Title: Forecasting future range of sea scallops using a trophically-linked species distribution model: Will climate change constrain scallop distribution in the Mid-Atlantic Bight?

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Associated NMFS Science Centers: Northeast Fisheries Science Center

FATE AND NEFSC Priorities: Our proposal addresses FATE priorities **2.1; 2.10; 4; 5**, and NEFSC Strategic Plan foci **B** and **F**.

Project Duration – 2 years

Total Funding Request: $191,721

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Year1 Institutional Budget Breakdown: Rutgers: $ 36,662; NEFSC: $75,833
Year2 Institutional Budget Breakdown: Rutgers: $ 38,393; NEFSC: $40,833

Summary

We propose to model the factors that determine the distribution of sea scallops in the Mid Atlantic Bight (MAB) and examine how this distribution may change under climate change scenarios. We will determine the realized niche for sea scallops with a correlative Species Distribution Model (SDM) based on habitat variables (primarily thermal parameters and substrate types) and compare this to a fundamental niche model based on documented thermal tolerances and preferred substrates. Spatial regions where the realized species distribution falls inside of the potential species distribution can be inferred to be areas where the distribution is constrained by other abiotic variables or biotic interactions (e.g., predation), which can then be used to further refine the SDM. The resulting trophically-linked SDM will integrate SDMs for other species that were identified as significantly constraining sea scallop distributions. This integrated SDM, that includes ecological interactions, can then be used with oceanographic hindcast and forecast simulations to examine how the geographic distribution of sea scallops may change under different climate scenarios.

Of particular interest is the central and southern Mid Atlantic Bight region where the southern and inshore distribution of sea scallops is limited by summer maximum bottom temperatures and the offshore extent of the distribution is probably limited by prohibitively high pre-recruit predation by *Astropecten americanus* sea stars that dominate benthic assemblages at greater depths in the MAB. The inshore extent of this predator, in turn, is limited by winter minimum bottom temperatures. Under this scenario, increased water temperatures would result in a contraction of sea scallop distributions in the MAB with summer maxima isotherms moving offshore and winter minima isotherms moving inshore. Sea scallops in this region are constrained to a narrow strip of habitat but currently support a large portion of the fishery. Thus, increasing bottom temperatures could result in a contracting species distribution and a substantial loss of much of this fishery.

Background

Atlantic sea scallops (*Placopecten magellanicus*) have supported the most valuable fishery in the U.S. during the past decade, with recent annual ex-vessel values averaging almost $500 million, about five times its value twenty years ago. Some of this increase is due to better management, including ending overfishing and an innovative rotational management plan (Hart 2003, NEFMC 2004, Hart and Rago 2006, Hart et al. 2013, NEFSC 2014), but environmental factors also played a role. In particular, landings in the Mid-Atlantic Bight (MAB) area have been unusually high in recent years; landings in this area were about an order of magnitude higher during 2000-2014 than they were during 1970-1984. This area is at the southern-most boundary of the sea scallops' range, and thus may be especially sensitive to climate change. We propose to investigate the effects of climate change on sea scallops in the MAB by using hindcast and forecasts of bottom temperatures and by taking into account both the direct effects of changing bottom temperatures on sea scallops and the indirect effects of temperature on scallops via changes in distribution of one of their major predators, the sea star *Astropecten americanus.*

Recent studies have examined or projected range shifts for fishes in the northwest Atlantic based on first-order temperature effects (Murawski 1993, Rose 2005, Nye et al. 2009, Overholtz et al. 2011, Pinsky et al. 2013). The importance of second-order biotic interactions in determining species ranges is poorly understood but may be significant (Murawski 1993, Holt and Barfield 2009). The importance of including second-order climate effects in species distribution models (SDMs) is becoming recognized, both for understanding the current niches and for forecasting the impacts of climate change on species distributions (Araújo and Luoto 2007, Tylianakis et al. 2008, Kearney and Porter 2009, Van der Putten et al. 2010, Watt et al. 2011, Araújo and Peterson 2012). Because individual species have different thermal tolerances and trophic interactions are often complex, climate change can alter species interactions in unexpected ways, resulting in non-intuitive shifts in species ranges (Van der Putten et al. 2004; Schweiger et al. 2008, Van der Putten et al. 2010).

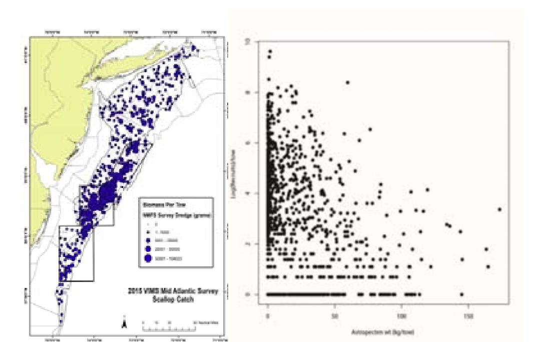

Figure 1. *Left*: Scallop biomass distribution, from the 2015 dredge survey. *Right*: Relationship between scallop recruitment and *A. americanus* biomass, from the 2000-13 dredge surveys

The inshore distribution of sea scallops in the MAB are generally constrained to depths greater than 30 m off of Long Island, increasing to about 40 m off Virginia, and latitudes greater than 36^{o}N, presumably due to summer thermal stress (Fig 1; Hart 2006). However, the outer depth limits of sea scallop in the MAB of about 85 m cannot be explained by thermal stress or other direct effects, since sea scallops are observed to depths of 120 m on Georges Bank, and even deeper in the Gulf of Maine (Schick et al. 1988, Hart 2006), so that the inclusion of other oceanographic processes and trophic interactions are necessary to accurately model the scallops' distribution. In particular, the sea star *Astropecten americanus* is a major predator of juvenile sea scallops and occurs in very high densities in deeper habitats adjacent to the sea scallop habitats (Fig 2, Franz et al. 1981, Franz and Worley 1982). It has been proposed that high densities of this sea star limit the offshore extent of the sea scallop distribution through high predation on early post-settlement juveniles (Hart 2006, Shank et al. 2012, Fig 1). This sea star is cold-stunned by

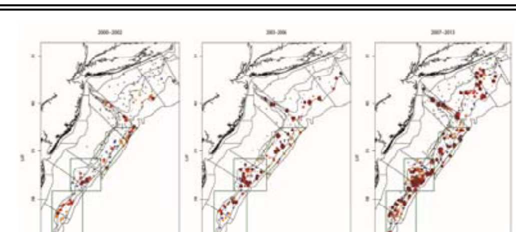

Figure 2. Changes in *A. americanus* distribution, 2000-2013, from the NEFSC sea scallop dredge survey

water temperatures below 5°C, resulting in the exclusion of sea stars from shallower shelf waters by winter minimum temperatures (Figure 1; Franz et al. 1981, D. Hart and A. Chute, pers.obs.). Significant shifts in the abundance of *A. americanus* have been occurring in recent years as it is moving into shallower and more northerly waters, likely due to warming winter bottom temperatures (Fig 2).

This niche trend in sea scallops is consistent with other examples, the most commonly known from rocky intertidal systems, of ecosystems in which a species' realized niche is limited by abiotic factors (eg., temperature) at one extreme, and biotic factors (eg., predation) at the other (Connell, 1961a,b). This realized niche phenomena and the factors controlling it are poorly explored in continental shelf species. Moreover, the consequences of a changing climate on niche dynamics have yet to be identified. We hypothesize that simple increases in both summer maxima and winter minima of water temperature may result in the exclusion of sea scallops from shallow waters while allowing sea stars to expand their distribution into current sea scallop habitats, respectively, resulting in a contraction of the sea scallop distribution in the MAB (Fig 3). Species distributions and population abundances are typically positively correlated, so it is probable that contractions and shifts in the sea scallop distribution will result in parallel effects on fishery yields (Fisher and Frank 2004, Nye et al. 2009).

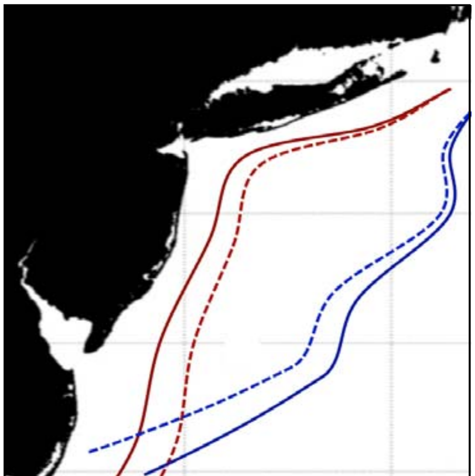

Figure 3. Hypothesized future niche contraction wherein the red inshore scallop thermal limit moves to deeper water (dotted line) and the blue offshore predator limit moves inshore (dotted line)

During fall and winter, cooling at the sea surface drives vertical homogenization of the water column at shallow to moderate depths, while in spring and summer surface heating re-stratifies the upper layer, isolating a remnant of the previous winter's cold mixed water at depth. This bottom-trapped pool of cold water is typically centered on the 40-60 m isobaths, bounded both inshore and offshore by warmer water, and may be important to determining the inshore extent of sea scallops. The Cold Pool breaks down in fall, gradually warming as surface waters are mixed downwards. Meanwhile, warm salty water from the slope keeps bottom temperatures in the deeper portion of the shelf relatively warm, allowing survival of *Astropecten* there. The spatial extent and temperature of the Cold Pool and deep water warming varies inter-annually in response to variations in this seasonal forcing. These changes in oceanographic conditions likely affect the quality and extent of sea scallop habitat.

Approach

We recognize 8 distinct stages in the development of this research project:

1. Production of a theoretical, fundamental niche model based on documented abiotic parameters that limit the geographic distribution of sea scallops.
2. Empirical production of a correlative species distribution (realized niche) model.
3. Comparison of the geographic extent predicted by the fundamental and realized niche models.
4. Refinement of the realized niche model by including biotic parameters.
5. Construction of species distribution models for other species identified as influencing sea scallop ranges.
6. Correlation of historic shifts in sea scallop ranges to major environmental oscillators.
7. Examination of the realized niche models under different climate change scenarios.
8. Examination of the realized niche model under predictions made by Intergovernmental Panel on

Climate Change (IPCC) and physical oceanography forecast models (ROMS).

(1) We will construct a fundamental niche model for sea scallops in the MAB based on published thermal habitat and benthic habitat parameters. The niche model will be mapped onto the MAB to create a climatological map of potential scallop habitat and year-specific spatial extents of the potential range. Bottom temperature distributions will be derived from a 50-year modeled hindcast of the oceanography of the region (Kang and Curchitser, 2013). The hindcast provides a spatially and temporally explicit time series of oceanographic conditions, capable of resolving the seasonal minimum and maximum bottom temperature distributions over the shelf. Outputs of hindcast bottom water temperature timeseries from that model have already been successfully applied to explain the physiological impacts of changing environmental conditions on stock redistribution in surfclams (Munroe et al., 2013, *In Revision*; Narváez et al., 2014). In parallel, we will utilize observations from the NMFS/NEFSC hydrographic database to construct empirical maps of bottom temperature and salinity, focusing primarily on spring and fall of each year when the annual minimum and maximum bottom temperatures occur. Habitat parameters will be extracted from rasters for water depth (NOAA National Geophysical Data Center, U.S. Coastal Relief Model), rugosity, and sediment type.

(2) We will construct a correlative Species Distribution Model (the realized niche model) for sea scallops using existing datasets for sea scallop populations and the abiotic datasets used in the fundamental niche model. The primary sea scallop dataset will come from the NMFS/NEFSC sea scallop dredge survey, conducted annually since 1979, and most recently conducted by coPI Rudders (VIMS) in 2015. This will be supplemented with data from HabCam optical scallop survey (annual from 2012) and from the NEFSC bottom trawl and clam dredge survey, and fishery-dependent data such as scallop commercial vessel monitoring system (VMS) and at-sea observer data. Scallop data will be simplified to presence / absence based on a minimum density threshold. We will develop different SDMs using regression-based methods such as general additive or logistic / double-logistic models on presence-absence data or machine learning techniques such as maximum entropy models on presence-only data.

(3) For each year, we will compare the extent of the fundamental and realized niche and correlate the model predictions and hindcasts. Geographic regions with persistent autocorrelated residuals will be used as evidence to formulate hypotheses for additional ecological and environmental parameters to be included in the niche models.

(4) We will refine the realized niche model for sea scallops by adding candidate ecological and environmental parameters and assessing the accuracy of updated models. For candidate ecological variables, semi-quantitative data is available for major benthic invertebrates throughout the time series and quantitative data on major predators (crabs and sea stars) has been collected since 2000 by the NEFSC sea scallop survey. Species with known ecological interactions with sea scallops (i.e. trophic linkages) and whose inclusion in niche models improves model accuracy will be interpreted as evidence of biotic influence on sea scallop ranges. Because scallop densities are generally below minimum profitable densities for the fishing industry at the limit of the species range, we do not we expect the fishery to affect the geographic extent of the species.

(5) We will then construct species distribution models for each relevant, trophically-linked species from standard abiotic parameters. We anticipate that *Astropecten* sea stars, among other biotic parameters, will be the most relevant for determining the maximum depth of sea scallops and that the minimum depth of sea stars, in turn, will be determined by winter minimum temperatures.

(6) Reconstructed histories of sea scallop distributions can then be correlated to oceanographic indices (e.g. summer/fall Cold Pool temperature and size; areal extent of winter temperature minimums) and to major environmental oscillators (NAO and AMO) with the expectation that sea scallop dynamics will lag the basin-scale oscillators by several years as changing thermal regimes directly and/or indirectly affect scallops. Inter-annual and multi-year shifts in sea scallop distributions that can be predicted by environmental oscillators have good potential for inclusion in stock assessment models with the capacity to project several years ahead.

(7) Once an adequate realized niche model with necessary trophic interactions has been constructed, we will apply different climate scenarios to the niche model and examine changes in the geographic ranges for sea scallops and linked species. Climate scenarios will include both changes in the mean and interannual variability in minimum and maximum bottom temperatures.

(8) Lastly, we will use IPCC-class climate models, specifically the high-resolution models from NOAA GFDL to project the spatial distribution of sea scallops up to the year 2100 under various greenhouse gas emission scenarios designated by the IPCC. A project has recently been funded through the NOAA Fisheries and Climate Change program, overseen by co-PI Curchitser that aims to forecast future oceanographic conditions using the Regional Oceanography Modeling System (ROMS) for an extensive area of the Atlantic Ocean and includes our region of interest. Forecast model output will be available to our project, allowing us to apply both the hindcast and forecast bottom water temperatures to the niche model to project future geographic ranges of sea scallops in the MAB predictions.

Benefits

FATE Priority 2.1 & 2.10 – Few trophically-linked species distribution models exist for marine systems, particularly for exploited species. The technique of comparing fundamental to realized niches for identifying and inferring the importance of biological interactions is also poorly developed. Also, the distribution and abundance of this species and its associated fishery is potentially strongly influenced by ecological interactions. Thus, the methodologies developed in this study will further develop existing frameworks for modeling spatial and temporal changes in population distribution and predator-prey interactions. Importantly, it will provide a mechanism by which to predict the impacts of climate and environmental climate change on fisheries (e.g., Hollowed et al. 2009).

FATE Priority 4 – This study will use historical data and ocean circulation model hindcasts to examine the how trends and variability of seasonal thermal minima and maxima affect the geographic distributions of scallops and relevant predators. Parameters derived from this will be used to forecast future distributions under different thermal trends and variability scenarios.

FATE Priority 5 – This project will use the most up-to-date science including IPCC climate scenarios and oceanographic (ROMS) model projections to make forecasts of ecological level (temperature and predator driven) shifts in scallop distribution. A critical habitat determinant for benthic sessile species like scallops is bottom water temperature – a characteristic that is poorly sampled in historic datasets, and is therefore much more challenging to forecast. The ROMS projections will be important for improving forecasting for scallop distribution because these models characterize bottom water much more accurately than IPCC projections available at this time.

NEFSC Strategic Plan Priorities*:* This proposal addresses the overarching goal of "Science in Support of Ecosystem-Based Fisheries Management", as well as goals B: "Improve quality, efficiency, and responsiveness of stock assessments and other science based advice", and F: "Improve understanding of the influence of climate, ecosystem, habitat factors, and species relationships on living marine resource dynamics in order to provide integrated scientific advice to managers."

Integration with assessment science*:* Two key members of the NEFSC sea scallop stock assessment team (Hart, Shank) are Pis on this project, and another PI (Rudders) oversaw the most recent (2015) cooperative dredge survey of the scallop stock in the MAB and serves on the NEFMC scallop PDT. The results of this project will be integrated with other information, such as spawning stock biomass, to produce a predictive model of sea scallop recruitment in the Mid-Atlantic Bight. Temporally-lagged relationships between sea scallop ranges and climate oscillators may be integrated into the stock assessment model to predict recruitment and adult mortality rates. Information on predicted short-term shifts in spatial distributions can be utilized to optimize the allocation of survey effort in annual surveys. Predicted long-term shifts in the distribution of sea scallops will be valuable to socio-economists with implications for the coastal communities that are supported by this fishery.

Deliverables

This work will be integrated into the stock assessment models for sea scallops: the CASA estimation model, the SAMS area management forecasting model, the SYM reference point model. The predictive model of recruitment will enhance the ability to forecast scallop yield in the MAB in the medium to long term, and can be combined with the effects of ocean acidification (Cooley et al. 2015).

We foresee producing two manuscripts from this research. The first manuscript would address the development of the trophically-linked species distribution model and the relative importance of including ecological interactions. The second manuscript would address climate change scenarios and shifting species distributions. In addition the results of this research will be shared at the American Fisheries Society annual meeting, the International Pectinid Workshop in Portland ME (2017) and at the FATE meetings. All data collected or produced will be entered and published in the NMFS Data Catalog and Metadata Repository, InPort (https://inport.nmfs.noaa.gov/)

Timeline

Timeline	Activity	Comments
May 2016	***Meeting (Rutgers):*** Project Initiation – All Hands	Investigators will discuss relevant literature, project scope and assign tasks for project goals in year 1.
May – Aug. 2016	Postdoc	Theoretical niche model development
	Postdoc	Realized (empirical) model development
	Postdoc	Comparison of theoretical & realized niche model predictions.
	Curchitser	Development of isotherm boundary datasets for hindcast
September 2016	All Hands Meeting (**Woods Hole**)	Meeting to discuss progress and refine tasks
Sept. 16 – Mar. '17	Postdoc	Refinement of niche models
	Postdoc	Construction of species distribution models
	Postdoc, Hart, Shank	Correlation of historic shifts with hindcast isotherm predictors
April 2017	***Meeting (Woods Hole):*** Project Update – All Hands	Investigators will discuss progress to date and assign tasks for project goals in year 2.
April – Aug. 2017	Postdoc	Realized niche predictions for climate change, IPCC and ROMS forecasts
June '17 – May '18	All Hands	Writing manuscripts and reports
Other:		
2017	Present Results at AFS and IPW 2017	
2017 and 2018	Attend FATE Meetings	

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