/running (mat stage U) herring from fall trawl survey by decade. Sample size is indicated; smaller number for samples in mat stage U and larger number for total sample size by decade. 100 m isobath is shown. Points are sample (tow) locations.

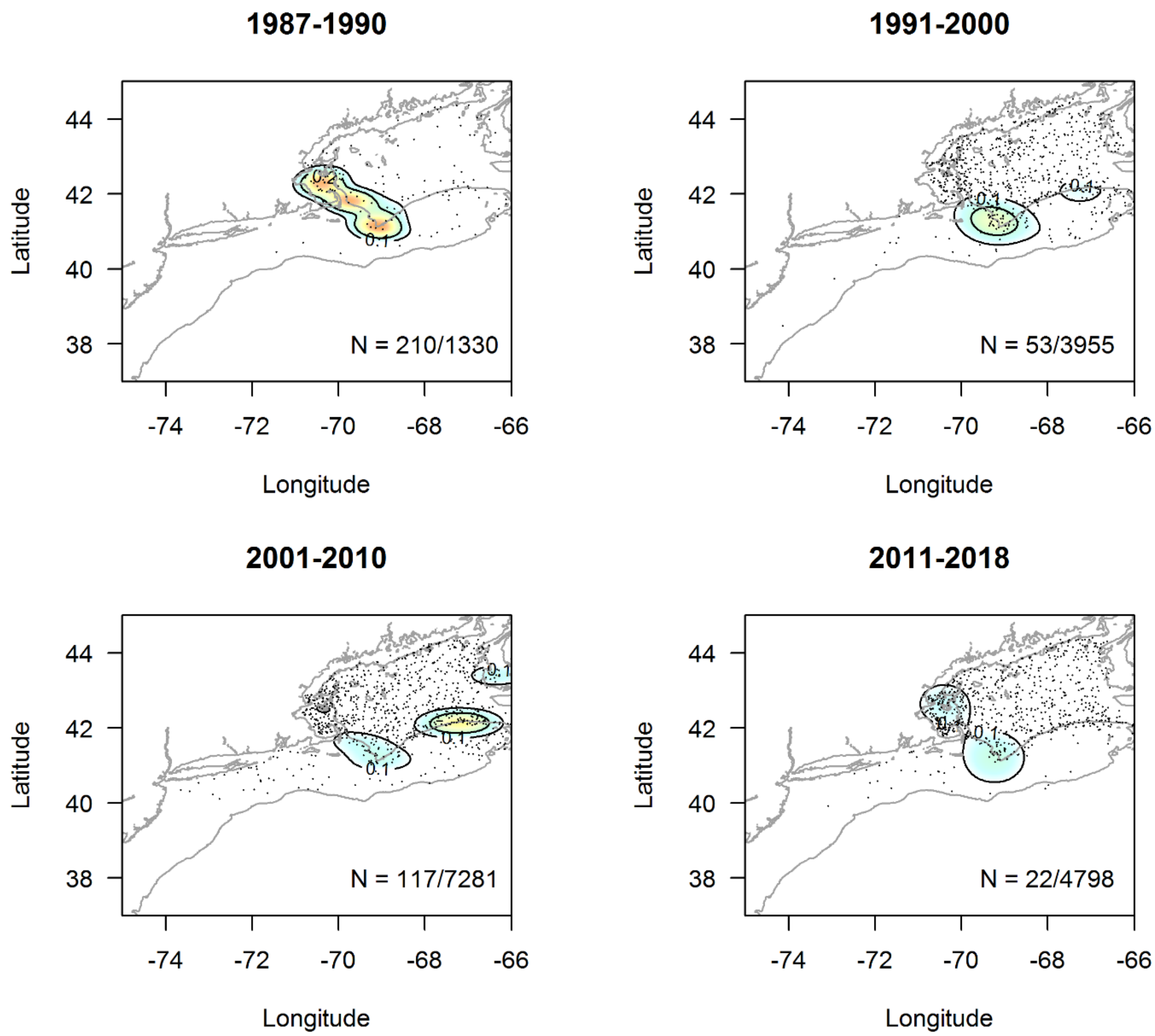
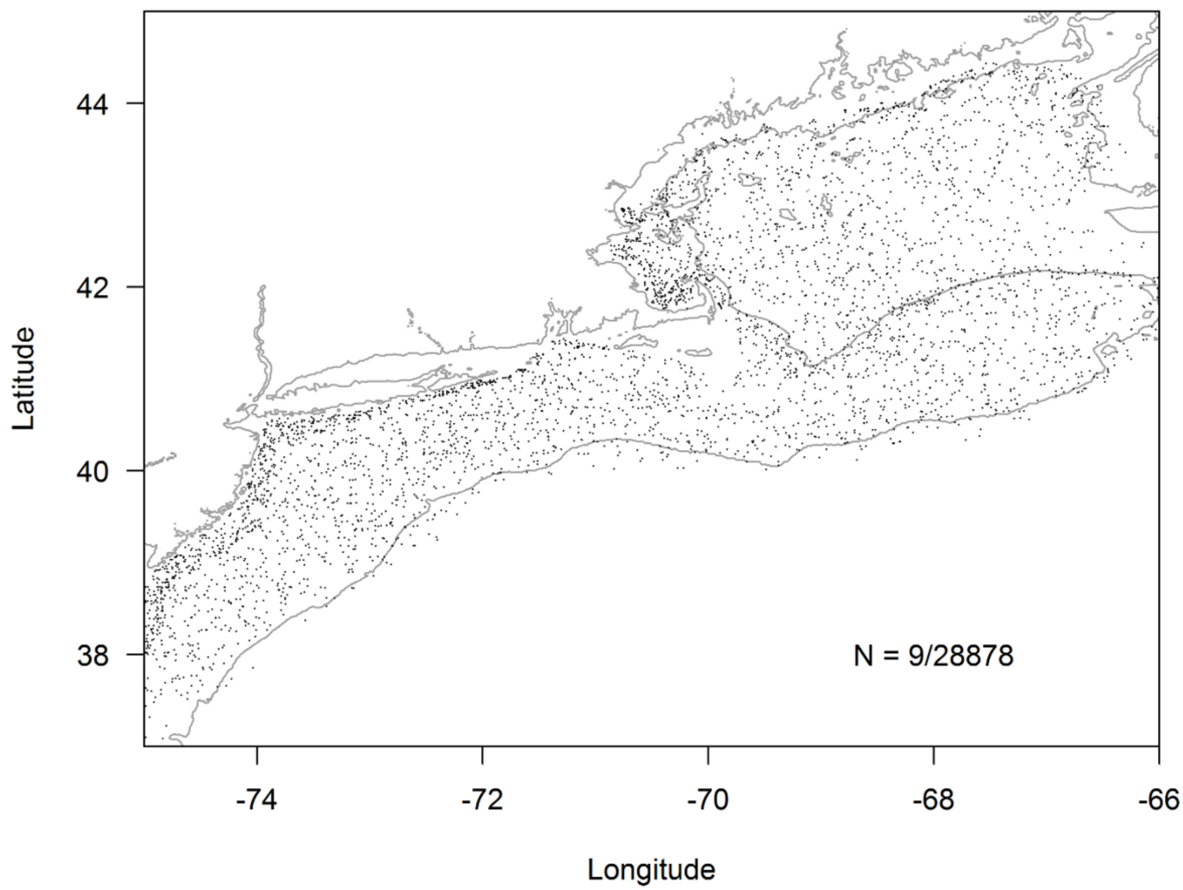


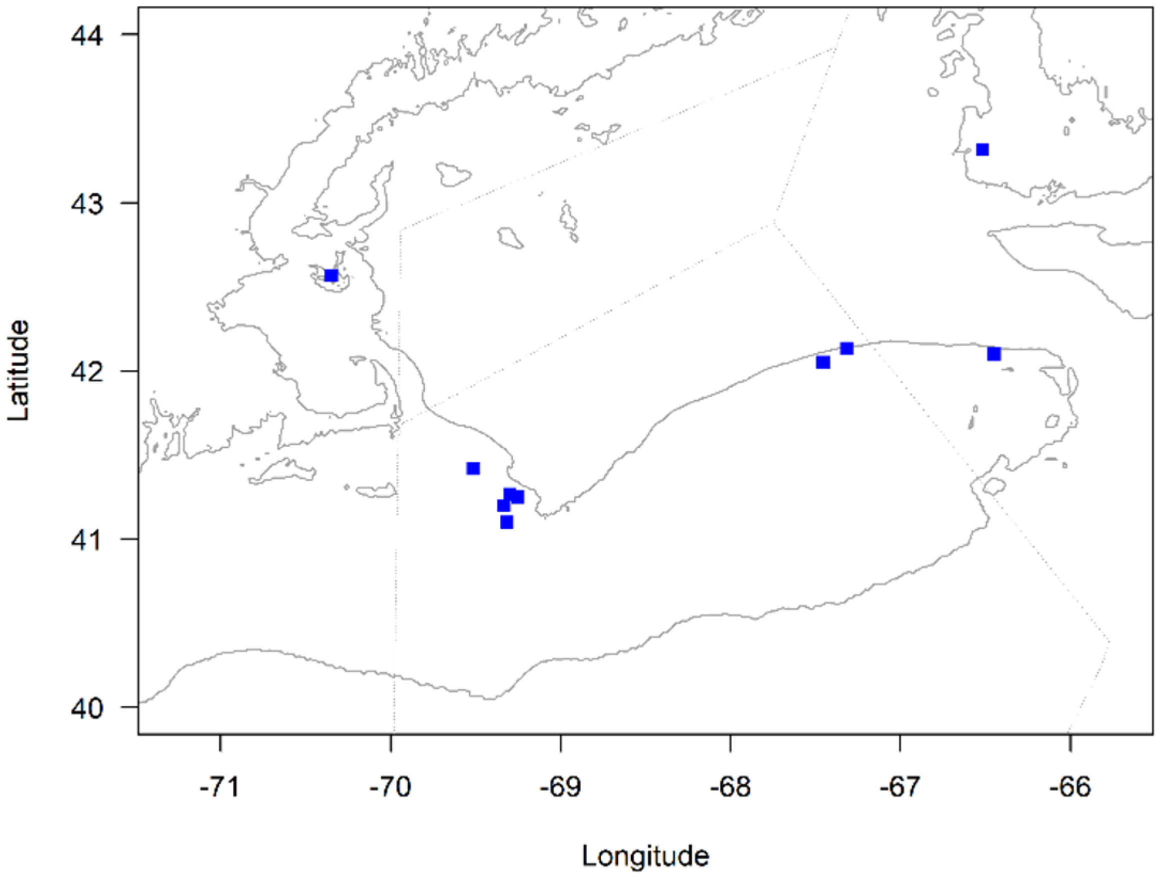
Figure 2.4.5. 2-dimensional kernel density estimates of ripe/running (mat stage U) herring from spring trawl survey (all years combined). Sample size is indicated; smaller number for samples in mat stage U and larger number for total sample size. No areas were indicated (i.e., coloring as in other figures) since there were no dense areas of ripe/running fish. 100 m isobath is shown. Points are sample (tow) locations.



2.5. Food Habits Database (Herring Eggs in Diet of Groundfish)

Food habits data from the Northeast Fisheries Science Center Food Web Dynamics Program were explored for occurrences of Clupeidae eggs and Atlantic herring (*Clupea harengus*) eggs as prey between 1973 and 2017 (B. Smith, pers. comm.). These data covered the entire Northeast US continental shelf. Of the 650,000 samples. only 113 observations (0.02%; from 10 hauls) contained herring eggs. Most of these samples were Clupeidae eggs and only a few were identified to the level of *Clupea harengus* eggs. All observations with eggs occurred between late September and early November and in the years 1989, 1993, 1994, 1995, 1997, 1998, and 2005. Due to the limited amount of data, we only examined the locations where these herring eggs were present, most of which were in the northeast section of Nantucket Shoals and a few occurances on the northeast edge of Georges Bank (Figure 2.5.1). These locations are generally consistent with herring egg essential fish habitat identified in Ammendment 5 to the Atlantic Herring Fishery Management Plan (Figure 2.3).

Figure 2.5.1. Locations of herring eggs observed in 113 NEFSC diet samples from 10 hauls (1989, 1993, 1994, 1995, 1997, 1998, 2005). 100 m isobath is shown. Faint lines are boundaries of herring management areas (see figure 1.4.3).



2.6. Industry Interviews

Representatives of each of the mid-water pair trawl vessels were interviewed to gain a perspective from industry on where spawning takes place for herring and their overall thoughts on the topic. This component of the herring fishing industry was the focus since they are the only vessels that target herring offshore. In general, industry felt that there was not one specific area that you would catch spawning herring and that it varies year to year. One group could not envision how a closure would work on Georges Bank due to the variability from year to year in spawning and cautioned that a closure on Georges Bank would cripple the midwater fleet. Another group did not believe that the midwater fleet is interacting with spawning herring on Georges Bank; in their experience, it is a rare event to catch spawning herring. This coincides with the fact that of the 17,529 herring sampled over the 50 year period by DMR, only 237 were in maturity stage 6 or U (ripe and running; Figure 2.2.9).

The fishing industry that was interviewed believe that the bottom type on Georges Bank where they fish (sandy bottom with no structure and a tide of 2 knots) is not conducive to spawning. They believe that fish are spawning more along the shoal waters along the Northern Edge of Georges Bank where the habitat is better suited for spawning (as is supported by the data; e.g., Figure 3.3). They do not fish in that area of Georges Bank due to the possibility of tearing up their nets. There was one fisherman who indicated the general areas where herring can be caught that have roe and where they spawn. Fish with roe can occur along the whole edge of Georges Bank from Canada to Cape Cod between August and November. There were a couple areas where he has caught spawning fish including the Northern Edge east of the 1300 line in 50 fathoms, near the "BB" buoy south of Chatham, and when there are small fish (non-spawning) to the east you can find the large spawning fish near Cultivator Shoal. He used to find spawning fish in the Great South Channel but has not seen any in four or five years. It was noted that most of the spawning fish were large and of very good quality.

Each representative had their own explanations on the decrease of herring and offered ways to remedy the issue. Many would like to see more sampling including tagging programs, otolith work, surveys that include multiple gear types and have industry data included in assessments. They believe that the small fish are more abundant than the latest assessment indicates and that it can be shown with more sampling. One captain was worried about herring shifting where they spawn. Until about ten years ago, he would catch herring from Virginia up to Long Island while targeting mackerel. He has heard reports that there have been eight trips to Georges Bank this fishing year, with no herring and fears that they have shifted to Canadian waters where there have been reports of herring landed in large quantities.

One of the captains highlighted that when he catches spawning herring, he also catches a larger amount of haddock than he has ever previously caught. He used to find only a couple haddock mixed in with spawning herring, but with the rebound of haddock, he is finding more and more haddock mixed in with the spawning herring. He believes that the haddock are consuming the herring as well as the eggs and either lowering the recruitment or possibly forcing the herring to spawn in new areas that may not be as suitable. It was also raised by a group of captains (who are also able to purse seine) that if they were allowed to target mackerel using a 3 inch brailer instead of the normal 1 inch brailer, it would reduce the amount of small mackerel as well as limit the herring bycatch in the mackerel fishery. This would reduce the pressure on herring while allowing them to fish on a healthy stock. The abundance of river herring is another concern, one captain has seen more than ever before and believes that the river herring are taking over prime areas. Historically, the large balls of sea herring were able to push the river herring away from the prime feeding areas but with the smaller amounts of sea herring he does not believe they can compete with the river herring for the prime areas. All of the groups we interviewed were appreciative that we reached out to industry and welcome more science and research into the issue.

2.7. Observer Data

Herring spawning condition is not identified in Northeast Fisheries Observer Data, but we explored the written comments made by observers from all gear types and fisheries for accounts of spawning Atlantic herring (1989-2019) and herring eggs (2008-2019) (G. Chamberlain, pers. comm). There were very few entries of hauls where captains classified catch as spawning herring. A large amount (> 5,000) of comments recorded by observers contained unclassified fish eggs or unclassified eggs, but observations could not be classified as Atlantic herring eggs with confidence. These comments were too limited to make inferences about location and timing of spawning herring or herring eggs.

3. Building a Consensus

Similar to DeCelles et al (2017), a consensus approach was applied to identifying spawning areas on Georges Bank and Nantucket Shoals. Polygons from multiple sources were layered to examine areas of overlap which were inferred as more consistent areas of spawning. Data layers for this exercise included larval data (Figure 2.1.1), DMR portside monitoring data (specifically, maturity stage 6; Figure 2.2.9), and trawl survey data (maturity stage U; Figure 2.4.3) and eggs in diet of groundfish (i.e., Food Habits database: Figure 2.5.1). Additionally, maps from previous publications were layered in including a historical representation of herring spawning on Georges Bank (Olsen et al 1977; Figure 3.1) and egg EFH[1] (NEFMC 2013; Figure 3.2). Maps were georeferenced in Google Earth where polygons were created and saved as KML files which were layered on top of each other in R. Resultant maps are shown in Figures 3.3 (colored by data source) and 3.4 (monochrome).

In general, all spawning associated activity, from ripe and running adults to evidence of eggs, occurred along the Northern Edge of Georges Bank from Cape Cod to the Northern Flank. However, there were also areas of high overlap of multiple data sources that may indicate more consistent spawning. These include an area to the west of the Great South Channel (northern Nantucket Shoals) and an area on the Northern Flank. Note how adults tend to aggregate to the north of putative spawning areas (in deeper water or near the edge of the bank), egg areas tend to be up on the bank and larval areas tend to be downstream of these areas. Figure 3.5 shows the areas of highest overlap (i.e., where 3 or more sources agreed). In this case, two distinct areas emerged; one to the west of the Great South Channel and the other on the Northern Flank.

Figure 3.6. shows overlap of data sources by decade. Here, only larval, DMR and trawl survey data were used since these had records that spanned multiple decades. While harder to infer consensus areas due to smaller data sets, spawning appeared to move from the west in the 1980s, to across the northern edge of the shelf in the 1990s and 2000s to distinctly west and east areas in the 2010s.

Overlap of areas of high density of maturity stage R + U herring from both DMR data and the trawl survey over each decade was also considered (Figure 3.7). Similar to other depictions, this showed areas of high overlap, among decades and data sets, at the Great South Channel and the

[1] The prior egg EFH designation was used because it focused on known locations of herring egg beds. The current, April 2018 designation from Omnibus Habitat Amendment 2 includes these egg bed locations plus locations where very small larvae were captured in plankton surveys. Since these same plankton data were used in separate analyses elsewhere in this report, the prior egg designation was found to be a more appropriate layer for the consensus exercise presented here.

Northern Flank. Consensus areas from this figure are shown in Figure 3.8 (where 4 or more polygons overlapped). Figure 3.9 shows how this compares to the consensus areas shown in Figure 3.5. Again, it appears that the adult spawning condition herring tend to aggregate slightly to the north and off the bank compared to consensus areas that include eggs and larval herring (more on the bank).

Figure 3.1. Known specific spawning grounds for various fishery species including Atlantic (sea) herring (dark red polygons; from Olsen et al. 1977).

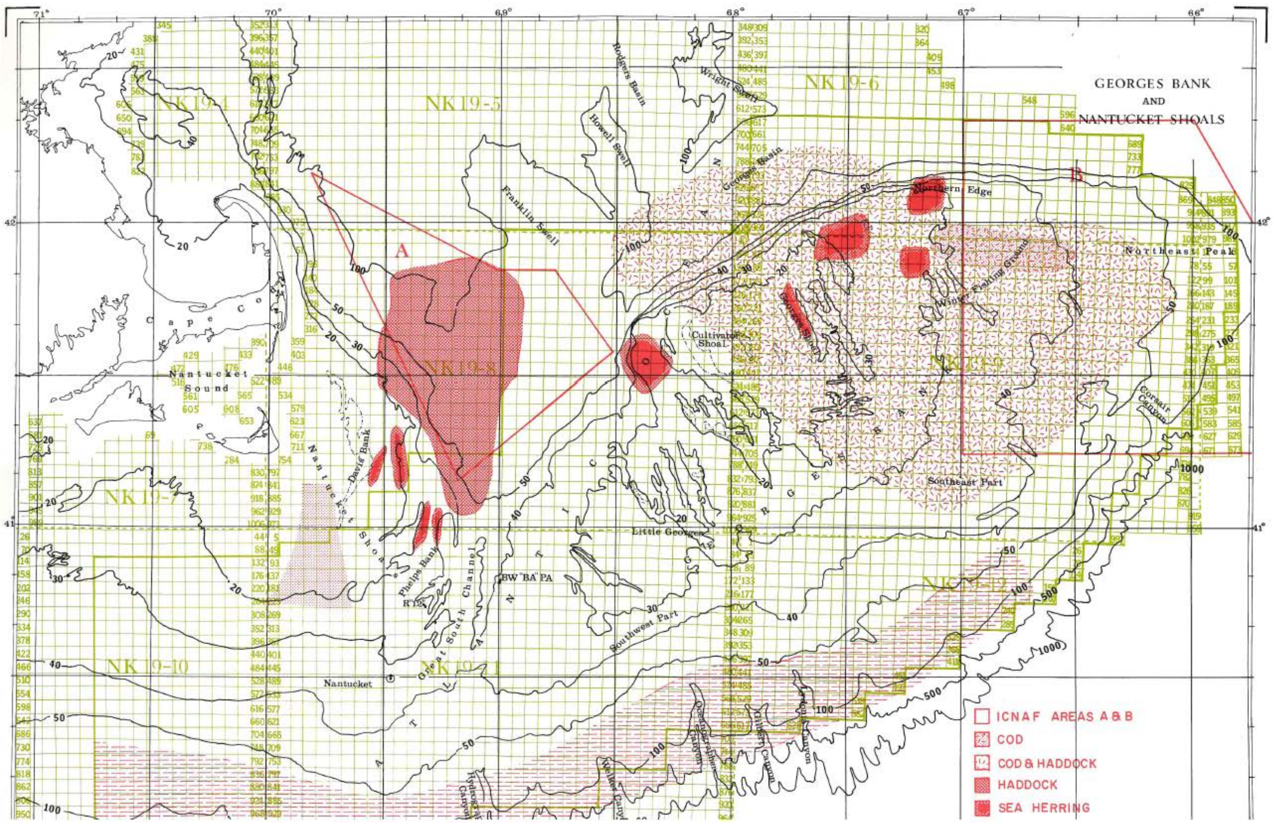


Figure 3.2. EFH for herring eggs from Amendment 5 to the Fishery Management Plan (FMP) for Atlantic Herring (NEFMC 2013).

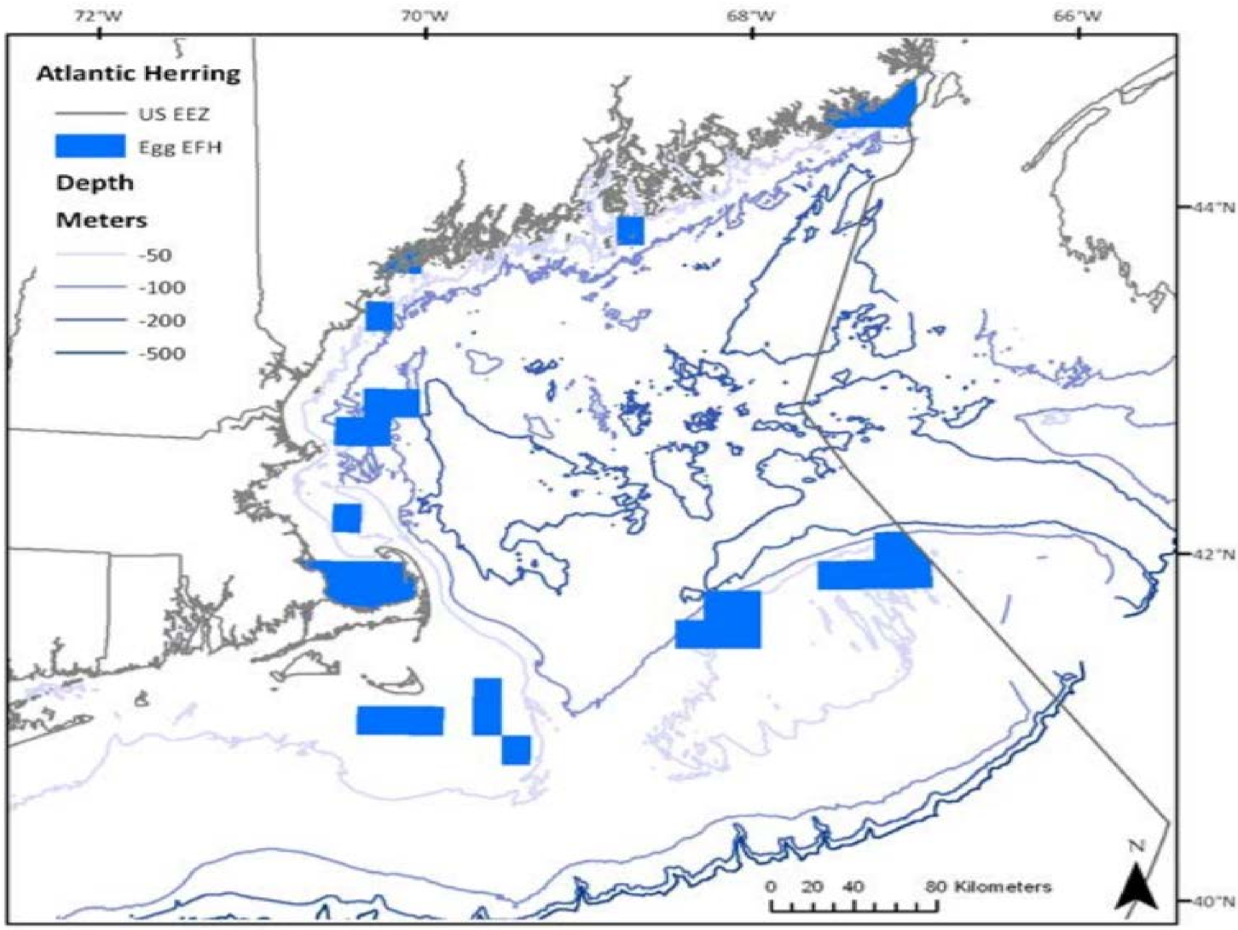


Figure 3.3. Areas of overlap between multiple data sources including data from food habits database (diet data; Figure 2.5.1), larval monitoring (Figure 2.1.1), egg EFH (Figure 3.2), historical spawning grounds (Figure 3.1), DMR portside monitoring (mat stage U; figure 2.2.9), and fall trawl survey (mat stage U; Figure 2.4.3). 100 m isobath is shown.

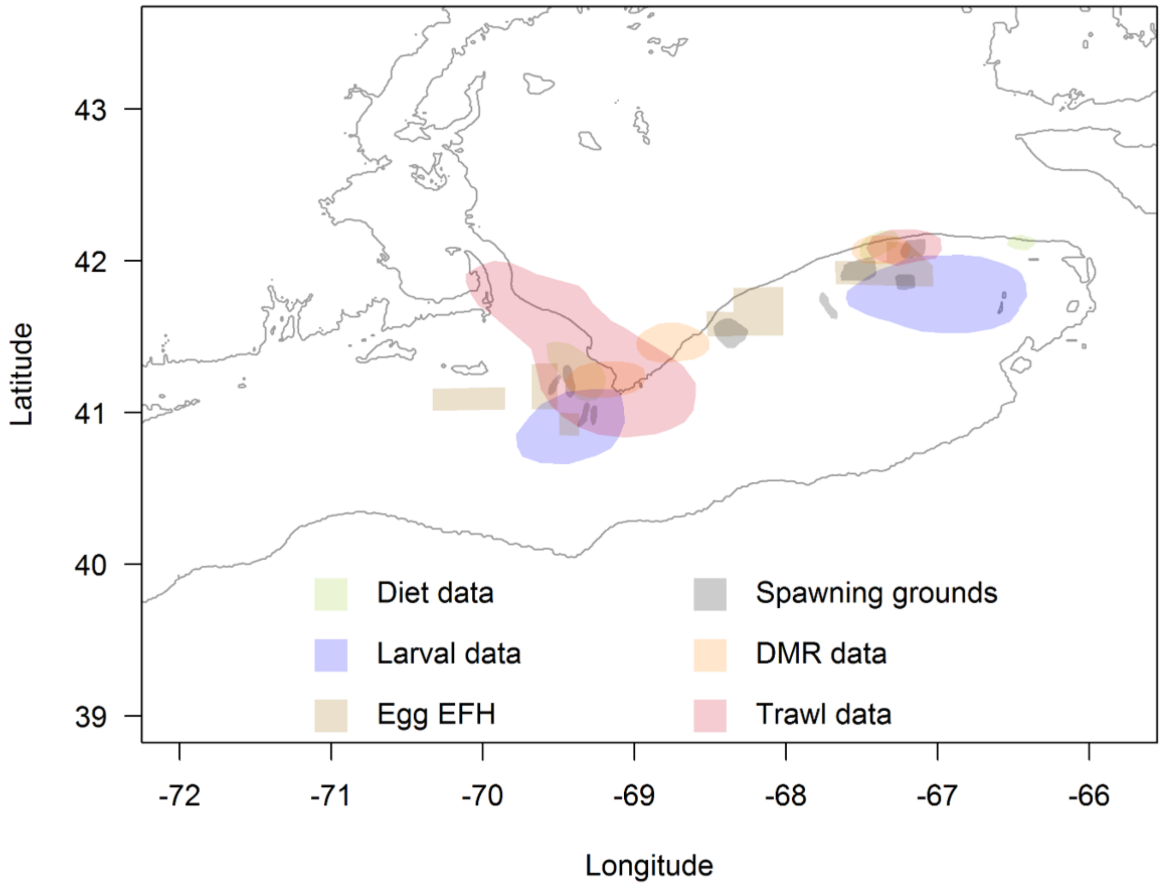


Figure 3.4. Same as Figure 3.3 but all in same color to highlight areas of overlap through darker shading. 100 m isobath is shown.

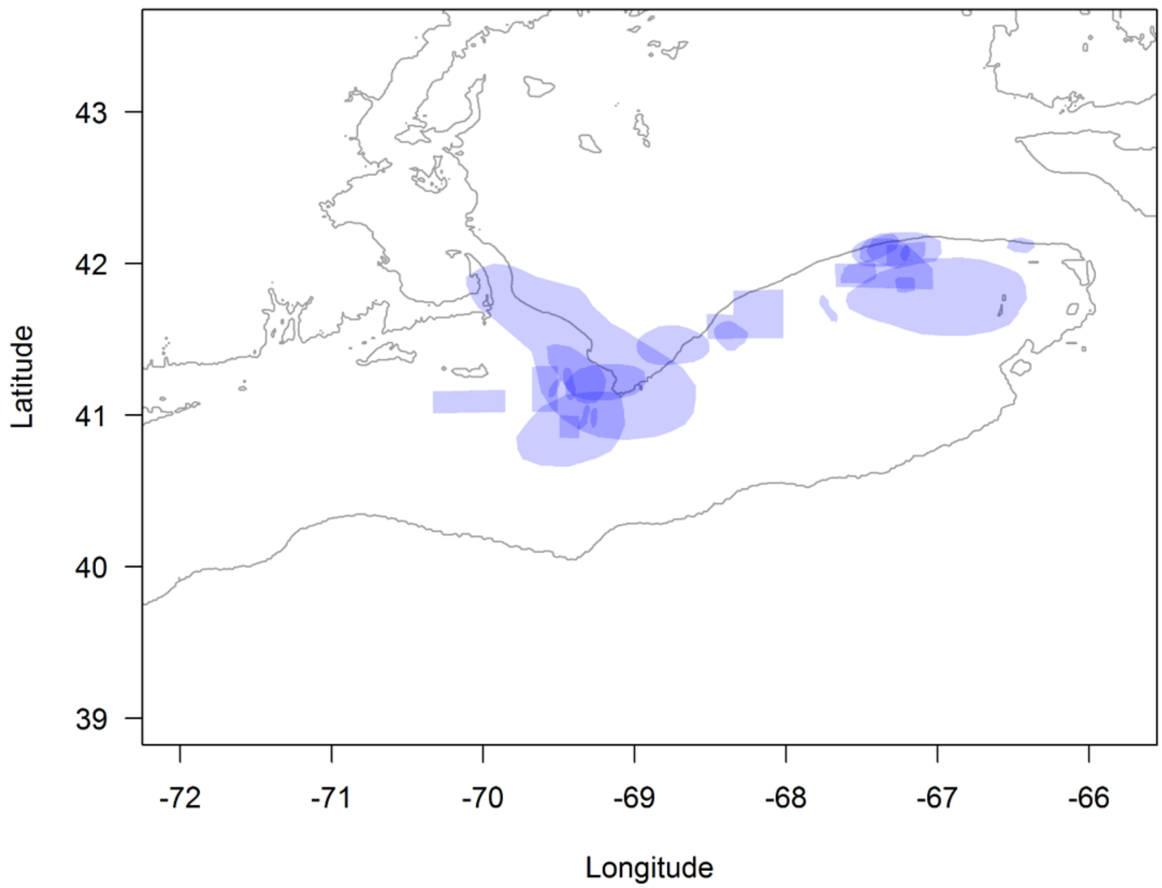


Figure 3.5. Consensus areas from Figure 3.4 where 3 or more overlaps occurred between different data sources. 100 m isobath is shown.

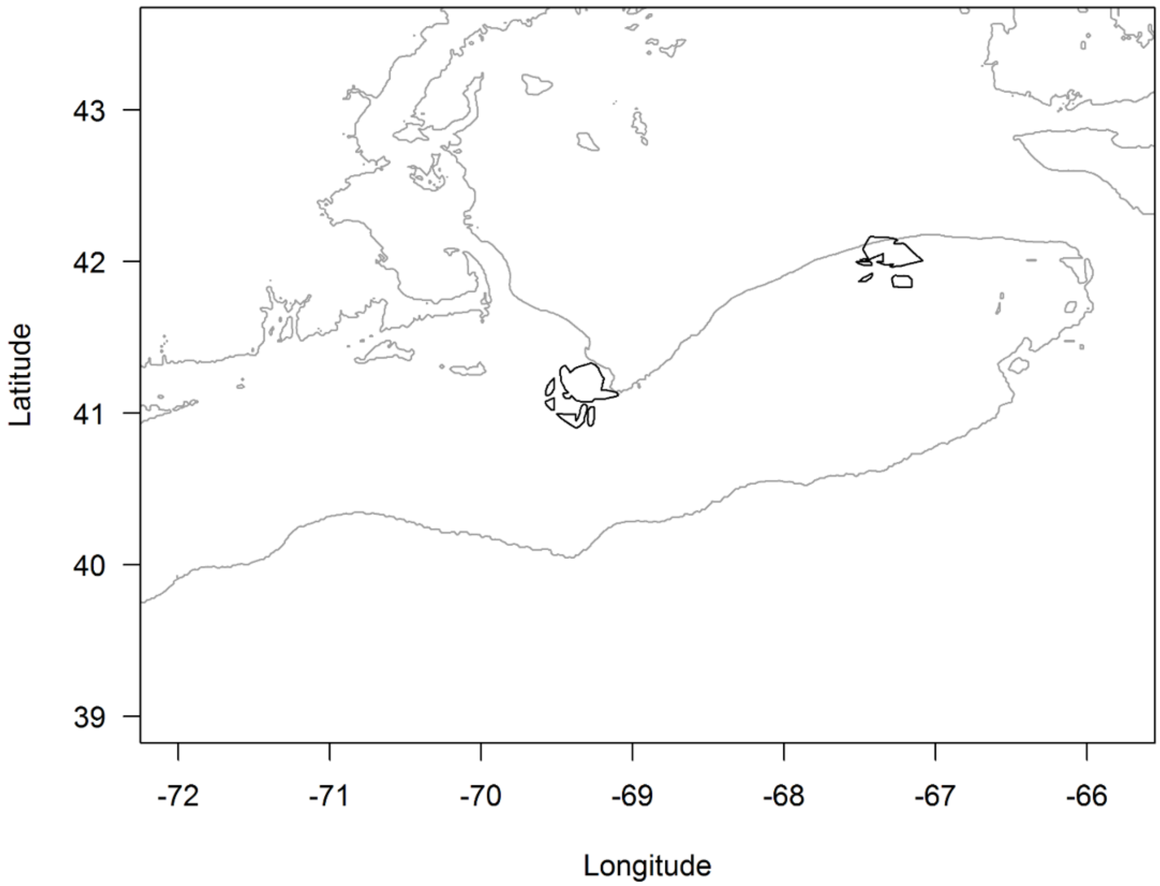


Figure 3.6. Overlap areas of spawning between different data sources by decade. 100 m isobath is shown.

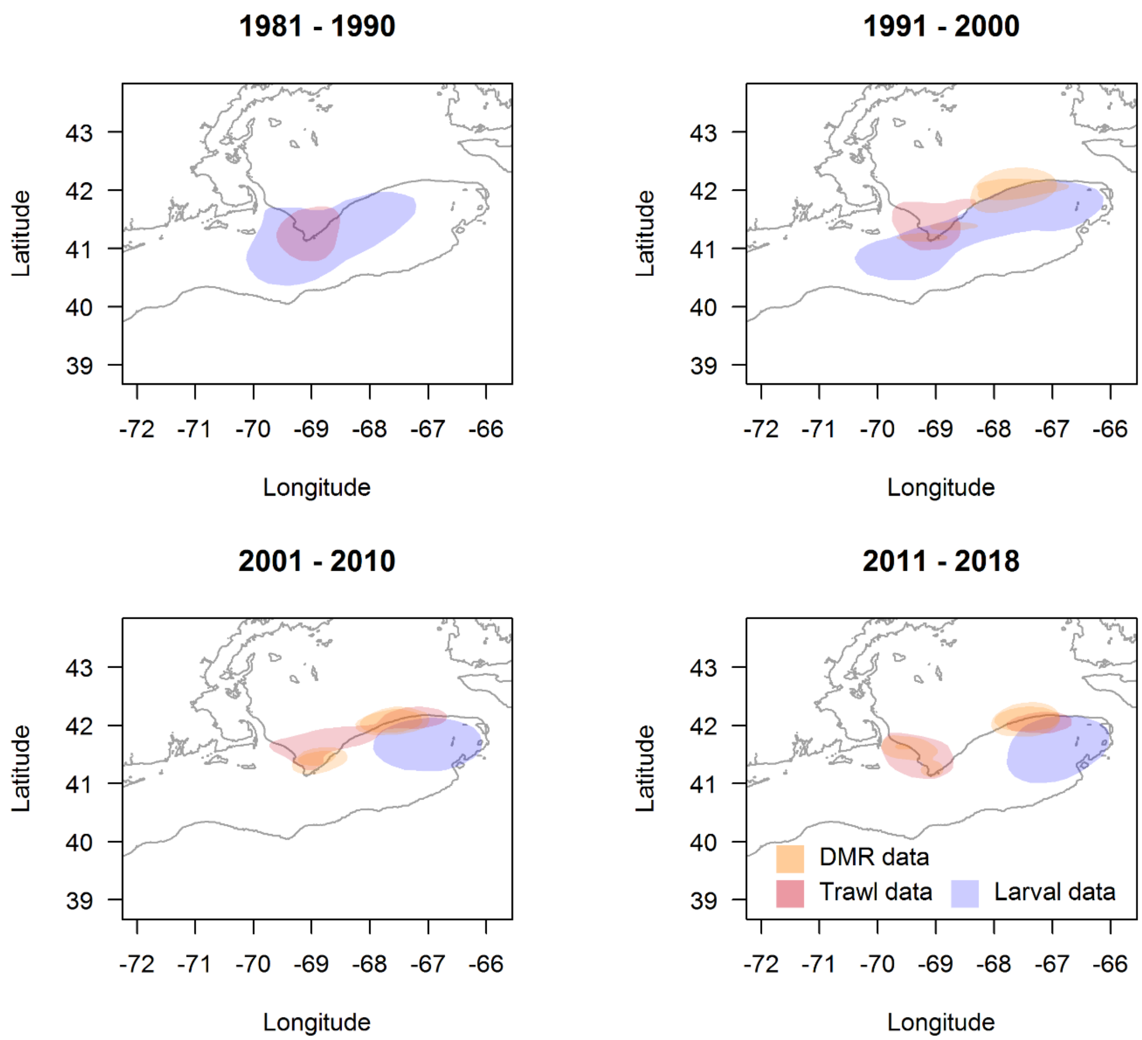


Figure 3.7. Overlap areas for maturity stage R+U herring from both DMR and trawl survey data sets for multiple decades (see Figure 3.6). 100 m isobath is shown.

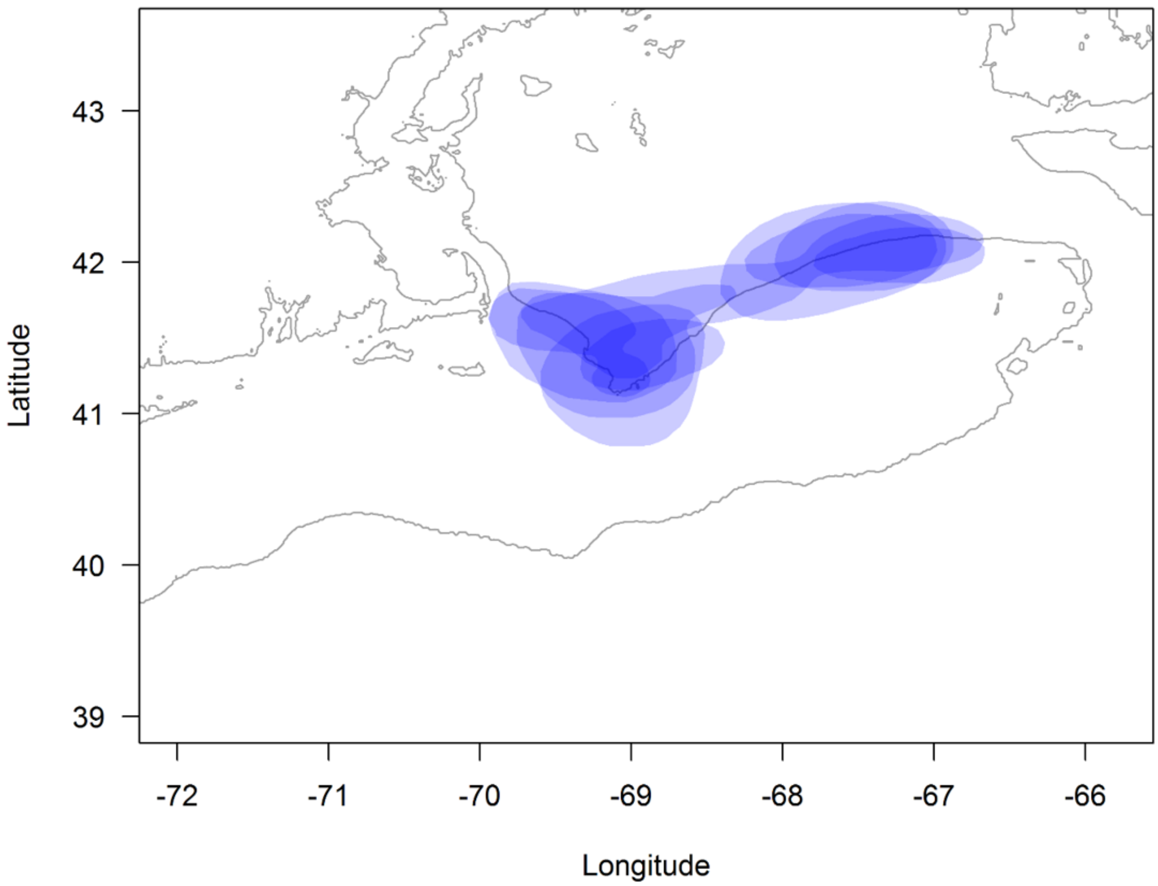


Figure 3.8. Consensus areas from Figure 3.7 where 4 or more overlaps occurred between different decades and data sources (DMR and trawl survey data). 100 m isobath is shown.

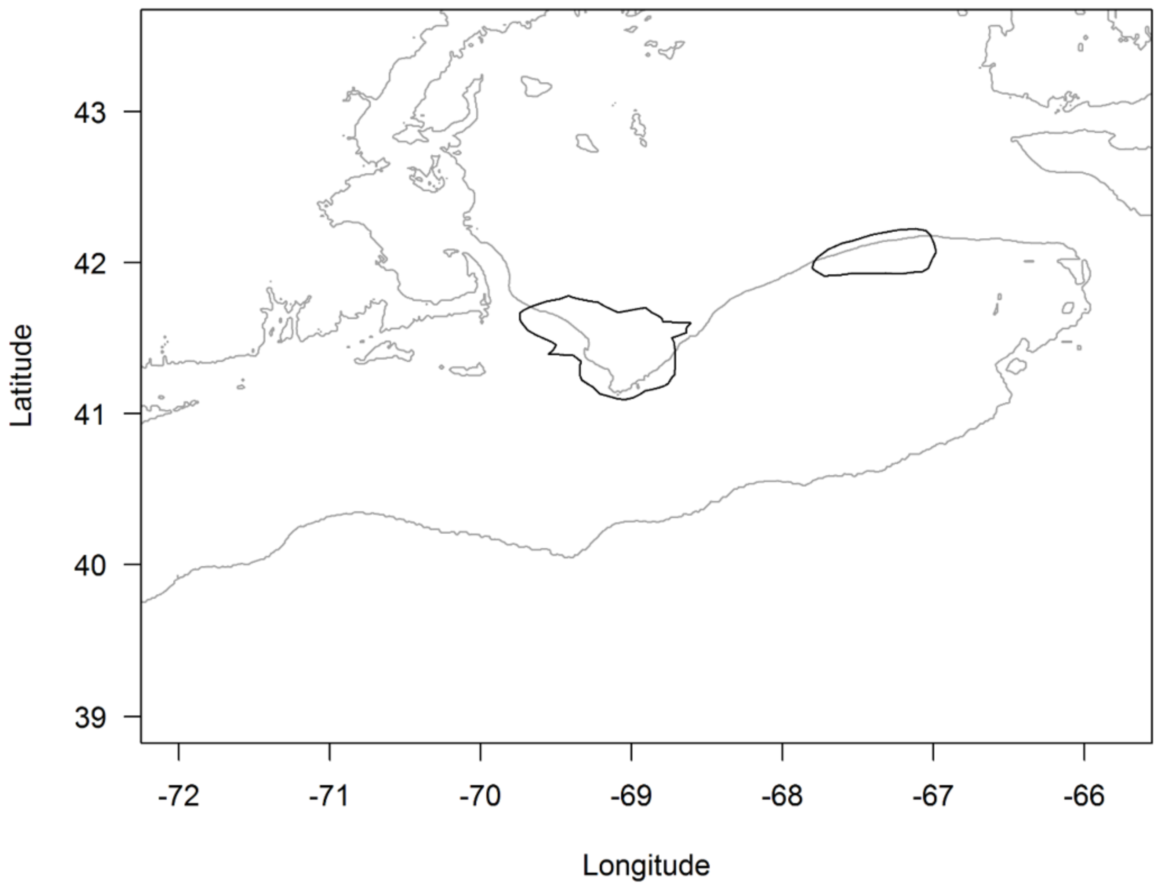
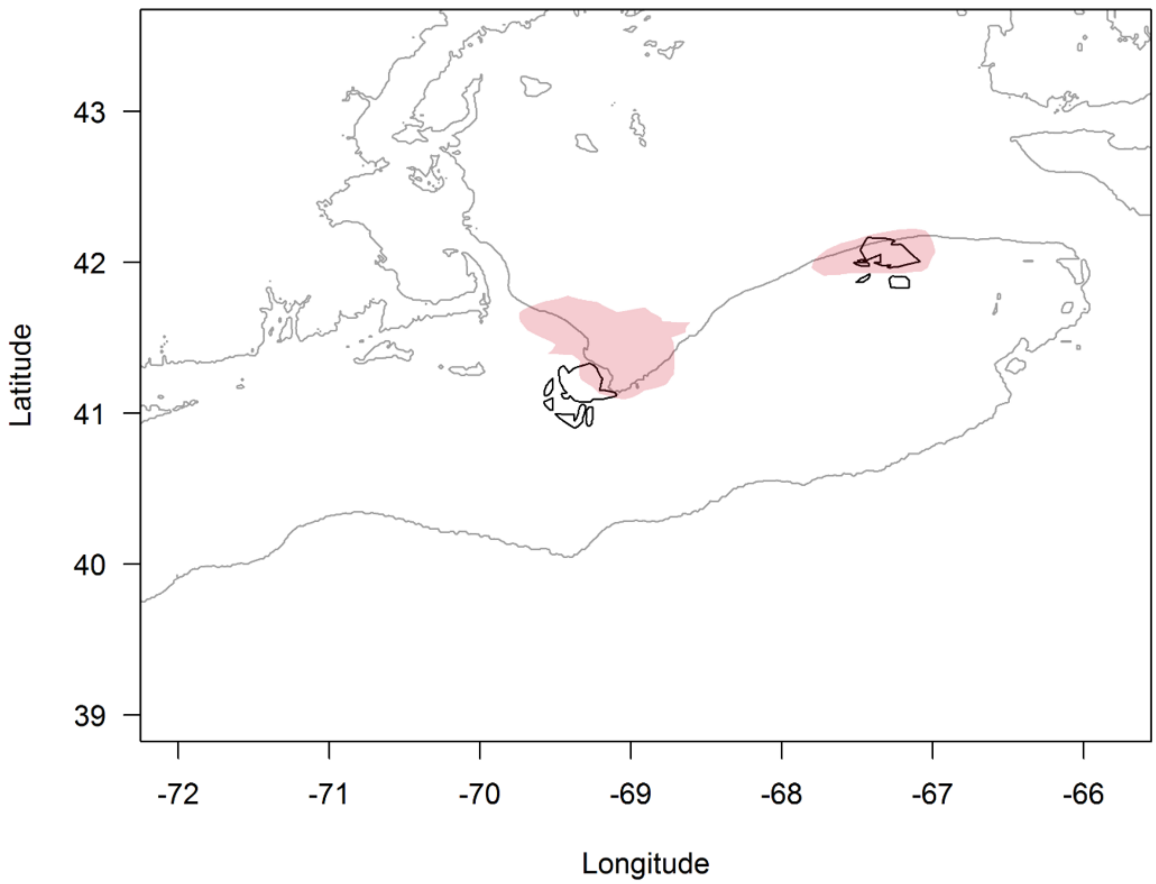


Figure 3.9. Comparison between consensus areas using all data sources (areas with black borders; from Figure 3.5) and those from multiple decades using mature fish (mat stage R+U) only (red shaded areas; from Figure 3.8). 100 m isobath is shown.



4. Herring Fishing Effort

Consensus spawning areas were compared to maps of fishing effort using two different approaches. First, the DMR portside monitoring database was used as a first layer since this approximates fishing effort in space. Figure 4.1 shows the 2-D kernel density estimates of sample locations from the whole DMR dataset. Fishing effort was concentrated along the northern edge of Georges Bank with high densities seen near the Northern Flank which overlapped partially with an area of high spawning activity. Another area of high sample density was seen to the east of the Great South Channel and did not overlap with the area of high spawning activity in that region. Figure 4.2. shows effort variation among decades from the DMR data. In every decade, there was some overlap with the spawning area at the Northern Flank and little to no overlap with the spawning area near the Great South Channel.

Second, effort data was examined in the form of raster layers of herring fishing revenue for the years 2007-2017 (Benjamin et al 2018). A similar picture emerged using this data.

Particularly, fishing effort was concentrated along the northern edge of Georges Bank and overlapped somewhat with the spawning area on the Northern Flank (Figure 4.3). Figure 4.4. shows how effort varies among sets of years. In the most recent years (2016/2017), herring revenue was concentrated near the Northern Flank spawning area and less spread out along the edge as in previous years.

Finally, consensus spawning areas were compared to different management areas and boundaries (Figure 4.5). The eastern Georges Bank spawning area overlaps to a high degree with Closed Area II and the Closed Area II Habitat Closure Area. The western spawning area did not overlap with previous groundfish closed areas. However, it overlaps to varying degrees with a new habitat management area (Great South Channel HMA) and the inshore mid-water trawl gear prohibition area proposed in Herring Amendment 8 to address potential localized depletion.

Figure 4.1. 2-dimensional kernel density estimates of fishing effort during spawning season (September and October; see Figure 2.3.1) for all years from DMR portside monitoring (i.e., location of industry samples). Total sample size is shown. Boxes enclose consensus spawning areas from Figure 3.5. 100 m isobath is shown. Points are sample locations.

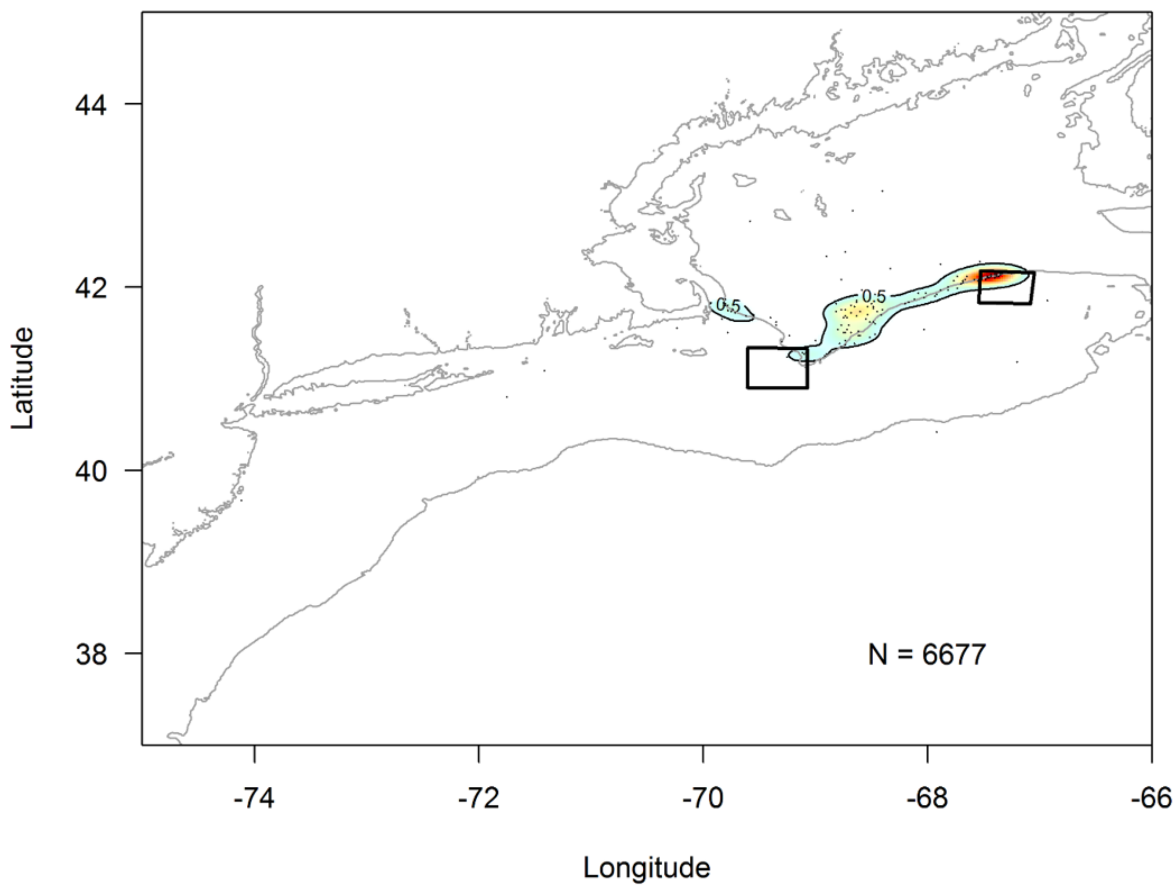


Figure 4.2. 2-dimensional kernel density estimates of fishing effort during spawning season (September and October; see Figure 2.3.1) by decade from DMR portside monitoring (i.e., location of industry samples). Sample sizes are shown. Boxes enclose consensus spawning areas from Figure 3.5. 100 m isobath is shown. Points are sample locations.

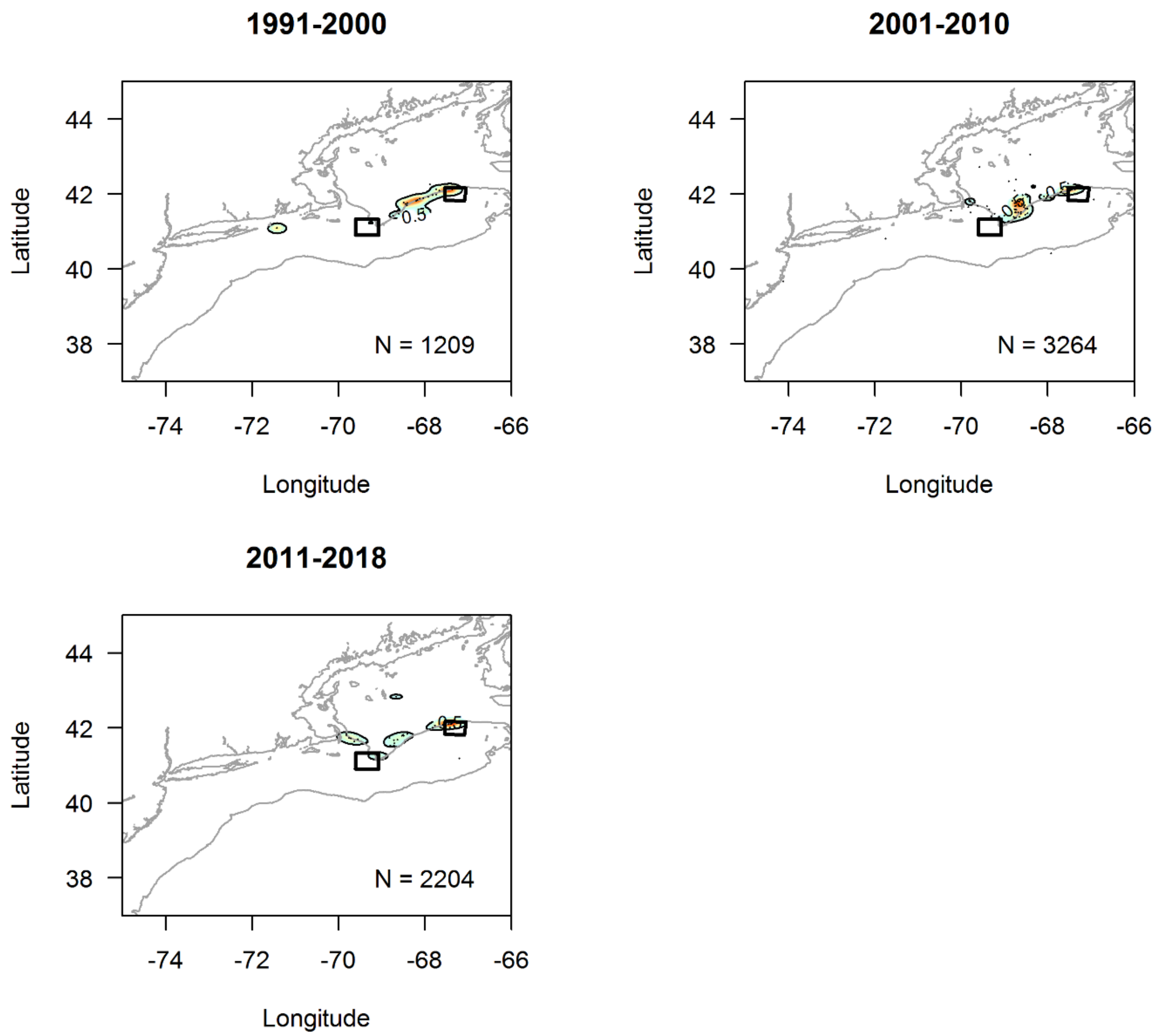


Figure 4.3. Fishing effort as herring revenue ($/0.25km2) for the period 2007-2017. Data from Benjamin et al (2018). Boxes enclose consensus spawning areas from Figure 3.5. 100 m isobath is shown.

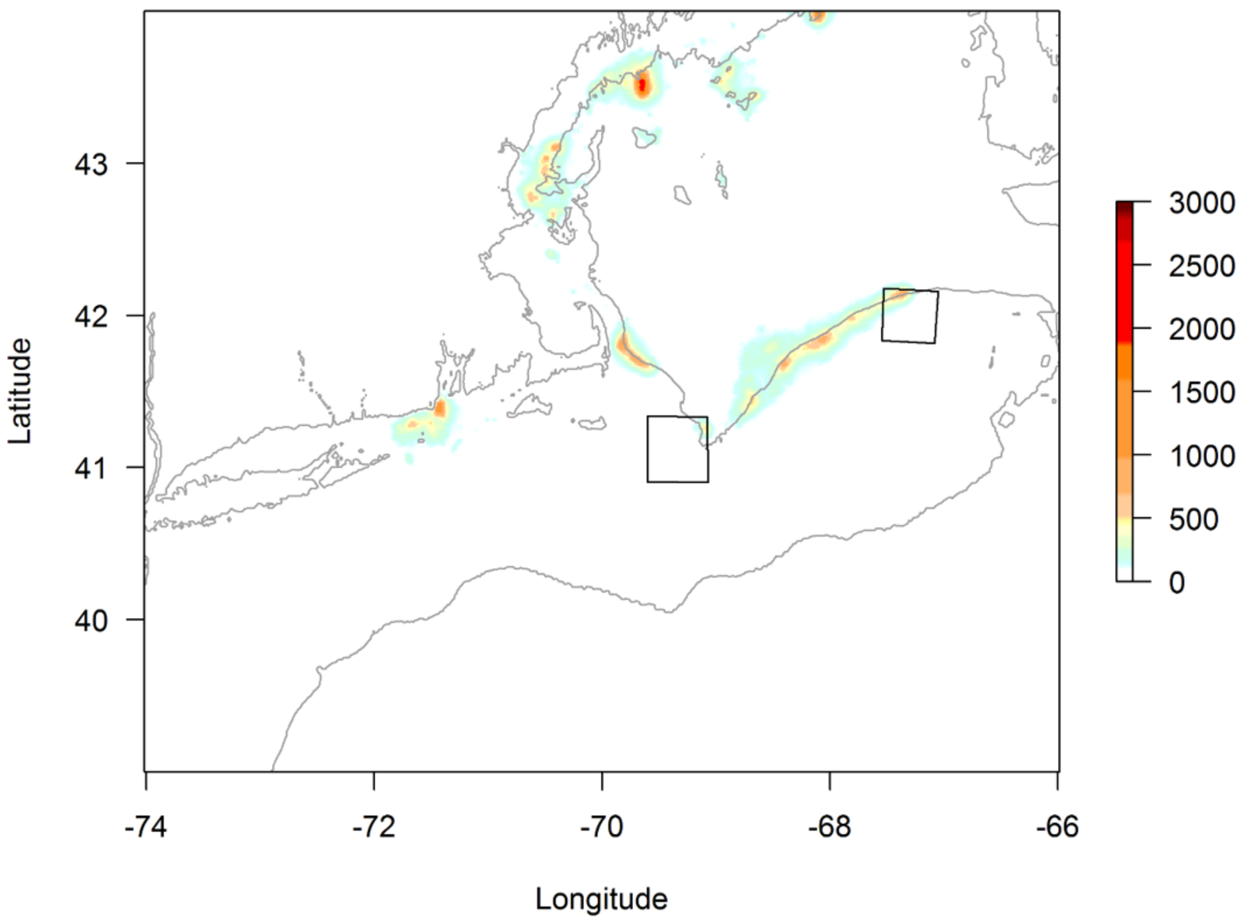


Figure 4.4. Fishing effort as herring revenue ($/0.25km2) for 4 3-year periods from 2007-2017. Data from Benjamin et al (2018). Boxes enclose consensus spawning areas from Figure 3.5. 100 m isobath is shown.

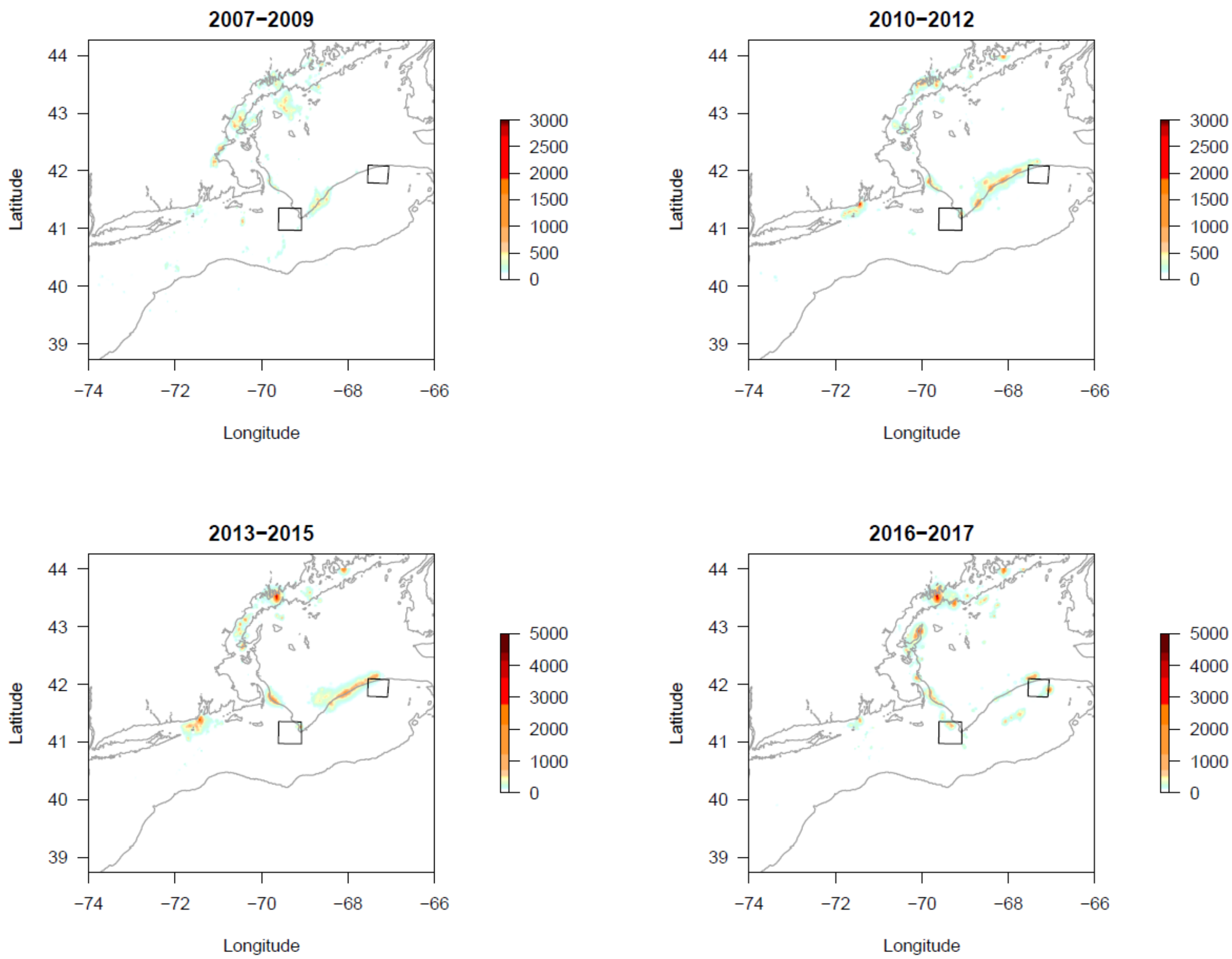
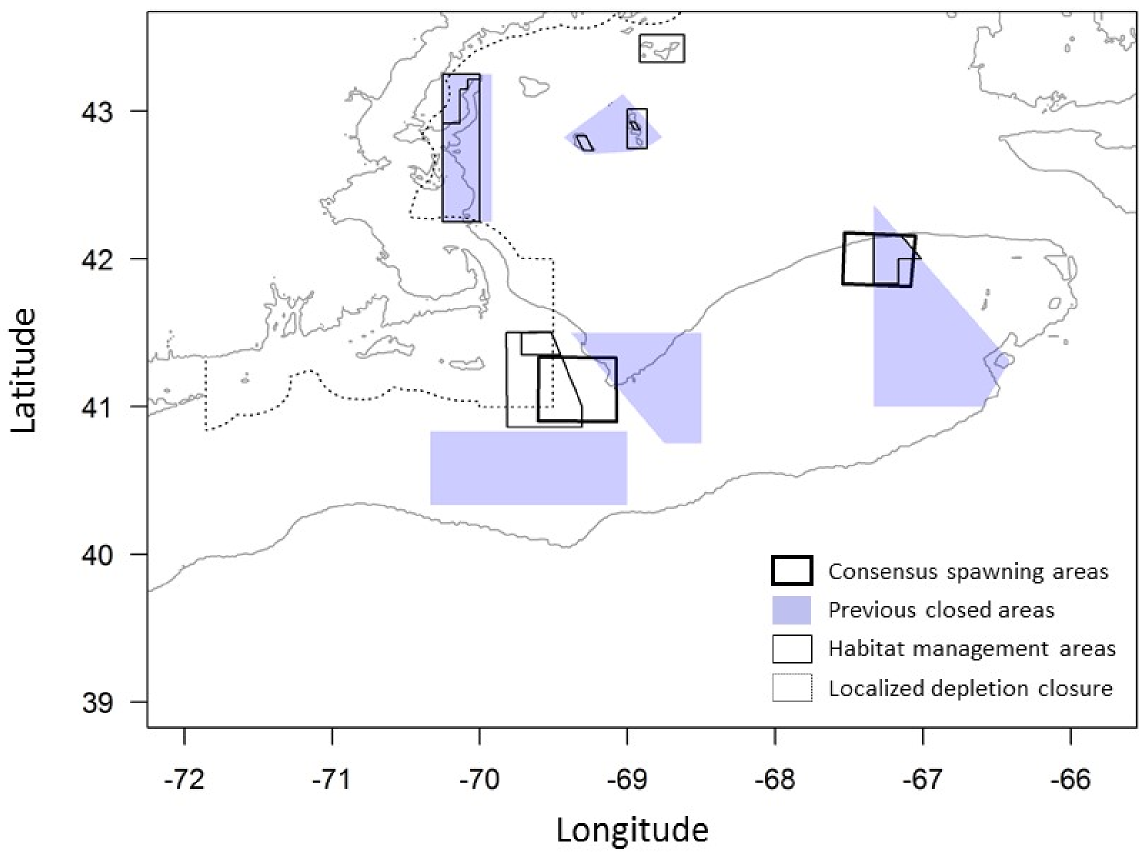


Figure 4.5. Consensus spawning areas in relation to groundfish closed areas, habitat management areas and the proposed localized depletion closure. The southernmost purple area, the Nantucket Lightship Closed Area, was removed in April 2018 via OHA2, and Closed Area I, to the east of the western herring spawning area, was made seasonal as described in the text. The remaining purple areas are still in effect as year-round closures (note that the boundary of the closure in the western Gulf of Maine was adjusted slightly via OHA2). 100 m isobath is shown.



5. Potential Impacts to Offshore Spawning from Other Sources

5.1. Potential Fishery Impacts

This document outlines existing information to infer most likely locations of herring spawning activity on Georges Bank. This takes into account information from multiple life stages of herring including areas of highest density of spawning adults, eggs and larvae. Directed fishing on spawning adults could affect spawner biomass, as well as potentially disrupt spawning activity (e.g., school formation; this has not been definitively shown although see Stockwell et al [2013] for possible effect of midwater trawling on non-spawning herring schools). However, directed herring fishing is less likely to impact eggs and subsequent larvae since eggs adhere to the bottom and herring fishing activity is primarily in the water column and not on the ocean floor. In this sense, fishing activities that directly interact with bottom habitat during the period of highest spawning activity (i.e., September and October; note that herring eggs hatch within 10-15 days of spawning; Bigelow and Schroeder 1953) may be expected to cause the highest risk to this stage of reproduction.

There are three main fisheries that interact with the bottom around the locations that have been identified as areas of likely spawning and egg deposition. These include groundfishing (bottom trawls), and the sea scallop and surf clam/ocean quahog fisheries (scallop and hydraulic dredges), all of which employ bottom-tending gear. Note that an exact spatial/temporal analysis of fishing activity in relation to herring spawning areas is beyond the scope of this review. The following is meant only to identify potential areas of overlap.

The multispecies groundfish fishery operates year-round on Georges Bank and appears to overlap with consensus herring spawning areas. Figure 5.1.1 shows groundfish vessel locations that are inferred to be fishing (i.e., speed less than 4 knots from vessel monitoring system or VMS for the years 2015-2016). Fishing activity is relatively high inside the western consensus herring spawning area, particularly throughout the central portion of the box which may contain the highest herring spawning activity. Only a small portion on the northeast corner of the western spawning box has been protected by a year round groundfish closure (i.e. Closed Area I; see Figure 4.5). Roughly half of the eastern consensus herring spawning area lies within Closed Area II (Figure 4.5) and is therefore protected from groundfish gear. However, the western half of the eastern box is not protected and has also seen a relatively high level of groundfishing activity which could potentially impact herring eggs. It should be noted that groundfish closed area boundaries have been modified in more recent years, and some of these boundaries are no longer relevant. For example, as of April 2018 Closed Area I is no longer closed year-round, a new area farther to the west is now closed to all bottom tending fishing year-round (Great South Channel Habitat Management Area), and only the northern portion of Closed Area I is closed February 1 - April 15 as a groundfish spawning protection measure (NEFMC, 2016). Furthermore, the fishing effort maps that have been included here are annual maps because that is what was available. Seasonal effort maps (i.e. September – November) would be more relevant to assess the potential overlap and risk to herring spawning areas.

The sea scallop fishery operates year-round on Georges Bank and also appears to overlap to a substantial degree with consensus herring spawning areas (Figure 5.1.2). The location of highest scallop fishing intensity, as inferred from VMS (again for vessels moving less than 4 knots for the years 2015-2016), overlaps with consensus herring spawning areas primarily on western Georges Bank, but also in the northwest corner of the eastern spawning area (Figure 5.1.2). Habitat descriptions for scallops and where herring are likely to spawn are also similar. Specifically, sea scallop adults live on coarse substrate, usually gravel, shells and rock at depths ranging from 18-110m (Hart and Chute 2004). Atlantic herring also spawn on rocky, pebbly, or gravelly bottoms, shell substrates, and on clay to some extent, but probably never on soft mud (Bigelow and Schroeder 1953). Figure 5.1.3 shows how herring spawning areas coincide mostly with pebble and cobble dominated habitats. Again, seasonal effort maps would be more relevant to assess the potential overlap and risk to herring spawning areas from scallop fishing. In general the herring spawning areas do not overlap with rotational scallop closures, but rather with ‘open’ scallop bottom.

Figure 5.1.4 shows surfclam/ocean quahog fishing activity for 2015-2016 (VMS locations filtered for vessels moving at speeds less than 4 knots). Areas of highest fishing intensity do not appear to overlap appreciably with consensus herring spawning areas. In the eastern Georges Bank spawning area, there is no overlap, while in the western area there is some overlap on the western portion of the spawning box. It should be noted that the surf clam/ocean quahog fishery uses hydraulic dredges that mainly operate on soft bottom comprised of sandy sediment with the preference to be large grain sand (DeAlteris and Allen 2016) (Figure 5.1.3). It should also be noted that the areas where surfclam/ocean quahog fishing takes place has been changing in more recent years, with more effort shifting to areas farther offshore including Georges Bank (MAFMC, 2018). Vessels targeted surf clams on GB in the 1980s, and not again until 2009. The herring spawning areas are fished for surfclams, and not for ocean quahogs (NEFMC, 2019). As of April 2019, the Great South Channel HMA is closed to clam dredges; an action to reopen discrete exemption areas for clam and mussel dredging is currently under review by NMFS.

Figure 5.1.1. Spatial extent of multispecies groundfish fishery as inferred from VMS data where vessels are moving at a speed of less than 4 knots (2015-2016). Data from Northeast Ocean Data Portal; https://www.northeastoceandata.org/). Thick black boxes enclose consensus herring spawning areas (from Figure 3.5). 100 m isobath is shown.

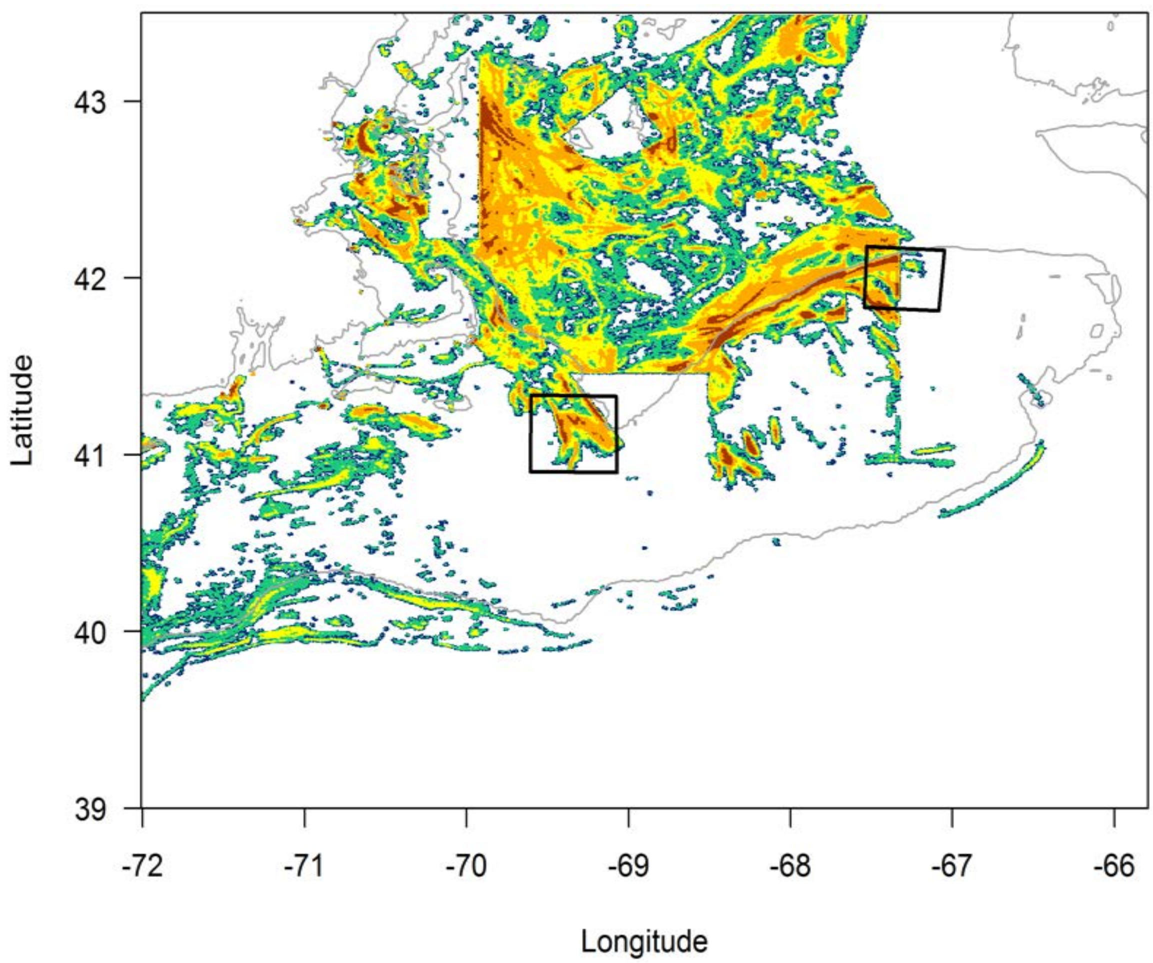


Figure 5.1.2. Spatial extent of scallop fishery as inferred from VMS data where vessels are moving at a speed of less than 5 knots (2015-2016). Data from Northeast Ocean Data Portal; https://www.northeastoceandata.org/). Thick black boxes enclose consensus herring spawning areas (from Figure 3.5). 100 m isobath is shown.

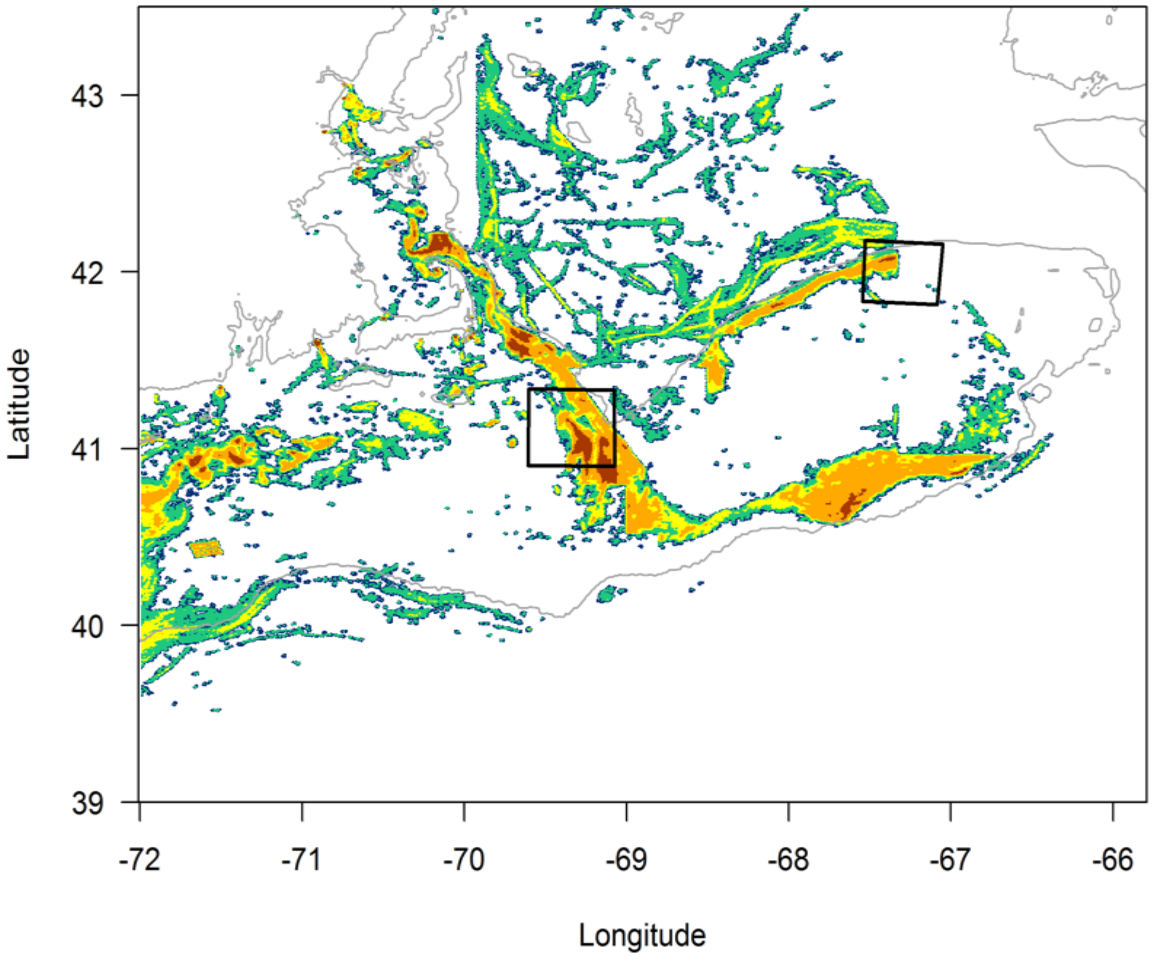


Figure 5.1.3. Predominant habitat type for Georges Bank and consensus spawning areas. Data from Harris and Stokesbury (2010). Prepared with aid from NEFMC staff. 100 m isobath is shown.

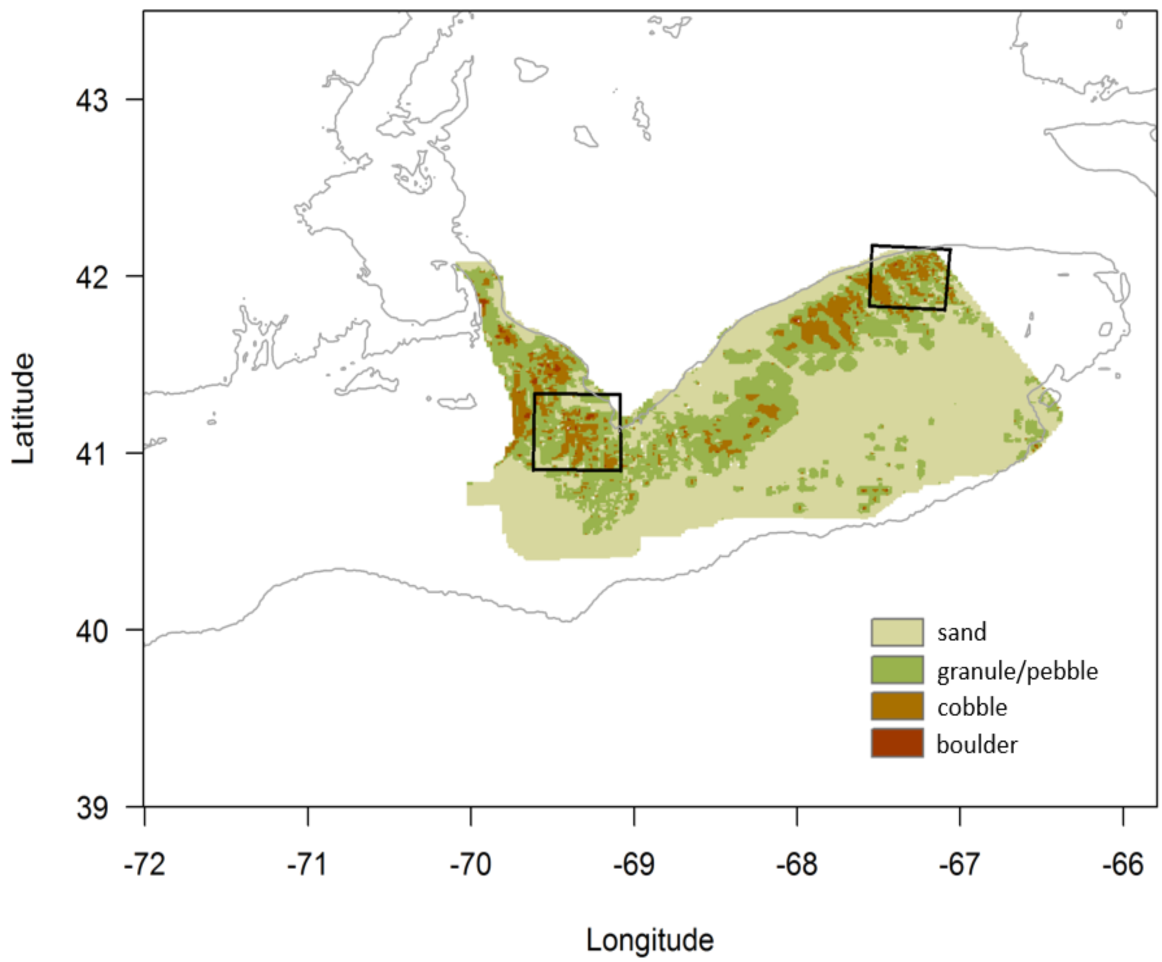


Figure 5.1.4. Spatial extent of surf clam/ocean quahog fishery as inferred from VMS data where vessels are moving at a speed of less than 4 knots (2015-2016). Data from Northeast Ocean Data Portal; https://www.northeastoceandata.org/). Thick black boxes enclose consensus herring spawning areas (from Figure 3.5). 100 m isobath is shown.

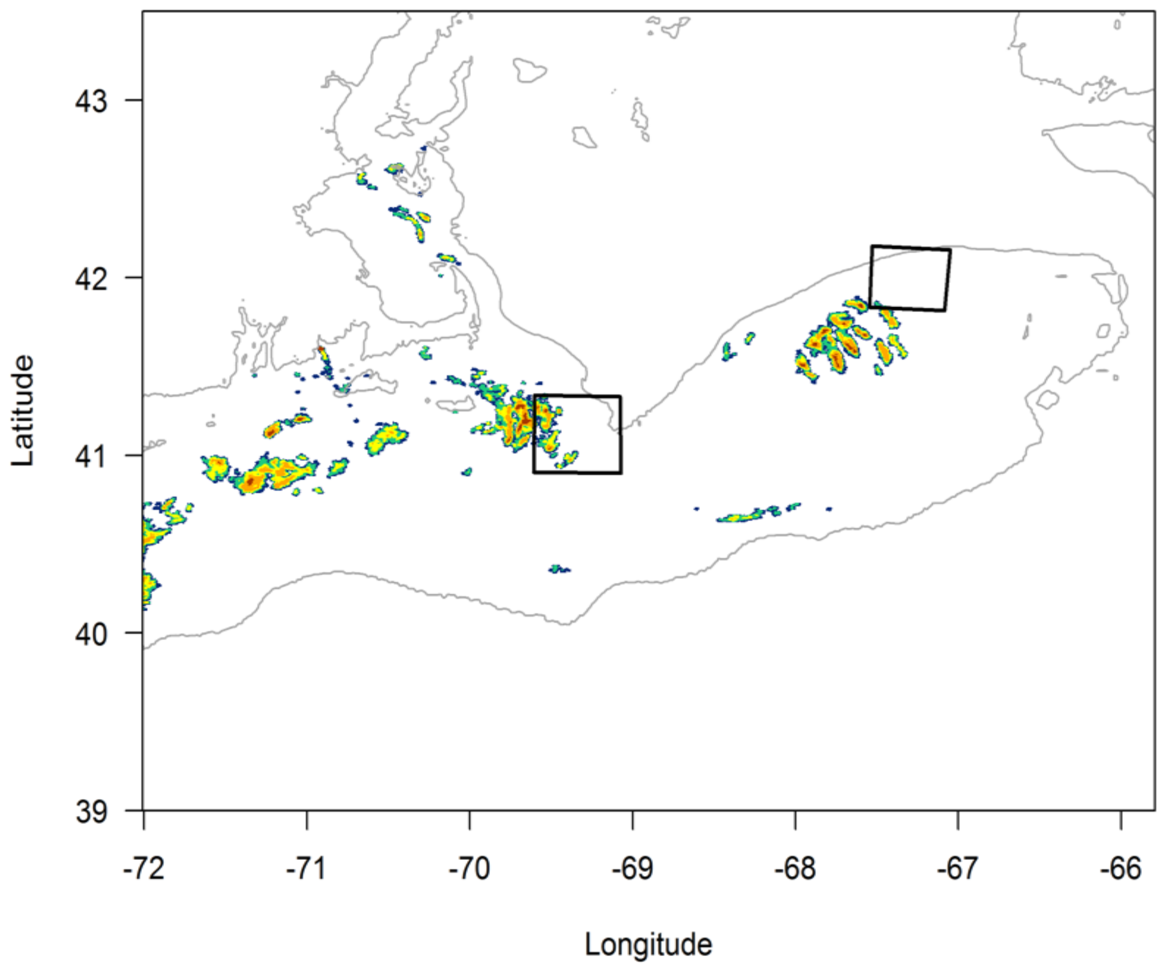
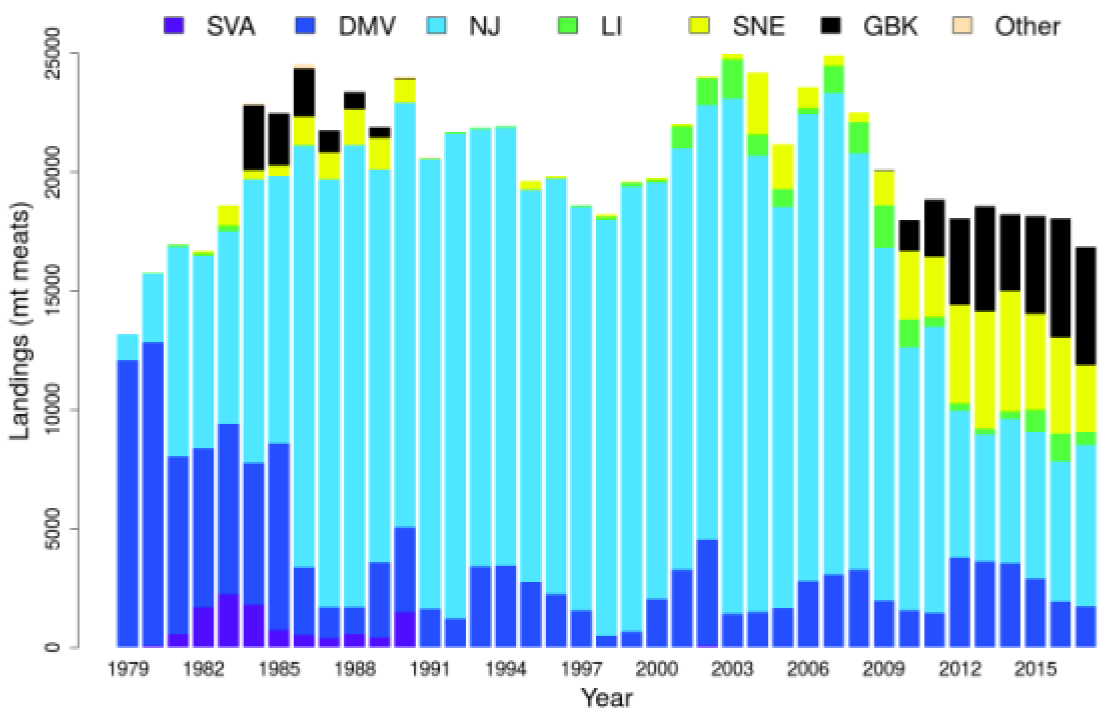


Figure 5.1.5. Average Surf clam landings from the US EEZ during 1979-2016, and preliminary 2017.



Source: Dan Hennen Pers. Comm., NEFSC 2018, as cited in MAFMC (2018a).

5.2. Potential Climate Threats

The Gulf of Maine is warming at a rate faster than 99% of the world's oceans (Pershing et al. 2015). This has had myriad effects on species distributions (Pinsky et al. 2013) and predator-prey interactions (Record et al. 2019) in the northeast. While many species may be acutely affected by warming water (e.g., Atlantic cod, which appear to show temperature-dependent increases in mortality; Pershing et al. 2015), other species may be less affected owing mostly to their increased mobility. Herring may be one species that may be somewhat buffered by its ability to shift distributions away from warming water. In their climate vulnerability assessment for northeast fish stocks, Hare et al. (2016) scored herring as being highly exposed to climate change but low in terms of their overall biological sensitivity to this change because of their ability to move. Predating this, Murowski (1993) found that with ocean warming, Atlantic herring will likely occur northward of their current distribution.

While herring show potential for distributional shifts which could shield them from the effects of warming, they do demonstrate strong natal homing for spawning (McQuinn 1997). This could be problematic for recruitment success and larval growth with warming waters and increasing ocean acidification (Leo et al. 2018, Nash and Dickey-Collas 2005). Hufnagl and Peck (2011) showed that using more northern spawning ground or delaying timing of fall spawning may not be as favorable for larval growth and survival due to the limitations of daylength and possible mis-match with prey abundances. Spawning site fidelity may also mean that certain spawning sites are abandoned altogether if conditions become too inhospitable. Sherwood et al. (2017) conducted an acoustic survey of Atlantic herring throughout the Maine coast from 2012 to 2016. They found that in warm (heatwave; Pershing et al. 2019) years, herring appeared to be overabundant in inshore Maine waters (Figure 5.2.1). That is, the entire spawning stock for the northeast stock complex appeared to use Maine coastal waters as a thermal refuge during the spawning season (August – October). While adults may have avoided the worst of warming effects, spawning may have been strongly affected in areas too warm to occupy.

Sherwood et al. (2017) also found that spawning appears to be less active in the easternmost region of Maine compared to historical records (see Figure 5.2.2). This agrees with a recent study by Record et al. (2019) who showed that *Calanus finmarchicus*, a preferred copepod prey for herring, has decreased in this region and also resulted in the westward shift of right whales which also prey on *C. finmarchicus*. Thus, climate change may also affect herring through changes to the food web and their prey. This is a particularly salient point since *C. finmarchicus* are predicted to be absent from the Gulf of Maine by 2050 as they are predominantly a north-temperate, sub-arctic species (Reygondeau and Beaugrand 2011). There are no substitutes for this lipid-rich prey in the Gulf of Maine.

Figure 5.2.1. Relationship between Gulf of Maine sea surface temperature (SST) anomaly and fraction of total spawning stock biomass that was observed (acoustically) in Area 1A inshore (< 90m) between 2012 and 2016. Proportions based on acoustic biomass from Sherwood et al. (2017) in relation to SSB from latest herring stock assessment (NEFSC 2018).

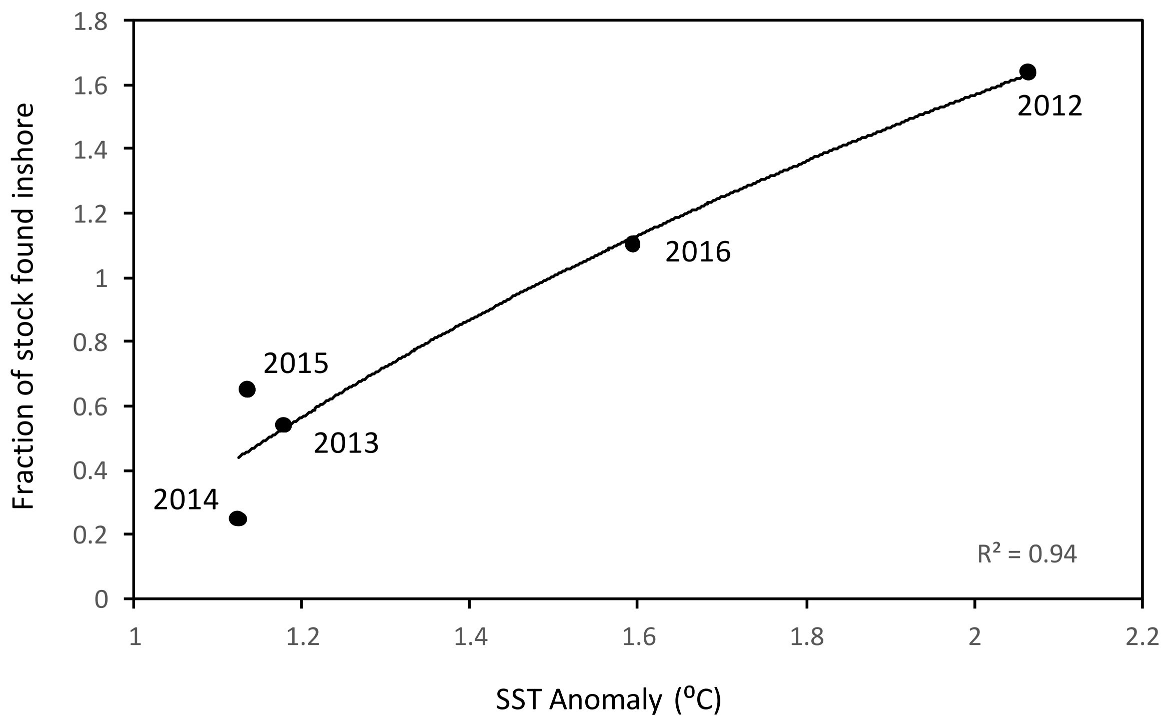
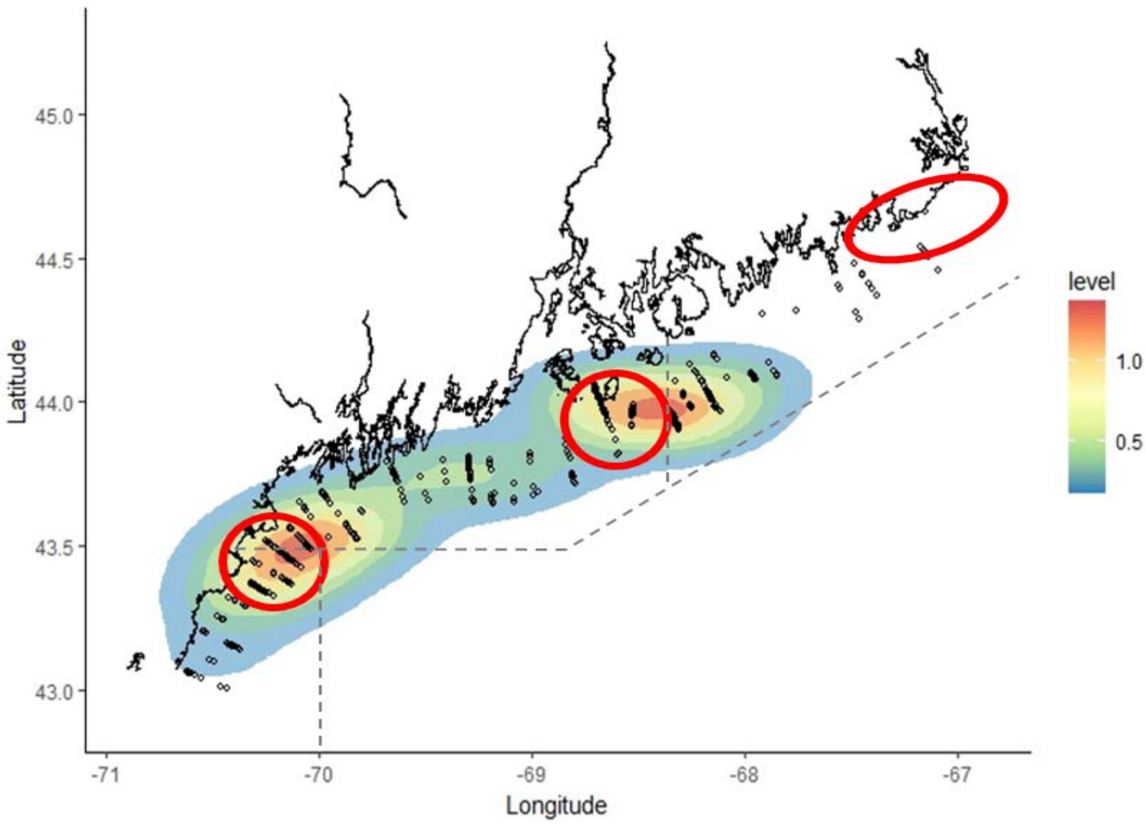


Figure 5.2.2. Kernel densities of spawning school distribution determined from acoustic survey conducted between 2012 and 2016 (Sherwood et al. 2017). Red ellipses are historical egg deposition areas (see Figure 3.2). Note that very little spawning activity was observed in eastern area.



5.3. Potential Threats from Predators

Herring are the preferred prey for a large number of predators including numerous groundfish, sharks, tuna, seabirds and whales (see NEFMC 2003 for a comprehensive review of "The role of Atlantic herring in the northwest Atlantic ecosystem"). The Northeast Fisheries Science Center's food habits database is one the most complete sources of information for quantifying the impact of predators on herring (Link and Almeida 2000). A list of predators from the database known to feed on herring in the northeast is shown in Table 5.3.1. Within these species, there exists some region- and sex-specific differences in herring predation as indicated. What is most relevant for this review is that the trend in predation pressure index (PPI; measures total predation by the listed species on herring) has varied mostly without trend near the time series mean (Deroba 2018). Thus, while individual predator species, and their impact on herring, may have fluctuated in abundance over time, the overall predation pressure appears to remain constant and therefore may not be a variable threat to spawning herring. It should be noted that this index only tracks predation by species captured in the food habits database (i.e., from the bottom trawl surveys).

What the food habits database does not capture accurately is the impact that certain predators may have on egg and larval stages of herring. Larvae may be subject to a range of different predators including other herring (e.g., Fuiman 1989), mackerel (Pepin et al. 1987) and even gelatinous zooplankton (Möller 1984); competition with these may also cause a decline in recruitment (Lynam et al. 2005). A number of different predators feed on herring eggs including haddock (*Melanogrammus aeglefinus*), Atlantic cod (*Gadus morhua*), pollock (*Pollachius virens*), winter flounder (*Pseudopleuronectes americanus*), yellowtail flounder (*Pleuronectes ferruginea*) and longhorn sculpin (*Myoxocephalus octodecimspinosus*). Of these, one species in particular may be strongly related to large changes in herring reproductive success in the northeast – haddock, which within the food habits database were the species most commonly observed to contain eggs in their stomachs (Figure 5.3.1).

Haddock have undergone major changes in abundance since the 1960's and herring recruitment seems to be highest when haddock are at low abundance (Figure 5.3.2). Indeed, Richardson et al. (2011) linked declines in the herring population with egg predation by haddock in the northeast. Bax (1998) also noted that haddock and cod predation on eggs can account for 40-60% egg mortality in Norway. More recently, haddock are at record high levels on Georges Bank (278% of target biomass; NEFSC 2017) and herring recruitment is at all-time lows (Figure 5.3.2). Spatially, haddock occupy the same areas as spawning herring (and eggs) and this has been particularly evident in the most recent decade (Figure 5.3.3). Interestingly, haddock seem to overlap with herring spawning at fine scales mostly in the eastern area and less so in the western spawning area. This is somewhat at odds with the larval data that show that larval herring are most abundant in the eastern area most recently (Figure 2.1.2) suggesting that egg predation is lower here. A potential reason for this is that the trawl survey may not necessarily capture haddock distribution at the exact time when herring eggs are on the bottom. It is also of note that very few herring eggs were observed in the diet of fish in the food habits database (Section 2.5). This could be because of a mismatch between sampling for fish and spawning, but also because eggs are likely to be highly digested and unidentifiable by the time stomachs are dissected. A more directed study of haddock predation on herring eggs would be warranted.

Figure 5.3.1. Number of stomachs by species observed to contain Clupeid or *Clupea harengus* (herring) eggs. Data from NEFSC food habits database.

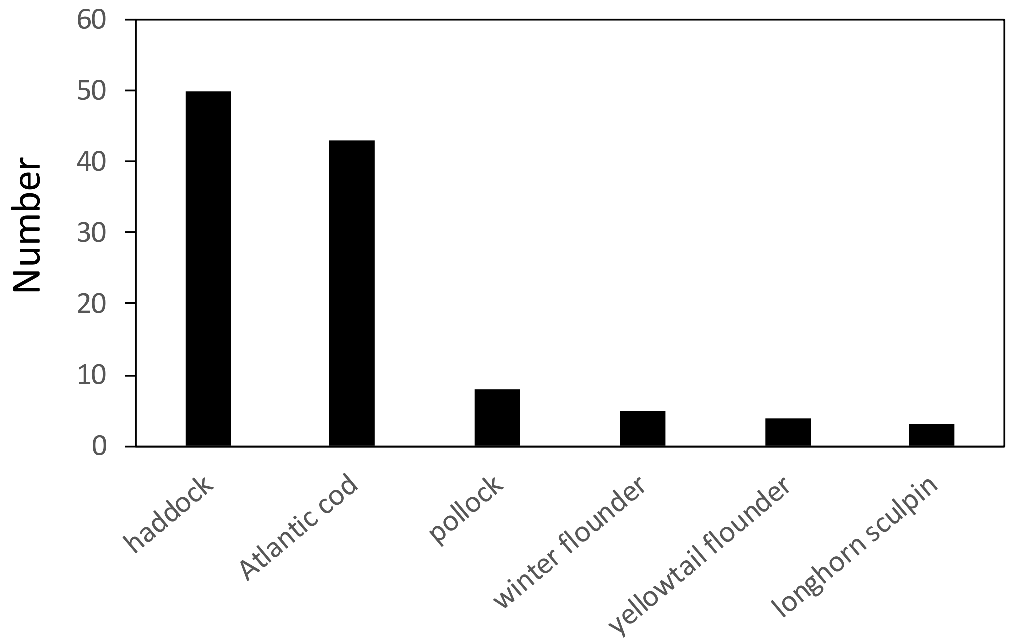


Table 5.3.1. List of predators on Atlantic herring that had at least 10 stomachs containing herring and positive occurrences of herring in at least 0.1% of stomachs, combined among all years and seasons from the food habits database (from Deroba 2018).

PREDATOR	Region (R) or Sex (S) distinctions
ATLANTIC_COD	R – Georges Bank, Gulf of Maine
ATLANTIC_HALIBUT	NA
BLUEFISH	NA
GOOSEFISH	R – North, South
HADDOCK	R – Georges Bank, Gulf of Maine
POLLOCK	NA
RED_HAKE	R – North, South
SEA_RAVEN	NA
SILVER_HAKE	R – North, South
SPINY_DOGFISH	S – Male, Female, Unidentified
STRIPED_BASS	NA
SUMMER_FLOUNDER	NA
THORNY_SKATE	NA
WHITE_HAKE	NA
WINTER_SKATE	NA

Figure 5.3.2. Time series of haddock spawning stock biomass (NEFSC 2017) and herring recruitment (NEFSC 2018) from the 1960s to the present.

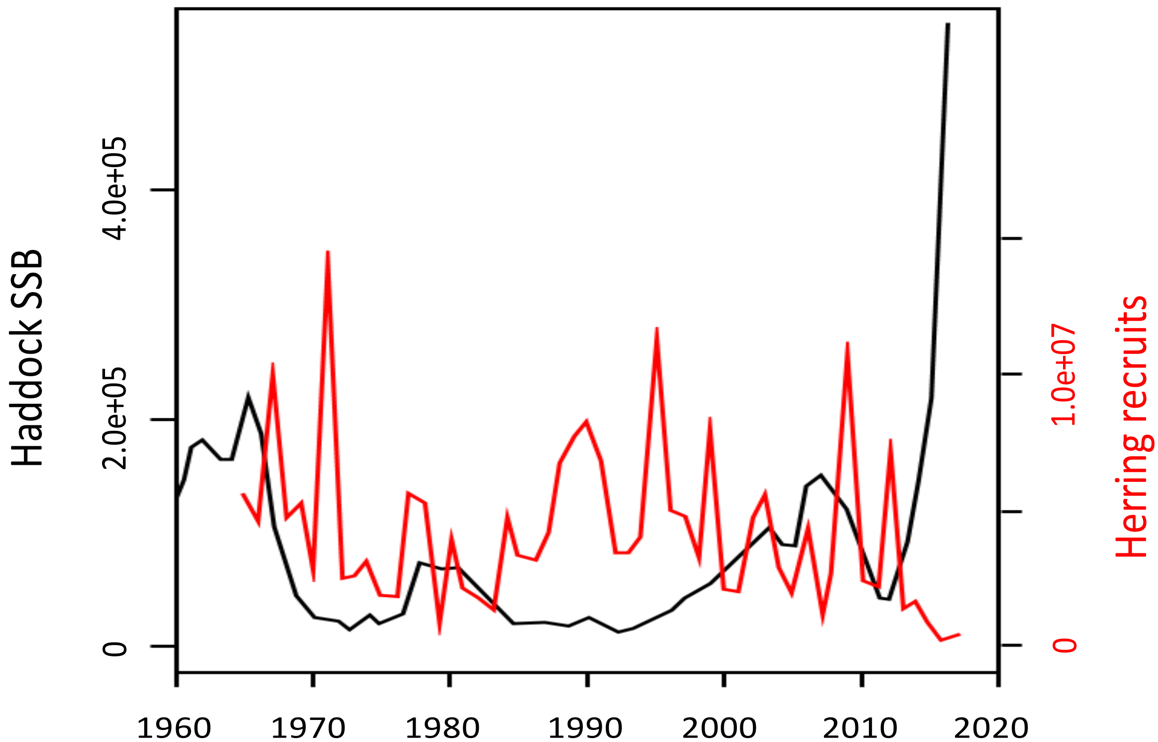
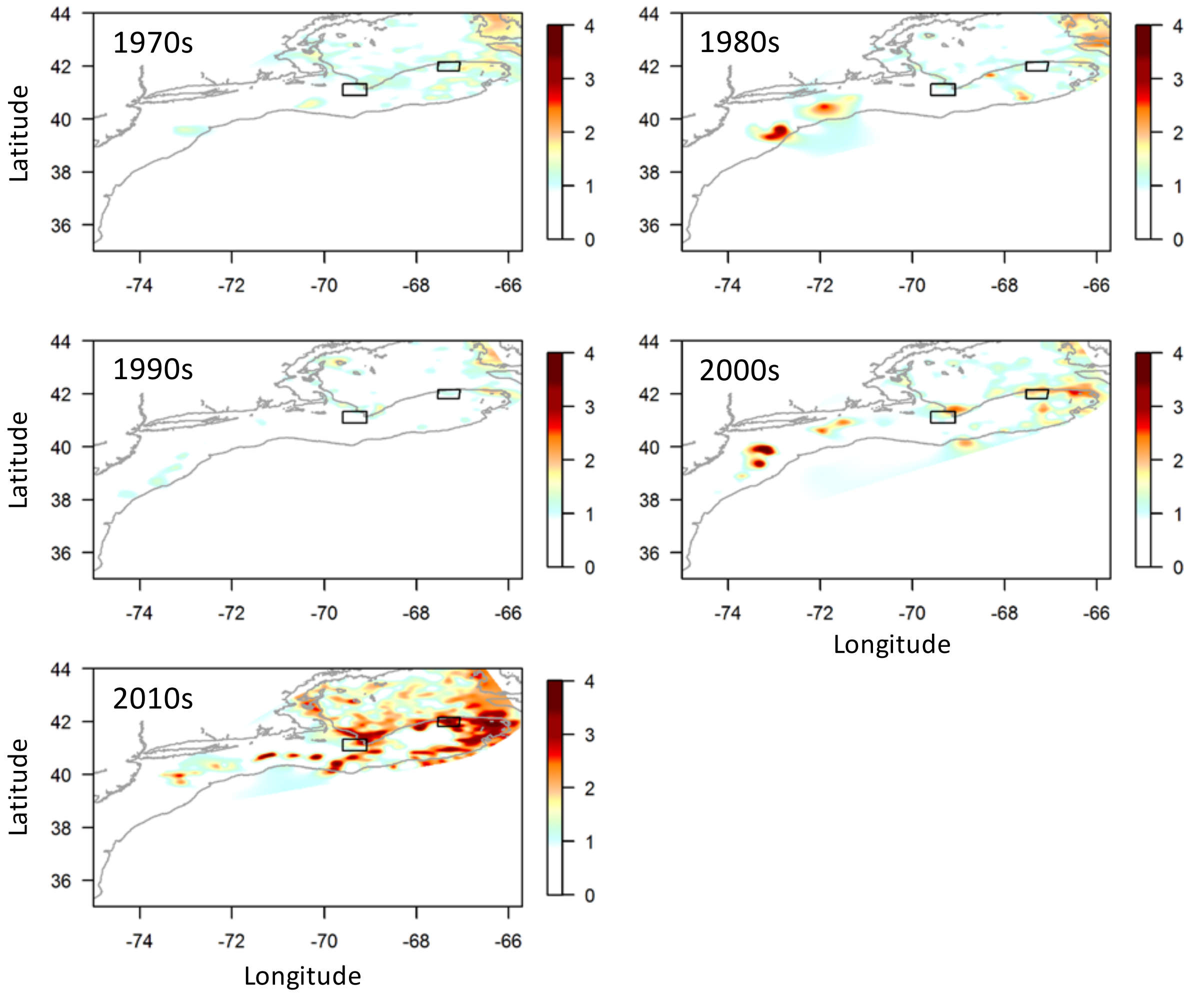


Figure 5.3.3. Spatial distribution of haddock as log abundance per tow by decade. Data from NEFSC fall bottom trawl survey. Consensus herring spawning areas (boxes) are shown. 100 m isobath is shown.



6. Research Recommendations

The following research recommendations were developed by the Herring PDT during review of this draft report. The Herring PDT includes all the members of the ASMFC Atlantic Herring Technical Committee. These recommendations are provided as input on future research in the region on this topic.

Overall PDT input: Overall, the easiest and most cost-effective approach is likely enhancing portside sampling efforts, followed by potentially enhancing collection of spawning data by at-sea observers and ASM. A fishery independent survey would be costly, and would take five or so years to complete; however, it would provide data from the entire area and season, not just where and when the fishery operates. Before a new survey is designed and implemented to support this subject, the goal of the survey should be defined so it is clear what benefits that survey would have over existing data collection methods. Finally, it is important to note that the herring stock is currently at low abundance; therefore, research conducted now may not be representative of spawning behavior when herring biomass is larger.

1. Enhance portside sampling efforts:

There is currently portside sampling occurring throughout the fishery, including herring trips from Georges Bank. However, the total number of trips from that region is much lower than the GOM for a variety of reasons, e.g. seasonality of the fishery, increased costs to fish offshore, sampling efforts are more concentrated in Maine and Massachusetts, etc. Therefore, while the current system is capable of sampling trips from GB, the current level is insufficient to track spawning activity on GB. The current portside sampling provides some information on seasonality of spawning on Georges Bank, but given how much this can change annually (approx. 5-6 weeks), there is a need for dedicated processing of portside samples over multiple years. An enhanced program could be designed to specifically target trips from GB during the spawning season. More resources could be used to increase the number of future samples, targeting trips from GB as described above, but it should be noted that the current level of sampling of GB trips would not be adequate to monitor a real-time spawning measure similar to the one that is in place for the GOM. If there are any samples that have not been processed those should be prioritized first, and then efforts to increase the number of samples from trips on GB.

2. Develop a new spawning survey of Atlantic herring on GB:

Fishery independent sampling of herring and spawning condition on GB would be useful, but may be cost prohibitive, i.e. $200,000 a year or more. Specific stations and seasons would need to be identified in advance, and could be sampled using fishing gear, survey gear, and/or acoustics. The overall design could be similar to the acoustic survey previously conducted by NEFSC on GB. The survey should probably span about five years to capture annual variability, with multiple stations targeting herring during spawning season across the area including places the fishery does not operate. While somewhat dated and limited, there is previous research and published literature on this topic that will hopefully be part of the NEFMC discussion document. Due to the relatively large expense of this approach, it may be prudent to fully evaluate past literature and research first, and then identify any knowledge gaps specific to management needs before a large spawning survey is funded.

3. Examine the feasibility of collecting spawning data at-sea by observers and ASMs, and on land by portside samplers:

The Fisheries Sampling Branch (FSB) could examine the possibility of collecting spawning data at sea on observed trips (NEFOP and ASM) if conditions allow. If it is feasible to collect these data at sea then new data fields could potentially be added or even a separate data collection sheet (e.g. total weight of fish, gonad weight, and spawning condition). Information like this could provide complementary spawning data, at a superior spatial scale (tow by tow vs averaging location in stat area), to what is being collected through portside sampling efforts. It is understood that adding fields would likely slow down the work of observers, and may require some post processing of fish samples taken at sea. It could cost more to have portside samplers do this work dockside, so it may even be possible for portside samplers to send NEFOP samples that could be worked up by NMFS at a later time instead.

The federal Atlantic herring fishery (midwater trawl) portside sampling program is scheduled to begin in April 2020. The collection of spawning data is not currently part of that sample design and was not included in draft regulations. Therefore, there would be additional costs and details that would need to be considered. The federal portside program may be a potential source of spawning data from landed catch in the future, but many details would need to be considered first.

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