Final Report to SCEMFIS IAB, dated October 19, 2023
Project title: Sea Water Temperature and Cod Spawning
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Statement of Problem

The Great South Channel Habitat Management Area (GSC-HMA) was approved by the New England Fishery Management Council (NEFMC) in April 2015. The GSC-HMA bottom type has been described as complex habitat suitable for cod spawning, and therefore valuable as a sanctuary for that purpose. The 2015 approval includes a recommendation that the northeast corner of the HMA be closed to all dredges and bottom trawls. Access to the GCS-HMA for the surfclam fishery remains limited. While an exempted fishing permit allows entry of a limited number of clam dredges, the differing opinions on the impact of dredging on this region remain stark. SCEMFIS has invested in this debate with prior fieldwork (Powell et al 2019a, 2019b, 2020; access at https://scemfis.org/shellfish-research/)

The long term prospects for cod spawning in the region are at the mercy of long term warming trends. Indeed, a recent publication by Kleisner et al (2017) projects a retraction of the southern boundary of the range to well north of Cape Cod within the decade. There is an expanding series of models and databases describing seasonal changes of bottom water temperature (BWT) at ever finer spatial scales for the mid-Atlantic, Georges Bank and Gulf of Maine regions. These include the Rutgers DOPPIO (Lopez et al, 2020) Regional Ocean Modeling System, and the Global Ocean Physics Reanalysis (GLORYS) reanalysis (du Pontavice et al 2023). Both the optimal temperatures for cod spawning, and the time and temperature requirements for development of cod egg, larval and juvenile growth are reasonably well documented in the literature[1]. The objective of this project is to assemble in GIS, the most recent data for cod spawning regions in southern New England with focus on the GSC-HMA, and describe the long term trends in terms of temperature minima and days within the optimal egg and larval development "windows" as a proxy for the designated region to serve as a cod spawning sanctuary in the past, present and into the coming decade.

Project activities: Procedures and Products

Mapping Cod distribution

Procedure: Historical for cod distribution was downloaded from the NEFSC *DisMap* data for cod (at https://apps-st.fisheries.noaa.gov/dismap/). Both spring and fall survey data was available for

[1] Langan et al (2020) estimated that cod in Rhode Island waters spawned "between late December and mid-February" in studies conducted in 2016 and 2017.
https://www.fi sheries.noaa.gov/species/atlantic-cod states that "Cod spawn near the ocean floor from winter to early spring"
https://thisfi sh.info/fi shery/species/atlantic-cod/ states that "Spawning, which usually happens in the coldest months between January and April...."
Review for Northeast Atlantic cod (Sando et al 2020) provides multiple citations in their table 1. It is included here as an Appendix.

the period 1974-2019. The downloaded data was used to create a spreadsheet including weight count, time (year), and location (LAT and LONG for each point). From this spreadsheet a layer of points was created representing every survey in the NAD 1983 (NSRS2007) UTM Zone 19N projection. Time sliders were added by taking slices of the spring data set by year. This process was repeated for the fall, but presentations only featured the spring visuals as the spring surveys occurred directly after cod spawning season.
Product: A bubble map was created from 1974-2019 for fall and spring surveys showing greater presence of cod in the surveys as larger circles, lesser presence as small circles, and absence as a small different colored dot. The time sliders can be grouped by any number of years.

GSC-HMA
Procedure: The GSC-HMA was located in the Essential Fish Habitat Mapper data from NOAA, and overlayed into the above described data. This allowed display of time sliders around the protected area to examine the presence cod in the region. This was valuable because surveys cannot be run through the protected area, so the immediate surrounding area was used as a reasoned proxy. The array of the cod survey data suggest movement away from the protected area.
Product: The cod bubble plot time sliders showing movement away from the GSC HMA by cod from 1974-2019.

Substrate types
Procedure: The Continental Margin Mapping Program (CONMAP) from USGS was used to represent the substrate type of the sea floor in the study area. The purpose was to illustrate places with complex bottom visually and incorporate areas with complex bottom into the suitability index model. [2] The bottom type was examined in relation to known cod distribution in the survey. The substrate layer was symbolized by color based on substrate data type in polygons. Each survey data point was assigned a corresponding substrate type. The data points were assembled into bar graphs demonstrating the steep decline in the quantity of cod per unit of area from complex bottomed habitats to areas of lower complexity. The complex bottom correspond to gravel and gravel-sand mixed substrates. In both a weighted analysis using the weight count measurements, and an unweighted analysis using only presence/absence points, the complex habitats had significantly greater presence of cod per unit of area than any other substrate type.
Product: A feature layer showing the substrates in the study area, with the ability to toggle data to superimpose cod data points. Analysis completed using spring cod survey data demonstrates the value of incorporating bottom type into the suitability index model. A layer to be incorporated into the raster[3] calculation of the suitability index model.[4]

Bathymetry
Procedure: Data was obtained from the "GEBCO gridded bathymetric data set, the GEBCO_2023 Grid." This was a raster that was symbolized using darker blue to represent

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[2] A website explaining what a habitat suitability index model is, can be found here.
[3] In its simplest form, a raster consists of a matrix of cells (or pixels) organized into rows and columns (or a grid) where each cell contains a value representing information, such as temperature. Rasters are digital aerial photographs, imagery from satellites, digital pictures, or even scanned maps.
[4] A calculation in the context of a suitability index model, refers to the process by which multiple "raster" datasets can combined to form one raster based on the value each pixel provides. This is process uses the raster calculator tool in ArcGIS. This is a standard way of combining many suitability factors into one suitability index.

deeper water and lighter blue for shallower water. Unweighted analysis was pursued using the spring cod survey points for the bathymetry data set to illustrate the mean, median, standard deviation (std), minimum (min), and maximum (max) depths of occurrence. This analysis, in conjunction with literature, identified a bathymetric range of 30-90 meters deep for cod spawning.
Product: A raster layer showing the ocean depths in the study area, with the option to visualize cod occurrence in a superimposed layer. Unweighted cod occurrence point data facilitates bathymetric ranges to be used in the index model, emphasizing that cod prefer shallower water. The layer is already in raster form and can be easily used in the suitability index model calculation.

Temperature
Procedure: The GLORYS data set, was provided to us by Hubert Du Pontavice. GLORYS is a three-dimensional data set that estimates bottom water temperature (BWT) in the study area from 1959-2021. It is a NetCDF layer,[5] Time sliders were created using red colors to show warmer temperatures and blue colors to show cooler ones. A literature review indicated that cod prefer to spawn in areas in a 4-8 degrees Celsius range. A time slider was created showing year by year data for temperature with the cod spring survey points time slider overlaid for presentations. This illustrated how the cod have moved with the 4–8-degree Celsius range in a northward trend over the study period.
Product: A time slider showing raster data sets of bottom water temperature from 1959-2021. This is incorporated into the suitability model and raster calculations and visualizes change in suitability by year. A version of the time slider with spring and fall time sliders also has been created to show general cod movement in concert with temperature changes.

Biomass
Procedure: This layer was taken from a csv file provided by Professor Eric Powell and converted into a GIS points layer. It shows points around the study area and the different species of marine life found at each point in the survey. It is symbolized by species type, and it has a time element as well. This allows for it to be used as a time slider and a proxy for cod spawning habitat. The future goal is to use the species in this data as another factor that indicates the cod spawning locations. For example, mussels are included in this layer, and they possess habitat needs similar to the ideal cod spawning ground. To help use mussels as a proxy for cod spawning habitats, a time series layer was developed to show parallel movement by mussels and cod spawning grounds over time. The time slider includes only points where at least one mussel was found and does not differentiate based on how many were found since all of the quantities recorded were 3 or less.
Final Product: A time slider webapp showing the location of mussels found in the survey from 1982-2011. Time sliders for each of the other species included in the dataset from 1978-2011 can be created easily from offline data.

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[5] Network Common Data Form (netCDF) is a file format for storing multidimensional scientific data (variables) such as temperature, humidity, pressure, wind speed, and direction. You can use tools from the ArcGIS software Multidimension Tools toolbox to create a raster layer, a feature layer, and a table view from a netCDF file.

Suitability index model
Procedure: The feature layer for substrate was converted to a raster and the calculator function employed to create a suitability index model taking the substrate, bathymetry and temperature factors to determine a ranking for the most and least suitable areas for cod. Each factor was considered in isolation and the different features within it ranked on a scale of 0 through 5 according to prior analysis. For cod spawning, a value of 0 was assigned for least suitable through 5 as the most suitable. For temperature a value of 5 for temperature was assigned in the 4–8^{o}C range, with one degree Celsius in each direction outside of this range causing the score to decrease by one until a value of 0 is recorded at Each temperature past that point was given a score of 0. For substrate type gravel received the 5 score for being the most complex, while a gravel-sand mix was given a 4. The remaining substrate types were assigned a value of 1 because they were much lower complexity but did have some cod populations present in surveys. For bathymetry range the 30-90 m depth range was assigned a value of 5, while each standard deviation of 60 (rounded) was a subtraction of one from the assigned value in a manner identical to the temperature data. This is detailed with images in the accompanying StoryBook presentation. Each pixel was then assigned a score based on the sum of assigned 0-5 scores given by the raster layers. A color was assigned to each score in the 1-15 range with dark red being the least suitable and dark green as the most suitable.

"Tuning" of the suitability index was explored using different weighting systems with the temperature. In the final report StoryMap, there is a demonstration of how weighting the factors differently can affect the results. Also, a series of maps was created identifying boundaries in a binary decision (suitable versus unsuitable corresponding to values of 1 or 0) for the above factors. These were created using different cutoff thresholds to determine what is considered "suitable habitat." This showed that how suitable a habitat needs to be considered suitable, needs to be examined as well. A more detailed demonstration and image can be found in the StoryMap as well.

In order to create suitability index layers, a tool was developed that allowed user input to a chosen year between 1959 and 2021, with the return of a suitability index map for that year - the developed model takes the algorithm created by author GB and provides suitability based on the temperature data from the selected year. Given that the temperature data employed herein is a retrospective estimate, the next step is to employ a projected temperature dataset in order to predict suitability in the future. The weightings and rankings of factors in work to date were based on expert opinion and available literature, but should be considered preliminary until a full matrix of options is considered. This will require additional expert opinion.
Product: A model and algorithm that creates suitability models based on predetermined factors. Many suitability map formats, one that ranks most versus least suitable as well as one that marks suitable areas vs non suitable areas. The code and procedure are set in place to create these easily as well.

Future Directions.
The model structure and algorithm that creates these indexes is sound and easily applicable to other species, areas, and timeframes. Future options and applications are many in number. As an example, the above described project strongly indicates that continued warming trends dictate that cod will use the HMA less and less as years progress. A recent working group on cod

population concluded that there may be as many as five distinct biological stocks (as opposed earlier suggestions of two stocks) in the New England, Georges Bank and Gulf of Maine region (https://seagrant.unh.edu/2021-atlantic-cod-stock-workshops). This conclusion has both impact on future use of the current HMA for cod stocks and distribution of future spawning sites across the current and future regions of surfclam fishing in New England and Georges Bank. Both recent modeling of future surfclam distribution, supported by SCEMFIS, and data from recent experimental fishing permits underscore Georges Bank as a long term region of fishing activity. But the geology of Georges Bank is that of a terminal glacial moraine, not the smooth sediments of the mid Atlantic. These moraines are complex habitats akin to the GSC-HMA. Will future expansion of the surfclam fishery onto Georges Bank encounter new HMA debates and, in the worst instance, closures? A project that builds on the prior HMA project to employ temperature projections to map future distribution of both cod spawning sites (will there be five stocks or will this number decrease?) and surfclam resources, and overlay both on extant substrate GIS layers will produce a tool to predict, prepare for, and preferably avoid future HMA conflicts driven by continuing warming trends.

Data Accessibility

To examine any of the visualizations of the data discussed in this article, use the following links to the interactive StoryMaps that were created to be readable and explain the project. Here is the link to the first public StoryMap. This includes all the background information and layers used in the suitability index model. Here is the link to the final report StoryMap. This includes all the analysis and demonstrations for the suitability index. These two StoryMaps provide similar information to the information found in this article, along with links to all public sources and interactive GIS layers.

To view any layer used in the project, go to the slide on the story map which discusses it and click the full screen button in the top right corner. This allows you to interact with any of the GIS layers that have been created or used with the project. The exception is the temperature dataset which can only be viewed as a video due to technical limitations. For webapps, there will be no Fullscreen button, only a button that takes you to the app. This allows you to interact with and view the layer as well.

The biomass layer was used to create a mussel's time slider. Here is the link to the mussel time slider webapp.

The contents of the project will be stored in the William & Mary Scholarworks as well as the SCEMFIS website.

Literature

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Appendix from Sando et al (2020)

TABLE 1. Criteria on temperature (T), salinity (S), depth and position used for NEA cod spawning in different papers of interest and in this study.

References	T [◦C]	S	Depth [m]	Period	Area
Bergstad et al.(1987)	4–6	–	50–100	15.3–15.4	Møre–Finnmark
Ottersen and Sundby (2005)	(2–4) (6–8)	(33–34) (34.8–34.9)	60–150	29.3–5.4	Møre–Finnmark
Höffle et al. (2014)	3	–	30–200		Lofoten–Vesterålen
Michalsen et al. (2014)	4–8		30–200	1.4–30.4	Lofoten–Vesterålen
Langangen et al. (2014)	(2–4) (6.5–7)	(33–34) (34.7–35)			Nordland–Finnmark
Righton et al. (2010)	4.8–7				Nordland–Finnmark
Reference study	4–6	34.0–34.9	50–150	1.3–30.4	Møre–Finnmark
Sensitivity studies	3–8	-	50–180	1.3–30.4	Møre– Finnmark

Note that Ottersen and Sundby (2005) and Langangen et al. (2014) refer to the water masses in the transition layer between the cold and fresh coastal waters and the warm and saline Atlantic Water.