Sea Grant
NEW YORK

Stony Brook University
IDC Building, Suite 221 • 500 Innovation Road
Stony Brook, NY 11794-5001
nyseagrant@stonybrook.edu • (631) 632-6905
nyseagrant.org

February 23, 2026

Dr. Yong Chen
School of Marine and Atmospheric Sciences
Stony Brook University
Stony Brook, NY 11794

RE: Completion Report (CR) needed for R/FBM-41-NYCT.

Dear Yong:

Our records indicate that your Sea Grant project R/FBM-41-NYCT, entitled Evaluating Changes in Suitable Habitat and Biogeography of Cold- and Warm Adaptive Fish Species in a Changing Long Island Sound to Inform Ecosystem-Based Management, ended on 2/28/2026 and should now be completed. Per Sea Grant requirements, the lead principal investigator must submit a completion report detailing the project results. Documenting the results and impacts of Sea Grant-funded projects is important for the New York and National Sea Grant Programs.

Please follow the attached NYSG Completion Report Instructions & Required Format sheet when preparing your report and submit it no later than **March 23rd** as an e-mail attachment (PDF or MS Word; full-sized graphs/photos should be sent as separate e-mail attachments) to me at e-mail: lane.smith@stonybrook.edu.

Note that project reports are considered internal documents. They will not be distributed to the public in their entirety unless permission is first obtained from the project's lead PI. Thus, you might receive such an inquiry from one of our staff or extension specialists. However, the "Scientific Abstract" and "Stakeholder Summary" sections may be used verbatim or shortened to inform the media, agencies, legislators, and the public about your project. By submitting your report, you acknowledge the use of these sections of the report. Every effort will be made to give the project lead PI the opportunity to review any material we produce before release. We consider any information submitted in reports to us to be preliminary until published in the peer-reviewed literature. The project PI is encouraged to inform NYSG whenever there is a publication resulting from this project is available.

If you have questions or anticipate a problem in meeting this deadline, please contact me immediately (voice: 631-632-9780). Thank you for your attention to this matter. We look forward to the final synthesis of your results and their impacts.

Sincerely,

Lane Smith
Research Program Coordinator
Attachment: NYSG Completion Report Instructions & Required Format Sheet

NYSG Completion Report Instructions & Required Format

Please include the following information for your project. The text of this report should be at least 5-8 pages and be composed for an audience of your peers. Other formats, or reports with incomplete sections, will not be accepted. The expectation is that information or material will be provided under each section.

REPORT WRITTEN BY: Claire Ober, Stephanie Arsenault, Sarah Praisner, and Yong Chen

DATE:

A. PROJECT NUMBER AND TITLE: R/FBM-41-NYCT - Evaluating changes in suitable habitat and biogeography of cold- and warm adaptive fish species in a changing Long Island Sound to inform ecosystem-based management

B. PROJECT PERSONNEL:

Table 1: Senior Personnel (list the PI, Co-PI(s), and AI(s), should match what was in the proposal (90-2 form).

Name	Role (PI, CO-PI, or AI)	Institution	Note
Yong Chen	PI	Stony Brook University	
Kurt Gottschall	Co-PI	Division of Marine Fisheries, Connecticut Department of Energy and Environmental Protection	
Kim McKown	Co-PI	New York State Department of Environmental Conservation	
John Maniscalco	Co-PI	Division of Marine Resources, New York State Department of Environmental Conservation	

Table 2: Postdocs

Name	Institution	Note

Table 3: Research Support Specialists

Name	Institution	Note

Table 4: Sea Grant Scholar Fellows and Research Assistants

Student Name	New or Continuing?*	Degree Program	Type (choose from list)	Graduation Date	Anticipated or Confirmed?+
Robyn Linner	Continuing	PhD	GRA	05/22/24	Confirmed
Claire Ober	Continuing	PhD	GRA	08/20/25	Confirmed
Stephanie Arsenault	Continuing	PhD	GRA	08/20/26	Anticipated
Sarah Praisner	Continuing	PhD	GRA	05/22/27	Anticipated

Table 5: Student Volunteers

Student Name	New or Continuing?*	Degree Program	Graduation Date	Anticipated or Confirmed?+

Table 6: Public Volunteers

Volunteer Name	Estimated Hours

Student notes or details:

Robyn Linner and Claire Ober contributed to the project planning, literature review, model development, and model running, paper writing, and stakeholder engagement.

Stephanie Arsenault and Sarah Praisner contributed to the literature review, model running, paper writing, and stakeholder engagement.

Krystina Braid, who is a PhD student, was initially involved in this project (but not paid from this grant), responsible for running models for black sea bass. She later took leave and was not involved in the later part of the research.

All students participated in and presented at the 2025 workshop. Claire, Stephanie, and Sarah contributed to writing the final report.

C. PROJECT RESULTS:

C1. Meeting the Objectives:

Objective 1: Describe and quantify changes in fish biogeography over time

Methods

Data Compilation and Validation

Survey, environmental, and climate projection data were compiled in a consistent format to address the project objectives (Table 1). We evaluated the observed and modeled environmental data and compiled the data so that their spatiotemporal scales were consistent with the survey data. For the modeled environmental data (FVCOM), we used the same approach as Li et al. (2017) to evaluate their quality by comparing modeled data and observed data collected in the surveys. Four quantitative metrics were used including correlation coefficient, average relative error, average absolute error, and root mean squared error.

Table 1. Fisheries independent, environmental, and climate data evaluated for this project.

Dataset	Years	Details	Data
CT DEEP LISTS	1984-2019	New London to Greenwich, CT; 5-46 m depth;14 m high rise otter trawl	Count, length, and weight of all species; temperature, salinity, and depth
FVCOM	1978-2019	Marine waters off New England and mid-Atlantic	Bottom temperature, bottom salinity, and depth
USGS	1962-2019	Atlantic continental margin of the USA, including LIS	Sediment grain size
CMIP6	2015-2054	Global ocean climate projection model; later cropped to LIS for downscaling	Climate projections; SSP5-8.5 scenario; anomalies calculated relative to historical baseline 1992–2014

Spatial Indicators

Spatial indicators were calculated for each study species using compiled survey data to characterize temporal changes in spatial distributions. Indicators were calculated annually and separately for spring (April-June) and fall (September-October) survey seasons. The spatial indicators developed included center of gravity (CG), inertia, positive area, and Camargo's evenness index. Center of gravity represents the mean geographic location of the surveyed population, weighted by abundance (Woillez et al. 2007, 2009). Inertia describes the spatial dispersion of the population around its center of gravity and can be expressed as the mean squared distance of individuals from the CG, providing a measure of spatial spread (Woillez et al. 2007, 2009). Positive area represents the total area (km²) occupied by non-zero abundances and is calculated as the sum of areas of influence associated with stations where the species was observed (Woillez et al. 2007, 2009). Evenness was calculated using a modified version of Camargo's evenness index (Camargo 1995; Payne et al. 2005; Chang et al. 2024). This adaptation evaluates the consistency of non-zero catches of a single species across sampling stations. Values range from zero (highly aggregated or patchy distributions) to one (evenly distributed). Spatial indicators, except for Camargo's evenness, were calculated using the RGeoStats package version 14.0.10 (Renard et al. 2014) in R version 4.4.2 (R Core Team 2024).

To account for variation in survey station spacing and sampling density, areas of influence were used as weighting factors in the calculation of all spatial indicators. Areas of influence were defined using Voronoi tessellation, in which each sampling station is assigned a polygon representing the area of space closer to that station than to any other (Woillez et al. 2007, 2009). This approach provides a non-subjective method for weighting observations and is appropriate for stratified random survey designs commonly used in fisheries monitoring (Woillez et al. 2009; Adams 2017). Weighting spatial indicators by areas of influence reduces bias associated with uneven sampling effort and ensures that stations represent their proportional spatial contribution to the survey domain.

The resulting spatial indicators were used to evaluate (1) whether species distributions shifted over time, (2) whether spatial distributions expanded or contracted, and (3) how spatial structure and aggregation varied among species and seasons. To facilitate interpretation of spatial indicator results, they were fitted with locally estimated scatterplot smoothing (LOESS) regressions. In addition to spatial indicators, annual spring and fall abundance indices were obtained from CT DEEP. Abundance indices were calculated as geometric mean catch per tow, with catch data log-transformed (loge) prior to averaging to reduce the influence of highly skewed catch distributions. Means were computed on the log scale and back-transformed to produce geometric means.

Results

Data Compilation and Validation

Prior to the spatial indicator analysis or development of HSI models, we explored the available CT DEEP LISTS length data to determine whether all catch data or only length-specific data should be used. For each life stage, there are generally different associations with habitat and not considering this could impact spatial indicator and habitat suitability results.

For each finfish species, to evaluate the availability of length data for each season and year, we compared the number of survey stations where non-zero catch occurred to the number of survey stations where length data was available for ≥90% of the individuals and calculated the percent of stations where length data was available. Then, we determined the percent of non-zero catch stations that cannot be used if length-specific data was used for each season

(Table 2). Many species, including both warm- and cold-adapted, had length data taken sporadically over the time series. Therefore, for these species, if length specific data was used instead of all catch data, more than 30% of sampling locations in the spring and fall would be omitted (Table 2). In contrast, black sea bass, summer flounder, scup, and winter flounder had consistent length data available over the time series and analyses separated by length was possible (Table 2). However, to be consistent across all species (including the crustaceans), we opted to use all catch data and not length-specific data.

A cross-validation of FVCOM and water quality observations for bottom temperature and bottom salinity was conducted. The selected metrics for FVCOM-LISS skill performance revealed a high correlation and small overall differences between modeled and observed data (Table 3) Therefore, FVCOM data was used for HSI model development.

Table 2. Percent of data non-zero catch stations per species omitted if length-specific data is used for each season.

Species	Thermal adaptation	Spring (% data)	Fall (% data)
Black Sea Bass	Warm	3.35	1.96
Butterfish	Warm	31.97	33.64
Northern Sea Robin	Warm	53.32	43.56
Striped Sea Robin	Warm	46.28	53.06
Summer Flounder	Warm	0.39	0.52
Scup	Warm	0.31	0.18
Red Hake	Cold	82.55	75.42
Spotted Hake	Cold	67.21	62.72
Silver Hake	Cold	80.87	75.39
Winter Flounder	Cold	0.08	0.46
Fourspot Flounder	Cold	53.22	58.94
Windowpane Flounder	Cold	41.93	44.82
Little Skate	Cold	89.33	88.09

Table 3. Summary of quantitative metrics for validation of bottom temperature and bottom salinity.

Variable	Season	Correlation coefficient	Average relative error	Average absolute error	Root mean square error
Temperature	Spring	0.96	1.19	1.43	1.9
Salinity	Spring	0.84	2.01	2.02	2.15
Temperature	Fall	0.87	0.35	0.72	0.91
Salinity	Fall	0.66	1.51	1.56	1.76

Spatial indicators for Warm-adapted Species

Across warm-adapted species, spatial indicator results revealed several consistent long-term patterns in both spring and fall. Most species exhibited an increasing abundance index and positive area through time, particularly from the 1990s onward, indicating both population growth and a broader spatial occupancy within the LIS. Increases in abundance indices and positive area were often more pronounced in the spring, where several species, such as black sea bass (Fig. 1), northern sea robin (Fig. 3), striped sea robin (Fig. 4), and summer flounder (Fig. 6), showed sharper post-2000 growth in abundance and spatial extent relative to the fall, which suggests seasonal differences in habitat use.

Center of gravity indicators showed a consistent temporal trend of the species population centers remaining in the center of the LIS, with the notable exception of northern sea robin (Fig. 3), which had stark seasonal differences in center of gravity changes. Inertia displayed moderate increases or were stable across most warm-adapted species, indicating

either an expanded or sustained use of spatial dispersion. Apart from striped sea robin in the fall, no warm-adapted species have shown strong long-term contraction, reinforcing the interpretation that warm-adapted species have maintained or expanded their spatial range within the LIS.

Evenness showed considerable decreases in spring and fall for black sea bass (Fig. 1), and less marked decreases for butterfish (Fig. 2) and northern sea robin (Fig. 3). Striped sea robin (Fig. 4), summer flounder (Fig. 5), and blue crab (Fig. 7) showed variations in evenness over time without a marked unidirectional pattern, while scup showed an increase in both spring and fall evenness (Fig. 6).

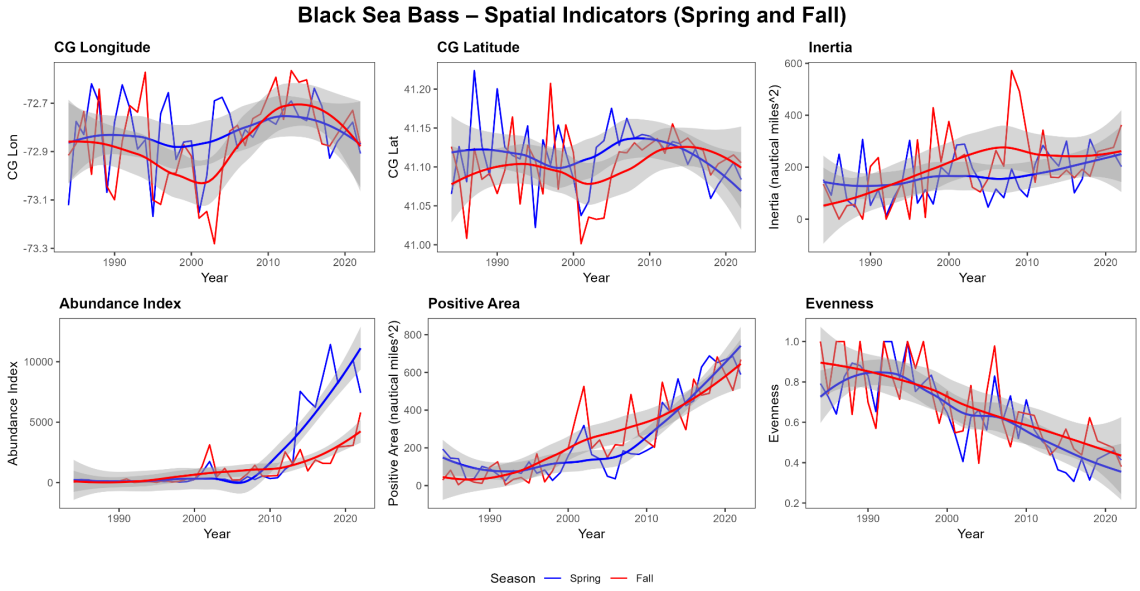


Fig. 1. Time series of spring (blue) and fall (red) spatial indicators for Black Sea Bass in the LIS from 1984-2022. Gray bands denoted 95% CI.

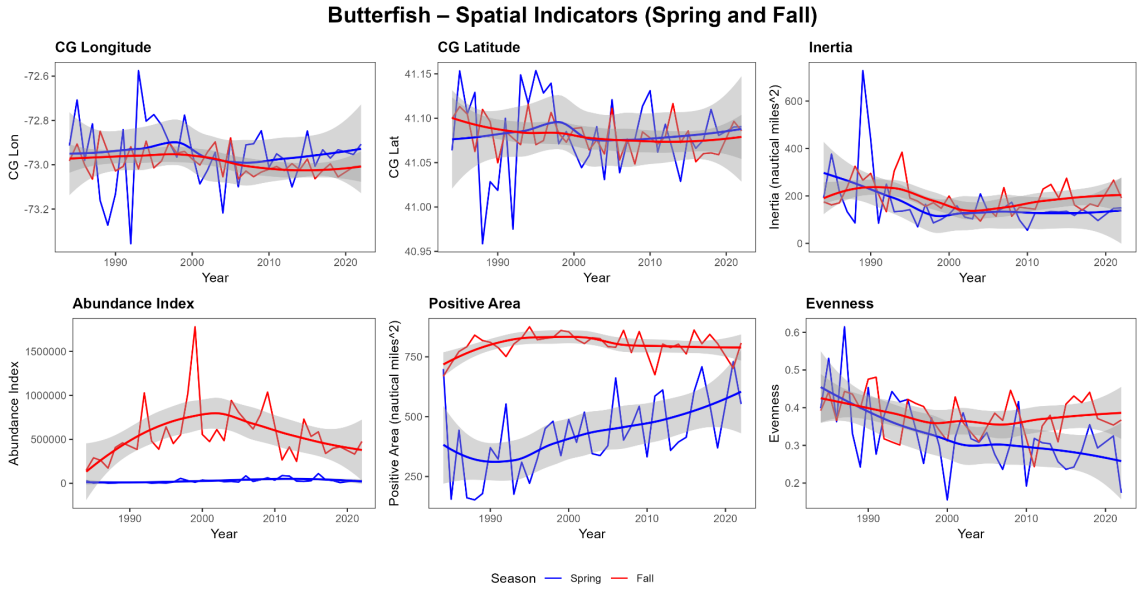


Fig. 2. Time series of spring (blue) and fall (red) spatial indicators for Butterfish in the LIS from 1984-2022. Gray bands denoted 95% CI.

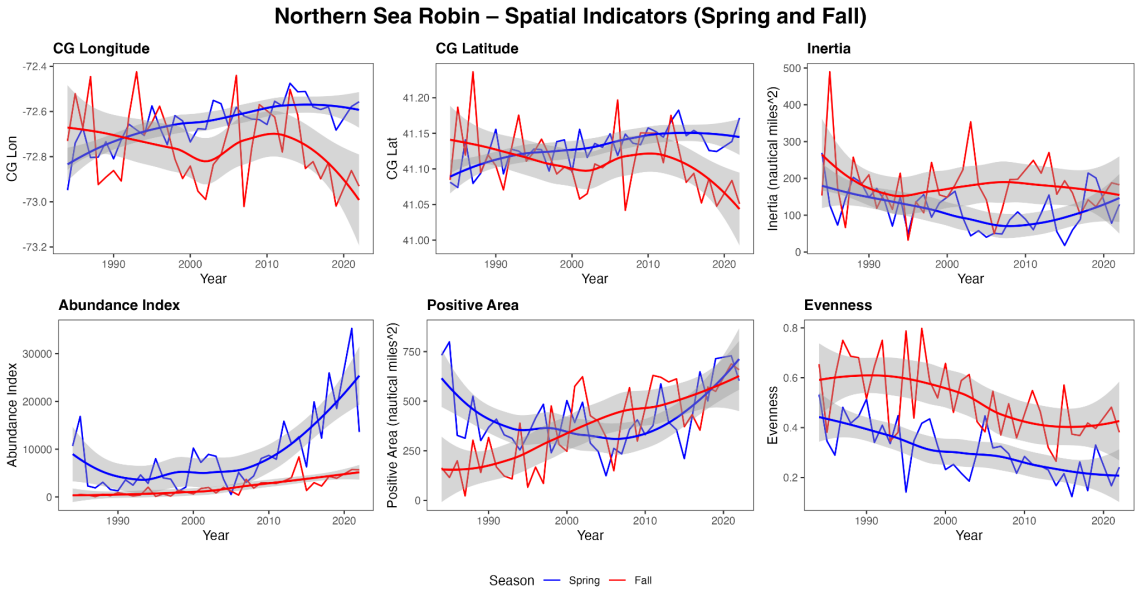


Fig. 3. Time series of spring (blue) and fall (red) spatial indicators for Northern Sea Robin in the LIS from 1984-2022. Gray bands denoted 95% CI.

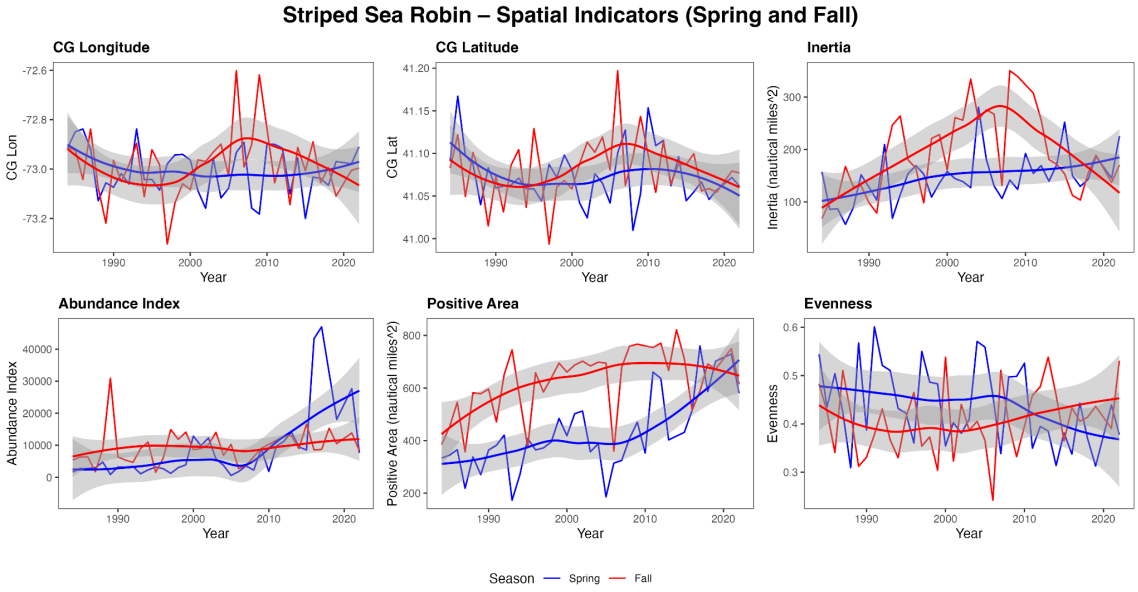


Fig. 4. Time series of spring (blue) and fall (red) spatial indicators for Striped Sea Robin in the LIS from 1984-2022. Gray bands denoted 95% CI.

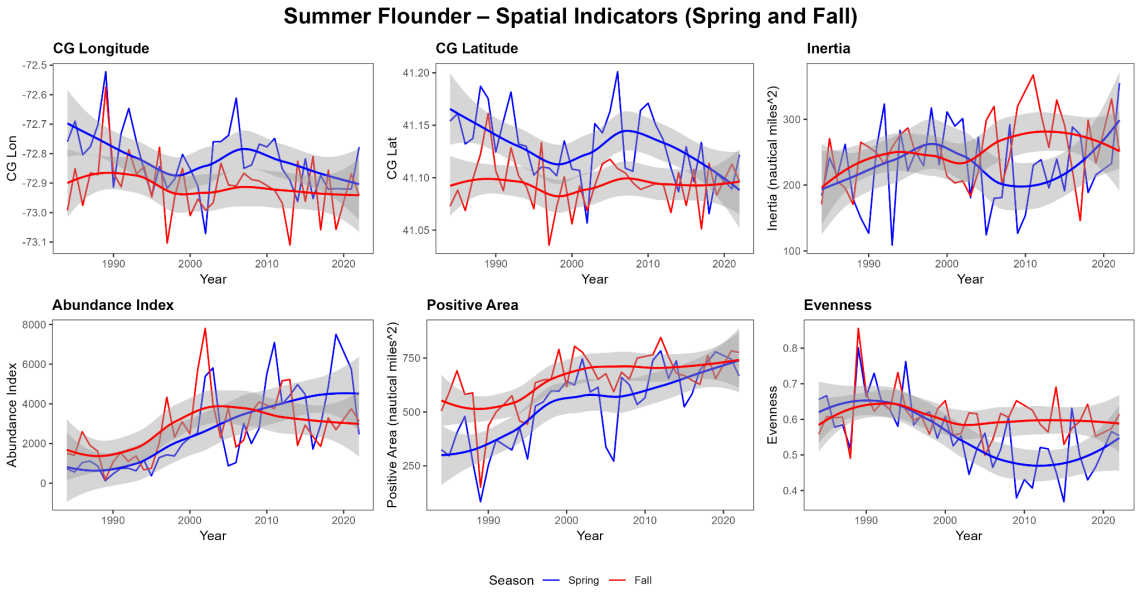


Fig. 5. Time series of spring (blue) and fall (red) spatial indicators for Summer Flounder in the LIS from 1984-2022. Gray bands denoted 95% CI.

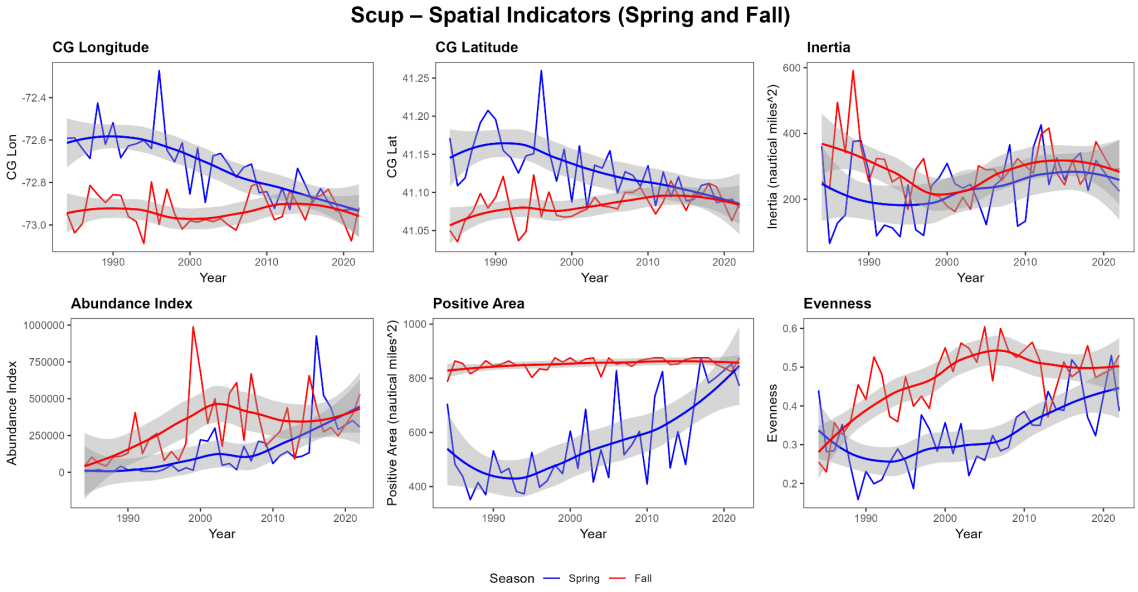


Fig. 6. Time series of spring (blue) and fall (red) spatial indicators for Scup in the LIS from 1984-2022. Gray bands denoted 95% CI.

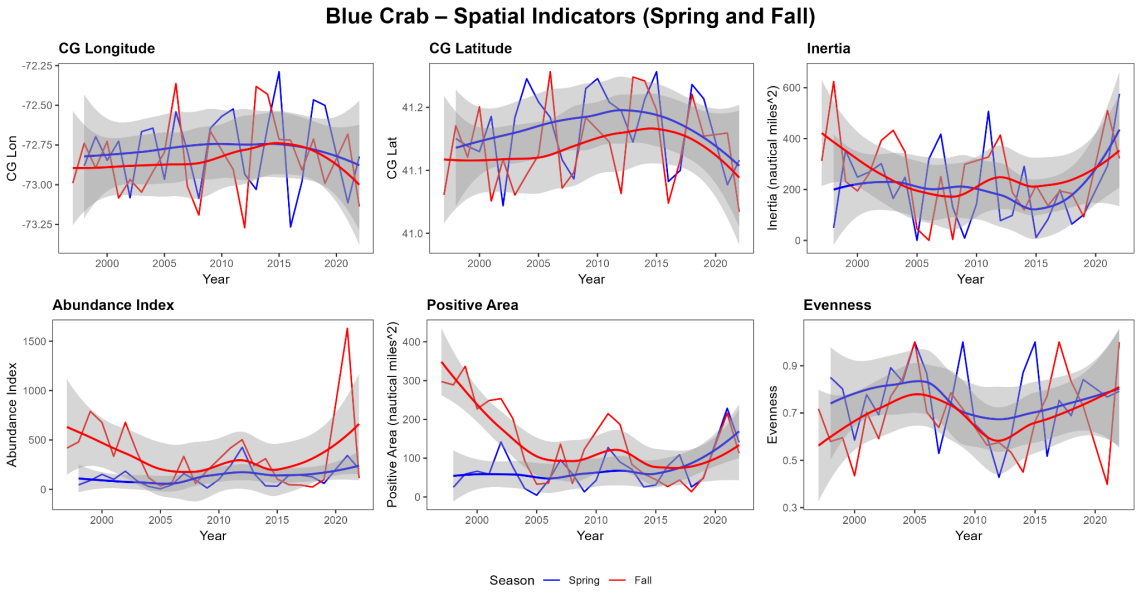


Fig. 7. Time series of spring (blue) and fall (red) spatial indicators for Blue Crab in the LIS from 1984-2022. Gray bands denoted 95% CI.

Spatial indicators for Cold-adapted Species

Most cold-adapted species showed a spatial contraction over the time series, and decreasing abundance (Figs. 8-15), although spotted hake showed increasing positive area in both spring and fall, and a slight increase in abundance (Fig. 9). It is important to note that most of the cold-adapted species are virtually absent from the LIS in the fall, so abundance is near zero. The positive area showed a drastic decrease in both seasons for winter flounder, fourspot flounder, windowpane flounder, little skate, and American lobster (Figs. 11-15). For several species including American lobster (Fig. 15) and little skate (Fig. 14), positive area and abundance neared zero by the end of the time series in both seasons.

Inertia showed variable trends across species and seasons but generally decreased or remained nearly the same across cold-adapted species. Evenness increased in the fall for several species including winter flounder, fourspot flounder, and windowpane flounder (Figs. 11-13), potentially due to low abundance and therefore low but consistent catch across stations. Evenness increased in spring for American lobster as well (Fig. 15). In spring, a shift in center of gravity across species showed movement towards cooler waters. Spring center of gravity fluctuated with no clear trend for the hake and flounder species. Fall center of gravity showed a slight southwesterly shift for some of the hake and flounder species, but little skate showed northeasterly movement across both seasons, to generally cooler waters (Fig. 14). American lobster showed a southern movement across both seasons, although due to near-zero abundance this likely comes from very few stations (Fig. 15).

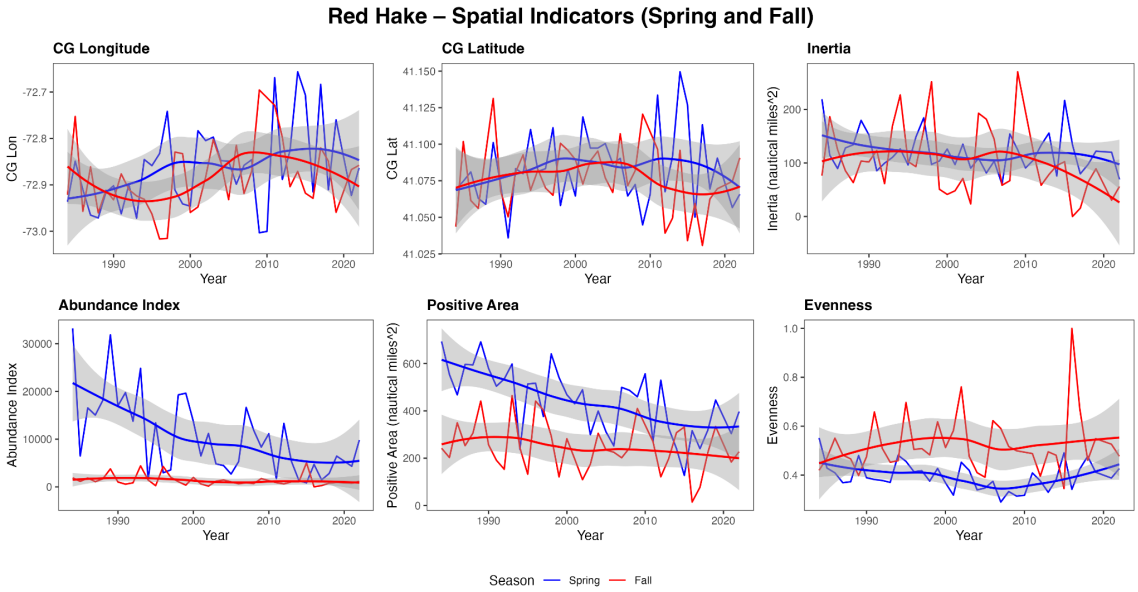


Fig. 8. Time series of spring (blue) and fall (red) spatial indicators for Red Hake in the LIS from 1984-2022. Gray bands denoted 95% CI.

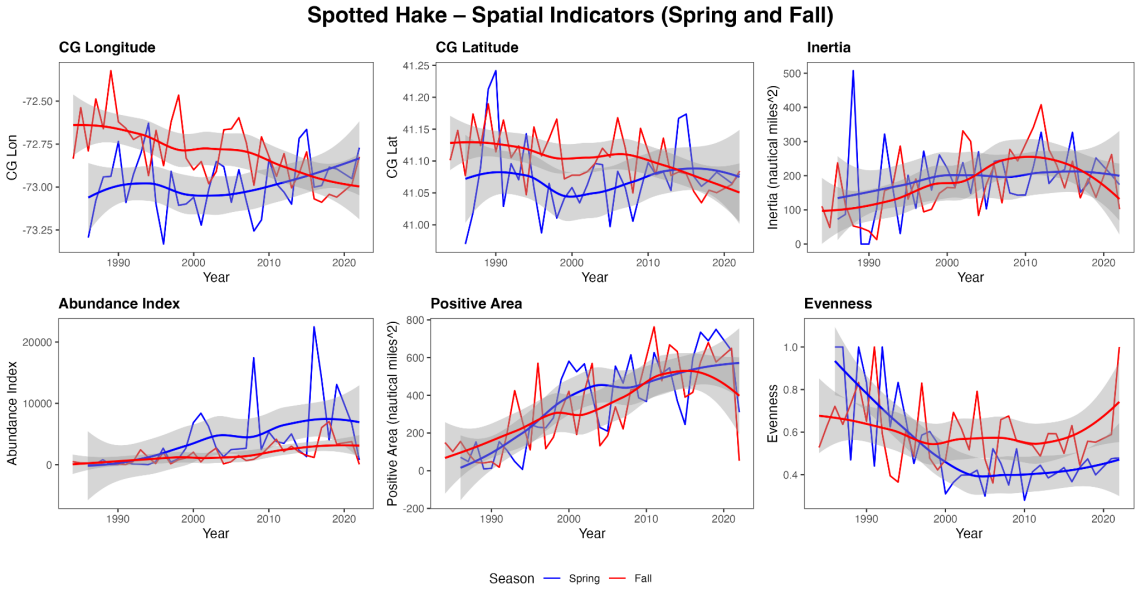


Fig. 9. Time series of spring (blue) and fall (red) spatial indicators for Spotted Hake in the LIS from 1984-2022. Gray bands denoted 95% CI.

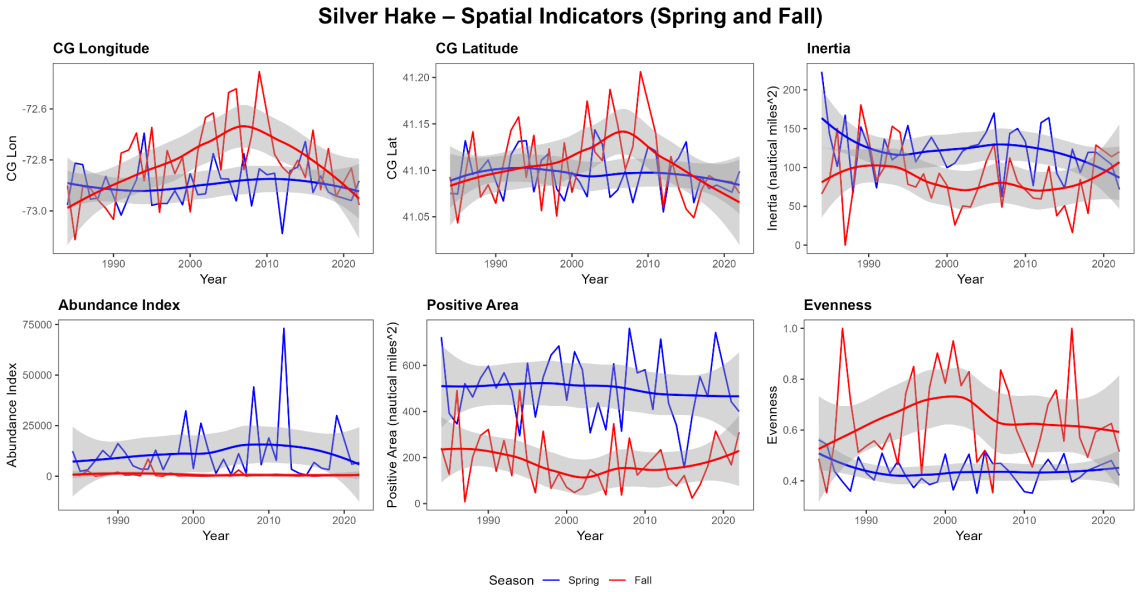


Fig. 10. Time series of spring (blue) and fall (red) spatial indicators for Silver Hake in the LIS from 1984-2022. Gray bands denoted 95% CI.

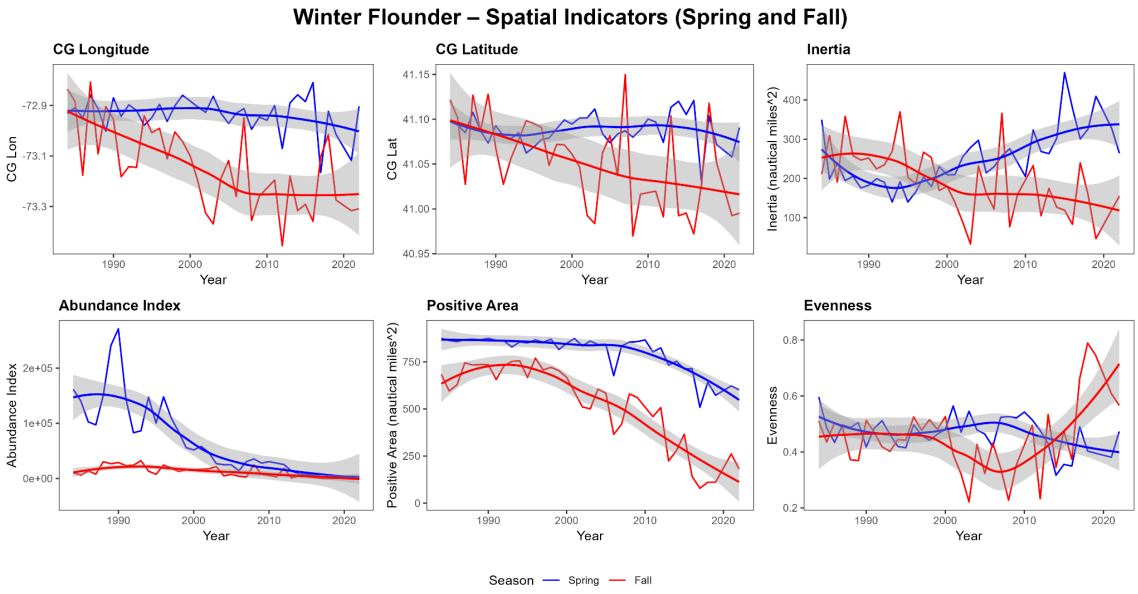


Fig. 11. Time series of spring (blue) and fall (red) spatial indicators for Winter Flounder in the LIS from 1984-2022. Gray bands denoted 95% CI.

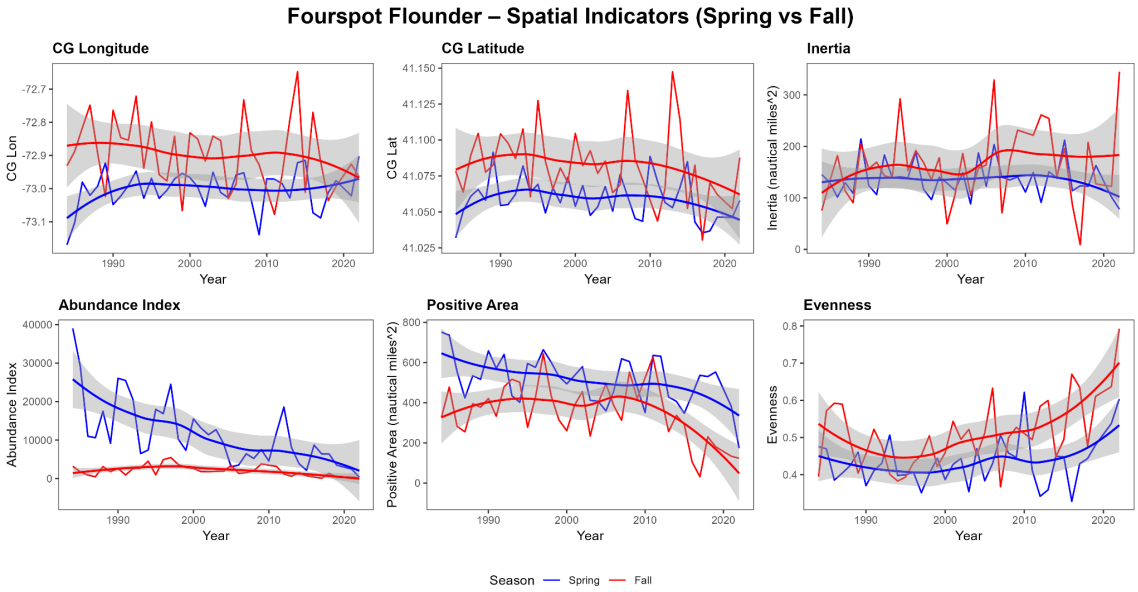


Fig. 12. Time series of spring (blue) and fall (red) spatial indicators for Fourspot Flounder in the LIS from 1984-2022. Gray bands denoted 95% CI.

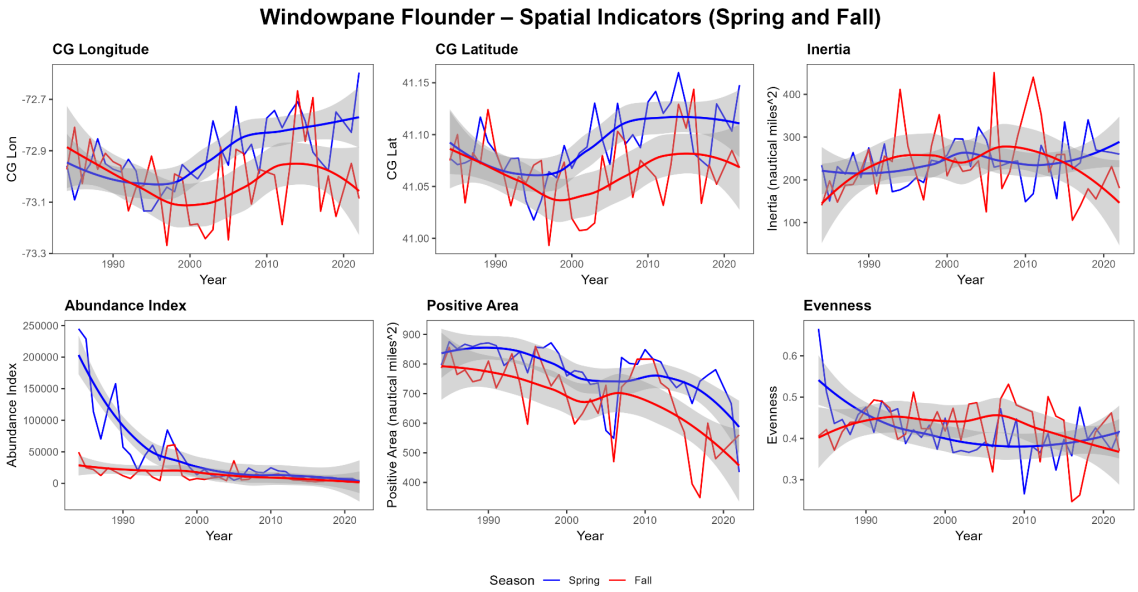


Fig. 13. Time series of spring (blue) and fall (red) spatial indicators for Windowpane Flounder in the LIS from 1984-2022. Gray bands denoted 95% CI.

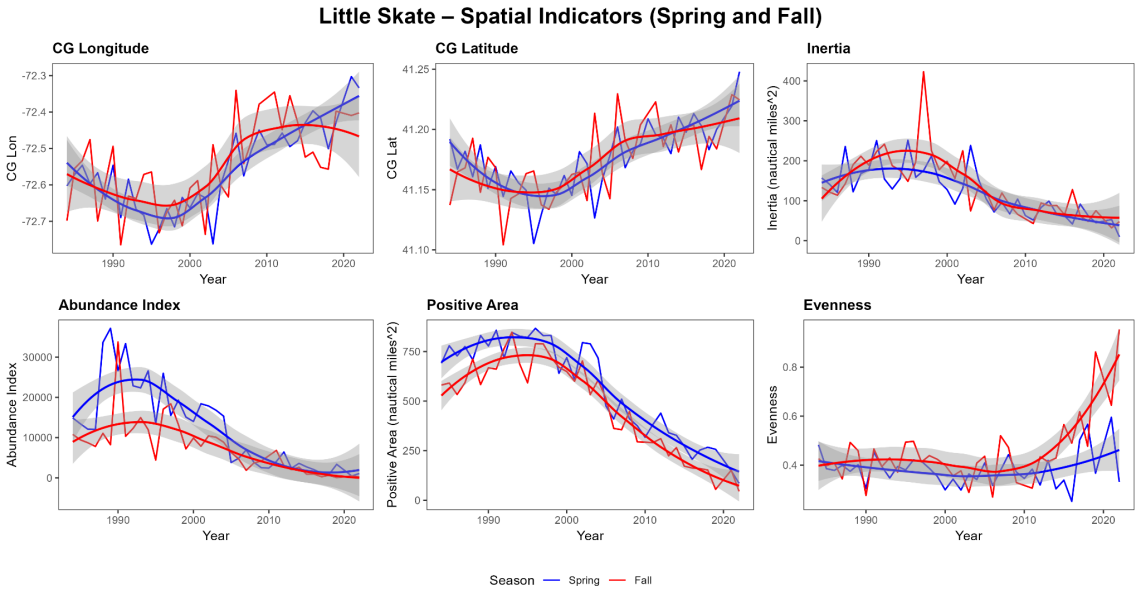


Fig. 14. Time series of spring (blue) and fall (red) spatial indicators for Little Skate in the LIS from 1984-2022. Gray bands denoted 95% CI.

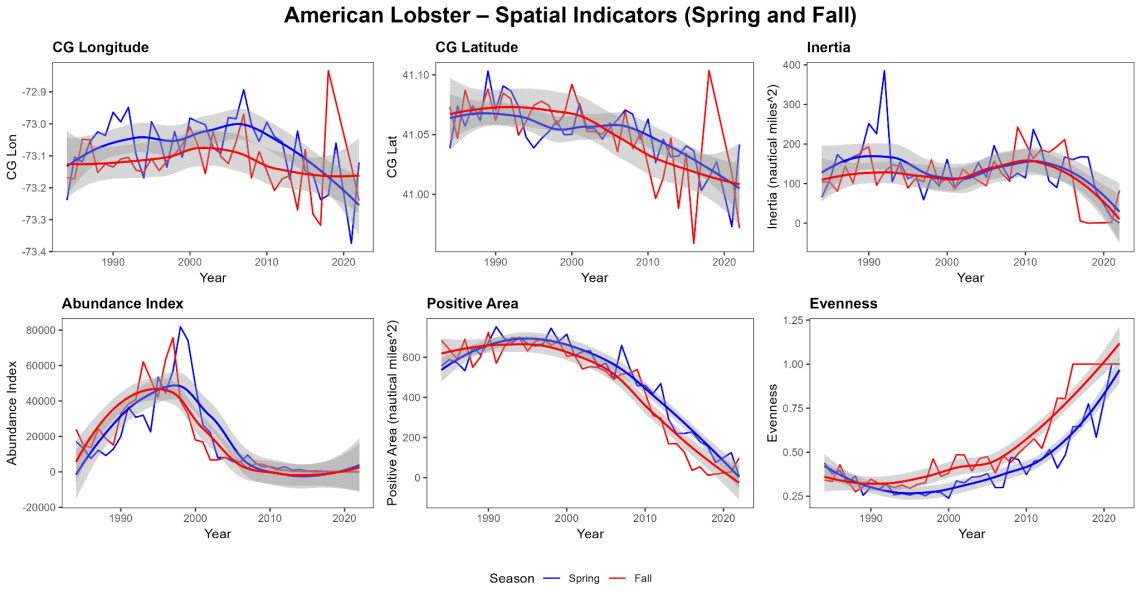


Fig. 15. Time series of spring (blue) and fall (red) spatial indicators for American Lobster in the LIS from 1984-2022. Gray bands denoted 95% CI.

References

Adams, C.F. 2017. Age-specific differences in the seasonal spatial distribution of butterfish (Peprilus triacanthus). ICES J. Mar. Sci. **74**(1):170-179.

Camargo, J.A. 1995. On measuring species evenness and other associated parameters of community structure. Oikos: 538-542.

Chang, H.Y., Richards, R.A., Townsend, D.W., and Chen, Y. 2024. Temperature and Abundance Effects on Spatial Structures of Northern Shrimp (Pandalus borealis) at Different Life Stages in the Oceanographically Variable Gulf of Maine. Fish. Oceanogr.

34(2): e12714.
Li, B., Tanaka, K.R., Chen, Y., Brady, D.C., and Thomas, A.C. 2017. Assessing the quality of bottom water temperatures from the Finite-Volume Community Ocean Model (FVCOM) in the Northwest Atlantic Shelf region. J. Mar. Syst. **173**: 21-30.
Payne, L.X., Schindler, D.E., Parrish, J.K., and Temple S.A. 2005. Quantifying spatial pattern with evenness indices. Ecol. Appl. **15**:507-520.
R Core Team. 2024. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.
Renard, D., Bez, N., Desassis, N., Beucher, H., and Ors, F. 2014. RGeostats: geostatistical package. R package version 10.0.8. http://rgeostats.free.fr/.
Woillez, M., Poulard, J.-C., Rivoirard, J., Petitgas, P., and Bez, N. 2007. Indices for capturing spatial patterns and their evolution in time, with application to European hake (Merluccius merluccius) in the Bay of Biscay. ICES J. Mar. Sci. **64**(3): 537-550.
Woillez, M., Rivoirard, J., and Petitgas, P. 2009. Notes on survey-based spatial indicators for monitoring fish populations. Aquat. Living Resour. **22**(2): 155-164.

Objective 2: Identify key environmental variables influencing fish habitat and distribution

A literature review was completed, including analysis of over 75 reports, essential fish habitat documents, stock assessments, and published manuscripts to learn about the study species' life history, stock status, and important environmental variables. We compiled a detailed spreadsheet containing information about each species' response to different habitat variables. Additionally, for each species a document was developed to summarize life history information, predator and prey interactions, and stock status and structure.

The literature review identified that the key abiotic variables relevant to LIS species ecology, include bottom temperature, bottom salinity, depth, and sediment type. Sediment was evaluated as a candidate predictor during initial habitat model development; however, the sediment data was spatially coarser and required interpolation, introducing greater uncertainty than the other environmental variables. In addition, initial HSI results that included sediment were producing results that were not biologically realistic and inconsistent across species and seasons, and therefore sediment was not retained in the final HSI model.

Prior to model development, candidate environmental variables were evaluated for collinearity using variance inflation factors (VIF), and variables with VIF values greater than 3 were excluded to minimize multicollinearity bias (Zuur et al. 2010).

References

Zuur, A.F., Ieno, E.N., and Elphick, C.S. 2010. A protocol for data exploration to avoid common statistical problems. Methods Ecol. Evol. **1**(1): 3-14.

Objective 3: Develop models to hind-, now-, and fore-cast changes in suitable habitat and distribution

Methods

Habitat suitability index (HSI) models were developed to quantify relationships between species distributions and key environmental drivers in the LIS, and to evaluate spatial and temporal changes in habitat suitability. HSI models are widely used to assess species–environment relationships and to identify areas of suitable habitat under historical, present, and projected environmental conditions (Tanaka and Chen 2016; Torre et al. 2019; Behan et al.

2022; Linner and Chen 2024). HSIs were developed separately for each species for spring and fall seasons to reflect seasonal differences in habitat use and environmental conditions. The HSI framework consists of two primary components: (1) individual suitability indices (SIs) that describe species responses to individual environmental variables, and (2) composite HSI values that represent overall habitat suitability across time and space. Suitability indices were developed for key abiotic variables relevant to LIS species ecology. For each species and season, the observed range of each environmental variable was divided into bins using Fisher's natural breaks classification. Mean species abundance within each bin was calculated and scaled to a suitability index ranging from zero (least suitable) to one (most suitable). Generalized additive models (GAMs) were used to smooth SIs to environment relationships and reduce noise associated with sparse observations at extreme environmental values. Individual SIs were combined to generate composite HSI values scaled between zero and one. Composite HSIs represent relative habitat suitability and were calculated for each grid cell, season, and year.

To evaluate potential future changes in habitat suitability for the study species under a climate change scenario, the HSI models were projected using future oceanographic conditions. Projected bottom temperature and salinity values were derived using a delta downscaling approach (Hare et al., 2012, Fogarty et al. 2008). This approach assumes stationarity in relationships between the variables. Ensemble mean anomalies for bottom temperature and salinity were extracted from CMIP6 climate projections under the SSP5-8.5 high-emissions scenario. The delta method first computes the difference between the future and historical climate conditions, then adds the model generated differences to observed climate data for the same historical period to produce a projection of the climate variables. These anomalies, representing end-of-century (e.g., 2080-2100) departures from historical baselines, were spatially interpolated to match the resolution of the project's FVCOM grid. The downscaled anomalies were then added to the historical seasonal mean FVCOM outputs to generate future climatological layers for bottom temperature and salinity across spring and fall. These projected environmental conditions were then input into the original HSI framework for each species by applying the previously developed SI curves. Depth was considered to remain static over time, and the future composite HSI values were calculated using projected temperature and salinity values combined with historical depth.

Results

Historical and Future Habitat Suitability for Warm-adapted Species

For each warm-adapted species, descriptions of the trends in historical and future habitat suitability are presented under the spring and fall figures. The individual SI curves for bottom temperature, bottom salinity, and depth, used to construct the historical and future HSI models are presented in Figures S16-22 in the Supplemental Material.

In general, for the warm-adapted species habitat suitability analyses showed consistent patterns of expansion and increased suitability for the historical period. Future projections of habitat suitability under a high-emission scenario, suggest that these trends will continue.

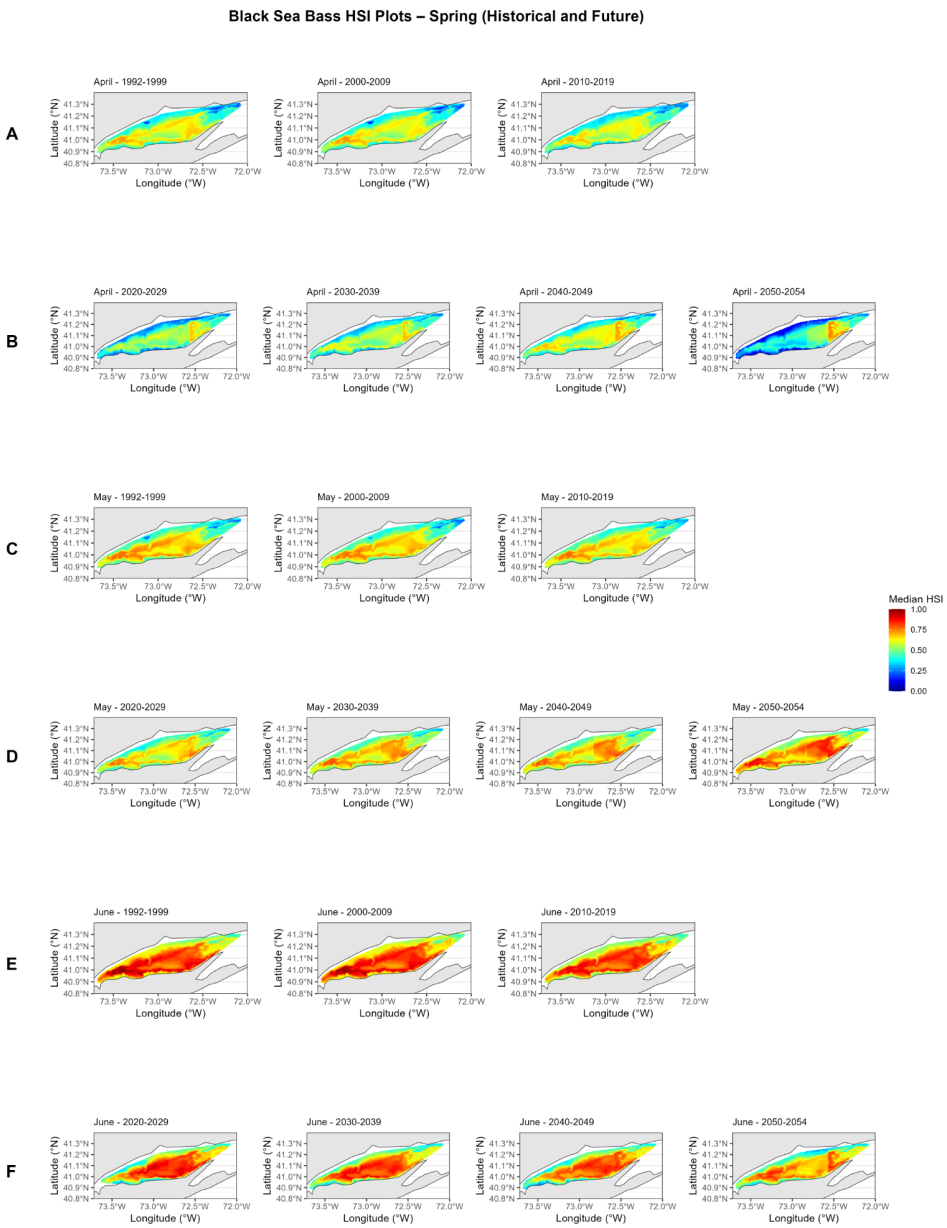


Fig. 16. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Black Sea Bass. Historical = 1992-2019; Future = 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

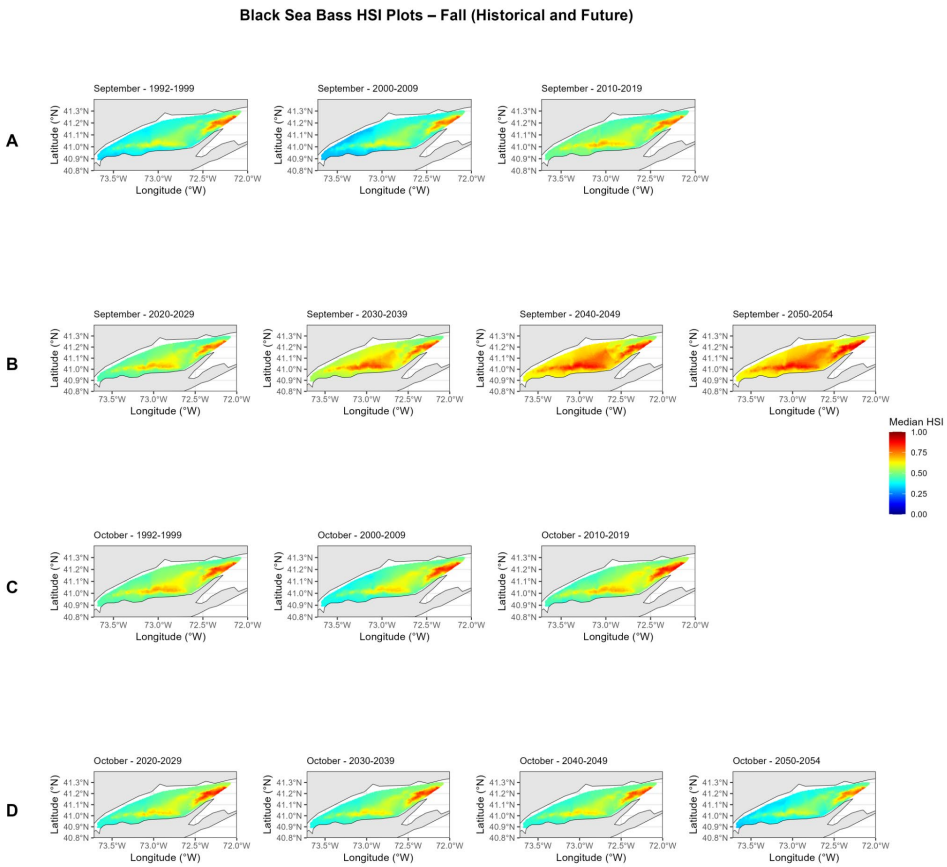


Fig. 17. Historical (A, C) and future (B, D) fall habitat suitability for Black Sea Bass. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Black sea bass exhibit seasonal differences in habitat suitability across the LIS, with higher suitability during spring compared to fall throughout both historical and projected periods (Figs. 16-17). Historically, June displayed the highest suitability, with consistently lower suitability earlier in the spring. Suitable habitat during spring was distributed across much of the central and western LIS, with comparatively lower suitability along the nearshore or coastal margins (Fig. 16). In contrast, fall habitat suitability remained lower compared to the spring throughout the historical period. September exhibited the higher suitability values, while October showed slightly lower but still limited suitability. Throughout the historical period suitability remained fairly uniform, suitable habitat concentrated in the central and eastern LIS (Fig. 17).

Future projections of black sea bass indicate stable or increasing spring suitability, particularly in June. There were declines in suitability in all spring months during 2050-2054 (Fig. 16). In fall, projected suitability remained stable, especially in October, with only minor spatial variability across decades. September suitability increased across decades, particularly 2040-2049 and 2050-2054, with areas of suitability distributed across the LIS (Fig. 17).

Observed abundance patterns show that while black sea bass were present in the LIS across the time period, abundance has dramatically increased in both spring and fall since 2010 (Fig. 1). As black sea bass continue to expand within the LIS, future updates to suitability indices incorporating additional years of survey data may improve the representation of projected suitable habitat conditions for this species.

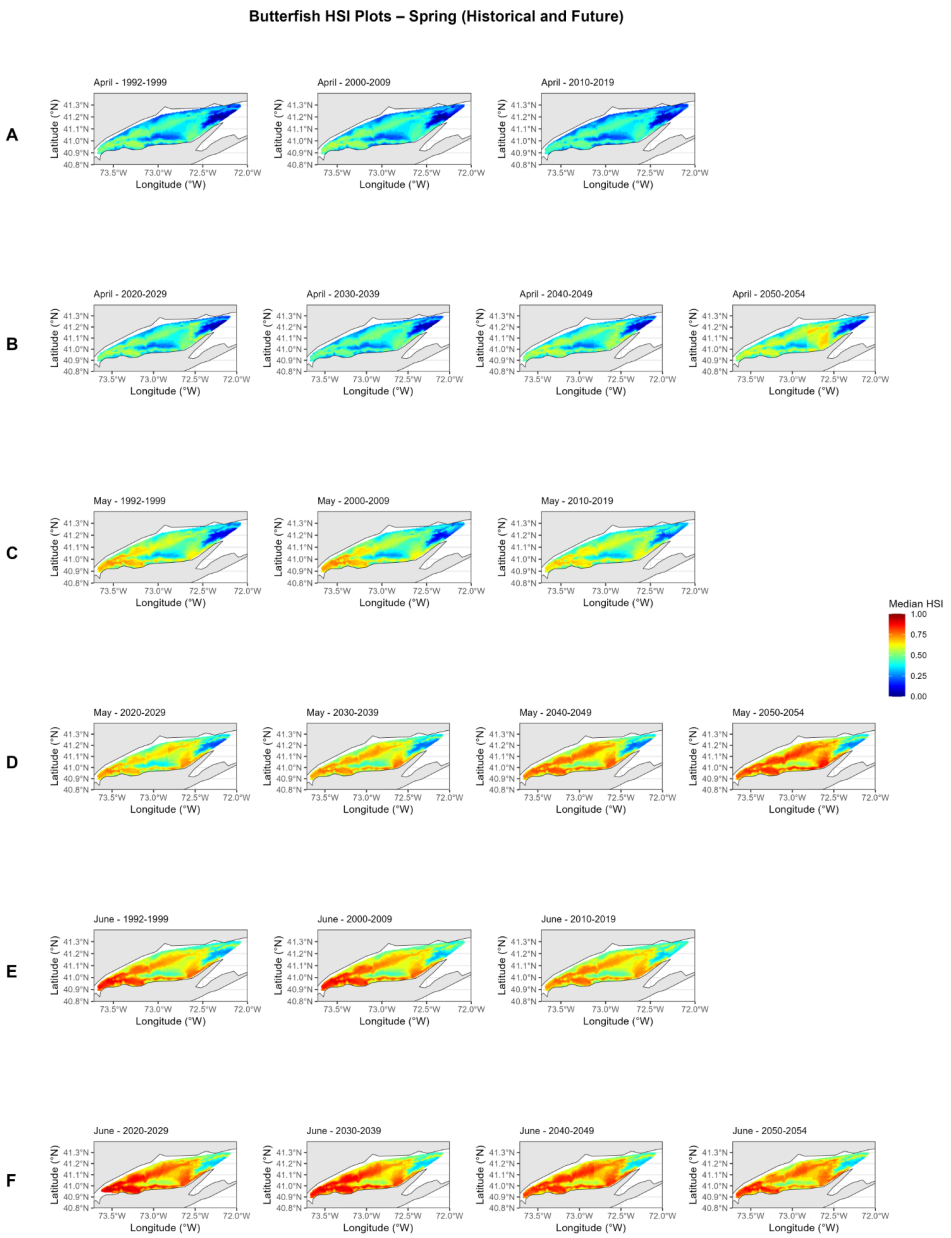


Fig. 18. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Butterfish. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

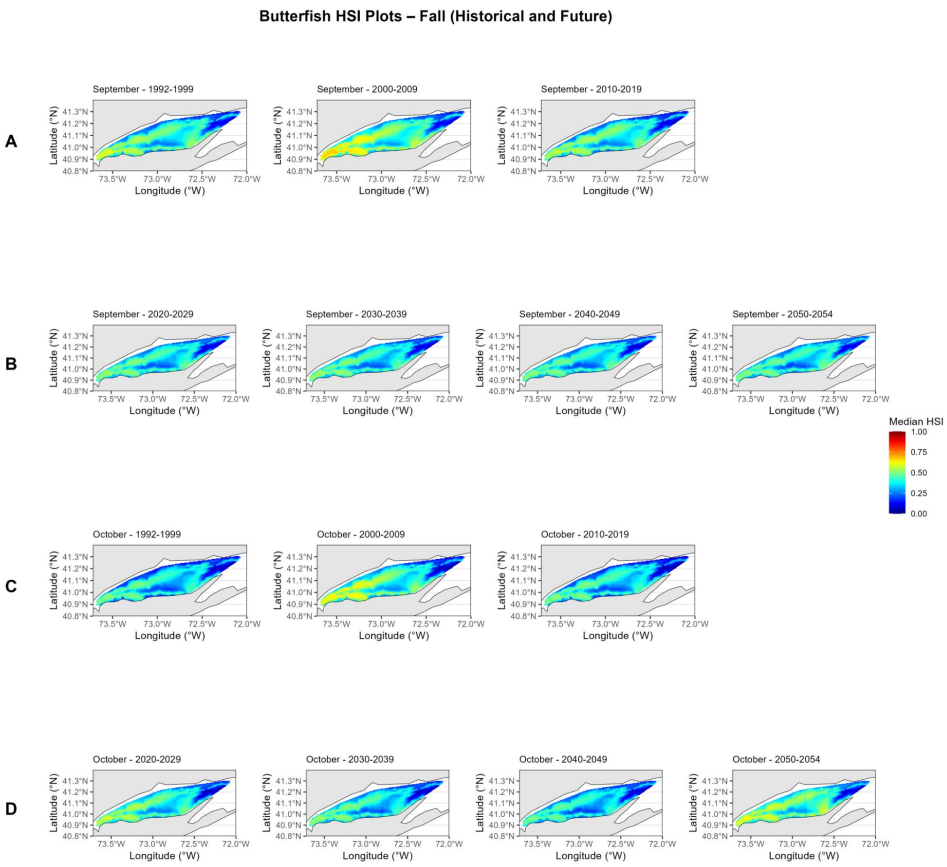


Fig. 19. Historical (A, C) and future (B, D) fall habitat suitability for Butterfish. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Butterfish exhibit strong seasonal differences in habitat suitability across the LIS, with higher suitability during spring compared to fall throughout both historical and projected periods (Figs. 18-19). Historically, June displayed the highest suitability, followed by May then April. Suitable habitat during spring was distributed across much of the central and western LIS, with comparatively lower suitability along the coasts and in the western Sound. Spring suitability declined in the later time periods (2010-2019), but overall, suitability remained relatively stable (Fig 18). In contrast, fall habitat suitability remained consistently low throughout the historical period. October exhibited the lowest suitability values, while September showed slightly higher but still limited suitability. Fall suitability increased during 2000-2009, but throughout the historical period suitability remained fairly uniform (Fig. 19).

Future projections of butterfish indicate stable or increasing spring suitability, particularly in May and June. June exhibited the most consistent gains in moderate to high suitability. April but did not exhibit any substantial increases in suitable habitat, except during 2050-2054. Future spring suitable habitat was distributed across the central and western LIS (Fig. 18). In fall, projected suitability remained low, especially in September, with only minor spatial variability across decades and minimal expansion of suitable habitat in October 2050-2054 (Fig. 19).

Observed butterfish abundance patterns show declining abundance in the fall since the 2000s (Fig. 2). Spring abundance remained low, despite HSI results showing stability or increases in spring habitat suitability. Butterfish habitat suitability in the LIS is strongly seasonal, with spring functioning as the primary period of favorable environmental conditions.

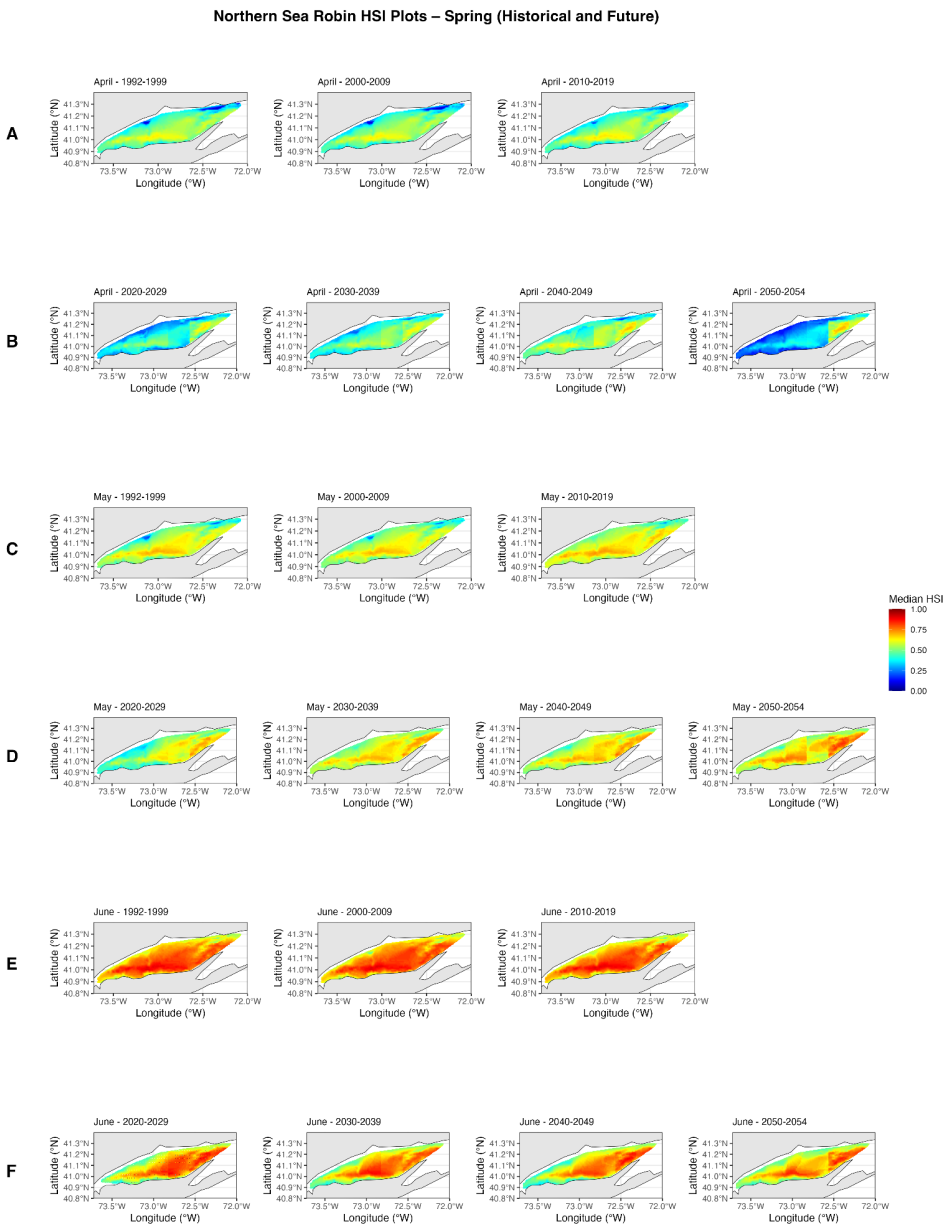


Fig. 20. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Northern Sea Robin. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

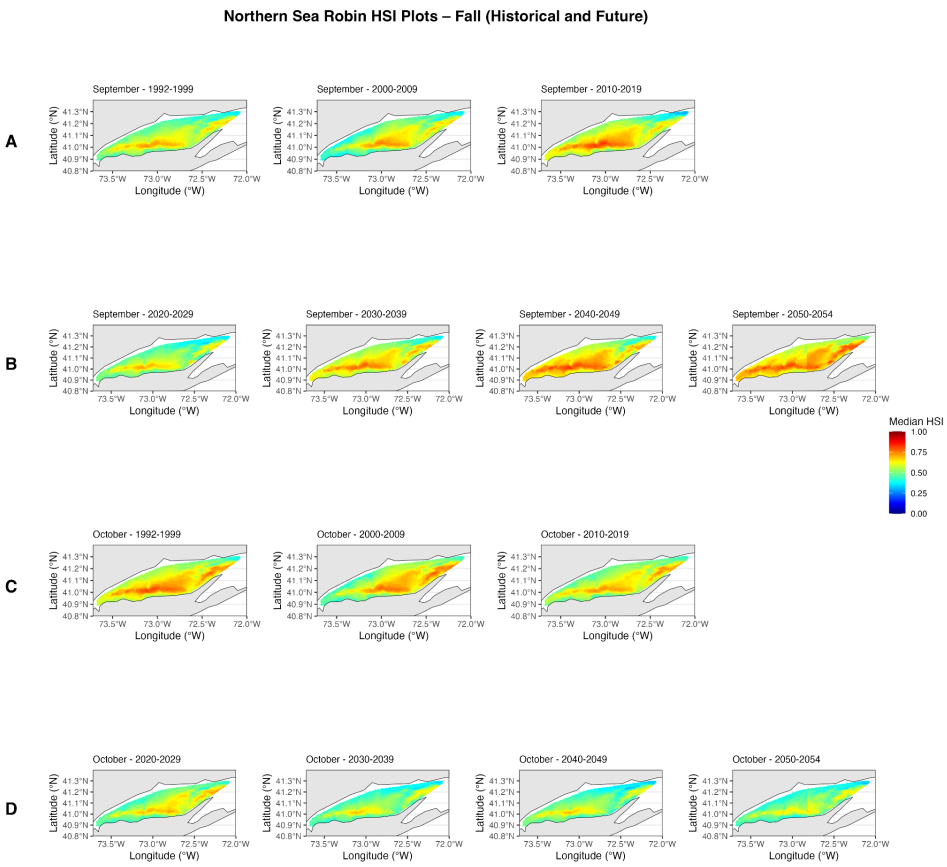


Fig. 21. Historical (A, C) and future (B, D) fall habitat suitability for Northern Sea Robin. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Northern sea robin exhibit slight seasonal differences in habitat suitability across the LIS, with higher suitability during spring compared to fall throughout both historical and future periods (Figs. 20-21). Historically, June displayed the highest suitability, followed by May then April. Suitable habitat during spring was distributed across much of the central LIS, with comparatively lower suitability along the coasts and western LIS. Over time, spring suitability remained stable in May and April, with June suitability increasing. Similarly, fall habitat suitability remained consistent throughout the historical period. September exhibited the lowest suitability values, while October showed slightly higher suitability (Fig. 21). Throughout the historical period suitability remained fairly uniform.

Future projections of northern sea robin indicate stable or increasing spring suitability, particularly in June, with areas of suitable habitat concentrated in the southwest LIS (Fig. 20). In fall, projected suitability increased in September across decades, with only minor variability across decades in October (Fig. 21).

Observed abundance patterns show increasing abundance, particularly in the spring, since the 2000s. (Fig. 3), with HSI results showing stability or increases in spring and fall habitat suitability. Fall abundance remained low, compared to spring abundance, across the time series. Overall, northern sea robin habitat suitability in the LIS shows minor seasonal patterns, with spring as the primary period of favorable environmental conditions.

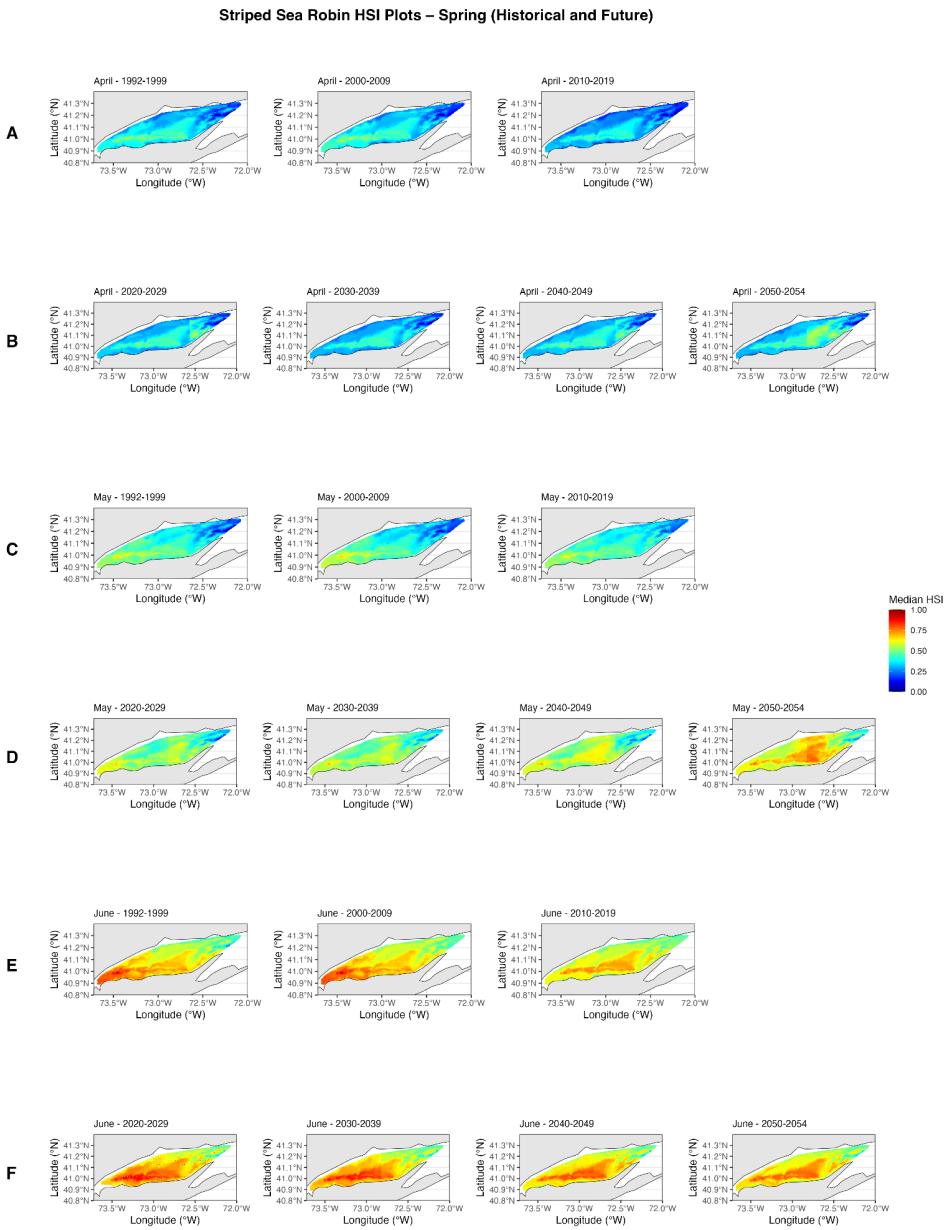


Fig. 22. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Striped Sea Robin. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

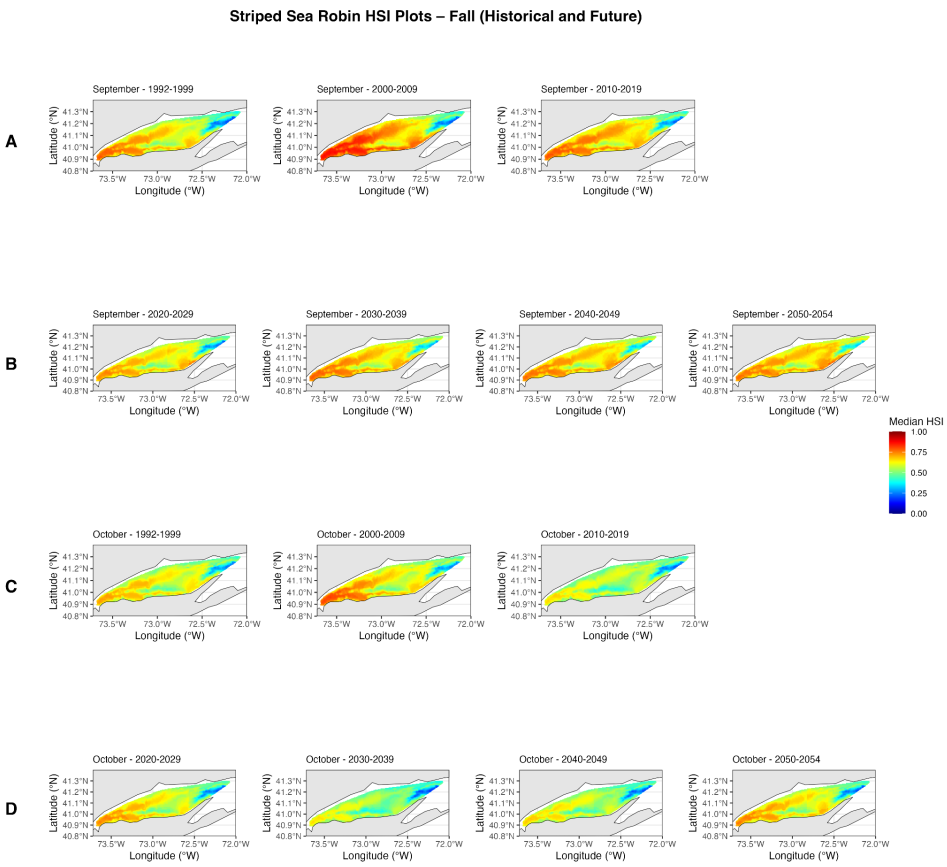


Fig. 23. Historical (A, C) and future (B, D) fall habitat suitability for Striped Sea Robin. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Striped sea robin HSI results show minor seasonal variation across the LIS, with generally higher suitability during fall than spring (Figs. 22-23). Suitable areas were broadly distributed across the central and western LIS during both seasons, with lower suitability in the eastern LIS. Historically, spring suitability was consistently lower during April and May, with higher suitability in June (Fig. 22). Fall results showed higher suitability in September than October across the time series. Suitability increased in the western LIS during both months in 2000-2009. However, during both months there was a decline in suitability in the most recent (2010-2019) part of the time series (Fig. 23).

Future projections indicate stable or increasing spring suitability, particularly later in the spring. June exhibited the most consistent gains in moderate or high suitability. April and May suitability remained lower than June but did not exhibit substantial trends over time (Fig. 22). In the fall, suitability remains relatively stable with increasing September and October suitability in 2050-2054. No substantial expansion of suitable fall habitat is expected (Fig. 23).

Abundance trends show stable fall abundance across the time series with increasing spring abundance since the late 2000s (Fig. 4) with HSI results showing stability or increases in habitat suitability during both seasons.

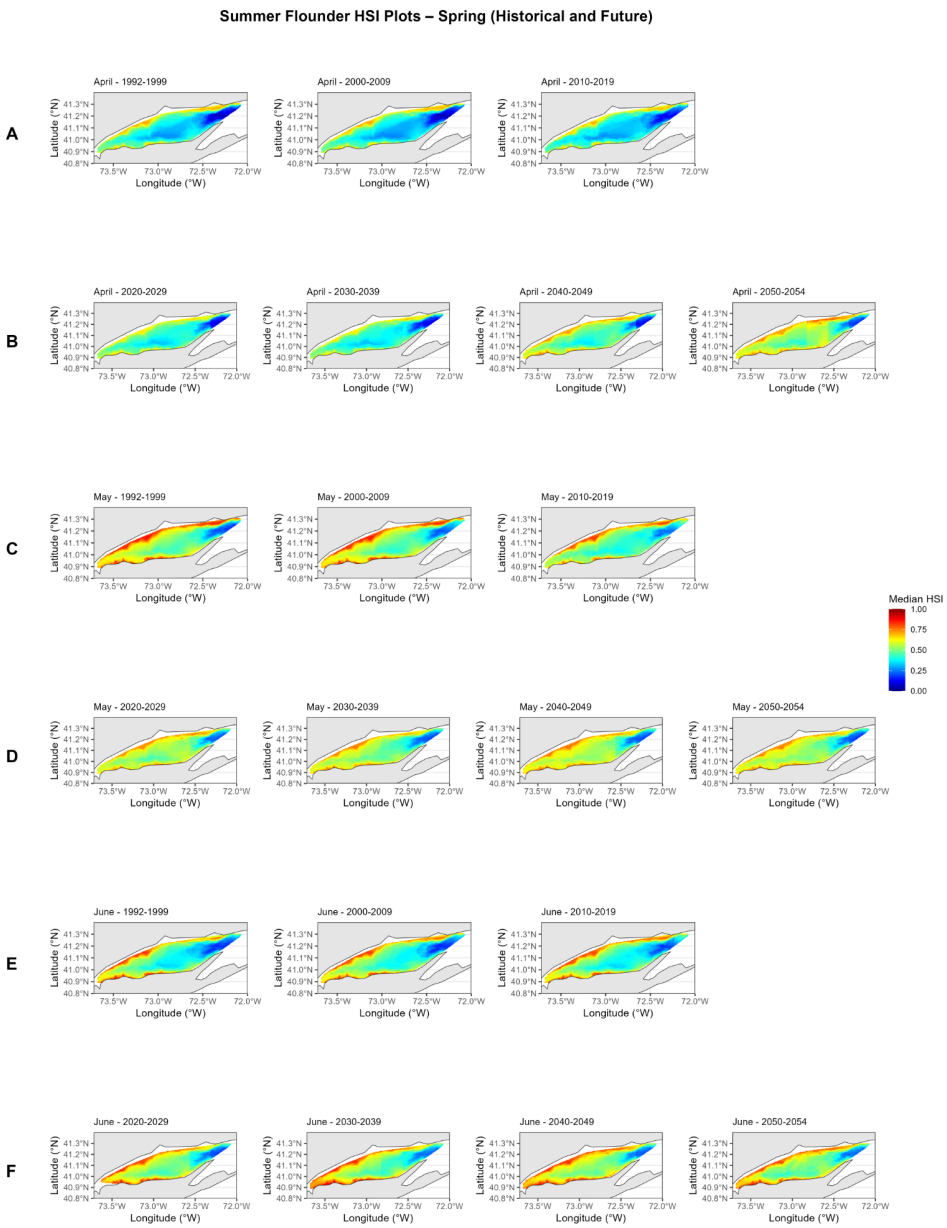


Fig. 24. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Summer Flounder. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

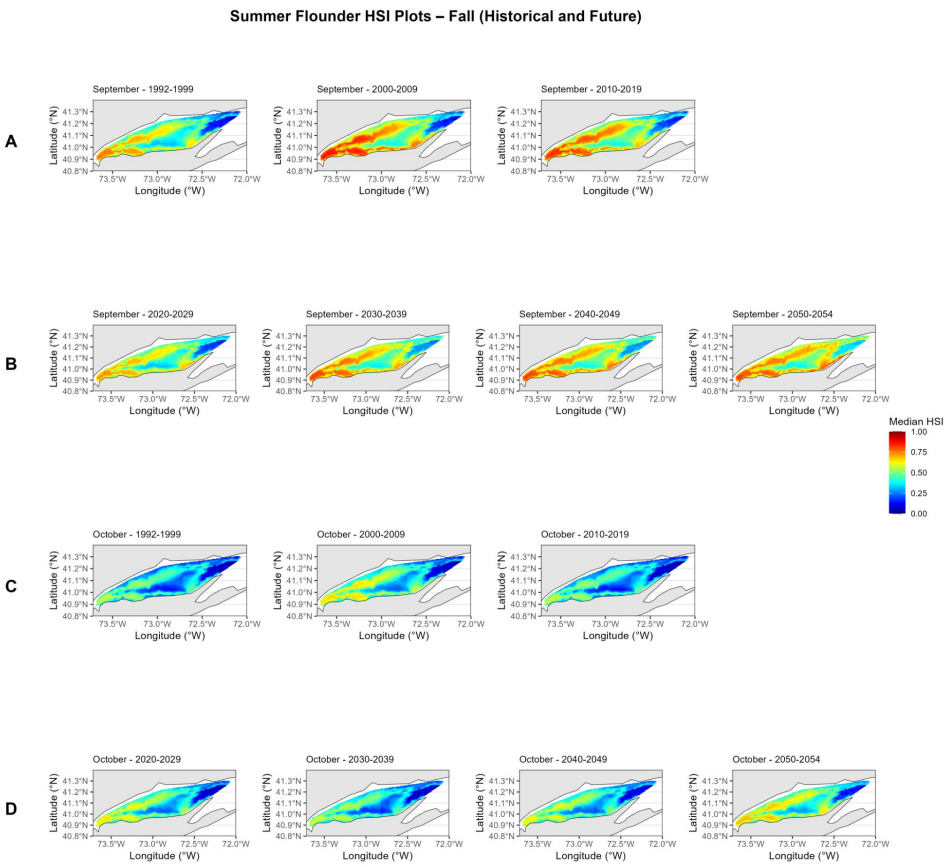


Fig. 25. Historical (A, C) and future (B, D) fall habitat suitability for Summer Flounder. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Summer flounder HSI results show strong seasonal differences in habitat suitability across the LIS, with strong gradients in suitability observed in most months (Figs. 24-25). Historically, spring suitability decreased slightly in May, but remained relatively unchanged in April and June (Fig. 24). Across all spring months, the western and coastal LIS were most suitable, with very low suitability in the eastern LIS (Fig. 24). The fall showed contrasting suitability between months, with very low suitability observed in October, and little net change in suitability over time, aside from a period of higher suitability from 2000-200 (Fig. 25). The highest suitability across spring and fall months was seen in September, with a slight increase in suitability, and high suitability in the western LIS (Fig. 25). Overall, across most months and areas of the LIS, little change in suitability was seen, with some slight increases and decreases.

Future projections of summer flounder habitat suitability show slight increases in projected suitability over time across both seasons (Fig. 24-25). May and June did not show clear changes in projected suitability over time, but April shows increased suitability across the sound, particularly from 2040 on (Fig. 24). In the fall, projected suitability generally increases for both September and October, with a maintained area of low suitability in the easternmost LIS (Fig. 25).

Abundance patterns show increasing abundance in both seasons (Fig. 5). Spring abundance steadily increased over the historical period, eventually surpassing fall abundance, which showed a generally increasing trend in the first half of the time series that leveled off (Fig. 5).

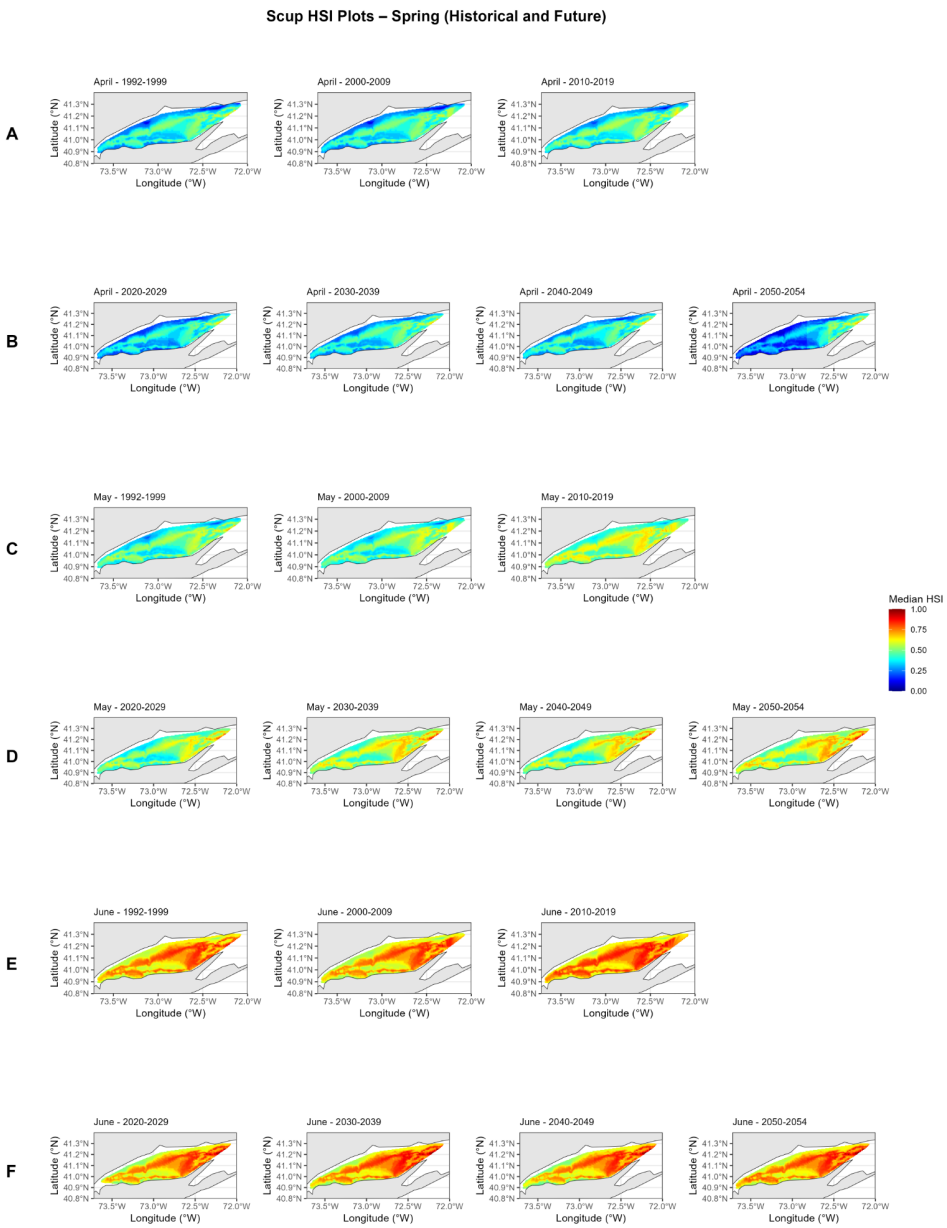


Fig. 26. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Scup. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

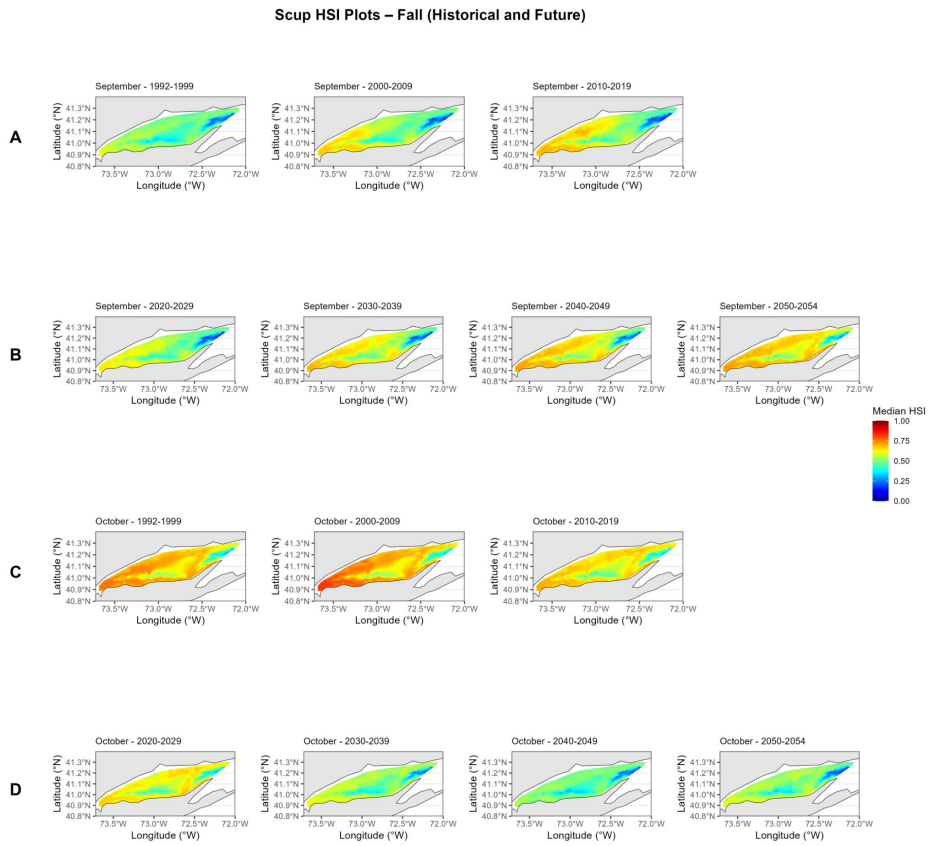


Fig. 27. Historical (A, C) and future (B, D) fall habitat suitability for Scup. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Scup HSI results show strong monthly differences in habitat suitability across the LIS, with strongest suitability in June for both historical and projected periods (Figs. 26-27). Historically, spring suitability increased slightly across all months, with April having considerably lower suitability than May, and June having very high suitability across most of the LIS (Fig. 26). Across all spring months, the coastal LIS was least suitable, with higher suitability in the eastern and central LIS (Fig. 26). The fall showed contrasting suitability intermediate to the low April and high June suitability observed in the spring (Fig. 27). In September suitability was typically moderate to low, with a pattern of decreasing suitability towards the eastern LIS, and increasing suitability in the western LIS over the historical period (Fig. 27). In October suitability was higher, but showed a net decrease over the historical period, with highest suitability in 2000-2009 (Fig. 27). Overall, across most months and areas of the LIS, increasing suitability was seen.

Future projections of scup habitat suitability show contrasting trends in spring months, with a decrease in April suitability, particularly in the western LIS, slightly increasing May suitability, and relatively unchanged June suitability (Fig. 26). All spring months show higher projected suitability in the eastern LIS (Fig. 26). In the fall, similarly contrasting monthly patterns are seen, with increasing September suitability across the sound and decreasing projected October suitability, particularly in the eastern LIS (Fig. 27).

Increasing abundance is seen across seasons (Fig. 6). Abundance is similar across seasons by the end of the historical period, but spring abundance starts very low and increases most in the second half of the time series, while fall abundance shows a marked increase in the

first half of the time series, before leveling off (Fig. 6).

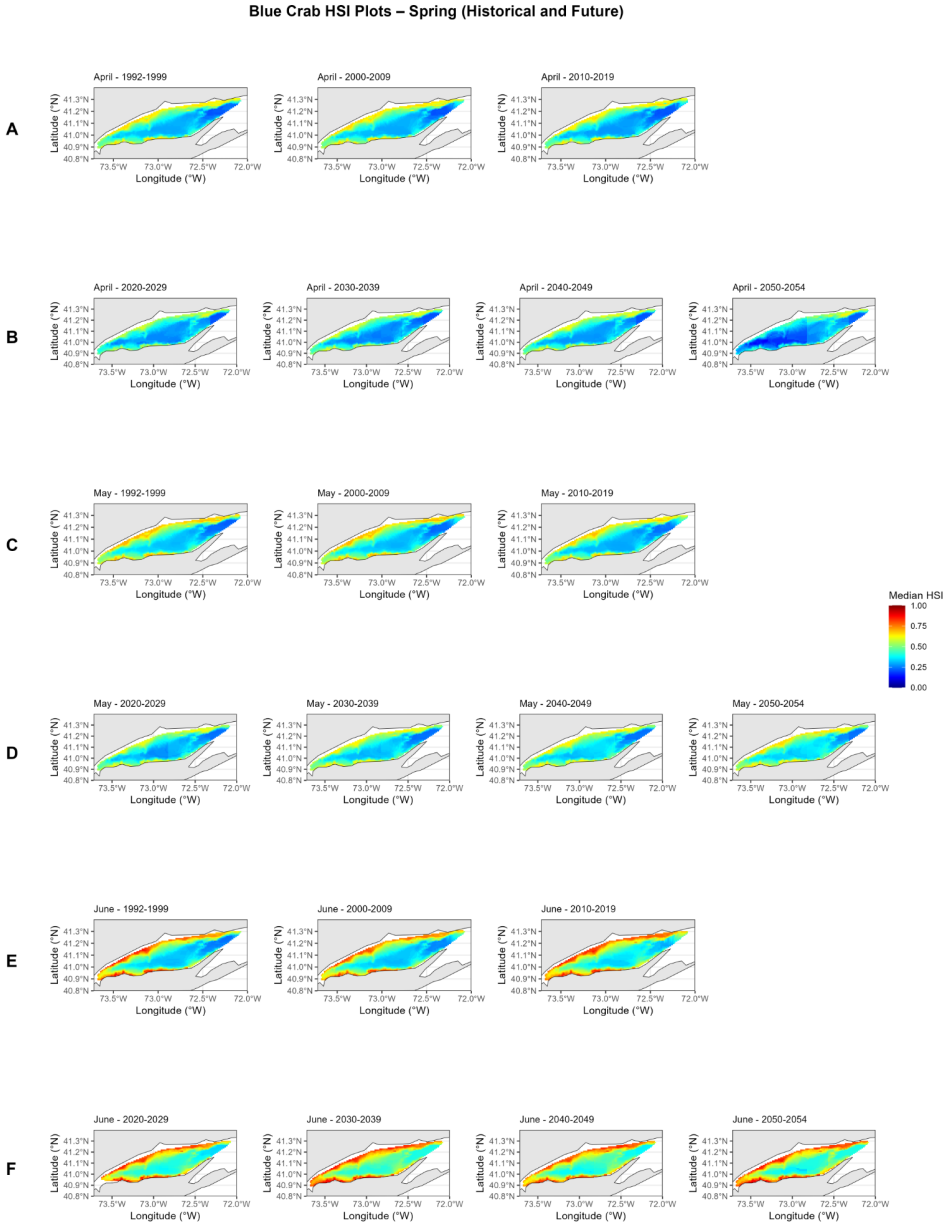


Fig. 28. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Blue Crab. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

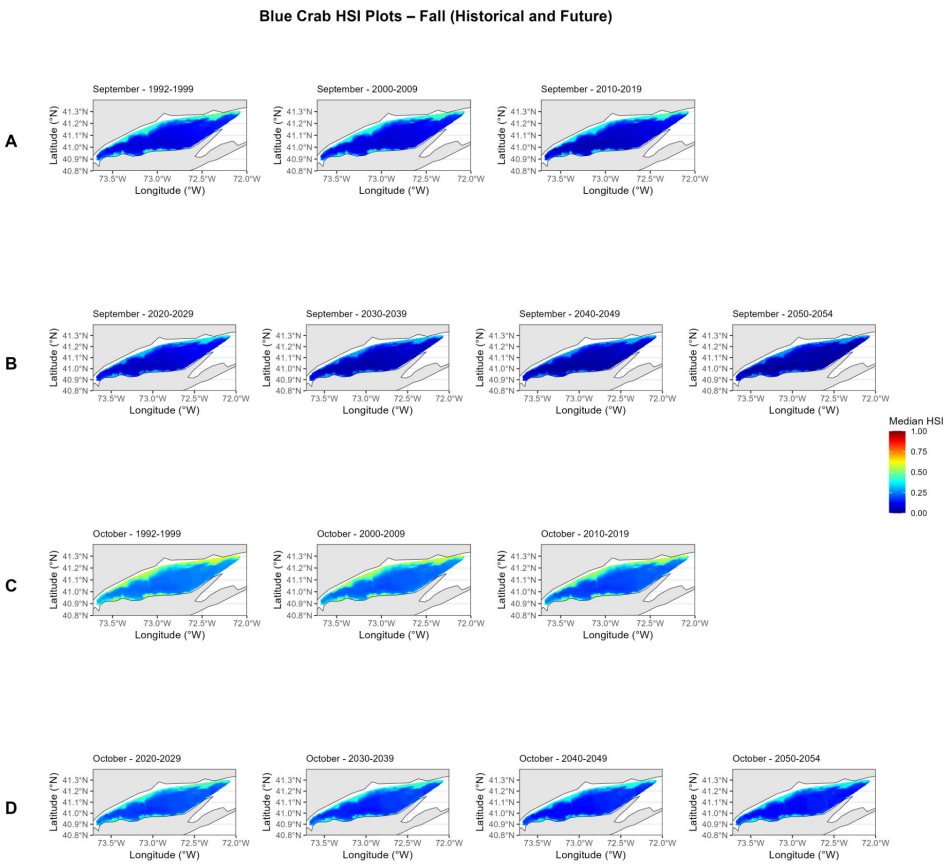


Fig. 29. Historical (A, C) and future (B, D) fall habitat suitability for Blue Crab. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Blue crab habitat suitability increased in April-June in the historical period, particularly along the coasts (Fig. 28). In the future, habitat suitability increased in the spring, most notably in June and towards the central LIS (Fig. 28). Historically, there was decreased suitability in the fall with slightly higher suitability along the coasts (Fig. 29). Under projected warming conditions, low suitability remains in the fall with coastal areas having higher suitability (Fig. 29).

Blue crab habitat suitability is strongly seasonal across the LIS, with higher suitability during the spring months compared to the fall (Figs. 28-29). During the historical period, suitability increased from April through June, with the highest suitability occurring in June. Suitable habitat is primarily concentrated along the coastal margins of the LIS, while the central basin of the Sound consistently demonstrated lower suitability. This spatial pattern remained consistent across the historical timeframe.

Future projections indicate increasing habitat suitability during spring months, with areas of moderate suitability expanding toward the central portion of the LIS while coastal areas continue to exhibit the highest suitability. In contrast, fall habitat suitability remained low throughout the projected period. September exhibited very low suitability across the entire Sound, while October showed slightly higher suitability along narrow coastal margins. Despite recent increases in blue crab abundance, projected fall HSI values remain generally low across much of the Sound. This pattern most likely reflects how the suitability indices were constructed from historical catch–environment relationships. Examination of the suitability index curves (Fig. S22) indicates that suitability is strongly constrained by depth and salinity. Suitability declines rapidly with increasing depth, with the highest values occurring in shallow coastal environments

(<10–15 m). Similarly, salinity suitability is concentrated within a relatively narrow range associated with nearshore and estuarine conditions, causing much of the deeper central basin of the Sound to fall outside the optimal environmental ranges represented in the suitability curves. Because the final HSI combines temperature, depth, and salinity suitability, moderate reductions in any single variable can produce low overall HSI values across broad areas.

Under projected conditions, fall bottom temperatures increase by approximately 1.5 °C and bottom salinity increases slightly (+0.47 ppt) relative to historical conditions. However, only a very small fraction of the model grid falls within the salinity bins associated with higher suitability. As a result, most locations remain within lower-suitability salinity ranges even under projected conditions. While blue crab abundance has increased in recent years, the fall HSI projections primarily reflect the historically observed catch–environment relationships embedded in the suitability curves, which thus far represent a relatively narrow portion of the environmental conditions present in the Sound. As blue crabs continue to expand within LIS, future updates to the suitability indices incorporating additional years of catch data may improve the representation of suitable habitat conditions for this species.

Historical and Future Habitat Suitability for Cold-adapted Species

For each cold-adapted species, descriptions of the trends in historical and future habitat suitability are presented under the spring and fall figures. The individual SI curves for bottom temperature, bottom salinity, and depth, used to construct the historical and future HSI models are presented in Figures S23-30 in the Supplemental Material.

In general, for cold-adapted species, habitat suitability analyses showed patterns of contraction and declines in suitability for the historical period. Future projections of habitat suitability under a high emission scenario, suggest that these trends will continue. Under future warming conditions, cold-adapted species will likely be limited to small areas of persistent suitability which may serve as thermal refuges.

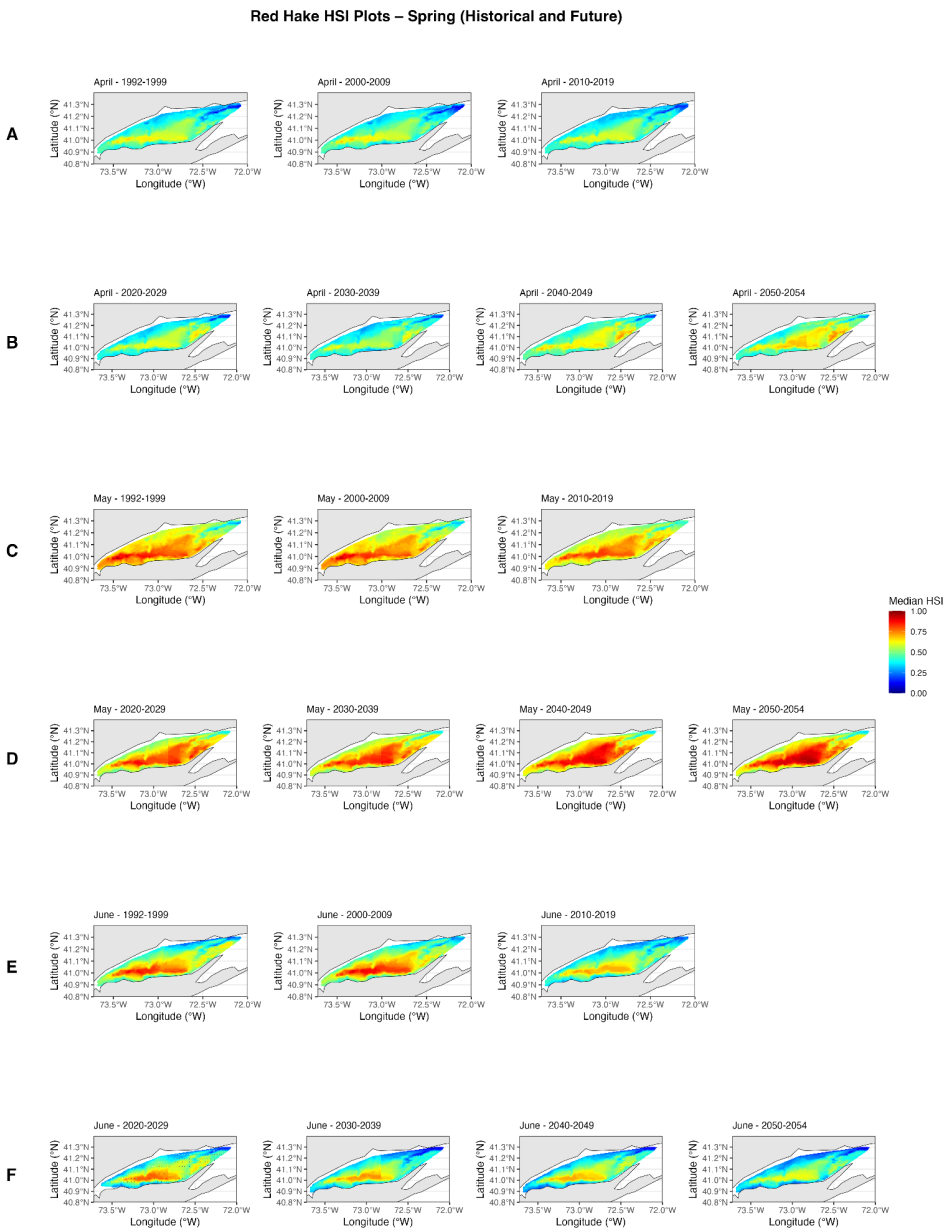


Fig. 30. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Red Hake. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

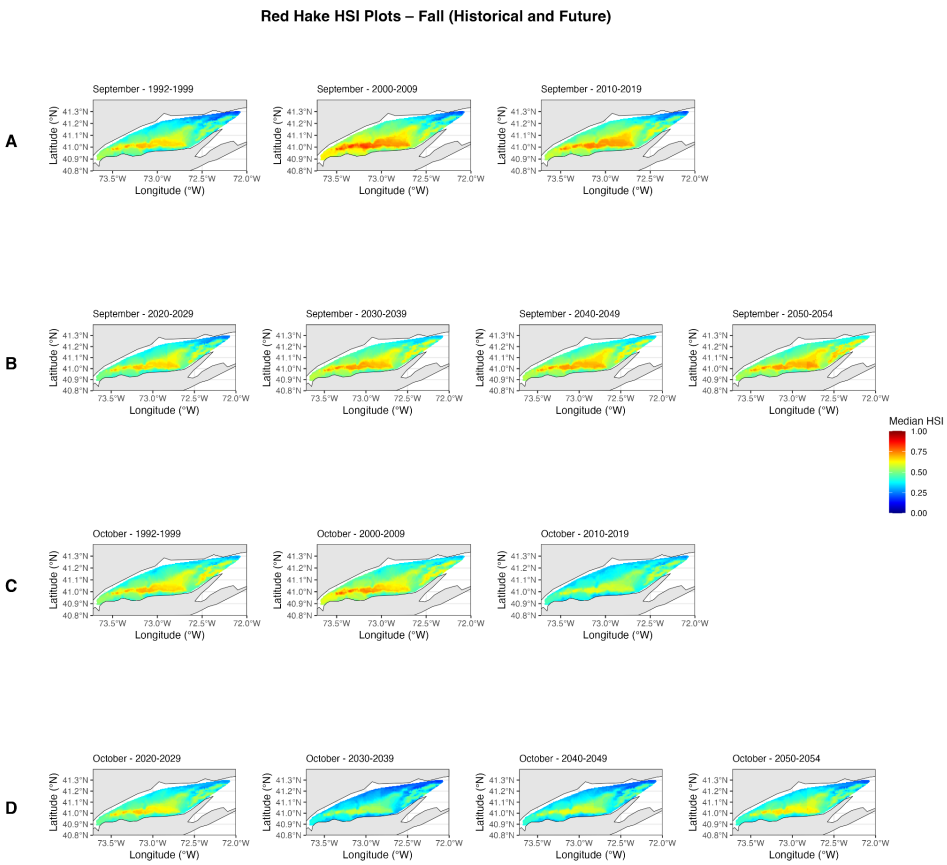


Fig. 31. Historical (A, C) and future (B, D) fall habitat suitability for Red Hake. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Red hake exhibit seasonal differences in habitat suitability across the LIS, with higher suitability during spring compared to fall throughout both historical and projected periods (Figs. 30-31). Historically, May displayed the highest suitability, followed by June then April, with April consistently lower than later in the spring. During the most recent part (2010-2019) of the time series, suitability decreased in both May and June (Fig. 30). Suitable habitat during spring was distributed across much of the central and western LIS, with comparatively lower suitability along the nearshore or coastal margins. In contrast, fall habitat suitability remained lower than spring throughout the historical period (Fig. 31). September exhibited higher suitability values with decreased suitability from 2010-2019, while October suitability remained stable over time.

Future projections of red hake indicate stable or increasing spring suitability, particularly in May. April suitability did not exhibit any substantial trends; May exhibited the most consistent gain of high suitability, while June future suitability did exhibit some declines (Fig. 30). In fall, projected suitability remained low, especially in October, with only minor spatial variability across decades and minimal expansion of suitable habitat in September (Fig. 31).

Observed abundance patterns show low or declining abundance, particularly in the spring across the time series (Fig. 8), time (Fig. 8), despite HSI results showing stability or increases in spring habitat suitability. Fall abundance remained low, consistent with lower suitability values observed across the fall months. Overall, red hake habitat suitability in the LIS is seasonal, with spring as the primary period of favorable environmental conditions.

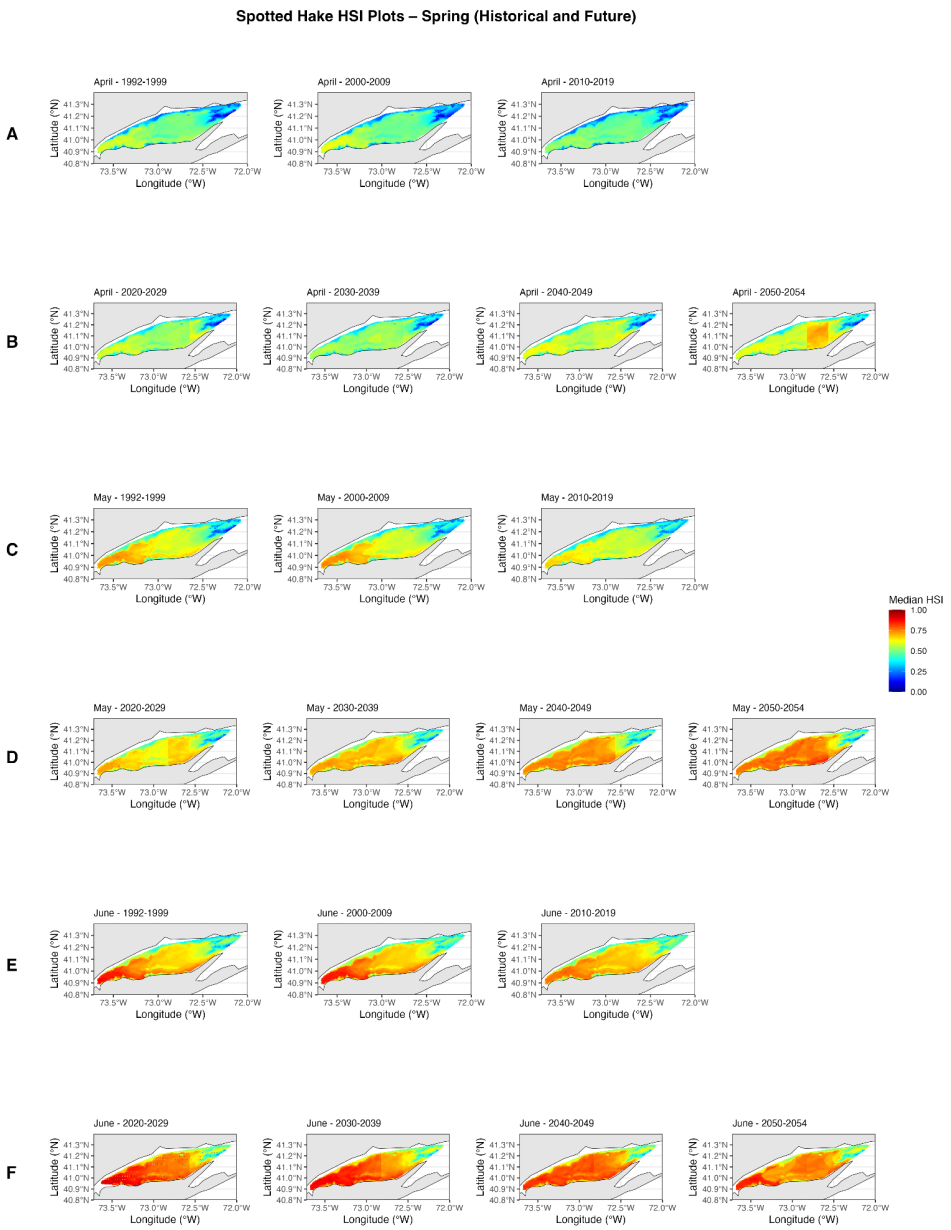


Fig. 32. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Spotted Hake. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

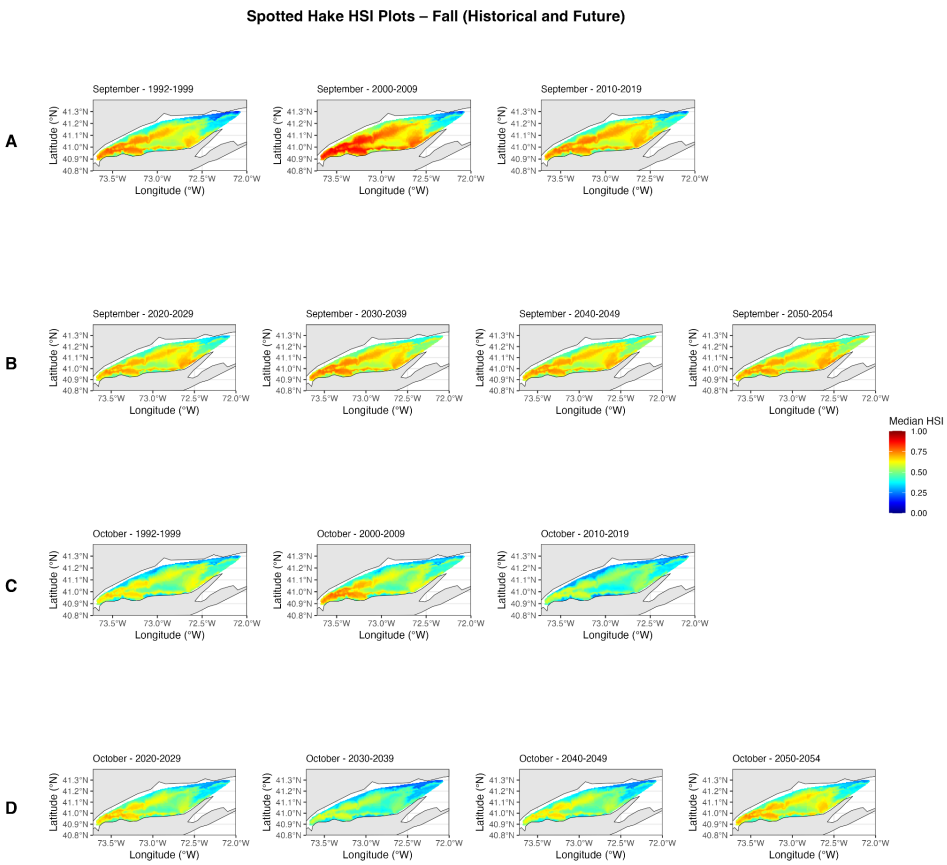


Fig. 33. Historical (A, C) and future (B, D) fall habitat suitability for Spotted Hake. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Spotted hake HSI results show differences in seasonal habitat suitability, with higher suitability in the spring throughout both historical and projected periods (Figs. 32-33). Historically, June displayed the highest suitability, with June consistently higher than early spring. During the most recent part of the historical period (2010-2019), suitability decreased in all spring months (Fig. 32). Spring suitable habitat was distributed across much of the central and western LIS, with comparatively lower suitability along the coasts and eastern LIS. In contrast, fall habitat suitability remained lower than spring throughout the historical period (Fig. 33). There was a noticeable increase in September suitability from 2000-2009 concentrated in the western LIS, while October suitability remained stable over time with a similar, but reduced increase in suitability in 2000-2009 (Fig. 33).

Future conditions indicate increasing or stable suitability, particularly in June (2020-2029, 2030-2039, and 2040-2019) with suitable habitat widely distributed across the central and western LIS. April exhibits stable suitability with a slight increase by mid-century, while May indicates increasing suitability under future climatic conditions (Fig. 32). Fall projections show suitability remaining comparatively stable during both months under future climate conditions and no substantial expansion of fall suitable habitat is projected (Fig. 33).

Spotted hake abundance remained low in both seasons across the time series. Spring abundance has slowly increased since the early 2000s (Fig. 9), despite HSI results indicating stable or increasing spring suitability. Overall, spotted hake habitat suitability in the LIS is seasonal, with spring as the primary period of favorable environmental conditions.

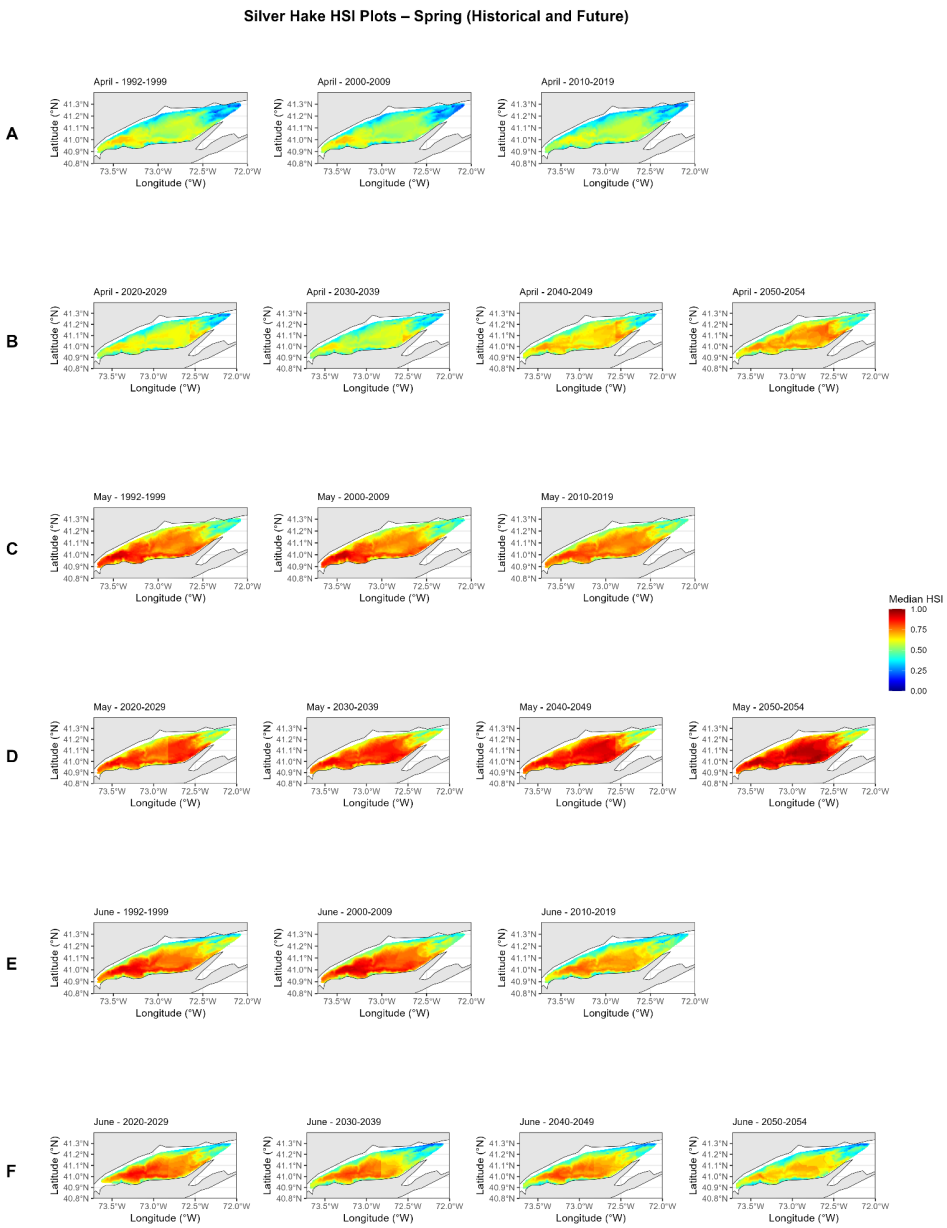


Fig. 34. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Silver Hake. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

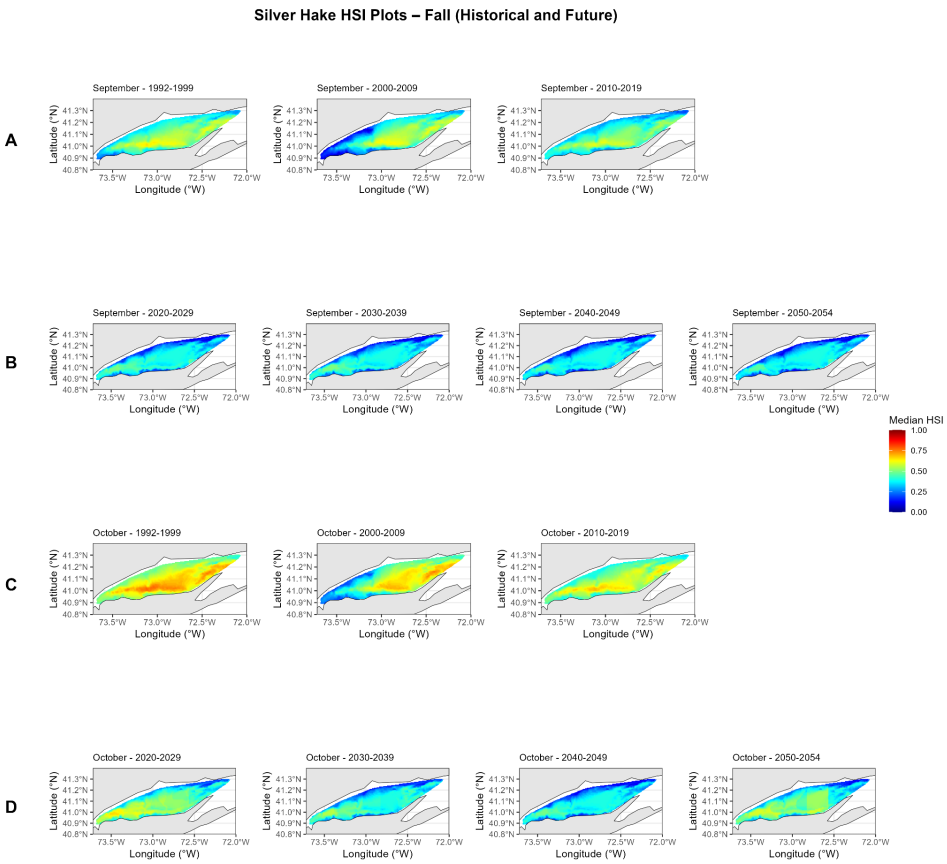


Fig. 35. Historical (A, C) and future (B, D) fall habitat suitability for Silver Hake. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Silver hake HSI results show seasonal differences in habitat suitability across the LIS, with stronger suitability in the spring for both historical and projected periods (Figs. 34-35). Historically, spring suitability decreased slightly across all months, with May and June being considerably more suitable than April for all decades (Fig. 34). Across all spring months, the eastern and coastal LIS were the least suitable areas, with moderate to high suitability in the rest of the LIS (Fig. 34). The fall showed much lower suitability overall, with net decreases in suitability across decades, and particularly low suitability in the western LIS for 2000-2009 for both September and October (Fig. 35). In September suitability was typically moderate to low, while in October suitability was higher (Fig. 35). Overall, across both seasons and most areas of the LIS, decreases in suitability are seen across this time series.

Future projections of silver hake habitat suitability indicate mostly increasing April and May suitability (Fig. 34). May suitability is projected to be very high in all of the LIS except the easternmost portion (Fig. 34). June shows decreasing suitability over time, particularly around the coastal LIS (Fig. 34). For the fall, maintained low suitability is projected, particularly for September, where most of the LIS is projected to be very unsuitable (Fig. 35).

Observed abundance patterns show near-zero abundance in the fall across the time series (Fig. 10). Slightly higher, but still low abundance is observed in the spring as well (Fig. 10), making silver hake a data-limited species for this project.

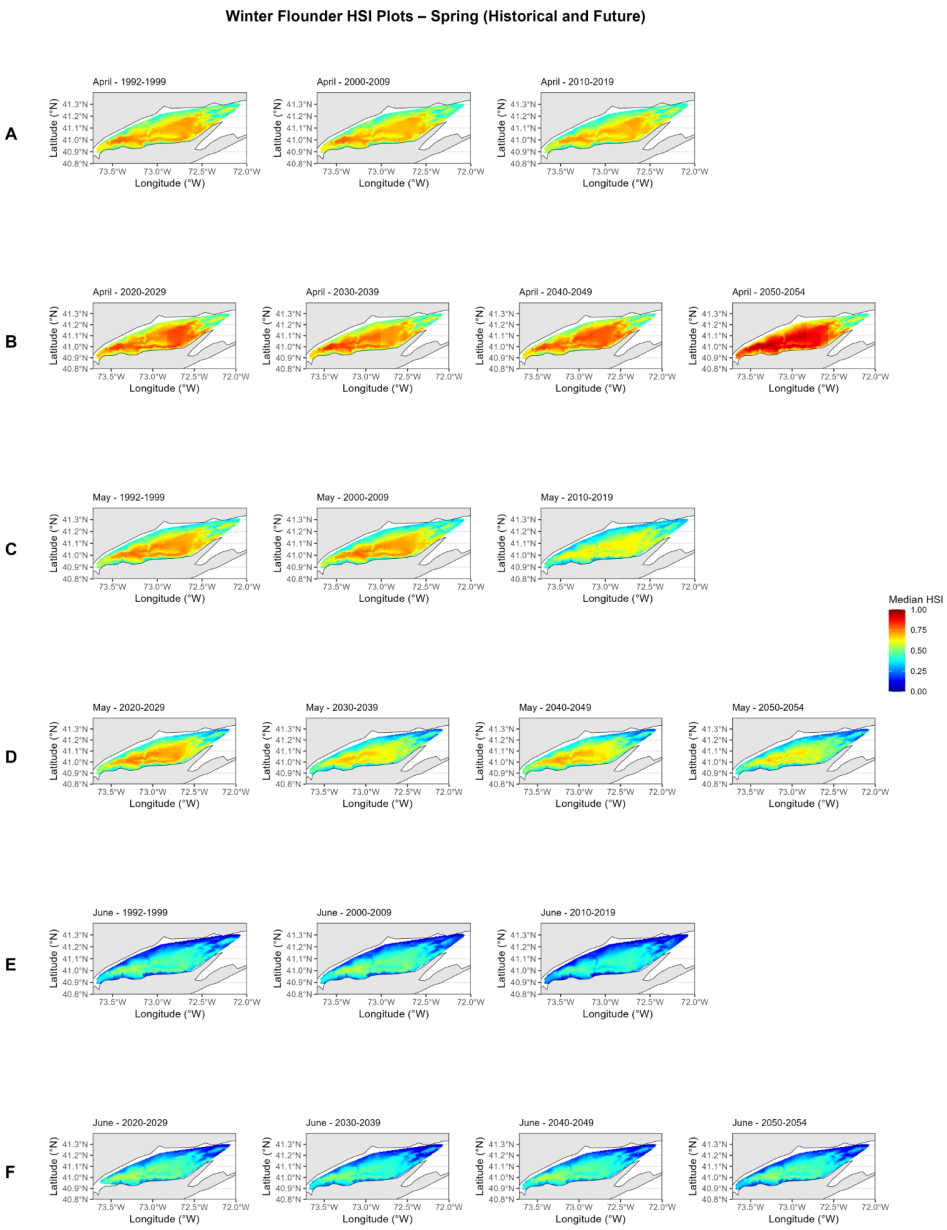


Fig. 36. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Winter Flounder. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

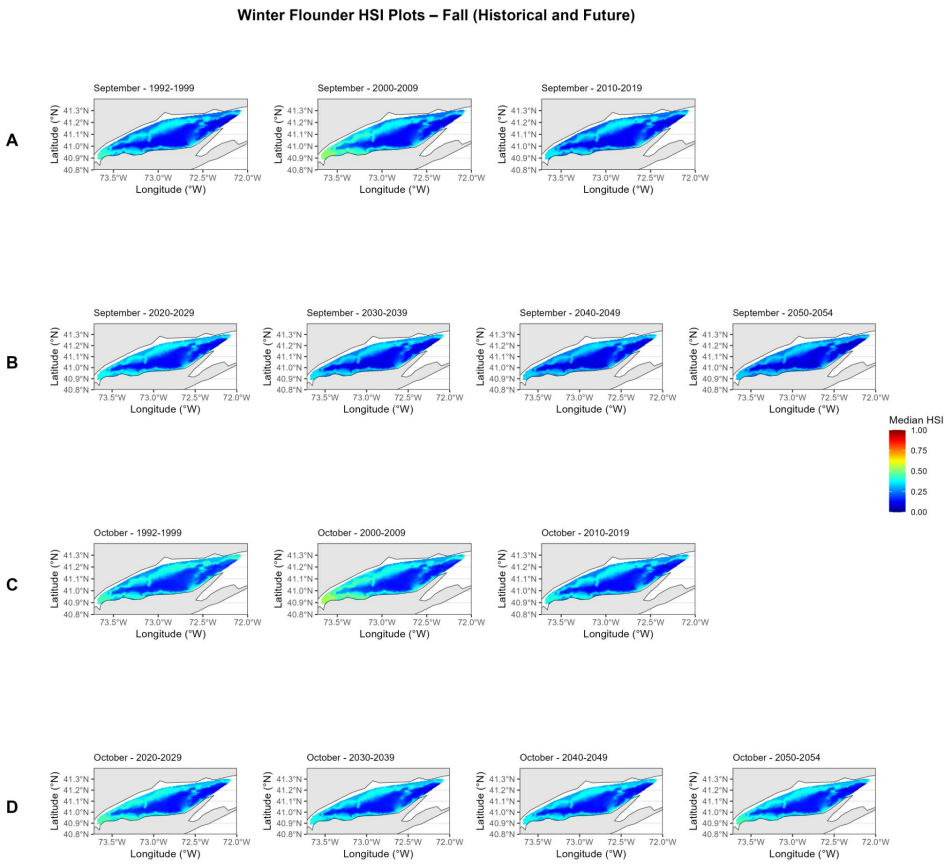


Fig. 37. Historical (A, C) and future (B, D) fall habitat suitability for Winter Flounder. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Winter flounder exhibit strong seasonal differences in habitat suitability across the LIS, with higher suitability during spring compared to fall throughout both historical and projected periods (Figs. 36-37). Historically, May displayed the highest suitability, followed by April, with June consistently lower than early spring. Suitable habitat during spring was distributed across much of the central and western LIS, with comparatively lower suitability along the nearshore or coastal margins. Over time, spring suitability declined in the later time periods, with April suitability remaining comparatively stable. In contrast, fall habitat suitability remained consistently low throughout the historical period (Fig. 37). September exhibited the lowest suitability values, while October showed slightly higher but still limited suitability. Throughout the historical period suitability decreased slightly but remained fairly uniform.

Future projections of winter flounder indicate stable or increasing spring suitability, particularly in April. April exhibited the most consistent gains in moderate to high suitability. June future suitability remained lower than April and May but did not exhibit any additional substantial declines (Fig. 36). In fall, projected suitability remained low, especially in September, with only minor spatial variability across decades and no expansion of suitable habitat in the fall (Fig. 37).

Observed abundance patterns show declining abundance, particularly in the spring, since the 1990s. (Fig. 11), despite HSI results showing stability or increases in spring habitat suitability. Fall abundance remained low, consistent with the low suitability values observed across the fall months. Overall, winter flounder habitat suitability in the LIS is strongly seasonal, with spring functioning as the primary period of favorable environmental conditions.

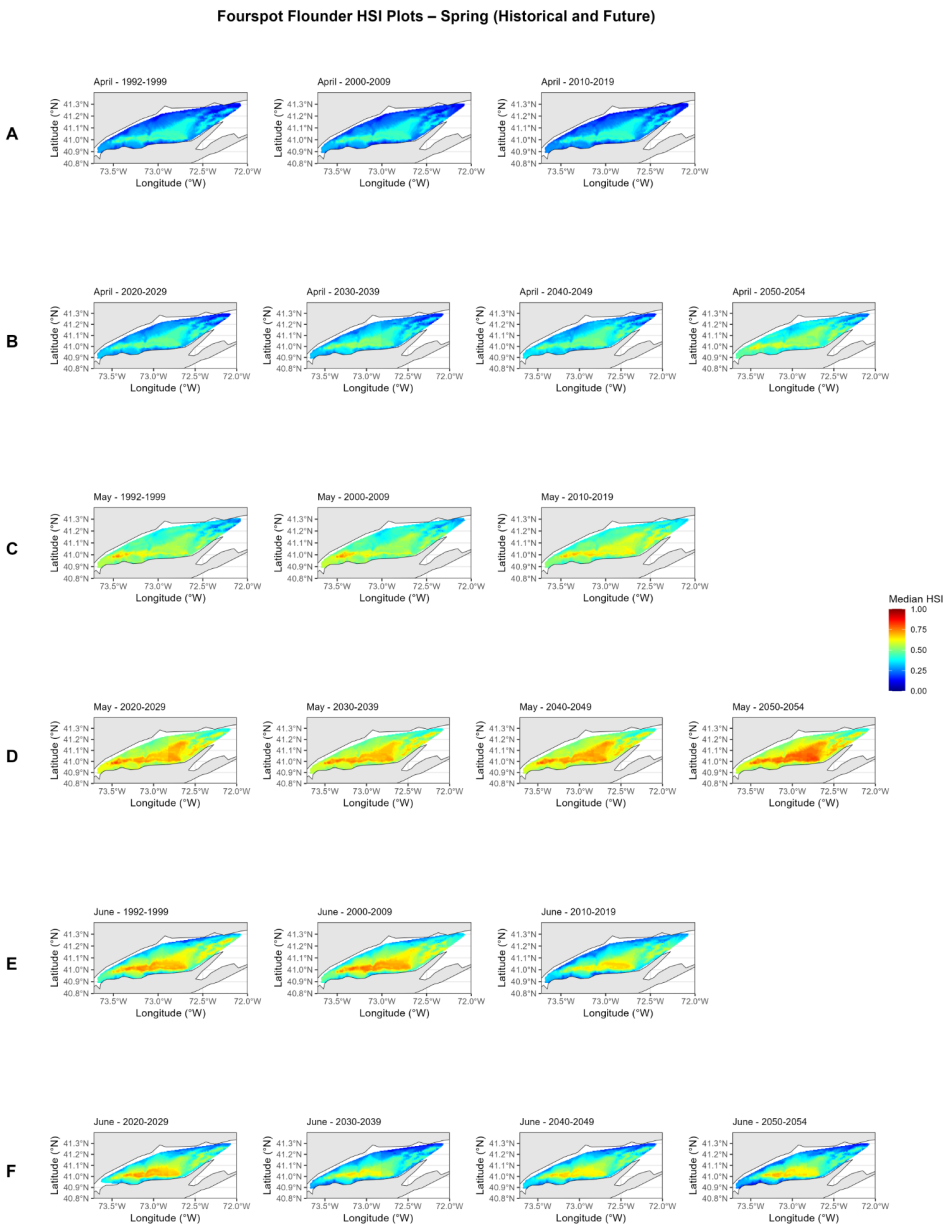


Fig. 38. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Fourspot Flounder. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

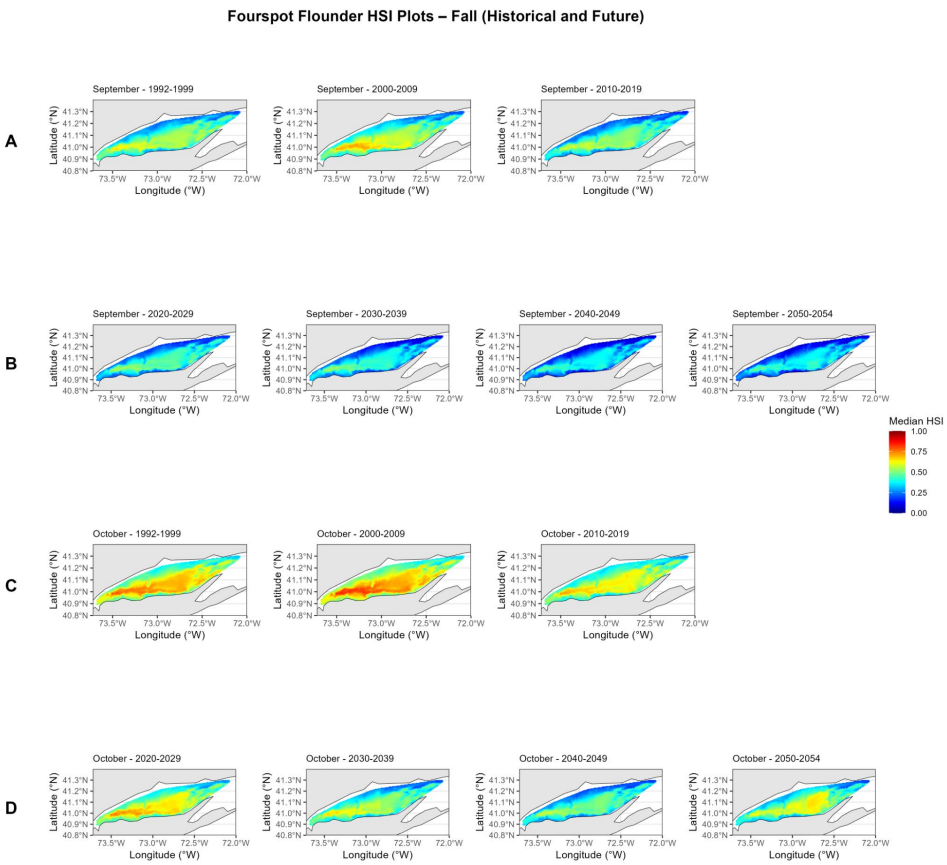


Fig. 39.Historical (A, C) and future (B, D) fall habitat suitability for Fourspot Flounder. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Fourspot flounder HSI results showed moderate seasonal variation across the Long Island Sound, with generally higher suitability during spring than fall (Figs. 38-39). Spatial patterns were broadly distributed across the central Sound in most months, with lower suitability along nearshore coastal areas. Historically, spring suitability remained largely stable across April and May, with relatively consistent spatial extent and median HSI values across the decades (Fig. 38). In contrast, June suitability declined over time, with reduced areas of moderate-to-high suitability evident in the most recent time period. Fall HSI results showed increasing suitability in September during 2000-2009, with expanded areas of suitability across the central Sound, however this increase was followed by a decline in the most recent (2019-2019) part of the time series (Fig. 39). October showed similar variability but remained moderate overall, with no consistent long term directional trend across decades.

Future projections indicate continued seasonal differentiation. In spring, April and May suitability increases, with expanded areas of moderate to high suitability projected through the mid-century. In contrast, June suitability declines further under future climatic conditions. Fall projections show slight decreases in suitability in both September and October, with reduced spatial extent of moderate suitability by mid-century (Fig. 39). No substantial expansion of fall habitat is projected.

Abundance trends show declining spring abundance across the time series (Fig. 12), and this pattern corresponds with the overall decline in habitat suitability observed.

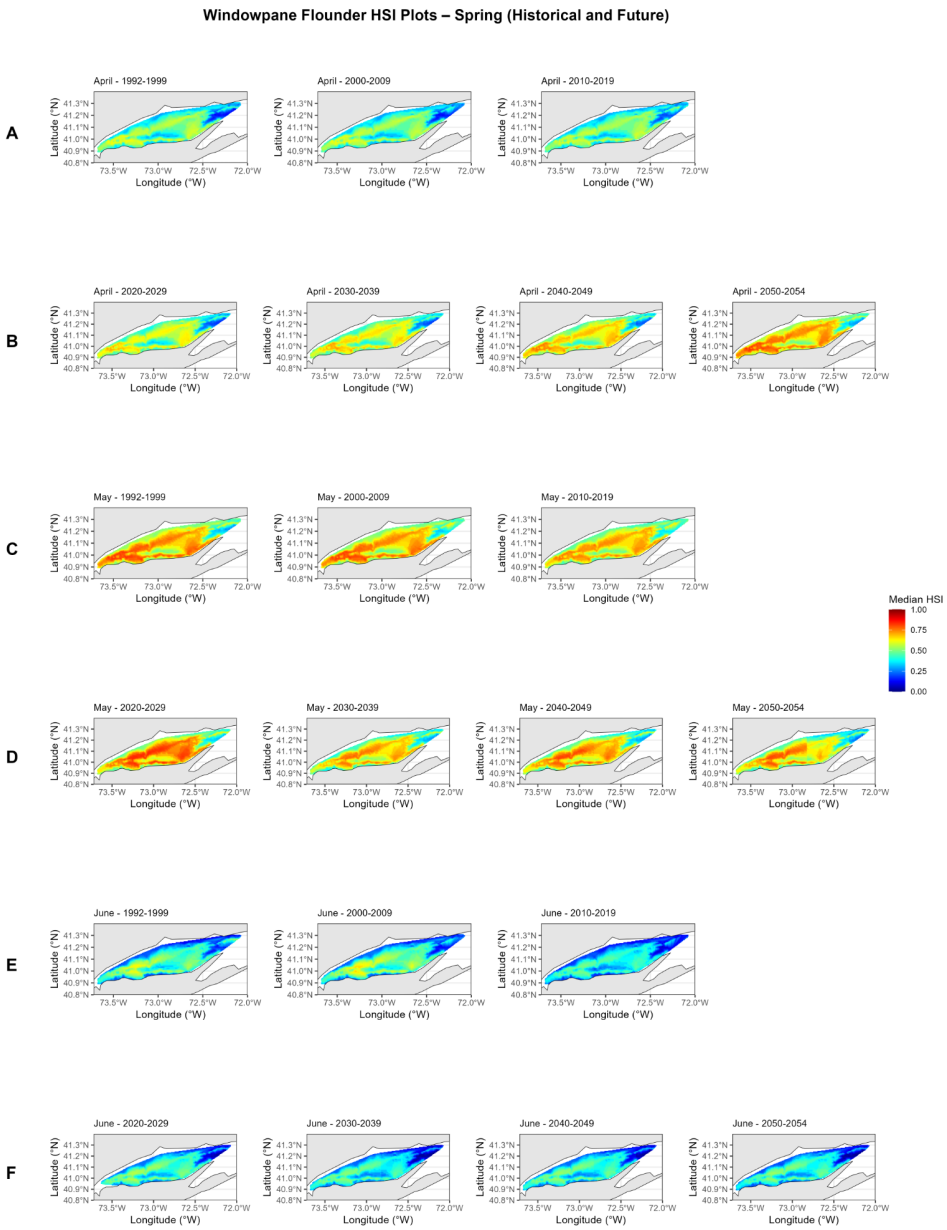


Fig. 40. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Windowpane Flounder. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

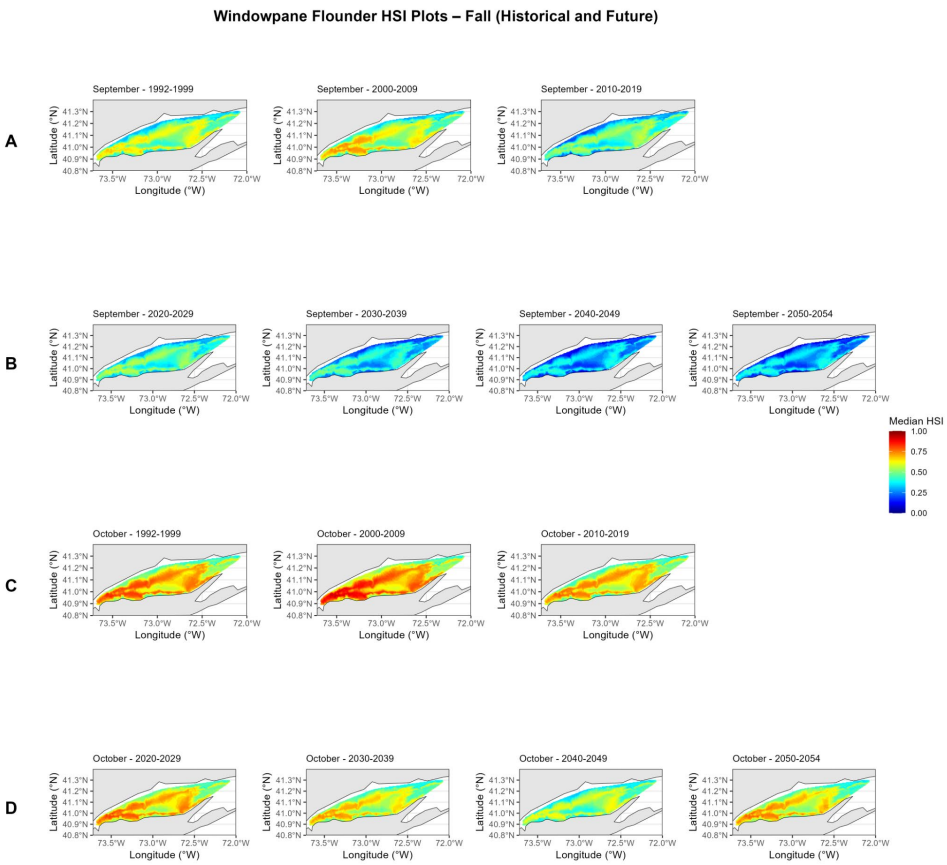


Fig. 41. Historical (A, C) and future (B, D) fall habitat suitability for Windowpane Flounder. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Windowpane flounder exhibit monthly patterns in habitat suitability, with high suitability occurring during both seasons (Figs. 40-41). The highest suitability was generally observed in May and October, while April and September exhibit more moderate suitability, and June consistently showed relatively lower suitability. Historically, April suitability remained relatively consistent across decades, with moderate suitability distributed throughout the central and western Sound. May displayed the highest overall spring suitability, with extensive areas of high SI values during the 1990s and early 2000s and declines in the most recent part of the time series, with reductions in both the spatial extent and magnitude of highly suitable habitat. In the fall, October consistently showed higher suitability than September, with extensive areas of high suitability across the Sound, particularly during earlier historical decades. Fall suitability declined the most in the most recent historical time period for both months.

Future projections indicate increasing suitability in April, with moderate to high suitability expanding across much of the LIS by the mid-century. Future projections demonstrate that the May suitability remains high, with a spatial contraction towards the middle of the Sound by the end of mid-century. Projected fall suitability declines across both months. September remains relatively moderate but does not show expansion of suitable habitat, while October exhibits reductions in highly suitable areas compared to historical patterns.

Observed abundance patterns indicate that windowpane flounder are rarely encountered in fall surveys and have experienced declining spring abundance since the 1990s with very low abundance observed after 2000 (Fig. 13). These abundance patterns correspond with the overall decline in habitat suitability observed in late spring and fall months.

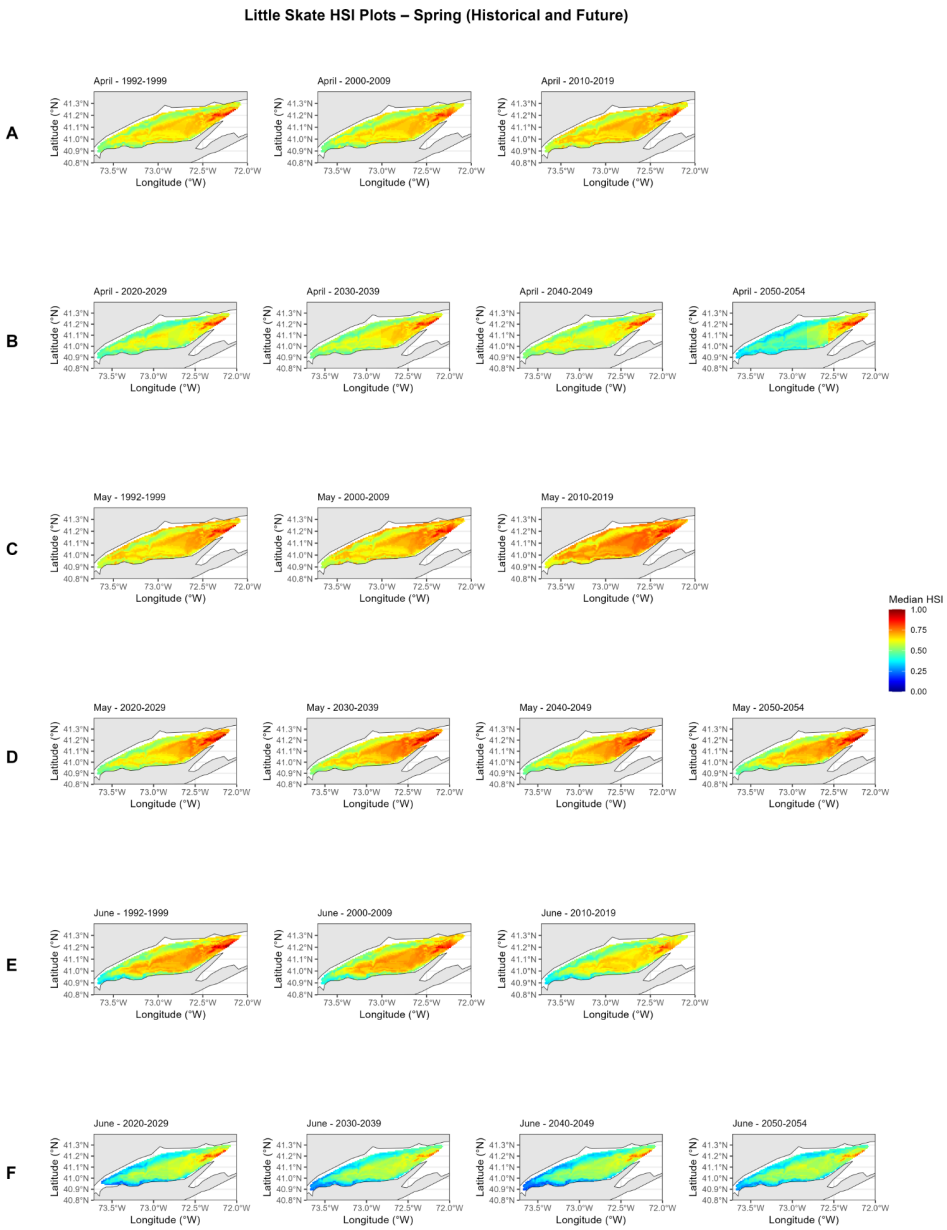


Fig. 42. Historical (A, C, E) and future (B, D, F) spring habitat suitability for Little Skate. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

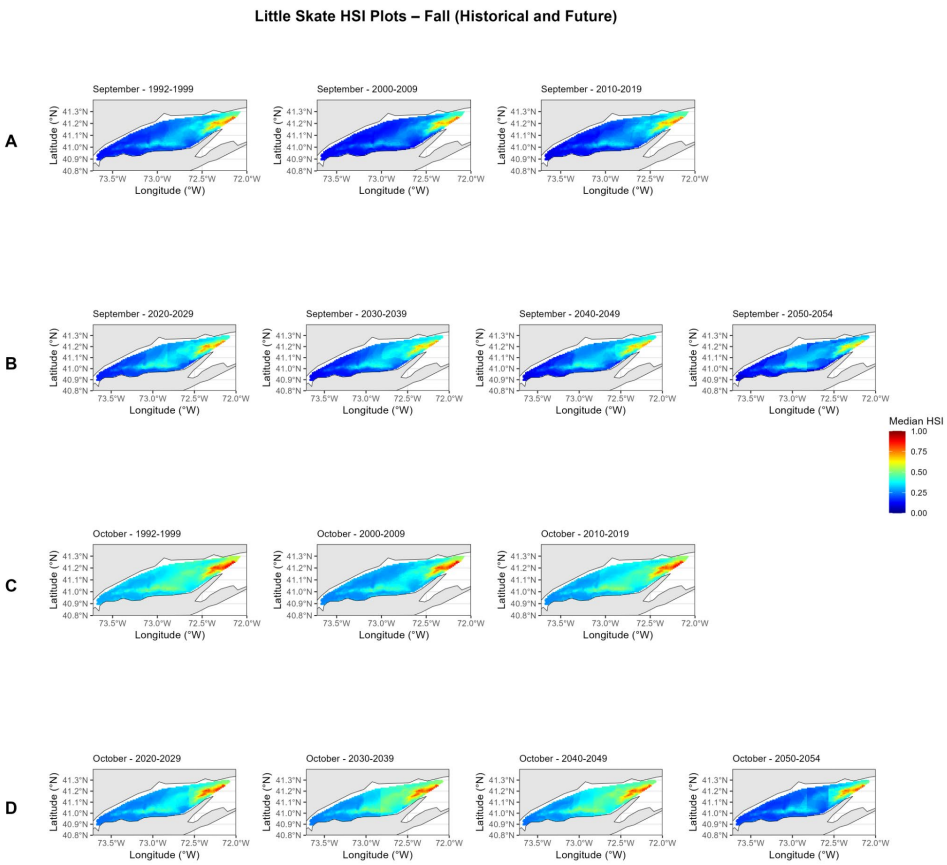


Fig. 43. Historical (A, C) and future (B, D) fall habitat suitability for Little Skate. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

Little skate habitat suitability shows strong seasonal differences, with higher suitability during spring months compared to the fall (Figs. 42-43). Across the historical period, May displayed the highest suitability values, followed by April, while June exhibited lower suitability relative to the earlier spring months. Suitable habitat during spring was broadly distributed across much of the Sound but was consistently highest in the eastern portion of the Long Island Sound across decades.

In fall, overall suitability was lower than in spring. September showed the lowest suitability values, while October has slightly higher suitability with small areas of moderate to high suitability occurring in the eastern Sound. Fall suitability remained relatively stable across historical decades, with persistent pockets of higher suitability in the eastern region.

Future projections indicate declining suitability across all spring months. Projected fall suitability remains relatively stable compared to spring but does show decreases in both months. September continues to have low suitability across most of the Sound, while October retains localized areas of moderate suitability in the eastern Sound. Observed abundance patterns indicate declines in both spring and fall abundance after the 1990s (Fig. 14). These patterns are consistent with overall reduction in suitable habitat observed in spring months, and the low suitability values during fall.

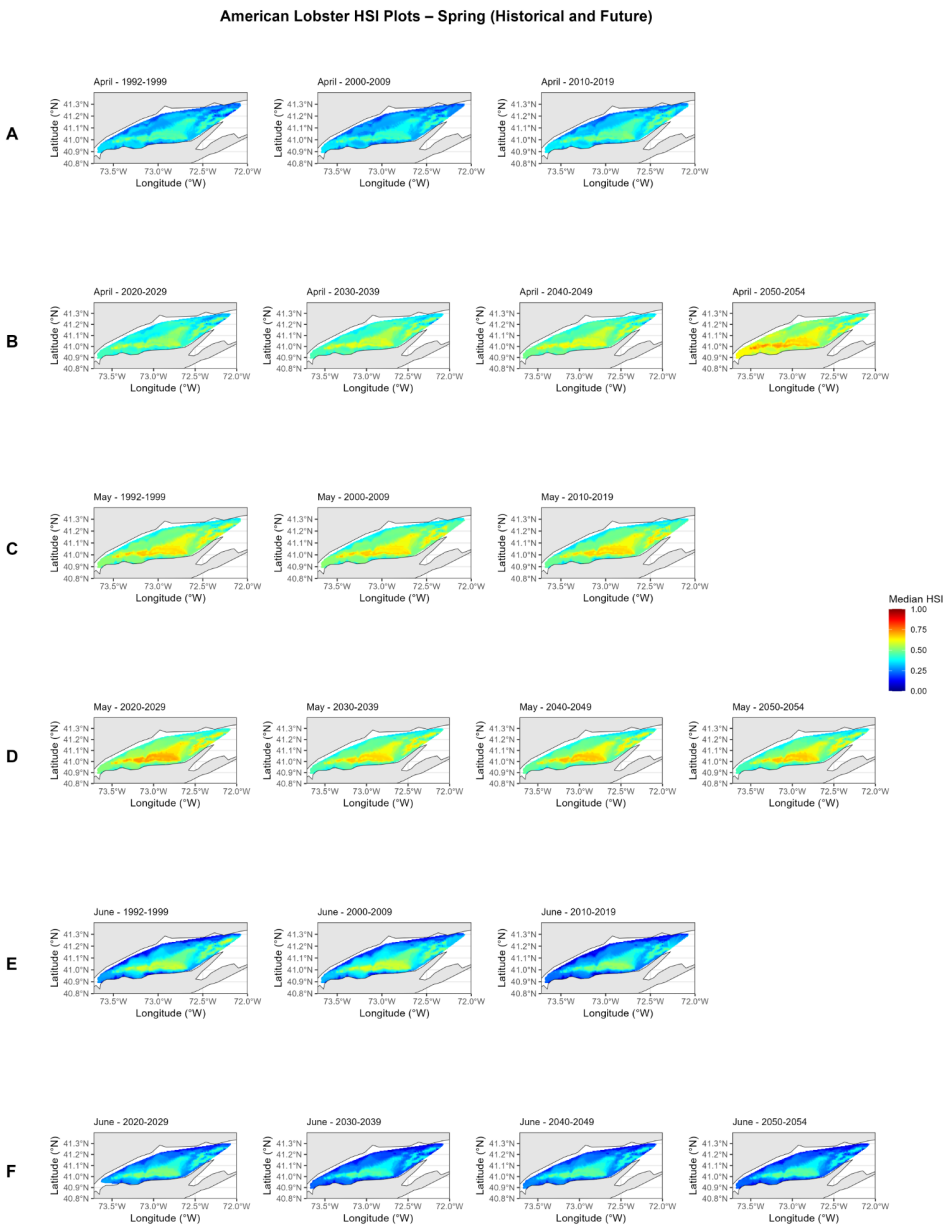


Fig. 44. Historical (A, C, E) and future (B, D, F) spring habitat suitability for American Lobster. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

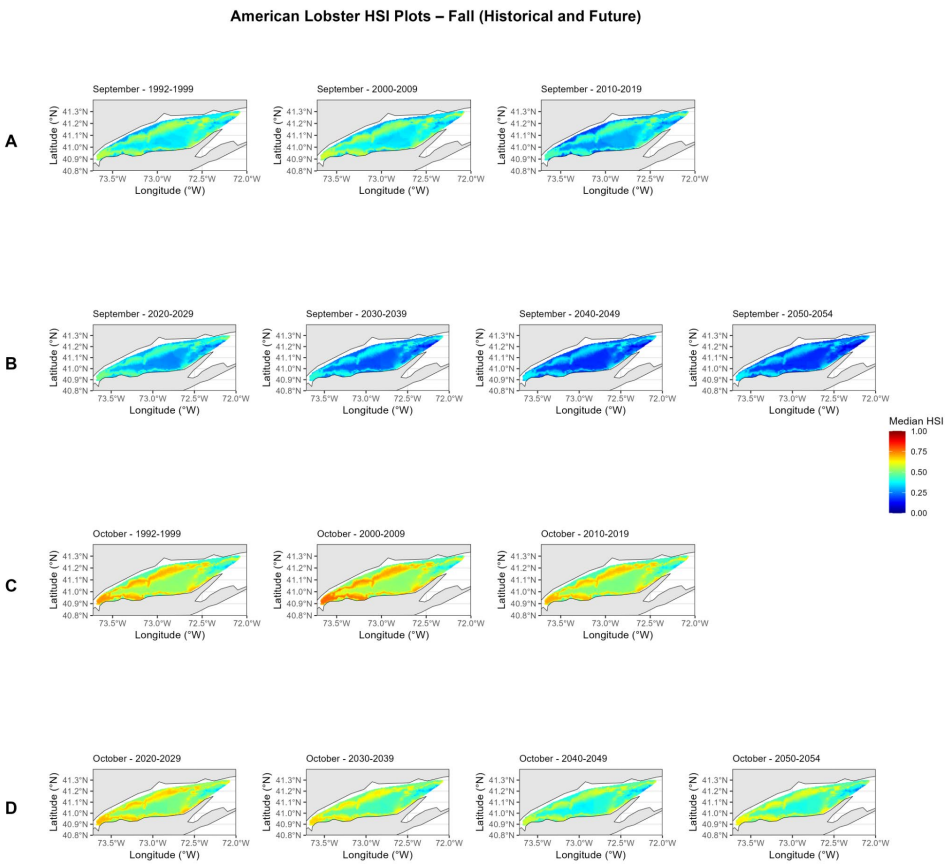


Fig. 45. Historical (A, C) and future (B, D) fall habitat suitability for American Lobster. Historical: 1992-2019; Future: 2020-2029, 2030-2039, 2040-2049, and 2050-2054 under SSP5-8.5 high-emissions scenario.

American lobster exhibited similar spatial patterns of habitat suitability across months, with the highest suitability consistently being in May and October throughout the historical period (Figs. 44-45). April and September showed moderate suitability across much of the Sound, while June consistently displayed lower suitability relative to the other spring months. Historically, May showed the highest suitability during spring, with moderate to high suitability distributed broadly across the Sound. April showed similar spatial patterns but with slightly lower overall suitability. In contrast, June suitability was consistently lower and more spatially limited compared to earlier spring months. In fall, October displayed the highest suitability values across decades, while September showed moderate suitability across much of the Sound.

Future projections indicate relatively stable suitability across most spring months. April and May maintain similar spatial patterns of moderate suitability through mid-century. However, June suitability declines in future decades, with reductions in both the magnitude and spatial extent of suitable habitat. Projected fall suitability decreases in both September and October relative to historical conditions. October remains the most suitable fall month overall but shows reduced areas of high suitability in later projected decades.

References

Behan, J.T., Hodgdon, C.T., and Chen, Y. 2022. Scale-dependent assumptions influence habitat suitability estimates for the American lobster (Homarus americanus): Implications for a changing Gulf of Maine. Ecol. Model. **470**: 110030.

Fogarty, M., Incze, L., Hayhoe, K., Mountain, D., and Manning, J. 2008. Potential climate change impacts on Atlantic cod (Gadus morhua) off the northeastern USA. Mitig. Adapt. Strateg. Glob. Chang. **13**(5): 453-466.

Hare, J.A., Manderson, J.P., Nye, J.A., Alexander, M.A., Auster, P.J., Borggaard, D.L., Capotondi, A.M., Damon-Randall, K.B., Heupel, E., and Mateo, I. 2012. Cusk (Brosme brosme) and climate change: assessing the threat to a candidate marine fish species under the US Endangered Species Act. ICES J. Mar. Sci. **69**(10): 1753-1768.

Linner, R.M., and Chen, Y. 2024. Evaluating the spatial transferability of habitat suitability models: implications for conservation and management. Can. J. Fish. Aquat. Sci. **81**(5): 589-599.

Tanaka, K., and Chen, Y. 2016. Modeling spatiotemporal variability of the bioclimate envelope of Homarus americanus in the coastal waters of Maine and New Hampshire. Fish Res. **177**: 137-152.

Torre, M.P., Tanaka, K.R., and Chen, Y. 2019. Development of a climate-niche model to evaluate spatiotemporal trends in Placopecten magellanicus distribution in the Gulf of Maine, USA. J. Northwest Atl. Fish. Sci. **50**: 37-50

Objective 4: Evaluate impacts of changes on the monitoring and management of the LIS fish community

Methods

To quantify changes in habitat suitability through time and identify potential areas of thermal refuge for the cold-adapted species, we conducted a grid-cell level comparison of seasonal Habitat Suitability Index (HSI) maps between a defined historical baseline period (2010-2019) and a projected future mid-century period (2040-2049) for each species. Analyses were performed separately by season to account for seasonal differences in habitat use and environmental conditions. Grid-cell comparisons of baseline and projected habitat suitability maps are commonly used in species distribution modeling to quantify habitat persistence, loss, and expansion under climate change (Cheung et al. 2009; Franklin 2010; Hollowed et al. 2013; Jones and Cheung 2015).

For each grid cell (n = 2,789), seasonal HSI values were classified into three suitability categories using predefined thresholds: high (HSI ≥ 0.7), moderate (0.3 ≤ HSI < 0.7), and low/unsuitable (HSI < 0.3). We then compared historical and future classifications for each grid cell to create a full suitability transition matrix, resulting in nine possible suitability transitions (e.g., High to High, High to Moderate, Moderate to Low). This category framework captures the complete spectrum of suitability shifts between time periods and allows for detailed spatial evaluation of habitat stability, degradation, and improvement.

In addition to the full transition matrix, we generated a condensed classification focused specifically on changes in high suitability habitat (HSI ≥ 0.7). Grid cells were categorized as: persistent high suitability (High to High), loss of high suitability (High to Moderate/Low), gain of high suitability (Moderate/Low to High), or never highly suitable (Moderate/Low to Moderate/Low). This condensed framework emphasizes changes in core habitat areas for the cold-adapted species that may function as climatic refugia or emerging suitable habitat under projected environmental conditions. All classifications were performed at the grid-cell level, allowing for spatially explicit mapping of habitat contraction, expansion, persistence, and

redistribution under future climate scenarios.

Results

Across the cold-adapted species, changes in habitat suitability generally reflected limited expansion of highly suitable habitat and widespread persistence of moderate suitability conditions across much of the LIS. For several species, including winter flounder, fourspot flounder, and American lobster, most of the Sound remained classified as never highly suitable habitat under both historical and projected conditions, with few or no areas exceeding the high-suitability threshold (HSI ≥ 0.7). In these cases, projected changes were primarily expressed as transitions between moderate and low suitability classes.

In contrast, some species exhibited shifts in highly suitable habitat, particularly during spring. Spotted hake showed the largest expansion of highly suitable habitat, with substantial areas of the western and central Sound transitioning from moderate to high suitability. Windowpane flounder and winter flounder also showed modest gains in high suitability during spring, although these changes were spatially limited. Little skate exhibited the most pronounced loss of historically suitable habitat, with a contraction of high-suitability areas in the central Sound and persistence remaining in the eastern Sound.

Seasonal differences were also evident across species. Spring projections generally showed greater changes in suitability classes, including both gains and losses of highly suitable habitat, whereas fall projections were more stable, with most areas remaining within the same suitability class between historical and projected periods. Collectively, these results suggest that changing environmental conditions are likely to result in species-specific redistributions of suitable habitat within the LIS, with most changes occurring as shifts between moderate and high suitability rather than emergence of new highly suitable habitat for the cold-adapted species.

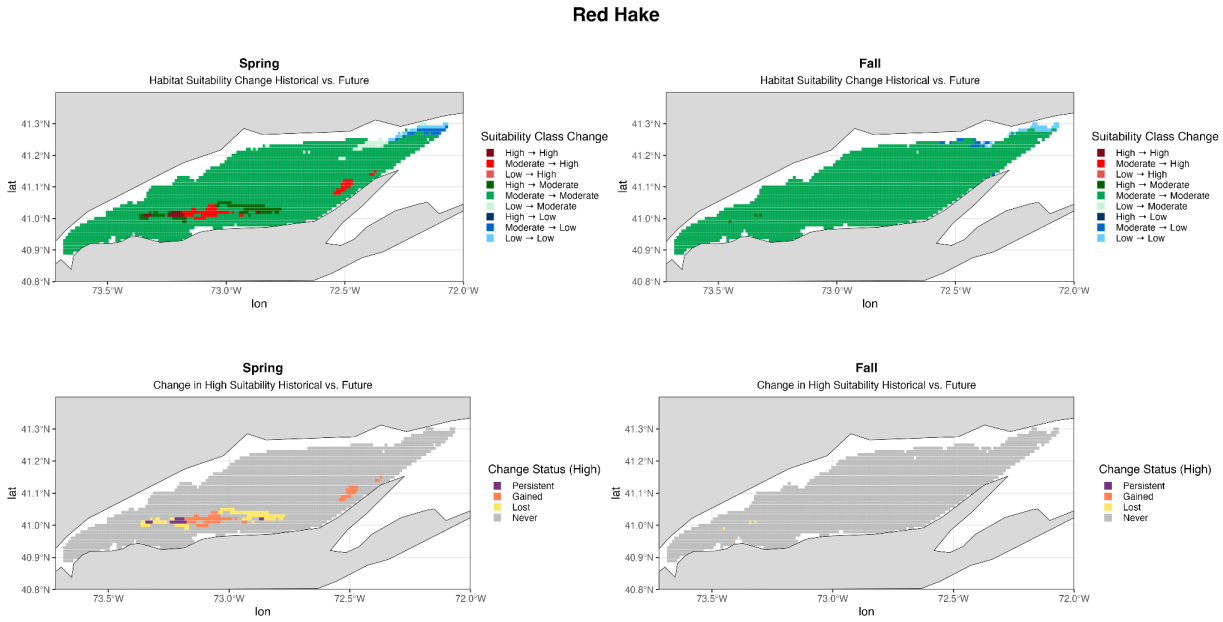


Fig. 46. Seasonal habitat suitability transitions for Red Hake comparing historical (2010-2019) and future (2040-2049) conditions. The top row shows changes in suitability class; bottom row shows persistence, gains, and losses of high-suitability habitat (HSI ≥ 0.7).

For red hake, changes between historical and future habitat suitability indicate that during the spring most of the LIS will remain moderately suitable (0.3 ≤ HSI < 0.7), while pockets of the southwest and southeast LIS become highly suitable, and portions of the easternmost LIS become unsuitable (Fig. 46). Focusing on changes in highly suitable habitat during the spring, only 2.8% of the LIS gained high suitability, 2.99% lost high suitability, and most of the LIS (93.59%) was never highly (HSI ≥ 0.7) suitable habitat (Fig. 46, Table S1). Similar trends are reflected in the fall, with much of the LIS remaining moderately suitable and small areas of the northeast LIS transitioning from moderate (0.3 ≤ HSI < 0.7) to low (HSI < 0.3) suitable habitat (Fig. 46). When looking at changes in high suitability habitat, 99.88% of the LIS was never highly suitable, and in the western LIS there was a 0.12% loss of highly suitable habitat (Fig. 46, Table S1).

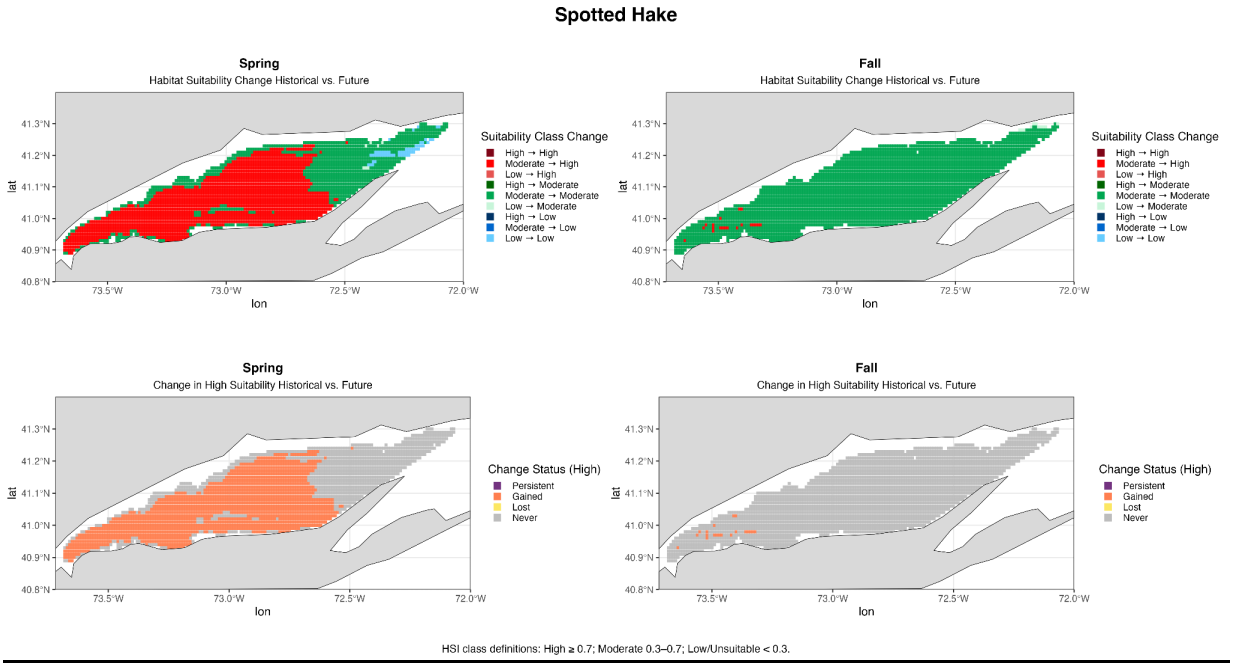


Fig. 47. Seasonal habitat suitability transitions for Spotted Hake comparing historical (2010-2019) and future (2040-2049) conditions. The top row shows changes in suitability class; bottom row shows persistence, gains, and losses of high-suitability habitat (HSI ≥ 0.7).

Comparison of historical and future spotted hake habitat suitability, show that in the spring, large portions of the western and central LIS transition from moderate (0.3 ≤ HSI < 0.7) to high (HSI ≥ 0.7) suitability. During the spring, the eastern LIS and along the coasts remains moderately suitable habitat (Fig. 47). These transitions in habitat classes are reflected by 61.9% of the LIS gaining high suitability habitat, no loss of high suitability, and less than 40% of the LIS was never highly suitable (Fig. 47, Table S2). In contrast, during the fall almost the entire LIS remains moderately suitable with pockets of habitat transitioning from moderate to high suitability in the western LIS (Fig. 47). Only 0.79% of the LIS gained high suitability habitat, while most of the LIS (99.21%) was never highly suitable. Between the historical and future period, there were no areas of persistent high suitability (Fig. 47, Table S2).

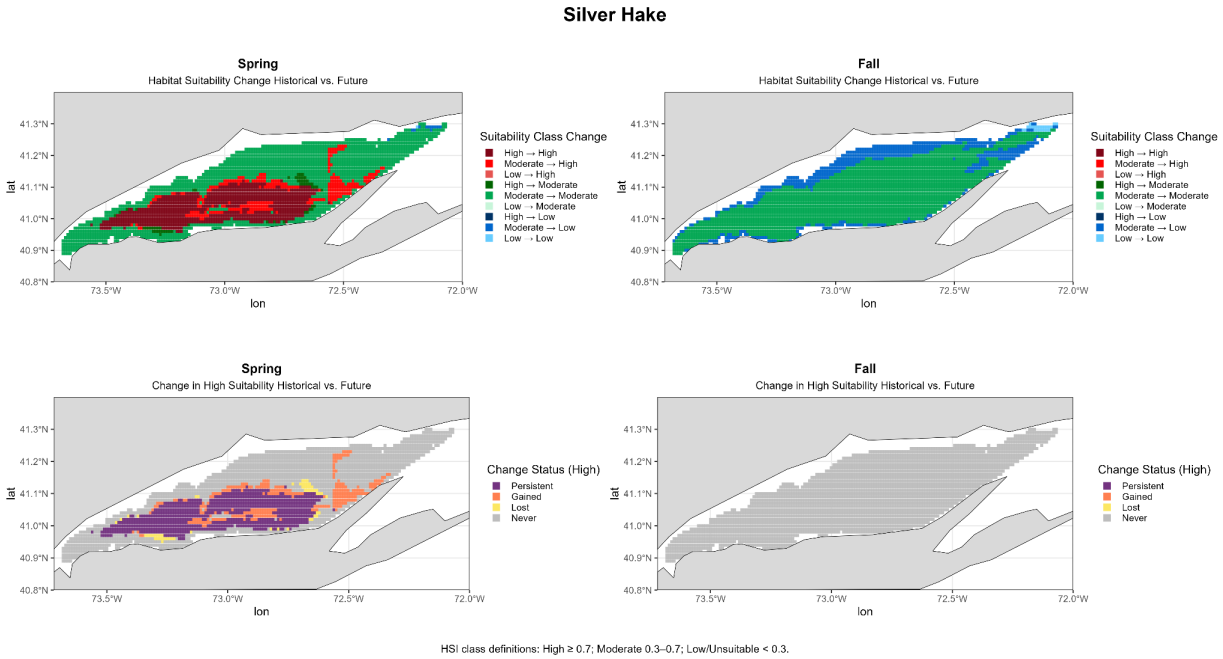
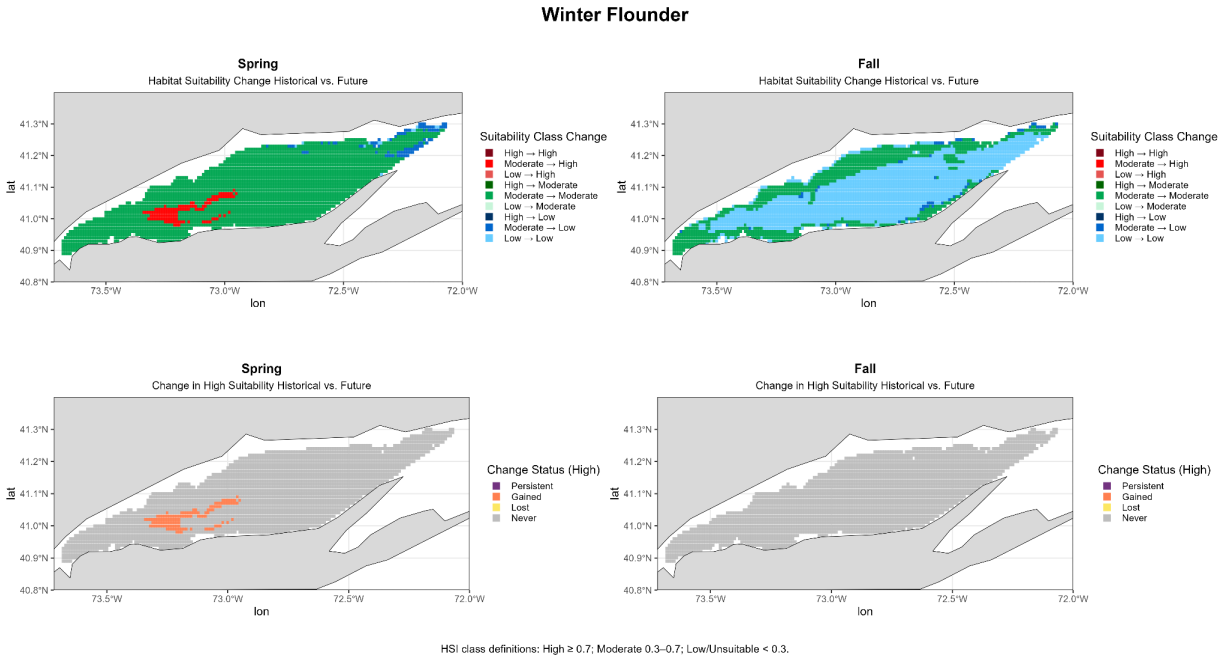


Fig. 48. Seasonal habitat suitability transitions for Silver Hake comparing historical (2010-2019) and future (2040-2049) conditions. The top row shows changes in suitability class; bottom row shows persistence, gains, and losses of high-suitability habitat (HSI ≥ 0.7).

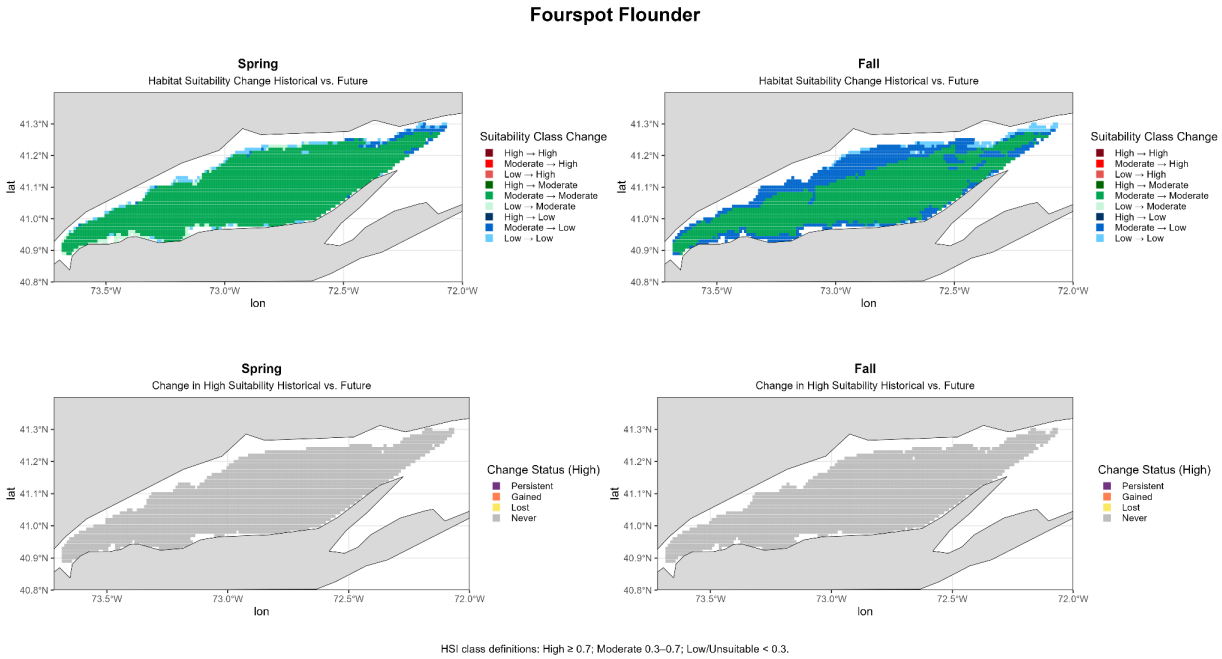
Comparison of historical and future silver hake habitat suitability demonstrates some changes in suitability classes across the LIS. During spring, most of the Sound remains within the same suitability class between historical and projected periods, with moderate suitability persisting across most of the coastal and eastern LIS, and high suitability persisting in most of the central LIS (Fig. 48). However, portions of the central and eastern LIS show changes from moderate to high suitability (Fig. 48). These transitions correspond to 10.92% of the Sound gaining high suitability habitat, while 58.49% of the Sound was never highly suitable, 28.33% was persistently suitable, and 2.25% of highly suitable habitat was lost (Fig. 48, Table S3). Fall projections also show little change in suitability classes across most of the LIS, with sustained moderate suitability, although some transitions from moderate to low suitability occur in the coastal LIS, and a small portion of the northeastern LIS remains in the low suitability class (Fig. 48). Despite these small shifts, no areas gained, lost, or maintained persistent high suitability habitat, and 100% of the Sound remained classified as never highly suitable (Fig. 48, Table S3).



HSI class definitions: High ≥ 0.7; Moderate 0.3–0.7; Low/Unsuitable < 0.3.

Fig. 49. Seasonal habitat suitability transitions for Winter Flounder comparing historical (2010-2019) and future (2040-2049) conditions. The top row shows changes in suitability class; bottom row shows persistence, gains, and losses of high-suitability habitat (HSI ≥ 0.7).

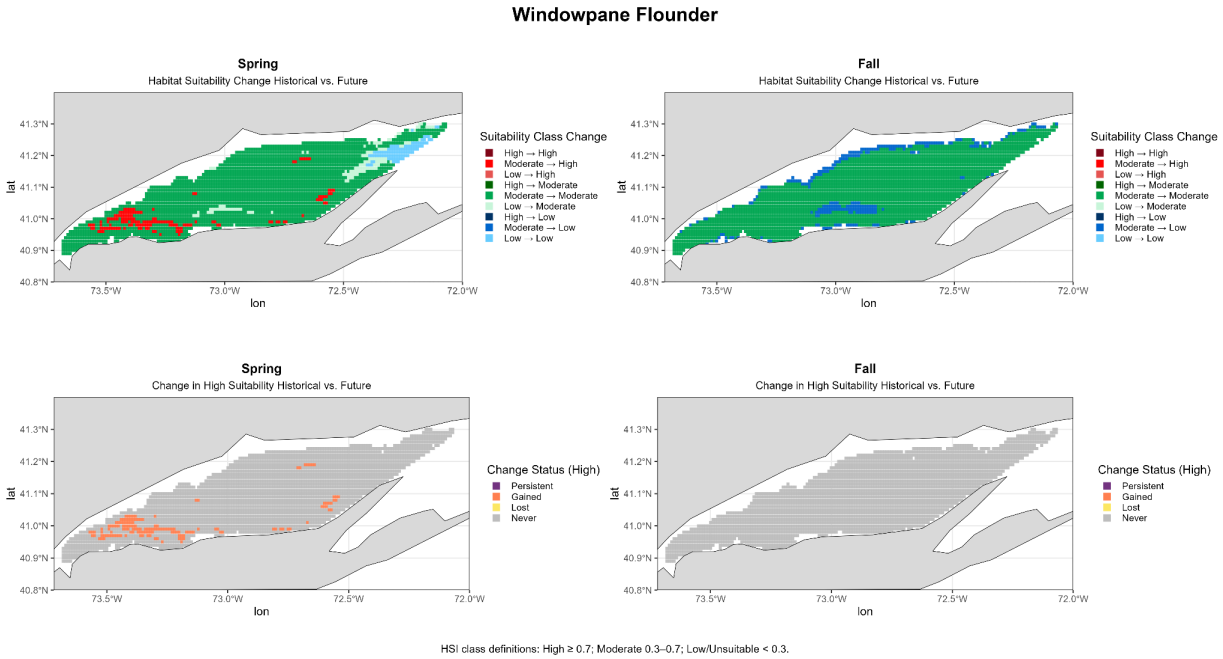
Comparison of historical and future winter flounder habitat suitability indicates limited change in suitability classes across the LIS. During spring, most of the Sound remains within the same “Moderate’ suitability class between historical and projected periods, with small areas of the western and central sound transitioning to higher suitability, and small portions of the eastern Sound transitioning to lower suitability (Fig. 49). These transitions are reflected by 4.7% of the Sound gaining high suitability habitat, while 95.3% of the Sound was never highly suitable, and no areas experienced loss or persistence of high suitability (Fig. 49, Table S4). In contrast, fall projections show declines in suitability in the eastern Sound, where areas historically classified as moderate transition to low suitability under projected conditions (Fig 49.) Despite localized decreases in moderate suitability, no areas historically classified as highly suitable were lost or gained, and 100% of the Sound remained classified as highly suitable habitat based on the high-suitability threshold (Fig. 49, Table S4).



HSI class definitions: High ≥ 0.7; Moderate 0.3–0.7; Low/Unsuitable < 0.3.

Fig. 50. Seasonal habitat suitability transitions for Fourspot Flounder comparing historical (2010-2019) and future (2040-2049) conditions. The top row shows changes in suitability class; bottom row shows persistence, gains, and losses of high-suitability habitat (HSI ≥ 0.7).

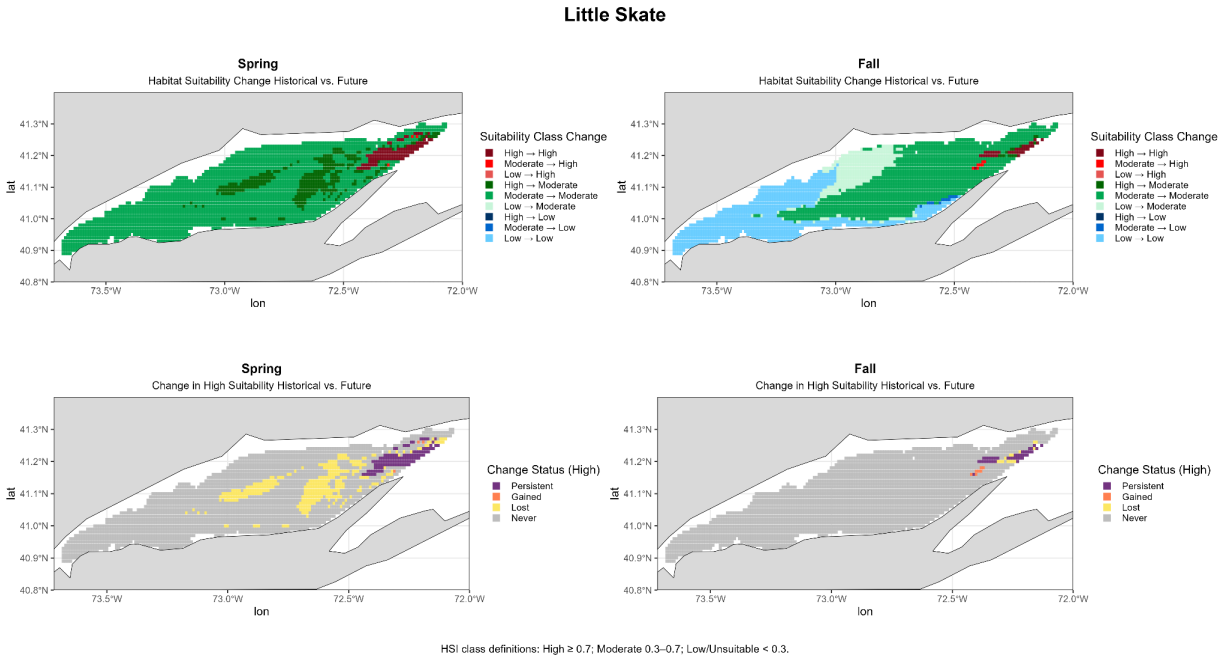
Comparison of historical and future fourspot flounder habitat suitability indicates that most areas of the Long Island Sound remain within the same suitability class between periods. During spring, most of the Sound remains classified as moderate suitability, with only minor transitions to lower suitability along portions of the northern and eastern sound (Fig. 50). Despite these small shifts, no areas of the Sound transitioned into or out of high suitability habitat and 100% of the Sound was classified as never highly suitable (Fig 50, Table S5). Similarly, fall projections show limited change in suitability classes across the Sound. Most areas remain moderately suitable, with more coastal portions of the sound transitioning from moderate to low suitability under projected conditions (Fig. 50). As with spring, no areas gained, lost, or maintained persistent high suitability habitat, and the entire Sound remained classified as never highly suitable (Fig. 50, Table S5).



HSI class definitions: High ≥ 0.7; Moderate 0.3–0.7; Low/Unsuitable < 0.3.

Fig. 51. Seasonal habitat suitability transitions for Windowpane Flounder comparing historical (2010-2019) and future (2040-2049) conditions. The top row shows changes in suitability class; bottom row shows persistence, gains, and losses of high-suitability habitat (HSI ≥ 0.7).

Comparison of historical and future windowpane flounder habitat suitability demonstrates some changes in suitability classes across the LIS. During spring, most of the Sound remains within the same suitability class between historical and projected periods, with moderate suitability persisting across much of the central Sound (Fig. 51). However, portions of the western and central Sound transition from moderate to high suitability under projected conditions. These transitions correspond to 5.64% of the Sound gaining high suitability habitat, while 94.36% of the Sound was never highly suitable, and no areas experienced loss of high suitability or persistence (Figure. 51, Table S6). In contrast, fall projections show little change in suitability classes across the Sound. Most areas remain moderately suitable, with some transitions from moderate to low suitability occurring in the central Sound and along the coasts (Fig. 51). Despite these small shifts, no areas gained, lost, or maintained persistent high suitability habitat, and 100% of the Sound remained classified as never highly suitable (Fig. 51, Table S6).



HSI class definitions: High ≥ 0.7; Moderate 0.3–0.7; Low/Unsuitable < 0.3.

Fig. 52. Seasonal habitat suitability transitions for Little Skate comparing historical (2010-2019) and future (2040-2049) conditions. The top row shows changes in suitability class; bottom row shows persistence, gains, and losses of high-suitability habitat (HSI ≥ 0.7).

Comparison of historical and projected habitat suitability for little skate indicates notable changes in suitability across the Long Island Sound. In spring, large portions of the central Sound that were historically classified as highly suitable transition to moderate suitability, resulting in a 12.94% loss of highly suitable habitat across the Sound. A small percentage (0.12%) of the Sound gained high suitability between the historical and future periods, and areas of persistent high suitability were concentrated in the eastern portion of the, constituting about 4.28%. Most of the Sound (82.67%) was never classified as highly suitable in either period (Fig. 52, Table S7). In fall, projected changes in high suitability habitat were comparatively minor and remained spatially restricted (Fig. 52). Only 0.55% of grid cells lost high suitability, 0.28% gained high suitability, and 1.59% of the Sound retained persistent high suitability (Table S7). Nearly the entire Sound (97.58%) was never highly suitable in fall across both historical and projected periods (Fig. 52, Table S7).

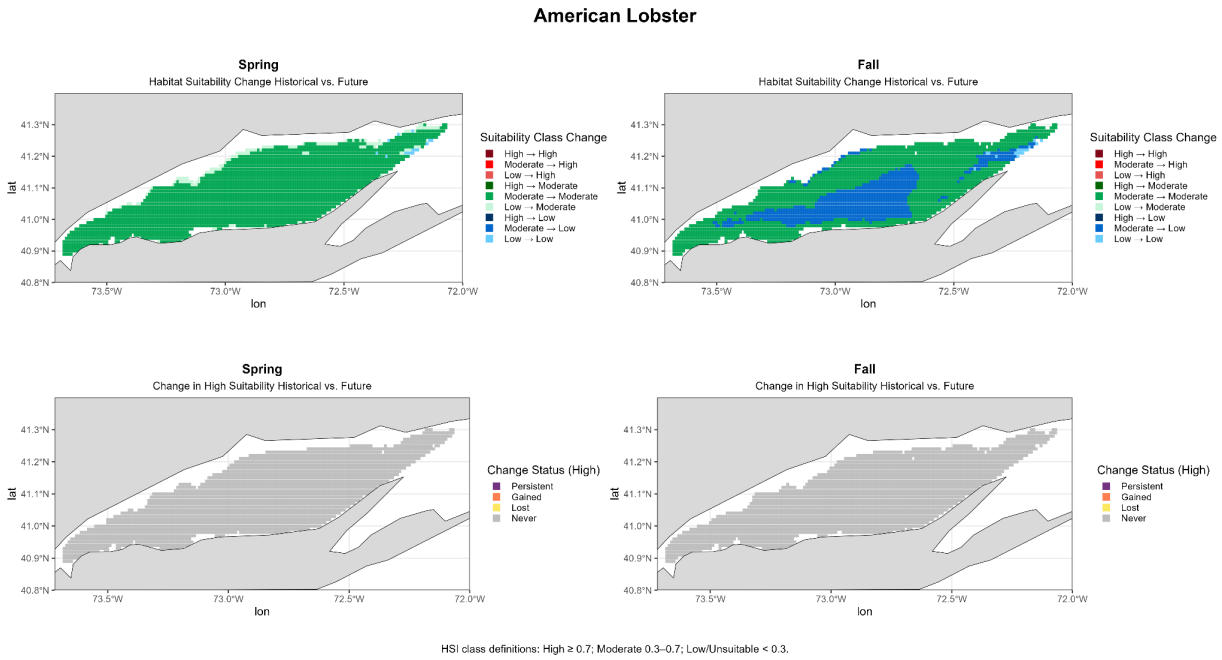


Fig. 53. Seasonal habitat suitability transitions for American Lobster comparing historical (2010-2019) and future (2040-2049) conditions. The top row shows changes in suitability class; bottom row shows persistence, gains, and losses of high-suitability habitat (HSI ≥ 0.7).

Comparison of the historical and projected habitat suitability for American lobster indicates that no areas of the Long Island Sound were classified as highly suitable in either the historical or projected periods for both the spring and fall seasons (Fig. 53, Table S8). Spring showed some minor suitability class changes along the more coastal edges of the Sound with some areas changing from low suitability to moderate and others in the eastern Sound remaining low. In the fall, low areas of suitability in the eastern Sound remained low between the historical and future periods, and a large portion of the central sound shifted from an area of moderate suitability to low suitability.

References

Cheung, W.W., Lam, V.W., Sarmiento, J.L., Kearney, K., Watson, R., and Pauly, D. 2009. Projecting global marine biodiversity impacts under climate change scenarios. Fish Fish. **10**(3): 235-251.

Franklin, J. 2010. Mapping Species Distributions: Spatial Inference and Prediction. Ecology, Biodiversity and Conservation. Cambridge University Press, Cambridge.

Hazen, E.L., Jorgensen, S., Rykaczewski, R.R., Bograd, S.J., Foley, D.G., Jonsen, I.D., Shaffer, S.A., Dunne, J.P., Costa, D.P., and Crowder, L.B. 2013. Predicted habitat shifts of Pacific top predators in a changing climate. Nat. Clim. Chang. **3**(3): 234-238.

Hollowed, A.B., Barange, M., Beamish, R.J., Brander, K., Cochrane, K., Drinkwater, K., Foreman, M.G., Hare, J.A., Holt, J., and Ito, S.-i. 2013. Projected impacts of climate change on marine fish and fisheries. ICES J. Mar. Sci. **70**(5): 1023-1037.

Jones, M.C., and Cheung, W.W. 2015. Multi-model ensemble projections of climate change effects on global marine biodiversity. ICES J. Mar. Sci **72**(3): 741-752.

Objective 5: Engage stakeholders for outreach and feedback to inform ecosystem based management

We coordinated with the co-PIs to develop an outreach program that would include workshops, presentations at local and national conferences, and peer-reviewed papers. Representatives from relevant state agencies were invited to the workshops to provide updates and receive feedback. All PIs worked together to develop strategies using the knowledge and information gained in this project about spatiotemporal changes in habitat quality and species distribution to inform planning and management of the LIS. The summary of outcomes from Objective 5 are presented in sections C5 and C6.

C2. Scientific Abstract:

Estuaries serve as critical transition zones connecting freshwater and marine ecosystems and provide essential habitat for species that rely on seasonal migrations to complete key life-history processes. These migrations are strongly influenced by thermal tolerance, and as climate change accelerates warming in coastal systems, both the composition and seasonal timing of estuarine fish communities are shifting. Long Island Sound (LIS), a semi-enclosed estuary on the east coast of the USA, has experienced rapid warming over the past several decades. Previous work identified a community-level shift from dominance by cold-adapted species in spring and warm-adapted species in fall to a system increasingly dominated by warm-adapted species across both seasons. However, that assessment was conducted more than 15 years ago, and continued climate forcing necessitates an updated, quantitative evaluation.

The overarching objective of this study was to evaluate distributional changes of cold- and warm-adapted species in the climatically altered LIS to inform monitoring and management. Using long-term data from the Connecticut Department of Energy and Environmental Protection Long Island Sound Trawl Survey (1984-2019), we quantified temporal changes in abundance and spatial structure for 15 key species through spatial indicators, including center of gravity, inertia, positive area, and evenness. We identified key environmental drivers (bottom temperature, bottom salinity, and depth) influencing habitat use and developed habitat suitability index (HSI) models to hindcast historical conditions, assess contemporary habitat, and forecast future suitability under a high-emissions climate scenario (SSP5-8.5). Results indicate clear divergence between thermal guilds. Warm-adapted species generally exhibited increasing abundance and spatial occupancy, with stable or expanding suitable habitat under projected warming. In contrast, most cold-adapted species showed declining abundance, spatial contraction, and reductions in highly suitable habitat, particularly in the western LIS. Projections suggest further concentration of cold-adapted species into limited areas of persistent suitability, highlighting potential thermal refuges and areas vulnerable to habitat loss.

By integrating spatial indicators with climate-informed habitat modeling, this project provides a spatially explicit framework for anticipating distributional shifts, identifying emerging habitat, and prioritizing monitoring and conservation efforts. These results support adaptive management strategies that account for ongoing warming and facilitate proactive, ecosystem-based decision-making in the LIS.

C3. Problems Encountered: None

C4. New Research Directions: None

C5. Outreach & Interactions:

A workshop was held at Stony Brook University School of Marine and Atmospheric Sciences on July 22, 2025, with both virtual and in-person attendees. Relevant stakeholder groups were invited to attend the workshop, including the New York State Department of Environmental Conservation (NYSDEC), University of Connecticut, New York Sea Grant (NYSG), and the Long Island Sound Study Climate Change and Sentinel Monitoring Workgroup. The workshop agenda included the following: (1) review of project objectives, deliverables, and relevant project timelines; (2) progress update on the spatial indicator analysis and results; (3) overview of parameterized habitat suitability index models and initial results; (4) presentation of next steps in the project and approach; and (5) group discussion and feedback on next steps and approach.

An article titled "Research Looks at Climate Change's Influence on the Sound's Fish Populations" was published in February, 2024 by the Long Island Sound Partnership as part of their Sound Spotlight. The segment gave an overview of the project and highlighted how the results can provide valuable information to management and monitoring programs in the LIS. In addition, Robyn Linner represented the research team to coordinate with Paul Focazio for a News 7 segment (https://abc7ny.com/13312894/) which aired Sunday May 28, 2023.

C6. Presentations & Publications:

Subsections of this larger grant were presented at various national and international conferences. A poster was presented at the 2026 Long Island Natural History Conference in Stony Brook, NY and the 2024 International Council for the Exploration of the Seas (ICES) Annual Science Conference in Gateshead, United Kingdom. Oral presentations were given at the 2025 New York Chapter of the American Fisheries Society Annual Meeting, as a part of the 2025 Long Island Sound Seminar Series at Southern Connecticut State University, the 2024 Long Island Sound Research Conference, and the 2024 Long Island Sound Study Climate Change & Sentinel Monitoring Workgroup- Fish Communities meeting.

A manuscript titled "Evaluating spatial and temporal dynamics of cold- and warm-adapted fish in a changing Long Island Sound" was prepared and submitted to the peer-reviewed journal Ecological Informatics where it is currently under review. This manuscript compares the spatial indicators developed for cold-adapted winter flounder with warm-adapted summer flounder, as they are uniquely positioned for comparison due to their key morphological similarities, life history differences, and different distributional changes over the past few decades. A second manuscript is in preparation, examining changes in historical and future habitat suitability for the cold-adapted fish species.

Publications: None

Presentations:

1. Ober, C., Arsenault, S., Praisner, S., and Chen, Y. 2026. Evaluating Changes in Suitable Habitat and Biogeography of Species in a Changing Long Island Sound. Long Island Natural History Conference, Seatuck Environmental Association. Stony Brook, NY, January 27. Poster presentation.

The Long Island Sound (LIS) is a semi-enclosed estuary on the east coast of the USA, where changes in species abundance and migration timing have been associated with climate-induced changes, as certain species have a lower thermal tolerance (cold-adapted) compared to others (warm-adapted). In recent decades, the LIS has shifted from a fish community dominated by cold-adapted species in the spring and warm-adapted species in the fall to a fish community dominated by warm-adapted species in both seasons, and the drivers of this change need to be explored. The overarching objective of this study is to evaluate distributional changes of cold- and warm-adapted species in the climatically altered LIS to inform monitoring and management. For 15 selected cold- and warm-adapted species, we address the following objectives: 1) understand changes in abundance and distribution over time by calculating spatial indicators including center of gravity, positive area, and evenness; 2) identify key environmental variables influencing habitat use through literature review and statistical models; 3) develop habitat suitability index models to hind-, now-, and forecast changes in suitable habitat; 4) evaluate the impacts of these changes on the monitoring and management of the LIS fish community; and 5) engage with stakeholders for outreach and feedback to inform ecosystem-based management. We hypothesize that the spatial distribution of cold-adapted species as well as their suitable habitat is contracting and becoming patchier over time while warm-adapted species' suitable habitat is expanding. The results of this study will help identify species that are experiencing the most change (both positive and negative), areas of thermal refuge for cold-adapted species, and whether these changing spatial patterns may be affecting monitoring and management of fishes in the LIS. This method can be applied to virtually any fisheries system to identify current and predicted changes in the spatial patterns of species to better inform ecosystem-based management of fishes as we move into a climatically uncertain future.

2. Ober, C., Linner, R., Arsenault, S., Braid K., Praisner, S., Gottschall K., McKown, K., Maniscalco, J., and Chen, Y. 2025. Evaluating changes in spatial and temporal dynamics of cold- and warm-adapted fish: winter and summer flounder in a changing Long Island Sound. New York Chapter & Northeastern Division of the American Fisheries Society Annual Meeting. Bolton Landing, NY, February 5-7. Oral presentation.

Species composition in the Long Island Sound (LIS) has shifted significantly over time due to changes in faunal distribution and variable environmental conditions, including climate-induced effects. Historically, LIS fish communities were dominated by cold-adapted species in the spring and warm-adapted species in the fall. However, recent decades have seen a transition to dominance by warm-adapted species year-round, underscoring the need to understand the drivers and implications of these changes. Using winter flounder (*Pseudopleuronectes americanus*), a cold-adapted species, and summer flounder (*Paralichthys dentatus*), a warm-adapted species, as representatives from a larger group of 15 selected cold- and warm-adapted species, we address three key objectives: 1) quantify temporal and spatial shifts in abundance and distribution by calculating spatial indicators, including center of gravity, positive area, inertia, and evenness; 2) identify significant periods of change through Bayesian Change Point (BCP) and Pruned Exact Linear Time (PELT) analyses, shedding light on abrupt versus gradual transitions in spatial and temporal patterns; and 3) evaluate the implications of these changes for monitoring and management strategies in LIS. Our findings provide insights into the ecological shifts occurring in LIS, improving the ability to manage the responses of fish communities to ongoing environmental and climatic changes.

3. Linner, R., Ober, C., Arsenault, S., Braid, K., Praisner, S., Chen, Y., Gottschall, K., McKown, K., and Maniscalco, J. 2025. Evaluating changes in suitable habitat and biogeography of cold- and warm adapted fish species in a changing Long Island Sound to inform ecosystem-based

management. Werth Center for Coastal and Marine Studies Seminar Series at Southern Connecticut State University. New Haven, CT, April 16. Invited oral presentation.

Estuaries function as critical transitional habitats for migratory species, whose seasonal presence is closely linked to thermal preferences and tolerances. As climate change drives sustained increases in water temperature, the timing, duration, and composition of estuarine fish communities are shifting. In Long Island Sound (LIS), these changes have manifested as a restructuring of seasonal community dynamics: a system once characterized by cold-adapted species dominating in spring and warm-adapted species in fall has transitioned toward increasing, and in many cases persistent, dominance of warm-adapted species throughout the year. This study aims to evaluate climate-driven distributional changes of cold- and warm-adapted species in the LIS to support ecosystem-based monitoring and management. Focusing on 15 representative species, our objectives are to: (1) assess spatial and temporal shifts in abundance and distribution using indicators such as center of gravity, positive area, and evenness; (2) identify key environmental drivers of habitat use through literature review and statistical modeling; (3) develop Habitat Suitability Index (HSI) models to hindcast, nowcast, and forecast suitable habitat; and (4) evaluate implications for long-term monitoring and management programs. Outcomes from this work will highlight species most vulnerable to change, identify potential thermal refugia, and assess whether current monitoring strategies remain effective under shifting climate conditions.

4. Linner, R., Ober, C., Arsenault, S., Braid, K., Praisner, S., Chen, Y., Gottschall, K., McKown, K., and Maniscalco, J. 2024. Evaluating changes in suitable habitat and biogeography of species occupying a climatically altered estuarine environment. ICES Annual Science Conference. Gateshead, UK, September 9-12. Poster presentation.

Estuaries connect freshwater and marine systems and provide important habitat for various species undergoing seasonal migrations to carry out their life history processes. A migratory species' entrance into or exit out of an estuary is largely driven by the species' thermal tolerance, and because climate change is rapidly altering water temperatures, the diversity of species present and the timing of their occupation in estuaries is changing. The Long Island Sound (LIS) is a semi-enclosed estuary on the east coast of the USA, where changes in species abundance and migration timing have been associated with climate-induced changes, as certain species have a lower thermal tolerance (cold-adapted) compared to others (warm-adapted). In recent decades, the LIS has shifted from a fish community dominated by cold-adapted species in the spring and warm-adapted species in the fall to a fish community dominated by warm-adapted species in both seasons, and the drivers of this change need to be explored. The overarching objective of this study is to evaluate distributional changes of cold- and warm-adapted species in the climatically altered LIS to inform monitoring and management. For 15 selected cold- and warm-adapted species, we address the following objectives: 1) understand changes in abundance and distribution over time by calculating spatial indicators including center of gravity, positive area, and evenness; 2) identify key environmental variables influencing habitat use through literature review and statistical models; 3) develop habitat suitability index models to hind-, now-, and forecast changes in suitable habitat; 4) evaluate the impacts of these changes on the monitoring and management of the LIS fish community; and 5) engage with stakeholders for outreach and feedback to inform ecosystem-based management. We hypothesize that the spatial distribution of cold-adapted species as well as their suitable habitat is contracting and becoming patchier over time while warm-adapted species' suitable habitat is expanding. The results of this study will help identify species that are experiencing the most change (both positive and negative), areas of thermal refuge for cold-adapted species, and whether these changing spatial patterns may be affecting monitoring and management of

fishes in the LIS. This method can be applied to virtually any fisheries system to identify current and predicted changes in the spatial patterns of species to better inform ecosystem-based management of fishes as we move into a climatically uncertain future.

5. Linner, R., Ober, C., Arsenault, S., Braid, K., Praisner, S., Chen, Y., Gottschall, K., McKown, K., and Maniscalco, J. 2024. Evaluating changes in suitable habitat and biogeography of cold and warm adapted species in a changing Long Island Sound. Long Island Sound Research Conference. Port Jefferson, NY, May 15. Oral presentation.

Species composition in the Long Island Sound (LIS) has not been consistent over time due to diverse patterns in faunal distribution as well as highly variable environmental conditions. Some of these changes in the abundance of cold- and warm-adapted species have been associated with climate-induced changes. In recent decades, the LIS has shifted from a fish community dominated by cold-adapted species in the spring and warm-adapted species in the fall, to a fish community dominated by warm-adapted species in both seasons. The initial work identifying this shift was completed more than 15 years ago, and as climate impacts intensify, more recent analysis is needed. The overarching objective of this study is to evaluate distributional changes of cold- and warm-adapted species in the climatically altered LIS to inform monitoring and management. Specifically, for 15 selected cold- and warm-adapted species, we address the following objectives: 1) understand changes in abundance and distribution over time; 2) identify key environmental variables influencing habitat use; 3) develop models to hind-, now-, and fore-cast changes in suitable habitat and distribution; 4) evaluate the impacts of changes on the monitoring and management of the LIS fish community; and 5) engage with stakeholders for outreach and feedback to inform ecosystem-based management. We hypothesize that the spatial distribution of cold-adapted species is contracting and becoming patchier over time while the distribution of warm-adapted species is expanding. These changes in spatial distribution may help inform more effective monitoring and management of LIS fishes as we move into an uncertain future.

6. Linner, R., and Ober, C. 2024. Evaluating Changes in Suitable Habitat & Distribution. Long Island Sound Study Special Meeting - Fish Communities. January 19. Invited oral presentation.

D. ACCOMPLISHMENTS:

D1. Impacts & Effects:

This project advanced scientific understanding of the historical distributional and habitat changes of warm- and cold-adapted species in the LIS, and how species may be impacted by future warming conditions under a high-emissions scenario. These findings contribute to resource management by identifying critical habitat for the cold-adapted species and informing adaptive strategies for habitat protection.

Although no direct socioeconomic gains were realized during the project period, the modeling tools developed provide a foundation for improved forecasting of habitat suitability for both warm- and cold-adapted species in the LIS. The framework we developed can support management decisions, lead to cost-effective conservation efforts, better-informed fishery regulations, and long-term social and ecological benefits.

D2. Patents: None

D3. Leveraged Funding: None

E. Stakeholder Summary:

This study provides a comprehensive, climate-informed assessment of distributional and habitat changes for cold- and warm-adapted species in Long Island Sound over nearly four decades. By combining long-term survey data with spatial indicators and habitat suitability modeling, we quantified how species abundance, spatial structure, and habitat availability have responded to sustained environmental change.

Findings reveal a consistent pattern of expansion and increased suitability for warm-adapted species, contrasted with spatial contraction, declining abundance, and shrinking high-quality habitat for most cold-adapted species. Projected warming under a high-emissions scenario suggests these trajectories are likely to continue, with cold-adapted species increasingly restricted to limited areas of persistent suitability that may function as thermal refuges. These areas warrant particular attention for conservation and monitoring.

The integration of spatial indicators and habitat suitability projections provides managers with a decision-support framework that links climate forcing to species-level responses. This framework can inform adaptive monitoring design, guide spatial prioritization efforts, and help anticipate changes in fish community structure that may influence fisheries productivity, ecosystem function, and stakeholder use.

Long Island Sound is undergoing measurable ecological transformation. Proactive, ecosystem-based management that incorporates projected habitat shifts will be essential to sustain fisheries resources, protect vulnerable species, and maintain ecosystem resilience under continued climate change.

F. Pictorial: None

K. OTHER: None

SUPPLEMENTAL MATERIAL

PROJECT NUMBER AND TITLE: R/FBM-41-NYCT - Evaluating changes in suitable habitat and biogeography of cold- and warm adaptive fish species in a changing Long Island Sound to inform ecosystem-based management

1. Center of gravity for warm-adapted species

The figures below provide additional visualizations of the center of gravity (CG) results for the warm-adapted species during the spring and fall seasons.

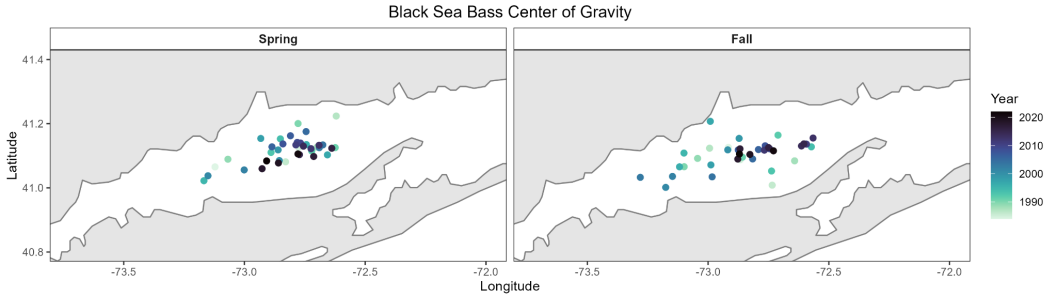


Fig. S1. Center of gravity (CG) plots for Black Sea Bass in the spring and fall.

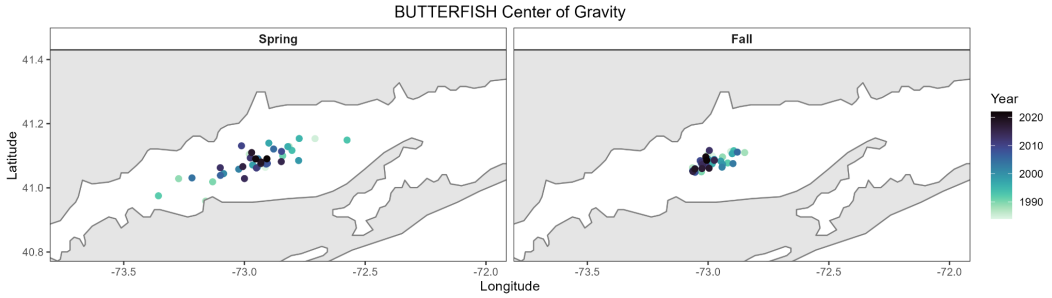


Fig. S2. Center of gravity (CG) plots for Butterfish in both the spring and the fall.

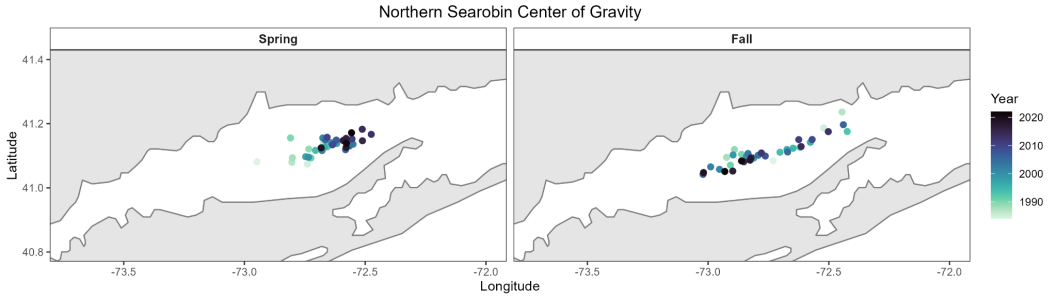


Fig. S3. Center of gravity (CG) plots for Northern Searobin in the spring and fall.

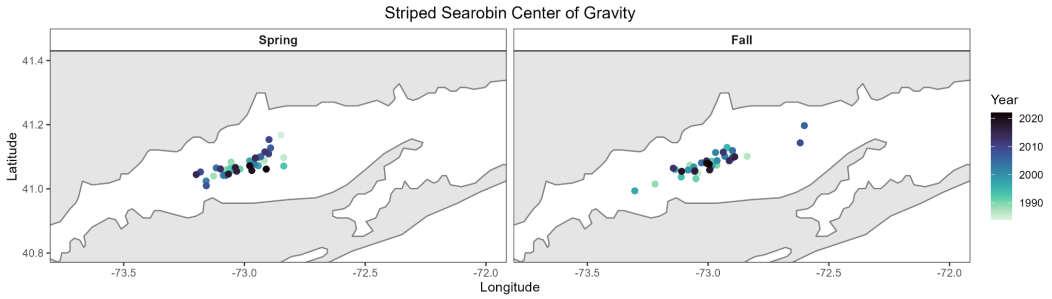


Fig. S4. Center of gravity (CG) plots for Striped Searobin in the spring and fall.

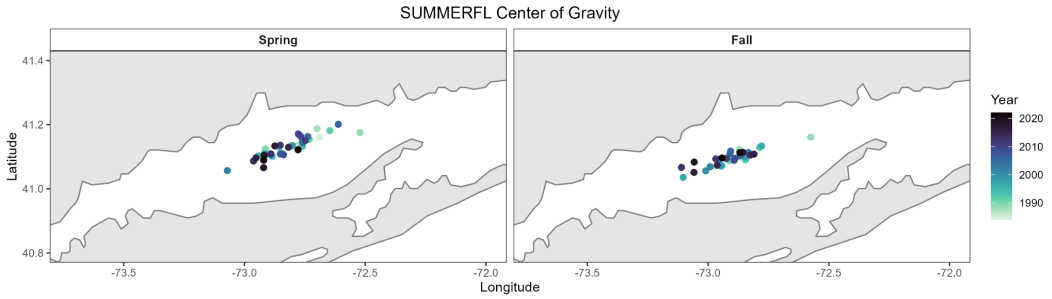


Fig. S5. Center of gravity (CG) plots for Summer Flounder in the spring and fall.

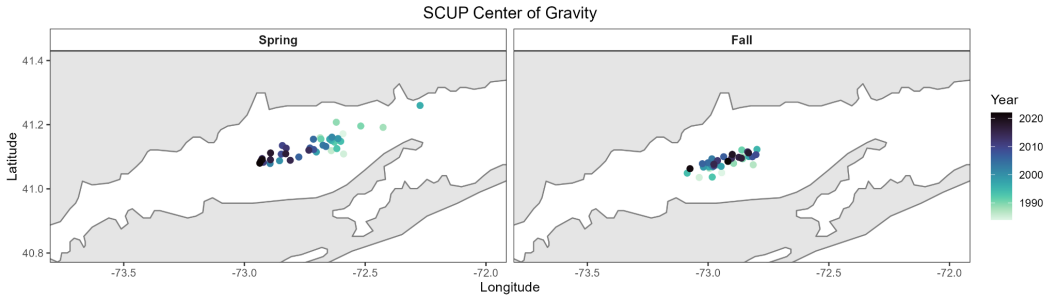


Fig. S6. Center of gravity (CG) plots for Scup in the spring and fall.

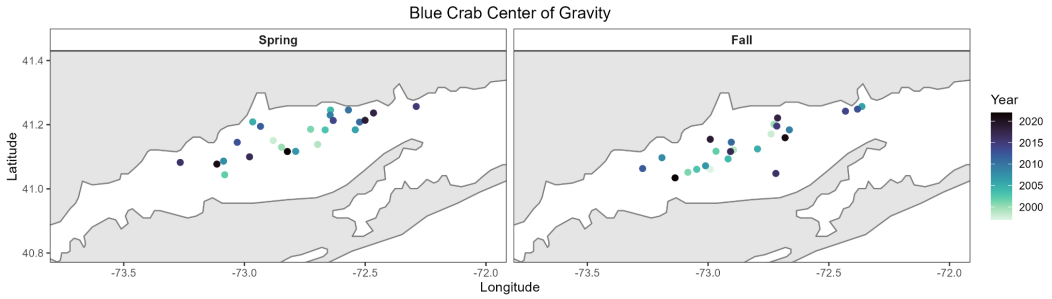


Fig. S7. Center of gravity (CG) plots for Blue Crab in the spring and fall.

2. Center of gravity for cold-adapted species

The figures below provide additional visualizations of the center of gravity (CG) results for the cold-adapted species during the spring and fall seasons.

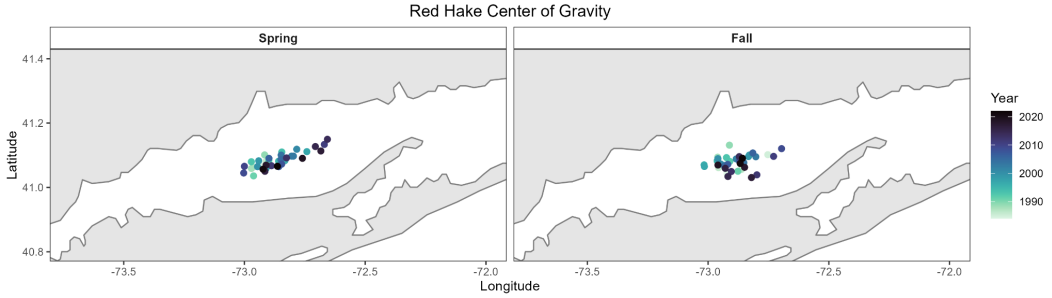


Fig. S8. Center of gravity (CG) plots for Red Hake in the spring and fall.

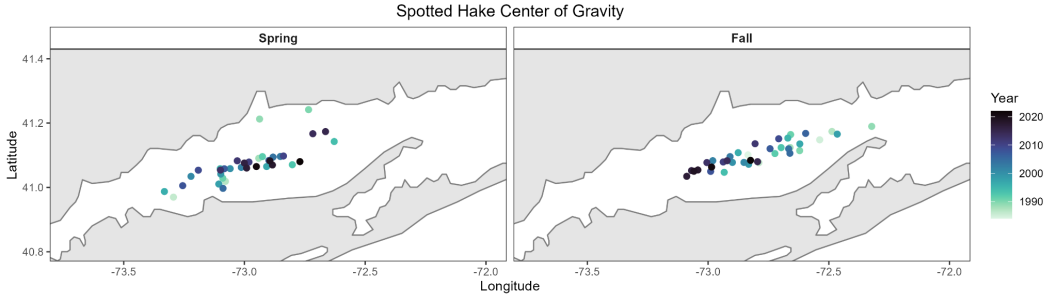


Fig. S9. Center of gravity (CG) plots for Spotted Hake in the spring and fall.

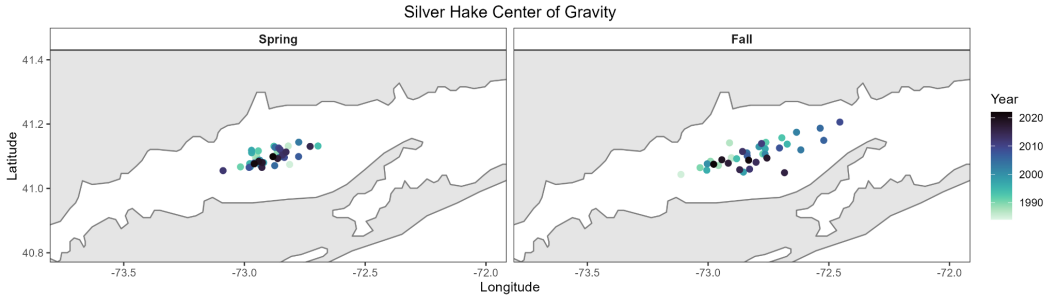


Fig. S10. Center of gravity (CG) plots for Silver Hake in the spring and fall.

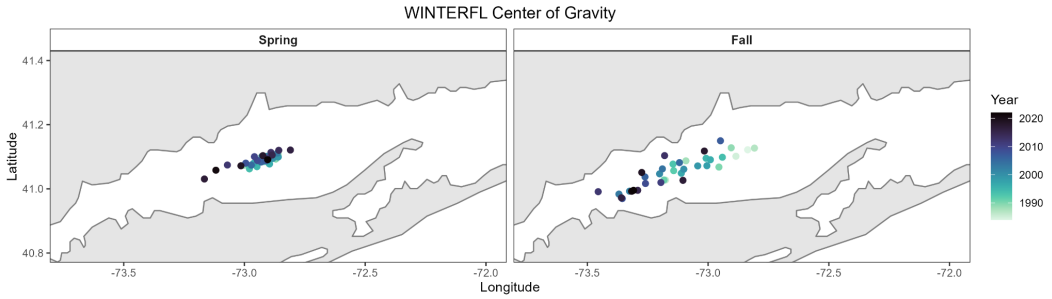


Fig. S11. Center of gravity (CG) plots for Winter Flounder in the spring and fall.

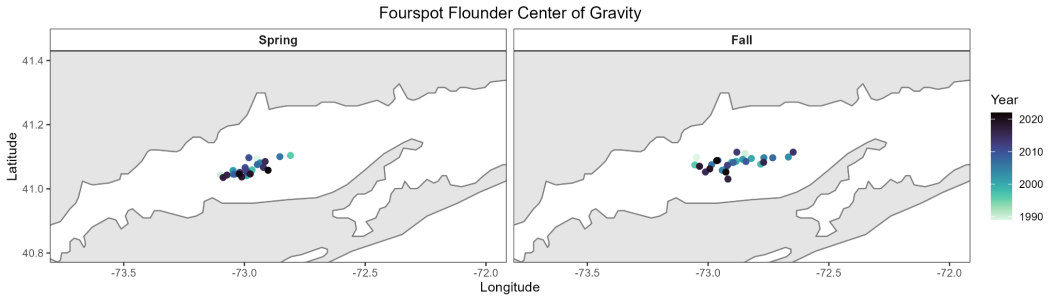


Fig. S12. Center of gravity (CG) plots for Fourspot Flounder in the spring and fall.

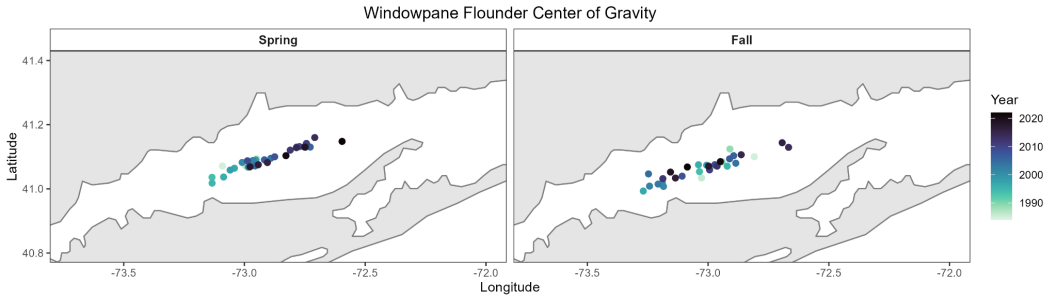


Fig. S13. Center of gravity (CG) plots for Windowpane Flounder in the spring and fall.

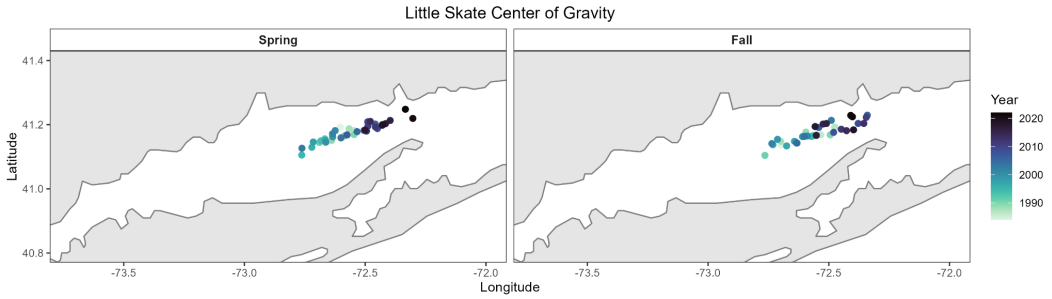


Fig. S14. Center of gravity (CG) plots for Little Skate in the spring and fall.

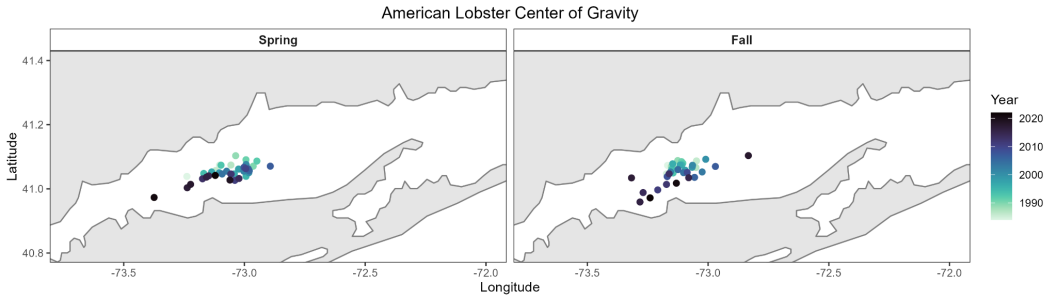


Fig. S15. Center of gravity (CG) plots for American Lobster in the spring and fall.

3. Suitability index curves for warm-adapted species

The figures below show the suitability index curves (SI) for bottom temperature (°C), depth (m), and bottom salinity (ppt) used to build the habitat suitability index (HSI) models for the warm-adapted species during the spring and fall seasons.

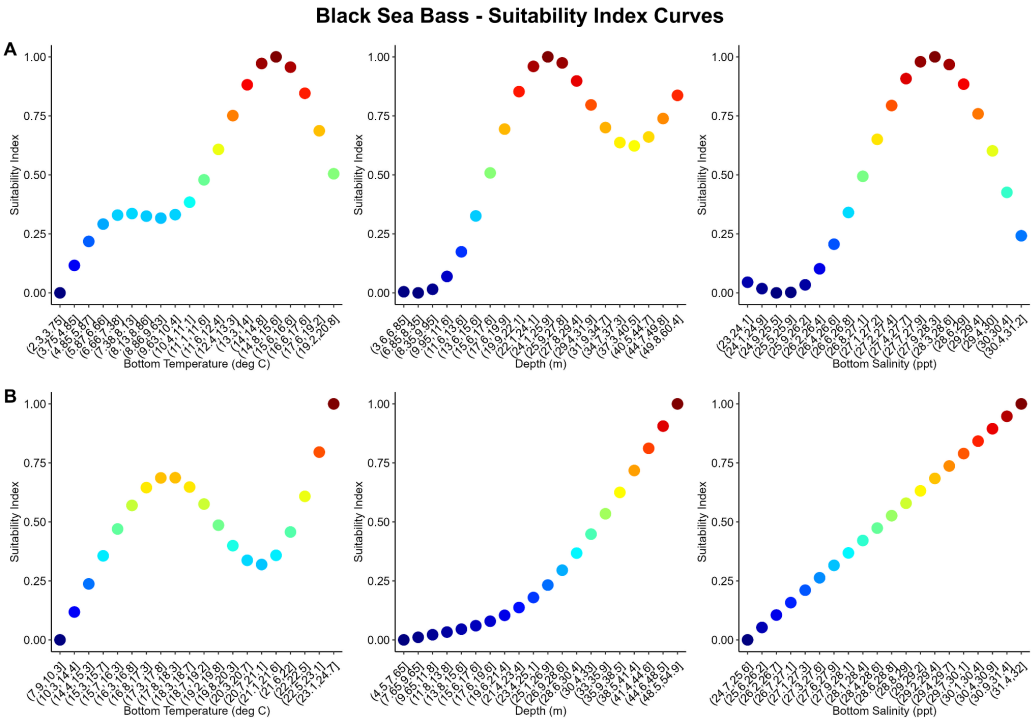


Fig. S16. Suitability index (SI) curves for Black Sea Bass in spring (A) and fall (B).

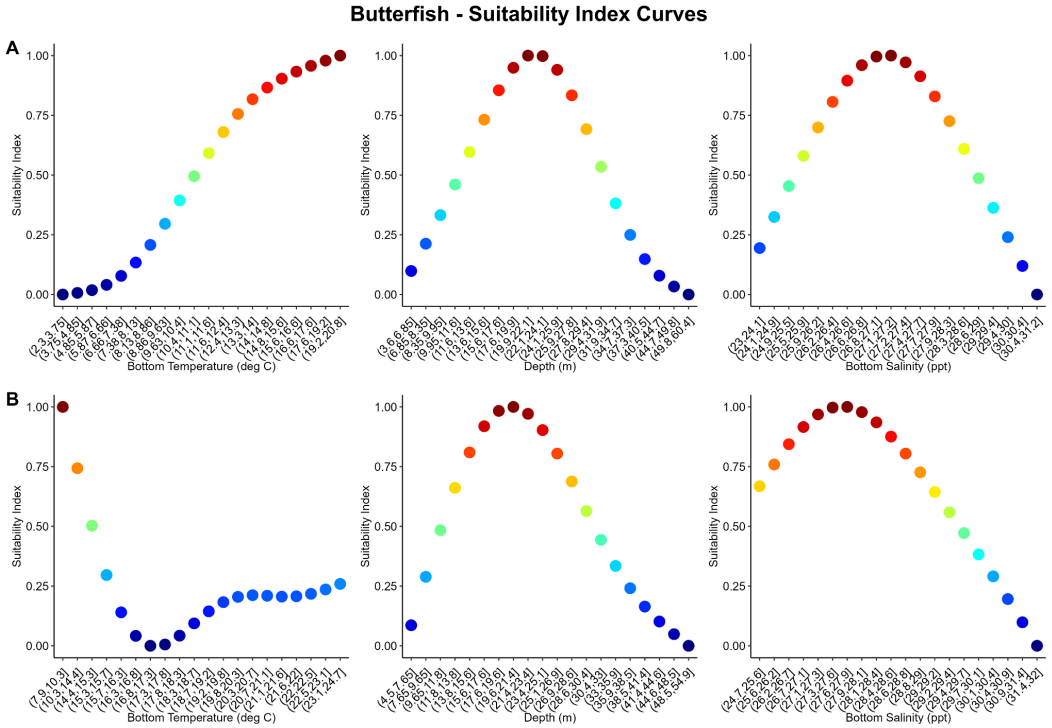


Fig. S17. Suitability index (SI) curves for Butterfish in spring (A) and fall (B).

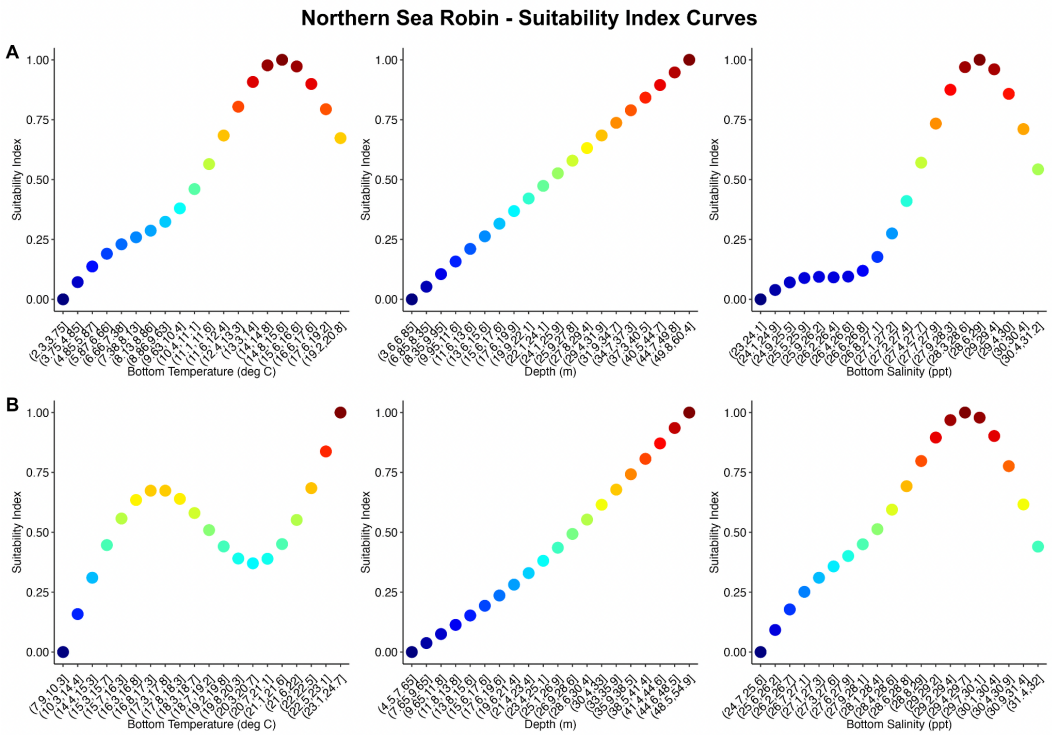


Fig. S18. Suitability index (SI) curves for Northern Sea Robin in spring (A) and fall (B).

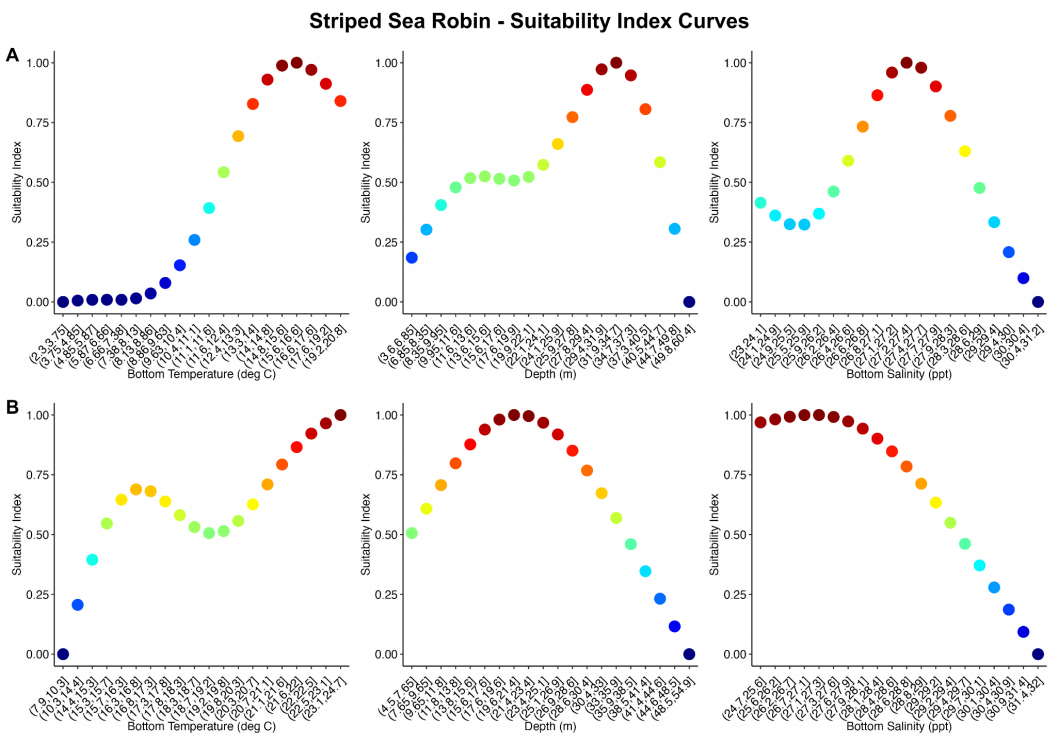


Fig. S19. Suitability index (SI) curves for Striped Sea Robin in spring (A) and fall (B).

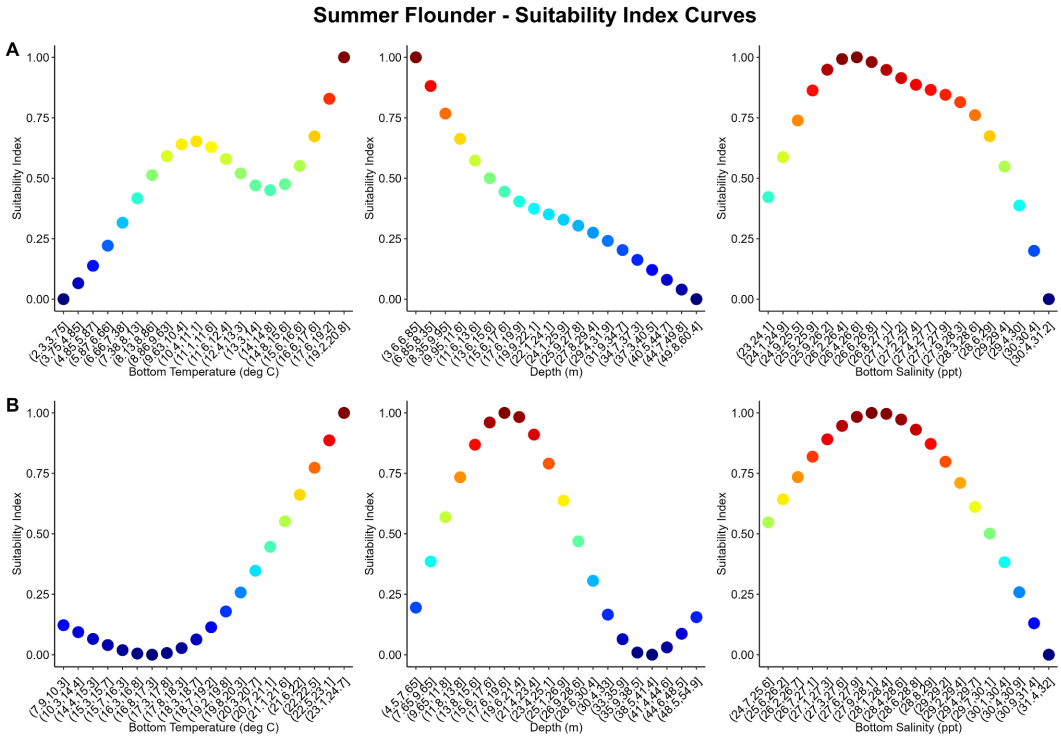


Fig. S20. Suitability index (SI) curves for Summer Flounder in spring (A) and fall (B).

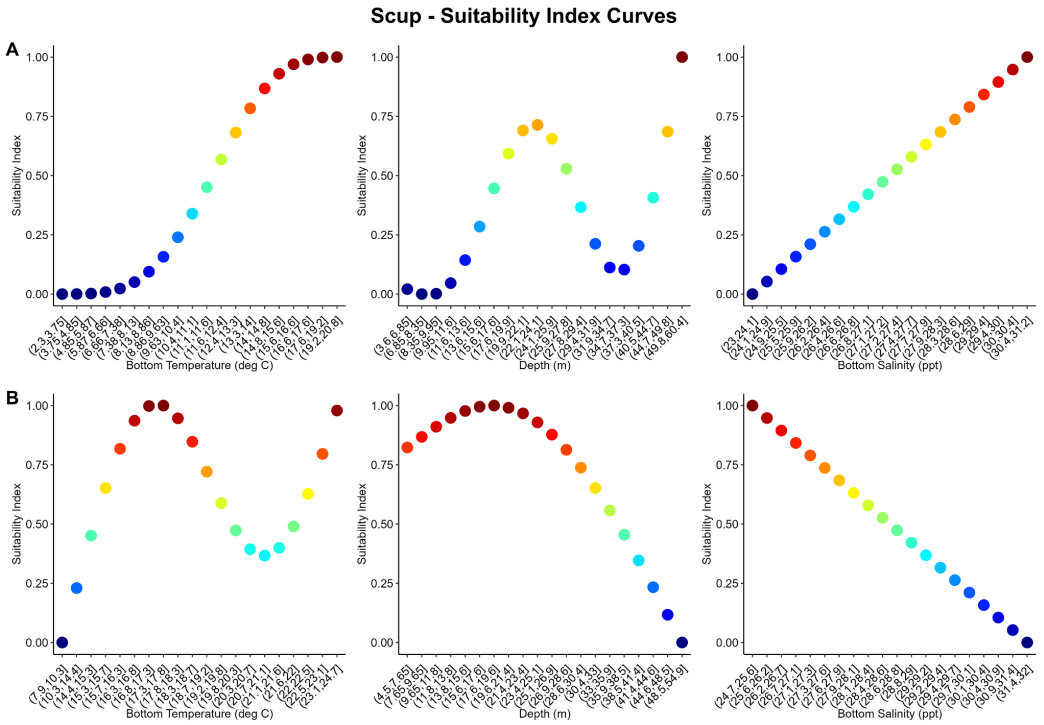


Fig. S21. Suitability index (SI) curves for Scup in spring (A) and fall (B).

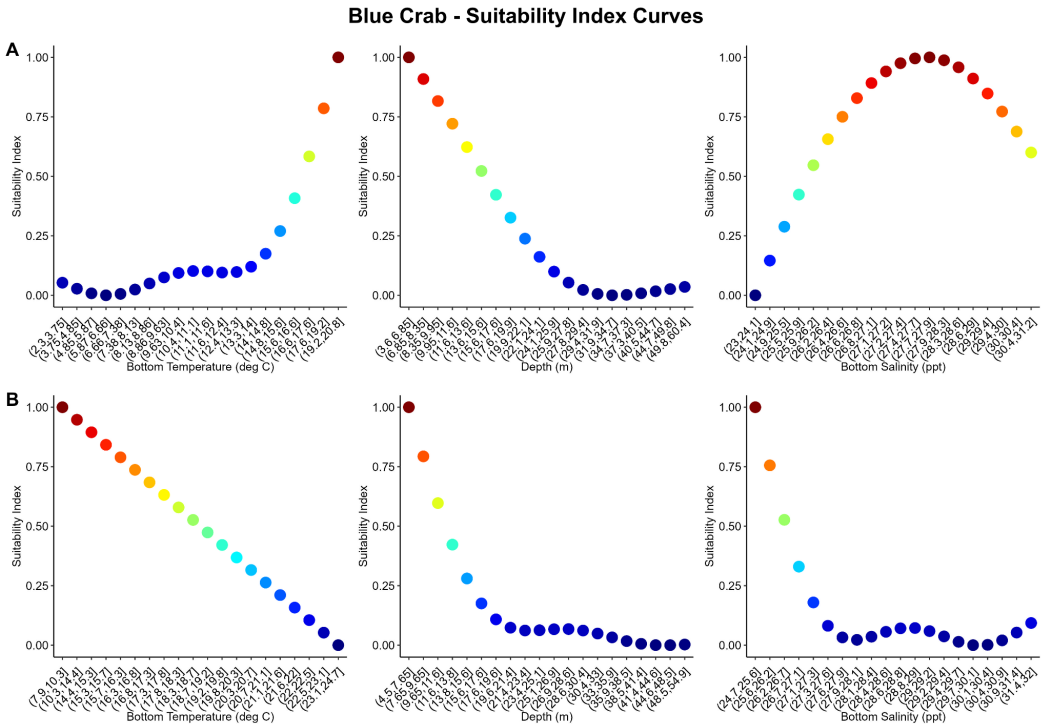


Fig. S22. Suitability index (SI) curves for Blue Crab in spring (A) and fall (B).

4. Suitability index curves for cold-adapted species

The figures below show the suitability index curves (SI) for bottom temperature (℃), depth (m), and bottom salinity (ppt) used to build the habitat suitability index (HSI) models for the cold-adapted species during the spring and fall seasons.

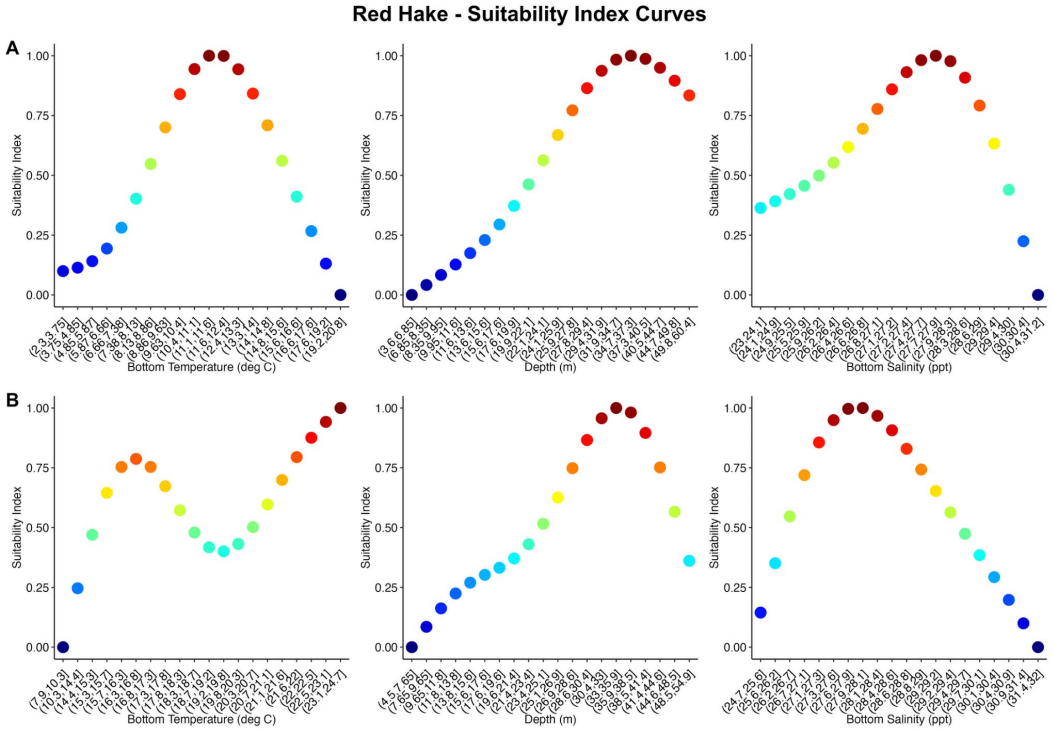


Fig. S23. Suitability index (SI) curves for Red Hake in spring (A) and fall (B).

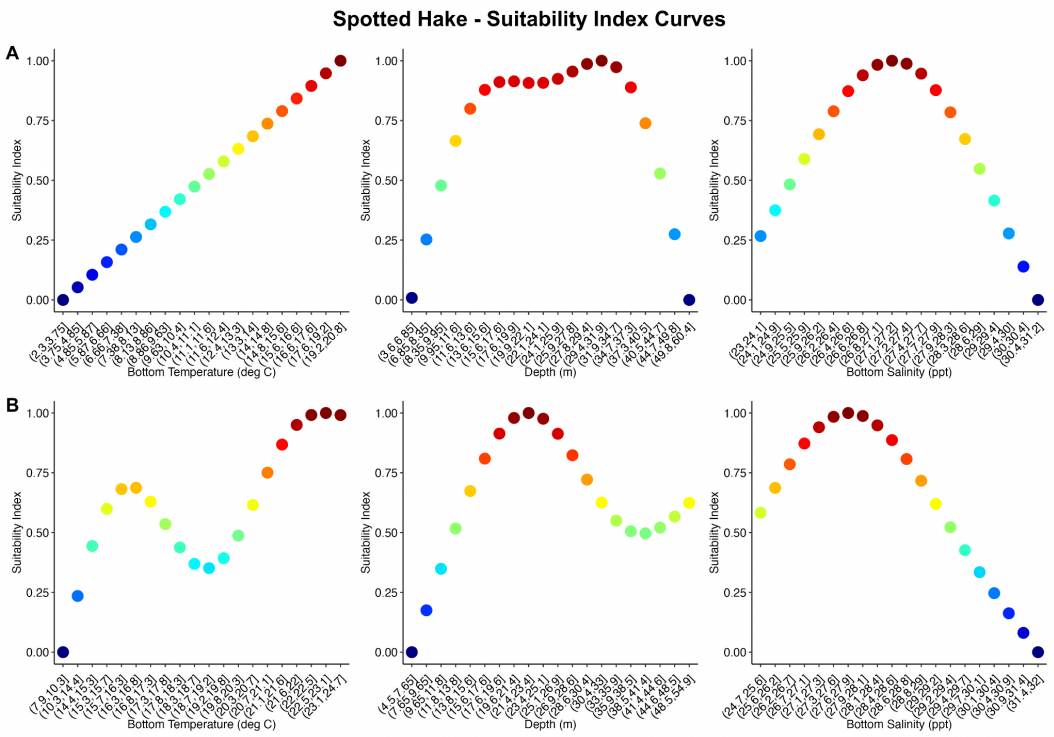


Fig. S24. Suitability index (SI) curves for Spotted Hake in spring (A) and fall (B).

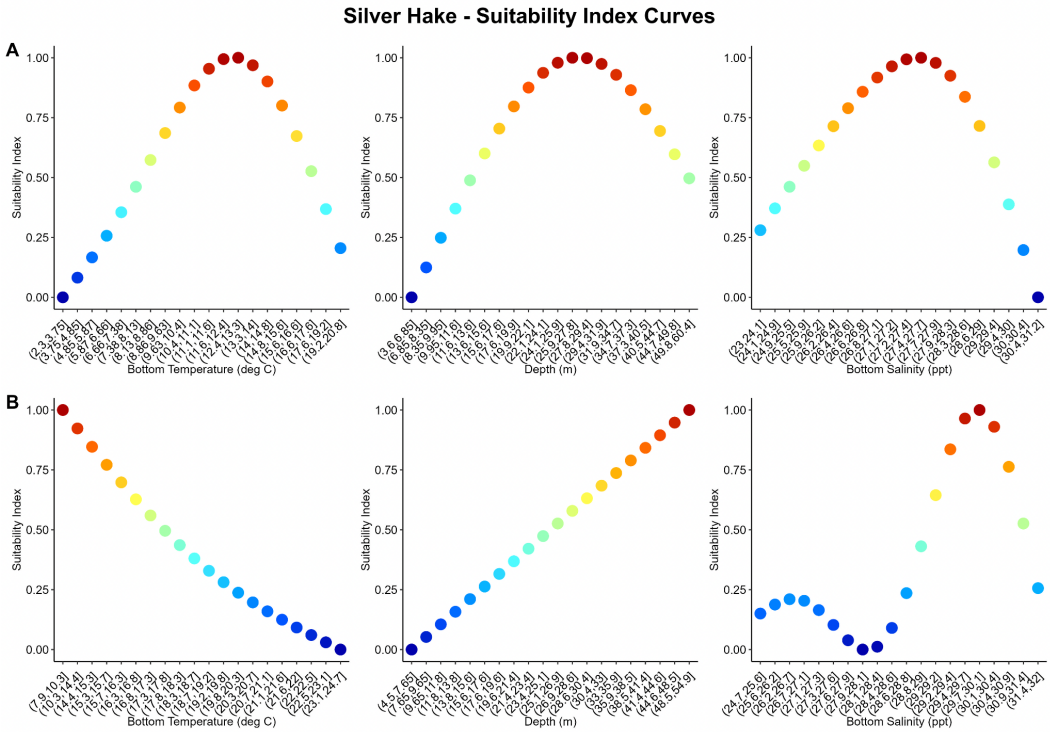


Fig. S25. Suitability index (SI) curves for Silver Hake in spring (A) and fall (B).

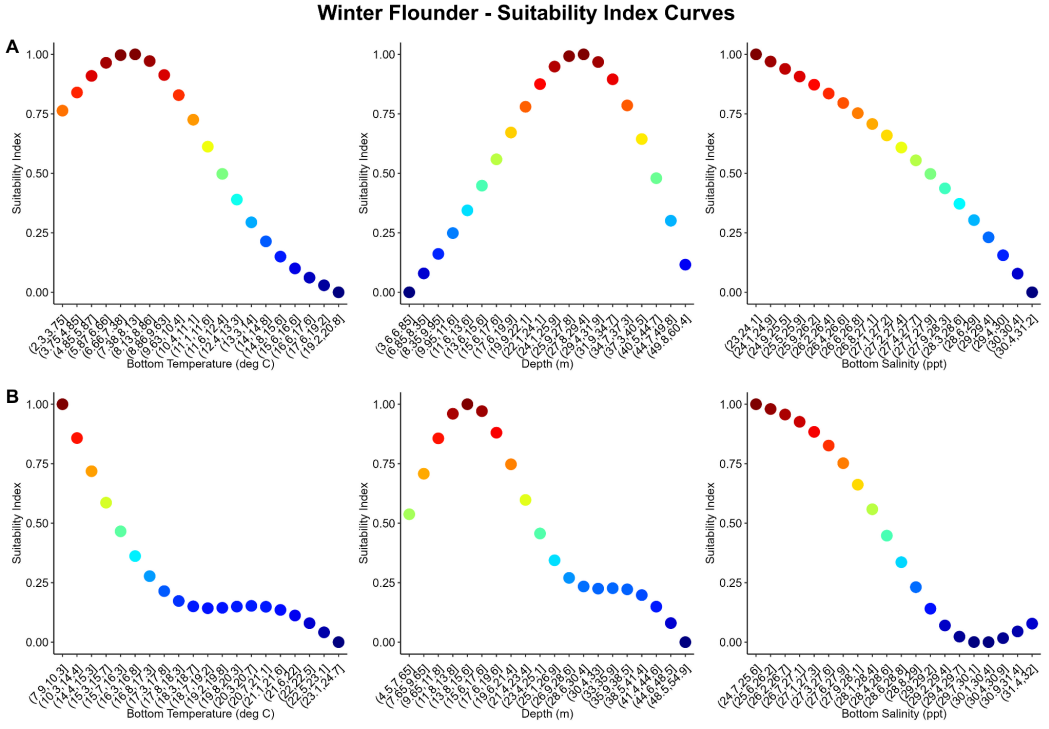


Fig. S26. Suitability index (SI) curves for Winter Flounder in spring (A) and fall (B).

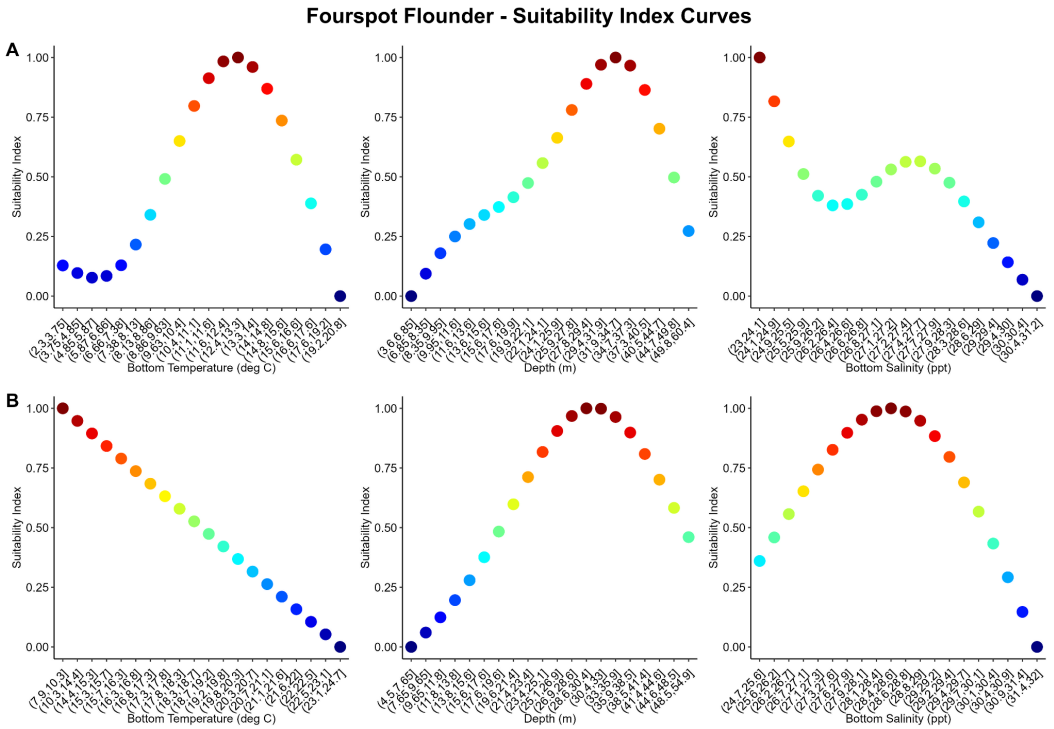


Fig. S27. Suitability index (SI) curves for Fourspot Flounder in spring (A) and fall (B).

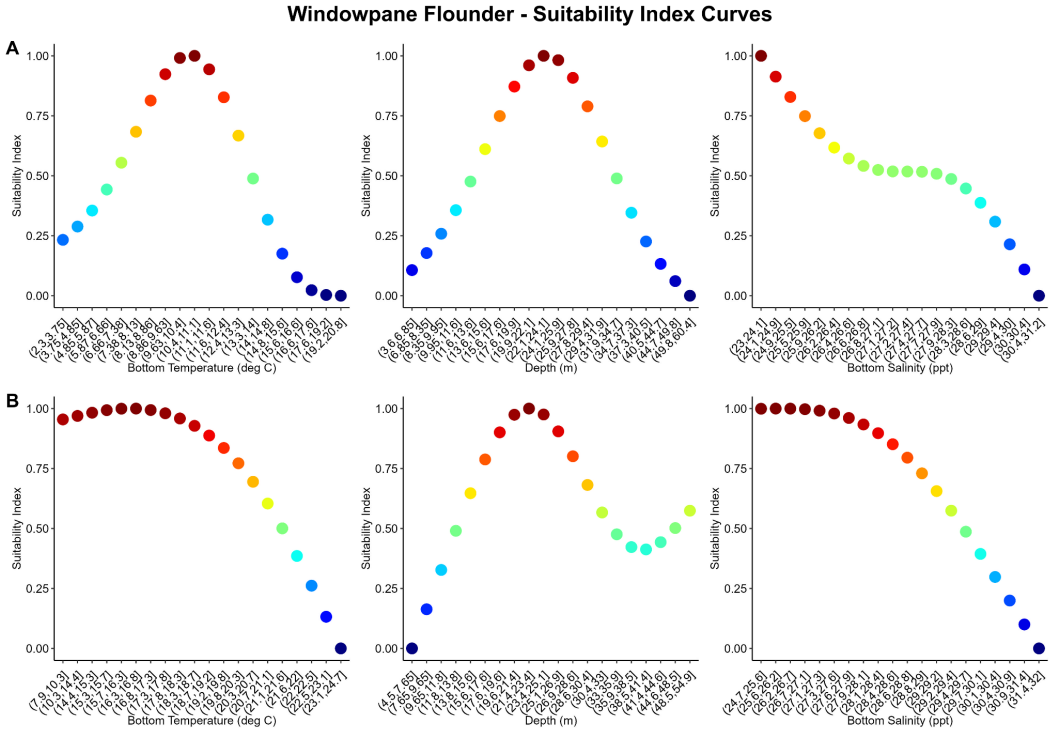


Fig. S28. Suitability index (SI) curves for Windowpane Flounder in spring (A) and fall (B).

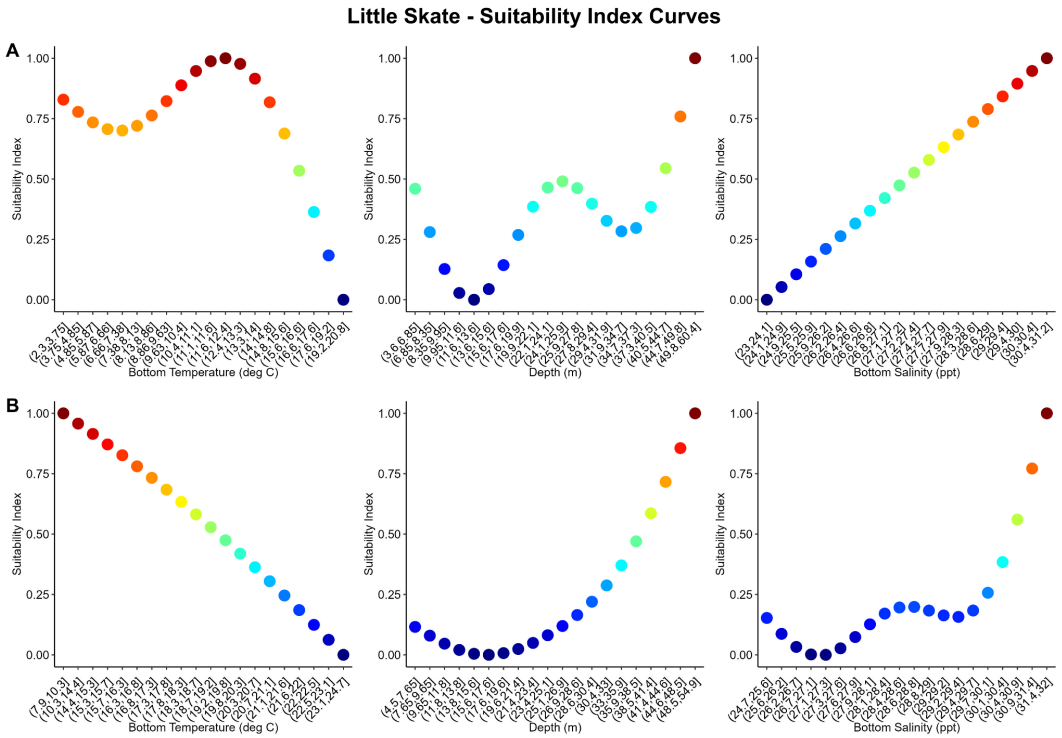


Fig. S29. Suitability index (SI) curves for Little Skate in spring (A) and fall (B).

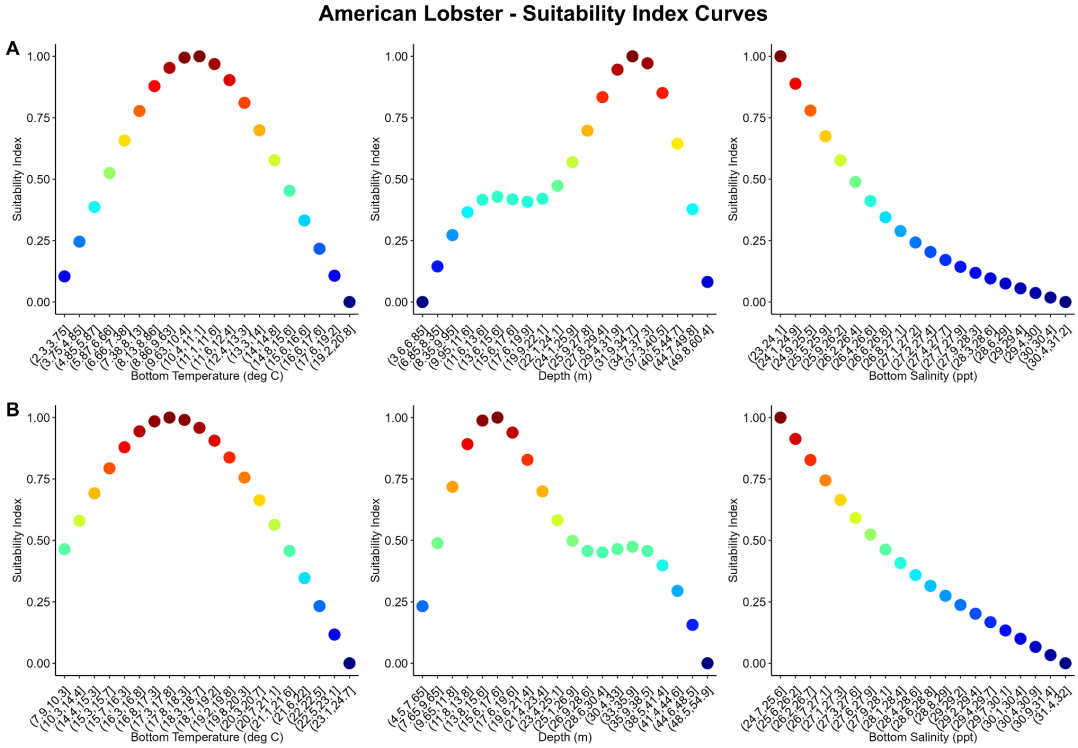


Fig. S30. Suitability index (SI) curves for American Lobster in spring (A) and fall (B).

5. Thermal Refuge

The tables below present a summary of Figures 46-53 and include the number (and percent) of grid cells (n= 2,789) that were categorized as: persistent high suitability (High to High), loss of high suitability (High to Moderate/Low), gain of high suitability (Moderate/Low to High), or never highly suitable (Moderate/Low to Moderate/Low) between the historical (1992-2019) and future mid-century period (2040-2049).

Table S1. Red hake: the number and percent of grid cells that gained suitability, lost suitability, were never suitable, or persistent suitability between the historical (1992-2019) and future mid-century period (2040-2049).

Season	Gained (n)	Gained (%)	Lost (n)	Lost (%)	Never (n)	Never (%)	Persistent (n)	Persistent (%)
Spring	72	2.8	77	2.99	2408	93.59	16	0.62
Fall	0	0	3	0.12	2520	99.88	0	0

Table S2. Spotted hake: the number and percent of grid cells that gained suitability, lost suitability, were never suitable, or persistent suitability between the historical (1992-2019) and future mid-century period (2040-2049).

Season	Gained (n)	Gained (%)	Lost (n)	Lost (%)	Never (n)	Never (%)	Persistent (n)	Persistent (%)
Spring	1592	61.9	0	0	981	38.13	0	0
Fall	20	0.79	0	0	2503	99.21	0	0

Table S3. Silver hake: the number and percent of grid cells that gained suitability, lost suitability, were never suitable, or persistent suitability between the historical (1992-2019) and future mid-century period (2040-2049).

Season	Gained (n)	Gained (%)	Lost (n)	Lost (%)	Never (n)	Never (%)	Persistent (n)	Persistent (%)
Spring	281	10.92	58	2.25	1505	58.49	729	28.33
Fall	0	0	0	0	2572	100	0	0

Table S4. Winter flounder: the number and percent of grid cells that gained suitability, lost suitability, were never suitable, or persistent suitability between the historical (1992-2019) and future mid-century period (2040-2049).

Season	Gained (n)	Gained (%)	Lost (n)	Lost (%)	Never (n)	Never (%)	Persistent (n)	Persistent (%)
Spring	121	4.7	0	0	2452	95.3	0	0
Fall	0	0	0	0	2523	100	0	0

Table S5. Fourspot flounder: the number and percent of grid cells that gained suitability, lost suitability, were never suitable, or persistent suitability between the historical (1992-2019) and future mid-century period (2040-2049).

Season	Gained (n)	Gained (%)	Lost (n)	Lost (%)	Never (n)	Never (%)	Persistent (n)	Persistent (%)
Spring	0	0	0	0	2573	100	0	0
Fall	0	0	0	0	2573	100	0	0

Table S6. Windowpane flounder: the number and percent of grid cells that gained suitability, lost suitability, were never suitable, or persistent suitability between the historical (1992-2019) and future mid-century period (2040-2049).

Season	Gained (n)	Gained (%)	Lost (n)	Lost (%)	Never (n)	Never (%)	Persistent (n)	Persistent (%)

Spring	145	5.64	0	0	2428	94.26	0	0
Fall	0	0	0	0	2523	100	0	0

Table S7. Little skate: the number and percent of grid cells that gained suitability, lost suitability, were never suitable, or persistent suitability between the historical (1992-2019) and future mid-century period (2040-2049).

Season	Gained (n)	Gained (%)	Lost (n)	Lost (%)	Never (n)	Never (%)	Persistent (n)	Persistent (%)
Spring	3	0.12	333	12.94	2127	82.67	110	4.28
Fall	7	0.28	14	0.55	2462	97.58	40	1.59

Table S8. American lobster: the number and percent of grid cells that gained suitability, lost suitability, were never suitable, or persistent suitability between the historical (1992-2019) and future mid-century period (2040-2049).

Season	Gained (n)	Gained (%)	Lost (n)	Lost (%)	Never (n)	Never (%)	Persistent (n)	Persistent (%)
Spring	0	0	0	0	2573	100	0	0
Fall	0	0	0	0	2573	100	0	0