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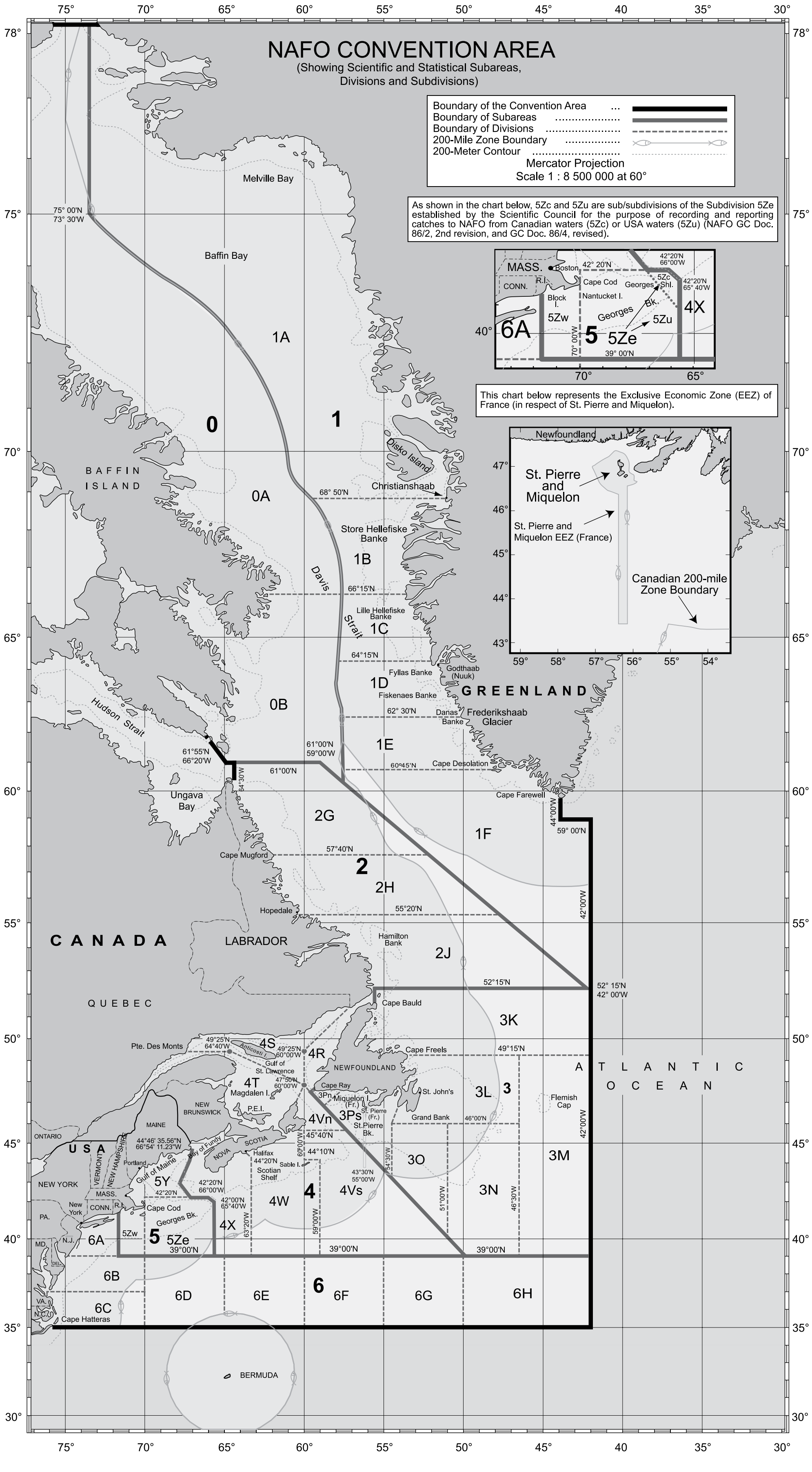
Scientific publications by ICNAF and NAFO have been in existence since ICNAF began in 1949 with the ICNAF Special Publication series dealing with proceedings of scientific symposia. The *ICNAF Research Bulletin* was started in 1964 to provide a means of publishing results of scientific research relevant to ICNAF. The ICNAF Research Bulletin was terminated in September 1979 after the issue of Number 14. The first volume of the NAFO *Journal of Northwest Atlantic Fishery Science* was published in December 1980, after NAFO came into force replacing ICNAF in 1979.

The Northwest Atlantic fisheries have a rich history, and a great deal of research has been sponsored and encouraged by NAFO and its predecessor ICNAF. NAFO has been a leader amongst international organizations in the application of science to fishery management and in the regulation of fisheries in areas beyond national jurisdiction. In accordance with its mandate to disseminate information on fisheries research to the scientific community, the Scientific Council of NAFO publishes the *Journal of Northwest Atlantic Fishery Science*, which contains peer-reviewed primary papers, and *NAFO Scientific Council Studies*, which contains unrefereed papers of topical interest and importance to the Scientific Council. Lists of these and other NAFO publications are given on the back of this issue.

Editorial Policy

The Journal provides an international forum for the primary publication of original research papers, with emphasis on environmental, biological, economic and social science aspects of fisheries and their interactions with marine habitats and ecosystems. While the Journal is intended to be regional in scope, papers of general applicability, and methodological and review papers, irrespective of region, are considered. Space is available for notes and letters to the editor to facilitate scientific discussion of published papers. Both practical and theoretical papers are eligible. All papers are peer-reviewed to determine their suitability for primary publication. Associate Editors arrange for the peer-reviews and ensure that the papers accepted for publication meet the high standards required for the Journal. Manuscripts approved for publication are accepted with the understanding that they are not copyrighted, published or submitted elsewhere except in abstract form. There are no page charges.

Editorial Board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(Showing Scientific and Statistical Subareas, Divisions and Subdivisions)
Boundary of the Convention Area
Boundary of Subareas
Boundary of Divisions
200-Mile Zone Boundary
200-Meter Contour
Mercator Projection
Scale 1 : 8 500 000 at 60°
As shown in the chart below, 5Zc and 5Zu are sub/subdivisions of the Subdivision 5Ze established by the Scientific Council for the purpose of recording and reporting catches to NAFO from Canadian waters (5Zc) or USA waters (5Zu) (NAFO GC Doc. 86/2, 2nd revision, and GC Doc. 86/4, revised).
This chart below represents the Exclusive Economic Zone (EEZ) of France (in respect of St. Pierre and Miquelon).
St. Pierre and Miquelon
St. Pierre and Miquelon EEZ (France)
Canadian 200-mile Zone Boundary
Newfoundland
Melville Bay
Baffin Bay
BAFFIN ISLAND
Davis Strait
Hudson Strait
Disko Island
Christianshaab
Store Hellefiske Banke
Lille Hellefiske Banke
Fyllas Banke
Fiskenaes Banke
Godthaab (Nuuk)
GREENLAND
Frederikshaab Glacier
Danas Banke
Cape Desolation
Cape Farewell
Ungava Bay
Cape Mugford
Hopedale
Hamilton Bank
CANADA
LABRADOR
QUEBEC
Cape Bauld
Cape Freels
NEWFOUNDLAND
St. John's
Flemish Cap
Grand Bank
ATLANTIC OCEAN
Pte. Des Monts
Gulf of St. Lawrence
Magdalen I.
P.E.I.
NEW BRUNSWICK
NOVA SCOTIA
Halifax
Sable I.
Scotian Shelf
Bay of Fundy
Gulf of Maine
Cape Cod
Georges Bk.
USA
MAINE
Portland
NEW YORK
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0 1 2 3 4 5 6
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Foreword

The Scientific Council of NAFO publishes the Journal of Northwest Atlantic Fisheries Science, containing peer-reviewed primary literature detailing original research of relevance to fisheries science and management in the northwest Atlantic Ocean. Articles are published electronically under a Creative Commons (Canada) 2.5 license, and are freely available at http://journal.nafo.int. NAFO Scientific Council has resolved to produce annual bound print volumes and these represent a compilation of the web based articles published throughout the year. Additionally, the journal supports the use of digital object identifiers (doi) for electronic media and encourages others to support this initiative.

As always, this issue covers a range of topics representing ongoing research in the northwest Atlantic, including the survey design, management frameworks and planktonic distribution and production.

I would like to extend my thanks to all the authors who submitted works during 2014, to the Associate Editors and reviewers who make production of the journal possible, and to Alexis Pacey, publications manager at the NAFO Secretariat for her support and assistance. I would particularly like to thank Hajo Rätz, who, after several years of service to the journal has decided to step down, and welcome Lisa Hendrickson to the editorial board in his place.

December 2014

Neil Campbell
General Editor,
Journal of Northwest Atlantic Fishery Science

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Decadal Distribution and Abundance Trends for the Late Stage Copepodites of *Pseudocalanus* spp. (Copepoda: Calanoida) in the US Northeast Continental Shelf Ecosystem

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Abstract

The average annual cycle of abundance and the bimonthly distributions of the copepod *Pseudocalanus* spp. are described for U.S. Northeast continental shelf waters from samples collected on broad-scale plankton surveys 1977–2012. Population levels begin to increase during January–February, surge in March–April, and peak throughout the region during May–June. The copepod's population density declines sharply after June and becomes minimal from September–December. Spatially, seasonal high levels persist throughout the year in coastal waters surrounding and adjacent to the Cape Cod peninsula. During late spring, dense concentrations are found in Gulf of Maine coastal waters and in a high abundance band that extends southwestward from Georges Bank into the northern half of Middle Atlantic Bight waters. *Pseudocalanus* spp. interannual abundance variability was substantial; displaying several extended low and high periods through the time series. In general, numbers were high from the late 1970s through the early 1980s, low in the mid-1980s, elevated in the 1990s, and low again in the 2000s. This pattern was correlated negatively with temperature and positively with phytoplankton abundance trends. It is proposed that the copepods low abundance in the 2000s may have been caused by warmer temperatures that indirectly depressed the abundance of phytoplankton that this copepod uses for food. Survey data also indicate that predation pressure from salps and perhaps some additional species may contribute to the precipitous summer decline of *Pseudocalanus* spp. The copepod's abundance was found to be independent from the climatic variation associated with either the North Atlantic or Arctic Oscillation.

Keywords: *Pseudocalanus* spp., abundance, distribution, temperature, phytoplankton

Introduction

The waters of the U.S. Northeast Shelf Ecosystem extends from the Gulf of Maine south to Cape Hatteras, encompassing 260,000 km^2 that form one of the most productive regions of the world's oceans. The ecosystem has supported large commercial fisheries for nearly four centuries, and contributes at least one billion dollars annually to the economies of the adjacent coastal states (Sherman *et al.,* 1996). However, the region has been impacted by substantial environmental and anthropogenic perturbations in recent years, resulting in fundamental changes to ecosystem structure and function that now threaten the sustainability of the region's fish stocks (Ecosystem Assessment Program, 2009).

It has long been recognized that the year-class strength of important commercial fish species is affected by environmental conditions during their early life stages. Given that many fish larvae and juveniles feed on zooplankton, it is logical to hypothesize that there must be a relationship between zooplankton abundance and the size of future fish stocks. However, time series correlations between measures of plankton and recruitment have not been well established in marine ecosystems. It is generally believed these relationships are masked or confounded by the interaction of complex physical and biological processes that operate on different spatial and temporal scales (Heath and Lough, 2007). Nonetheless, recent studies in the Gulf of Maine and Georges Bank regions have begun to utilize lengthening time series to link fish recruitment with variations in zooplankton abundance (Pershing *et al.*, 2005; Mountain and Kane, 2010; Friedland *et al.*, 2013)

Pseudocalanus is a genus of small calanoid copepods that often dominate plankton samples collected in neretic waters of the Northern Hemisphere (Corkett and McLaren, 1978). Since their production cycle coincides with the spring bloom of diatoms, they are usually classified as winter-spring species in the Northwest Atlantic (Davis, 1987). There is a large body of literature showing that the different species of *Pseudocalanus* are the predominant prey item of many species of larval fish found in northern waters (*e.g.* Kane, 1984, Buckley and Durbin, 2006, Heath and Lough, 2007). A modeling study suggested that the apparent preference of early larvae for this copepod was caused by its high density and inherent behavioral traits that enhance detection by larval predators (Kristiansen *et al.*, 2009). As fish larvae become older, they actively select for *Pseudocalanus* spp., preying especially on egg-carrying females as a means to maximize energy intake per attack (Robert *et al.*, 2011). These findings all suggest that the abundance variability of this copepod is a critical factor determining the recruitment success of fish species found in such ecosystems.

Stegert *et al.* (2010) forecast that if the ocean continues to warm at its current pace, *Pseudocalanus* spp. will be less abundant in the North Atlantic. Their model predicts that climate induced changes will shorten the seasonal extent of the copepod's growth cycle and reduce its spatial distribution, affecting the food supply and the recruitment success of the region's fish stocks. NOAA Fisheries has monitored the zooplankton component of the U.S. Northeast Shelf Ecosystem with broadscale surveys that have collected plankton and hydrographic samples since the late 1970s. This paper utilizes this extensive data set to describe the average distribution and abundance patterns of *Pseudocalanus* spp. during the years 1977–2012. Interannual abundance variability is examined to determine if the current warming trend has already impacted the copepods life history. In addition, to gain insights into factors controlling the copepod's abundance, its variability was compared with year-to-year fluctuations in temperature, salinity, phytoplankton, and regional climatic indices.

Materials and Methods

Plankton Data

Bimonthly plankton sampling in the Northeast Continental Shelf Ecosystem (Fig. 1) was initiated in 1977 as part of the NOAA Fisheries MARMAP program (Sherman, 1980) and continues today as the ECOMON program (Hare and Kane, 2012). All samples were collected with a 0.333 mm mesh net fitted on one side of a 61 cm bongo frame that was equipped with a calibrated flowmeter and towed at approximately 1.5 knots. Cruise tracks and detailed sampling procedures for plankton and other measurements on surveys before 1988 were summarized by Sibunka and Silverman (1984, 1989). The only major change in sampling methodology after 1987 was attaching a CTD instrument above the bongo frame to monitor the tow profile and collect simultaneous oceanographic data. The different survey sampling schemes employed during the time series have been described by Kane (2003).

In the laboratory, samples were reduced to approximately 500 organisms by subsampling with a modified box splitter. Zooplankton in the aliquot was identified to the lowest possible taxa and counted at the Plankton Sorting Center, Szczecin, Poland. The abundance of *Pseudocalanus* spp. is expressed here as numbers/100 m^3 and includes only adults and copepodite stage five. Younger copepodite stages found in the samples were excluded because 0.333 mm mesh nets undersample other copepods of similar size (Anderson and Warren, 1991).

It is important to note that the data presented here do not represent a single species. Molecular genetics have distinguished two congeners within the surveyed waters: *Pseudocalanus moultoni* and *Pseudocalanus newmani* (Bucklin *et al.*, 1998). The two species are so similar morphologically that taxonomists are unable to readily distinguish between them. Therefore, all specimens were identified and counted as *Pseudocalanus* spp. Though it has been reported that there are some distribution differences between them, both species have similar monthly mean abundance values and frequently co-occur in samples from these waters (McGillicuddy and Bucklin, 2002). Thus, any bias introduced into this study by different proportions of these species is likely minimal.

The annual abundance cycles of copepod invertebrate predators captured in survey nets were examined to determine which ones would be mostly likely to cause the seasonal decline of *Pseudocalanus* spp. Five predators were chosen for analysis based on their high abundance just before or during the copepod's seasonal decline: the omnivorous copepods *Centropages typicus* and *Centropages hamatus*, chaetognaths, salps, and siphonophores. If the interannual variability of the potential predators were negatively correlated with *Pseudocalanus* spp. trends, then top-down control from them could be inferred.

Phytoplankton data were collected concurrently with a Continuous Plankton Recorder (CPR) towed at about 10 m depth along two transects that crossed the ecosystem (Fig. 1). Surveys were conducted at approximately monthly intervals across the Gulf of Maine and from off the coast of New York City southeastward towards Bermuda. The time series (1977–2009) of total phytoplankton counts, diatoms, and dinoflagellates from shelf waters were compared with the annual patterns of *Pseudocalanus* spp. abundance. The methods used on the CPR surveys along these two routes have been described by Jossi and Benway (2003).

Environmental Data

Temperature and salinity measurements were made routinely on all broad scale surveys. Surface temperature measurements from 1977–1999 were made with a stem thermometer from a surface bucket sample or were recorded via a thermistor attached to the vessel. From 2000 onward, temperature was measured with a CTD instrument. Samples for bottom temperature, surface salinity, and bottom salinity were collected with Niskin bottles from 1977 to 1986, while later years utilized the CTD.

Climate variability was indexed with the winter phase of the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO), the Gulf Stream North Wall Index (GSI), and the Atlantic Multidecadal Oscillation (AMO). The NAO is an index which is based on the difference of

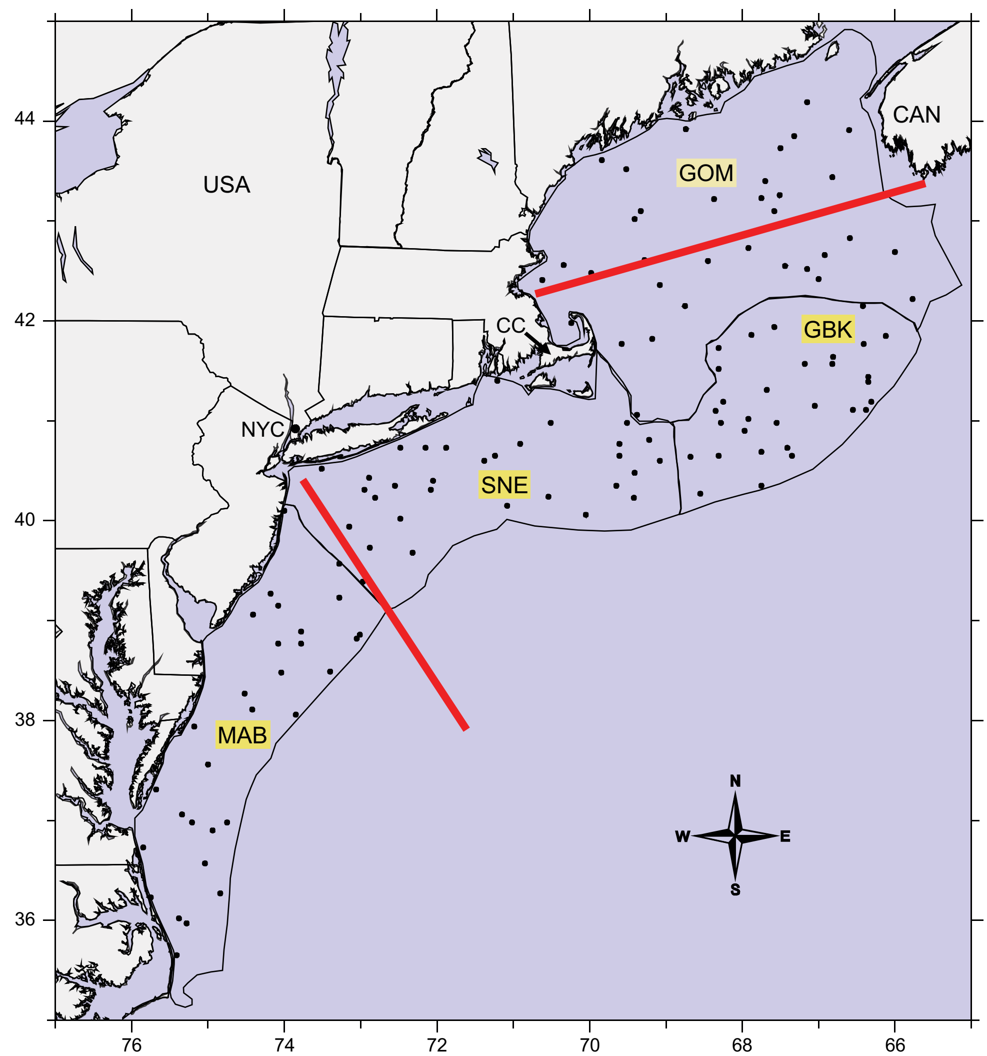

Fig. 1. Orientation map of area sampled during broad scale plankton surveys of the U.S. Northeast Shelf ecosystem. The survey area was divided into four subareas: 1) Gulf of Maine (GOM), 2) Georges Bank (GBK), 3) Southern New England (SNE), and 4) Middle Atlantic Bight (MAB). Markers on the map indicate the location of stations occupied during the 2009 May–June survey. The horizontal red lines are the approximate location of the CPR transects. Place name abbreviations: NYC = New York City, CC = Cape Cod.

normalized sea level pressures between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland from the months of December through March (Hurrell, 1995; data retrieved from: https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based). The AO is a climate index of the state of the atmospheric circulation over the Arctic that indicates if polar air is locked in place or if it is allowed to penetrate south into middle latitudes (Thompson and Wallace, 1998; data retrieved from: http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/JFM_season_ao_index.shtml). The GSI is a measure of the position of the north wall of the Gulf Stream as it diverges from the North American coastline (Taylor, 1995; data retrieved from: http://www.pml-gulfstream.org.uk/Web2013.pdf). The AMO is a mode of natural variability occurring in the North Atlantic that is primarily associated with long duration changes in sea surface temperature (Kerr, 2000; data retrieved from: http://www.esrl.noaa.gov/psd/data/correlation/amon.sm.data). These four indices of climate variability are all known to affect physical and biological measurements across the North Atlantic.

Analysis of the copepod's abundance variability was facilitated by dividing the ecosystem into four subareas whose boundaries are defined by oceanographic characteristics (Ingham *et al.*, 1982): the Gulf of Maine (GOM), Georges Bank (GBK), Southern New England (SNE), and the Middle Atlantic Bight (MAB) (Fig. 1). Interannual variability was examined by calculating yearly anomalies for each variable within each region. To reduce the bias caused by sampling variability and to allow comparison between years, the average annual cycle of each variable was computed by fitting a spline curve function to the time series log10(n+1) transformed bimonthly or monthly (CPR data) mean values. This generates the expected value on any day of the year. Survey means were then subtracted from the projected values on the median day of that particular cruise. Anomalies from the seasonal cycle were then averaged over each year to produce an annual index. Sampling was too infrequent on broad scale surveys to calculate the annual anomaly in the GOM for the years 1989 and 1990, in the SNE region for 1989, and in the MAB from 1989–1994.

Spearman's rank correlation analysis of annual anomalies was used to show connections between and among zooplankton and environmental variables. Autocorrelation in the data was accounted for by adjusting the effective degrees of freedom (N^*) of each test using the following procedure (Pyper and Peterman, 1998):

$$\frac{1}{N^*} = \frac{1}{N} + \frac{2}{N}\sum_{j}^{N/5} r_{xx}(j) r_{yy}(j)$$

where N is the number of sample pairs,

and $r_{xx}(j)$ and $r_{yy}(j)$ are the sample autocorrelation of x and y at lag j (Box and Jenkins, 1976). The probability of rejecting a true null hypothesis was set low (0.01) to ameliorate the effects of multiple hypothesis tests. Abundance anomalies were also correlated with one, two, and three year lag periods of climatic indices to determine whether conditions in preceding years affect the copepods productivity.

Contoured bimonthly and seasonal distribution maps of abundance were generated using the Surfer 9 software package (Golden Software) to interpolate abundance surfaces with kriging gridding methods at default settings.

Results

Distribution and Abundance

The annual abundance cycle of *Pseudocalanus* spp. is similar throughout the study regions. The population begins to increase during winter from its annual low, surges upward in March–April, and reaches its annual maximum in May–June (Fig. 2). Mean abundance declines sharply after June and is minimal from September through December. The copepod's highest May–June abundance is usually measured in the SNE subarea, while the lowest

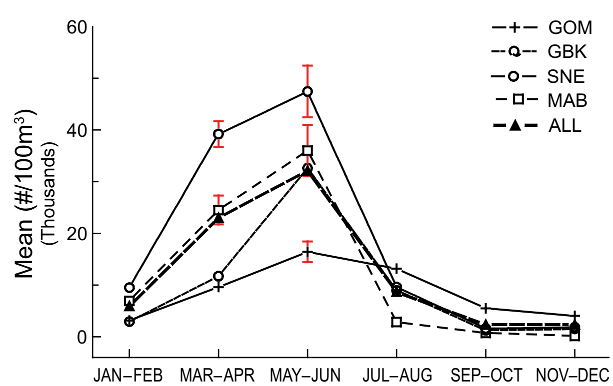

Fig. 2. The time series annual mean abundance cycle of *Pseudocalanus* spp. in the U.S. Northeast Shelf ecosystem and in each of its four subareas. Markers are the mean of annual means from samples collected in the bimonthly periods. Isolated points during the spring season have error bars to indicate the 95% confidence interval of the mean.

is found in the GOM. However, the summer decline is comparatively moderate in the latter region, elevating GOM mean abundance above all other regions during the second half of the year (Fig. 2).

The pattern of the copepods abundance cycle was persistent throughout the time series on GBK, but displayed decadal variability in other surveyed regions (Fig. 3). Peak abundance was delayed in the GOM until July–August during the 1980s (Fig. 3A) and occurred earlier (March–April) in SNE waters during the 1990s (Fig. 3C). These were only temporary shifts; both regions had the time series mean pattern return in the following decade. However, the *Pseudocalanus* spp. spring maximum may have permanently shifted in MAB waters. During the late 1970s and 1980s peak abundance was usually recorded there in March–April, while in the 1990s and 2000s it was measured two months later during May–June (Fig. 3D). This delay caused a marked reduction in the copepods early spring abundance during the 2000s (Fig. 3D).

Spatially, *Pseudocalanus* spp. is usually found year round, except in the southernmost tip of the region during November–December (Fig. 4). There is always present a year-round band of elevated abundance that extends from GOM coastal waters, around Cape Cod, and across Nantucket shoals. A pocket of high abundance off the southwestern coast of Nova Scotia also persists throughout the year. The abundance of *Pseudocalanus* spp. is usually higher in the shallower areas (<100 m) of the ecosystem (Fig. 4).

The perennial high abundance region of *Pseudocalanus* spp. expands during winter, reaching across GBK and into SNE coastal waters (Fig. 4). In early spring this region enlarges along coastal waters and expands into offshore waters. During the late spring maximum, high concentrations are found in GOM coastal waters and in a large belt that extends from GBK southwestward across SNE and into MAB waters. The band constricts sharply in summer and by early fall is confined to GOM coastal waters. *Pseudocalanus* spp. becomes very sparse in MAB waters during the autumn months (Fig. 4).

Distribution patterns were relatively stable through the time series with no major poleward or longitudinal shifts (data not shown). However, contrasting seasonal abundance levels through the decades reinforced the changing spring pattern described earlier for the MAB region. New time divisions used to pinpoint changes for early spring distributions revealed that the high abundance

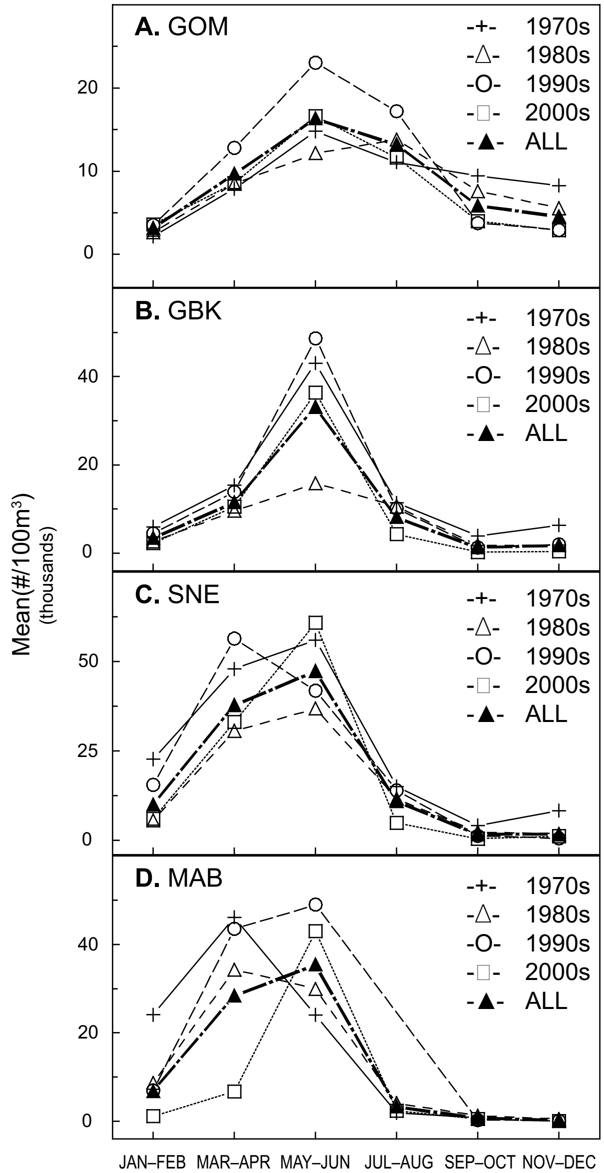

Fig. 3. The decadal annual abundance cycles of *Pseudocalanus* spp. in the **A**) GOM (Gulf of Maine), **B**) GBK (Georges Bank), **C**) SNE (Southern New England), and **D**) MAB (Mid-Atlantic Bight) regions.

that extended into the region during the first half of the time series began to withdraw northward during the late 1990s (Fig. 5). The band disappeared entirely after 2005 (Fig. 5), depressing mean abundance levels there to its time series low (Fig. 3D).

Pseudocalanus spp. interannual abundance exhibited two high and low multi-year abundance periods that

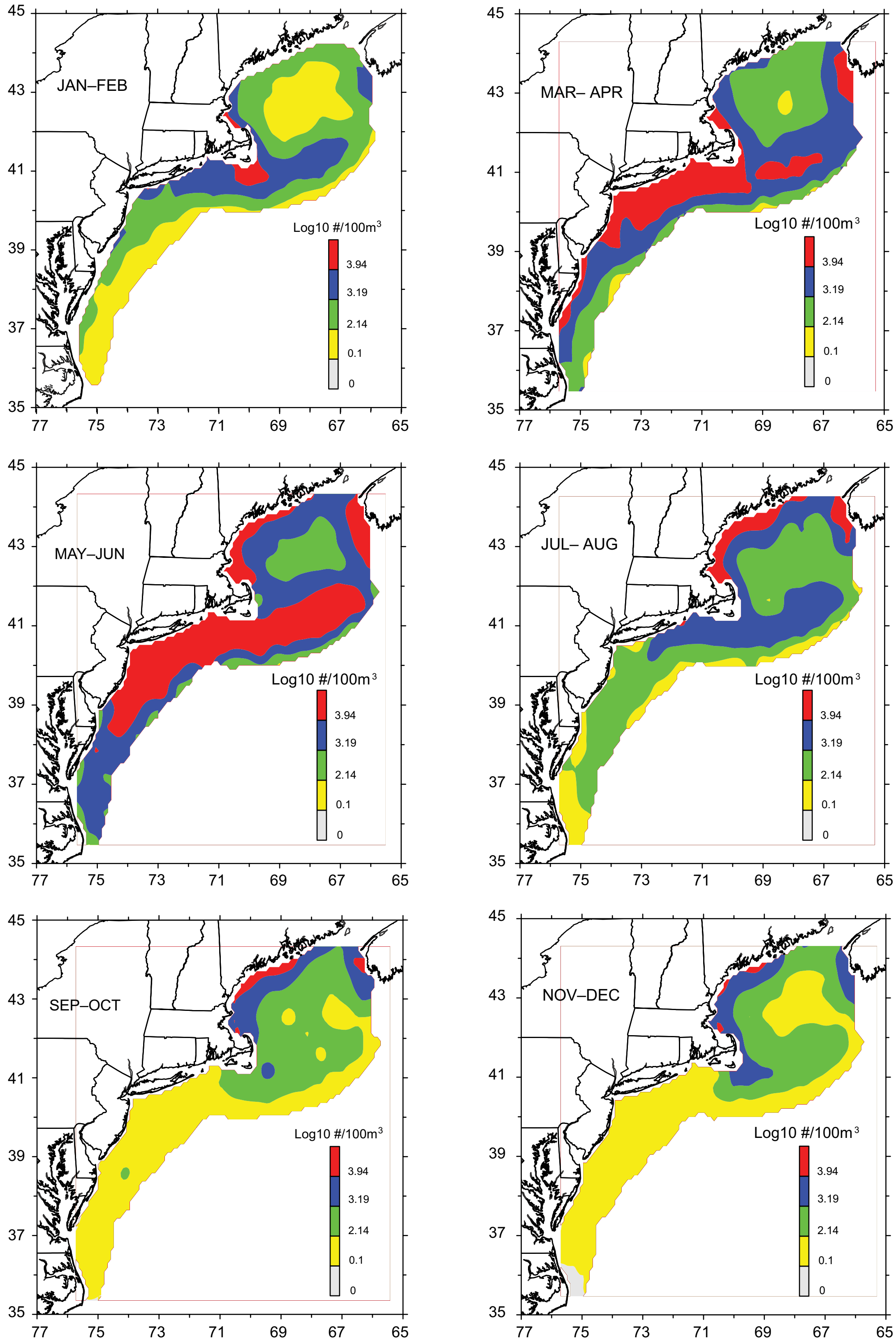

Fig. 4. Bimonthly composite distribution and abundance of *Pseudocalanus* spp. in the U.S. Northeast Shelf ecosystem.

were present throughout most of the ecosystem (Fig. 6). In general, abundance was high from the late 1970s through the early 1980s, low in the mid 1980s, elevated during the 1990s, and below average during the 2000s. This rollercoaster pattern was more distinct in the two more northern regions, while annual indices were more variable in the southern half of the ecosystem. The lowest abundance levels of the time series were recorded during the 2000s in all regions (Fig. 6).

Predation

Salps were found to be the most likely of the potential predators examined that have applied top-down pressure

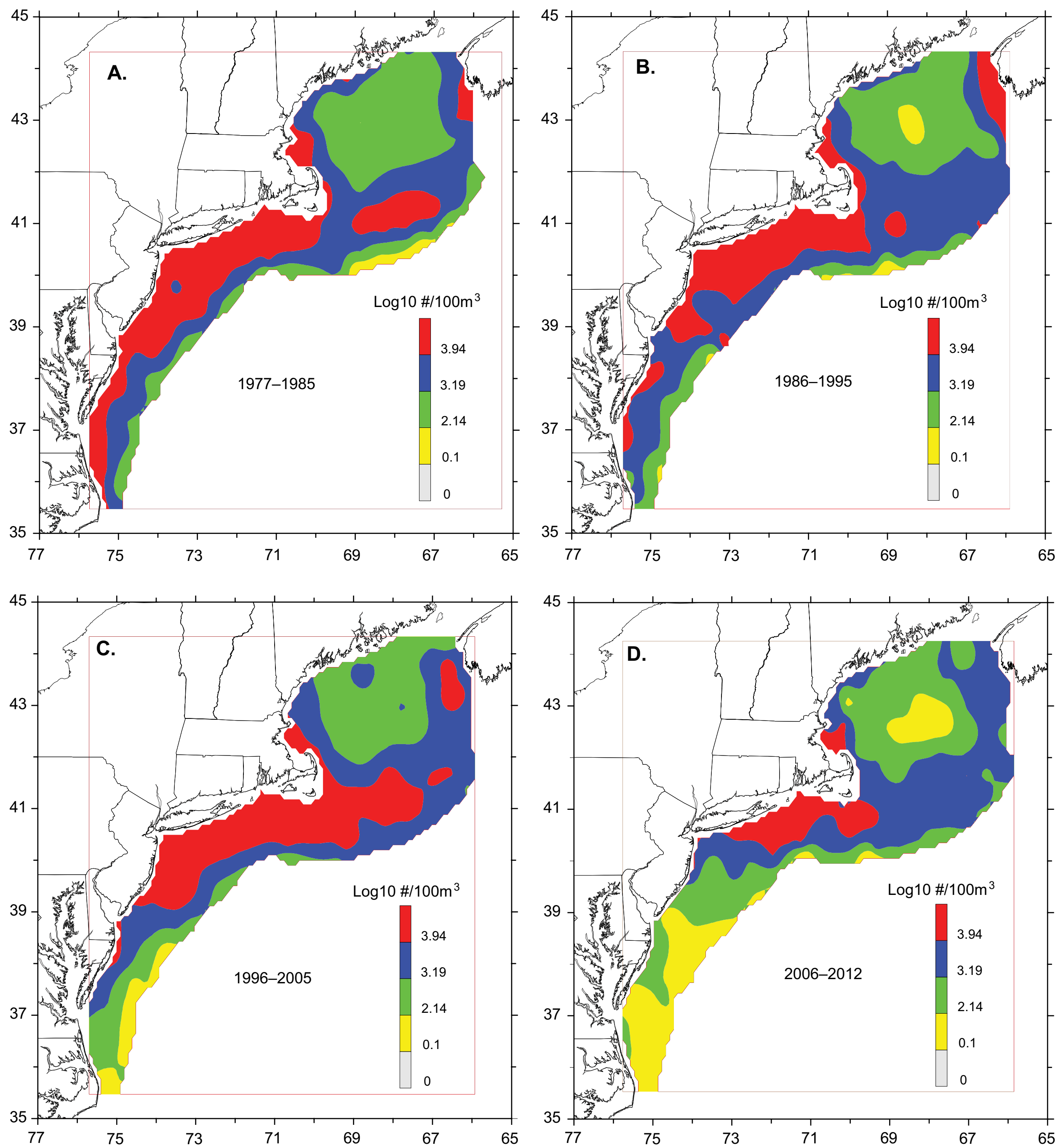

Fig. 5. Average early spring (March–April) distribution and abundance of *Pseudocalanus* spp. in the U.S. Northeast Shelf ecosystem during **A**) 1977–1985, **B**) 1986–1995, **C**) 1996–2005, and **D**) 2006–2012.

on the population levels of *Pseudocalanus* spp. Annual abundance trends of both taxa were negatively correlated throughout the ecosystem. Though their overall abundance is low on GBK (Fig. 7), there was a significant negative (p<0.01) relationship measured there and substantial (p<0.10) ones found in the SNE and MAB regions (Table 1). Salp abundance explodes throughout most of the ecosystem during the summer months when *Pseudocalanus* spp. numbers diminish (Fig. 7). These gelatinous organisms are common members of the zooplankton community during summer, dispersed throughout the shelf in an increasing north to south abundance gradient (Fig. 7).

Pseudocalanus spp. trends were also negatively correlated with both siphonophore and chaetognath abundance in the southern half of the ecosystem (Table 1). Though coefficients were moderate, in certain years these predators likely reduce the copepods abundance there. There was no evidence found that the omnivorous copepods *Centropages typicus* and *Centropages hamatus* affect the density of *Pseudocalanus* spp., correlations between annual abundance levels were positive throughout the ecosystem (Table 1).

Correlation Analysis

Annual trends of *Pseudocalanus* spp. abundance in all regions were negatively correlated with temperature and salinity measurements, with nearly half of them found to be significant (p<0.01) (Table 2). The highest correlations were found in the SNE region with surface and bottom temperature measurements (Table 2). Annual temperature anomalies in this region have been highly variable over the time series, but have been trending upward in recent years (Fig. 8A), as opposed to the downward trend observed for *Pseudocalanus* spp. abundance (Fig. 6C).

Climatic indices were also all negatively correlated with *Pseudocalanus* spp. annual abundance anomalies (Table 2). The relationship was significant for the AMO

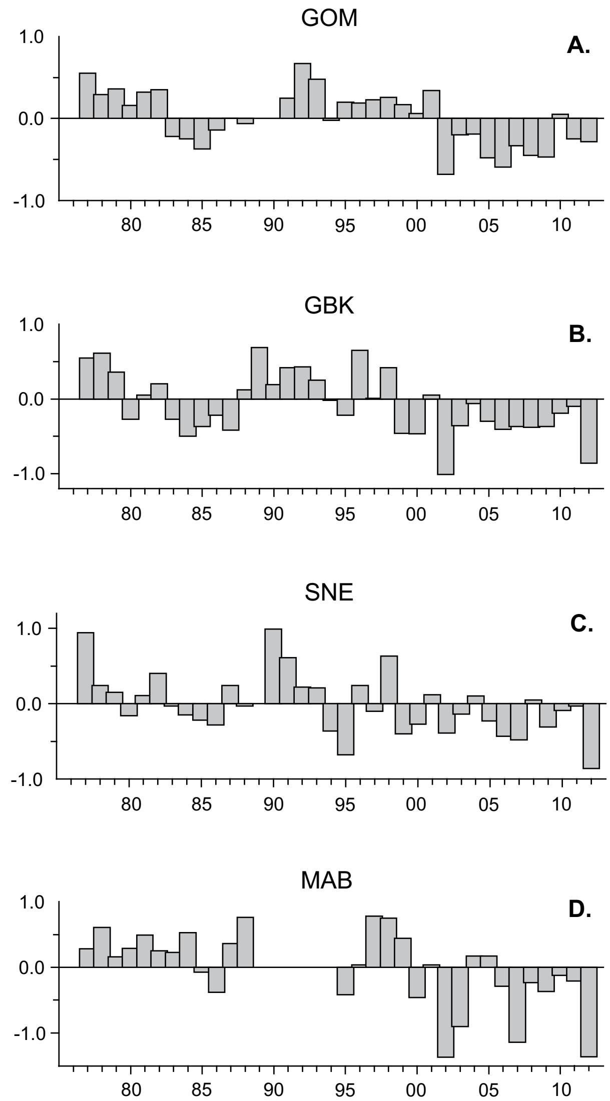

Fig. 6. Annual anomalies (1977–2012) of *Pseudocalanus* spp. abundance in the **A**) GOM (Gulf of Maine), **B**) GBK (Georges Bank), **C**) SNE (Southern New England), and **D**) MAB (Mid-Atlantic Bight) regions. Each bar represents the annual mean of survey log abundance anomalies.

Table 1: Spearman correlation coefficients between the regional annual abundance anomalies of *Pseudocalanus* spp. and taxa that are potential predators of the copepod. An asterisk placed after the coefficient indicates a significant (p<0.01) relationship.

Taxa	Gulf of Maine	Georges Bank	Southern New England	Middle Atlantic Bight
Centropages hamatus	0.11	0.11	0.34	0.40
Centropages typicus	0.62*	0.19	0.07	0.16
Salps	-0.08	-0.43*	-0.29	-0.33
Siphonophores	0.44	-0.14	-0.17	-0.26
Chaetognatha	0.57*	0.06	-0.25	-0.33

Table 2: Spearman correlation coefficients between the regional annual anomalies of *Pseudocalanus* spp. abundance and environmental variables. An asterisk placed after the coefficient indicates a significant (p<0.01) relationship.

Variable	Gulf of Maine	Georges Bank	Southern New England	Middle Atlantic Bight
North Atlantic Oscillation	-0.01	-0.08	-0.20	-0.12
Arctic Oscillation	-0.07	-0.10	-0.20	-0.28
Gulf Stream Index	-0.16	-0.22	-0.36	-0.51*
Atlantic Multi-Decadal Oscillation	-0.42	-0.40*	-0.32	-0.29
Surface Temperature	-0.29	-0.41*	-0.70*	-0.60*
Surface Salinity	-0.01	-0.20	-0.33	-0.57*
Bottom Temperature	-0.46*	-0.41*	-0.69*	-0.47*
Bottom Salinity	-0.28	-0.38	-0.38	-0.57*
Total Phytoplankton	0.71*	–	0.30	0.61*
Total Diatoms	0.69*	–	0.01	0.21
Total Dinoflagellates	0.57*	–	0.35	0.69*

in GBK waters and for the GSI in the MAB region. Correlation coefficients with the NAO and AO indices were all low and insignificant (Table 2). Lagging the climatic indices by one to three years did not substantially change correlations or reveal meaningful relationships (data not shown).

Total counts of phytoplankton, diatoms, and dinoflagellates along the GOM CPR transect were strongly positively correlated (p<0.01) with *Pseudocalanus* spp. abundance trends in the region (Table 2). Annual phytoplankton abundance anomalies there had sustained high and low periods (Fig. 8B), very similar to the copepod's yearly pattern (Fig. 6A). Total phytoplankton counts on the CPR transect that bisected the SNE and MAB regions were also positively correlated with *Pseudocalanus* spp. abundance in these regions. However, only relationships between total counts and the dinoflagellate fraction from the MAB were significant (p<0.01) (Table 2).

Discussion

The life cycle of *Pseudocalanus* spp. is the classic spring pattern found in temperate waters. The copepod's abundance increases sharply throughout the region during early spring and large populations are established in late spring. Numbers diminish during summer and are minimal through the autumn and winter months. Spatially, *Pseudocalanus* spp. is usually found in a decreasing inshore-offshore abundance gradient with high seasonal levels persisting throughout the year in coastal waters surrounding and adjacent to the Cape Cod peninsula.

The copepod's long term abundance trend displayed a roller coaster pattern, with high and low periods persisting for several years. Surface and bottom temperature readings collected on surveys were more variable, but annual indices of both measurements were found to be significantly negatively correlated to *Pseudocalanus* spp. patterns. This was largely driven by the low abundance measured in the 2000s, which coincides with the regions recent warming trend (Belkin, 2009). The copepods abundance was very low in 2012, when sea surface temperatures in shelf waters were the highest ever recorded (Mills *et al.*, 2013).

Sea surface temperatures measured on our surveys during the 2000s were on average 0.74°C higher then values recorded in the 1990s. The decline in *Pseudocalanus* spp. abundance is certainly associated with this warming trend, but it seems unlikely that this moderate increase in temperature would directly lower population levels. *Pseudocalanus* spp. can tolerate and thrive in a wide range of temperatures. On the U.S. Northeast Shelf, it was captured by the CPR at locations where temperatures ranged from 0.3–27.7°C. Modeling studies and laboratory experiments with *Pseudocalanus* spp. indicate that population growth is positive in waters where temperatures are less than 20°C (*e.g.* McLaren, 1966; Corkett and Zillioux, 1975; Dzierzbicka-Glowacka, 2004; Stegert *et al.*, 2010). This thermal adaptability has led investigators to hypothesize that the copepods summer decline is primarily caused by predation mortality, rather than the physiological effects of increasing temperatures (Davis, 1984; Ji *et al.*, 2009). Therefore, it seems unlikely that the

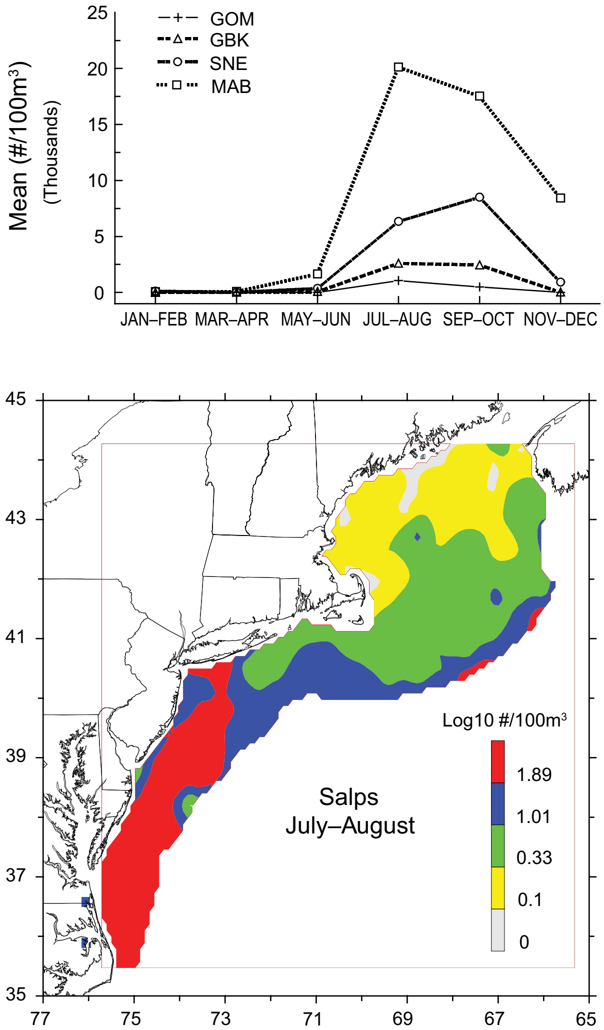

Fig. 7. Time series annual abundance cyle of salps in the four subareas of the U.S. Northeast Shelf ecosystem (upper panel) and their average July–August distribution (lower panel).

modest temperature increase in the 2000s directly lowered *Pseudocalanus* spp. population levels.

Phytoplankton abundance was the only variable examined that was positively correlated to the copepods interannual variability. Patterns of annual abundance anomalies for both measurements were strikingly similar in the GOM (Figs.6A, 8B). Previous studies in this region have linked changes in phytoplankton phenology and productivity to the copepod's surge in the 1990s (Pershing *et al.*, 2005; Kane, 2007). Greene and Pershing (2007) proposed that this increased production in the lower trophic levels was caused by Arctic climate conditions that increased freshwater export into the North Atlantic that enhanced stratification and extended the phytoplankton growing season. However, additional observations in the 2000s found that reduced salinity did not always enhance zooplankton productivity (Hare and Kane, 2012). Correlation analysis of pre-2000 and post-2000 data subsets demonstrated that salinity was not a factor in the new decade. The decline of *Pseudocalanus* spp. and phytoplankton abundance was likely caused by conditions indirectly associated with the warmer temperatures measured in the 2000s. The increased temperatures would have accelerated phytoplankton growth and produced earlier blooms, perhaps shifting events out of phase with other elements that are needed for maximum production in the ecosystem. Warming would also increase stratification, which could play a major role limiting *Pseudocalanus* spp. production. Stratified waters impede the mixing of deep nutrient-rich waters into surface layers and suppress the availability of phytoplankton food stocks (Kamykowski and Zentara, 2005). New algorithms are currently being developed to provide a stratification time series to test this hypothesis. Warmer temperatures are also believed to be the cause of high precipitation and runoff in the GOM during the 2000s, which reduced light availability and lowered overall primary productivity (Balch *et al.*, 2012). Though it is uncertain which or what combination of biological-physical processes depressed phytoplankton levels in the 2000s, the effects cascaded further up the food web.

A modeling study analyzing *Pseudocalanus* spp. populations in the GOM also found strong connections to bottom-up processes, but the data indicate that predation may also have a major role determining abundance levels (Ji *et al.*, 2012). Out of all the predator groups sampled in our surveys, evidence was found that salps were the most likely to depress the copepod's population in summer. They are large, gelatinous zooplankton that grow rapidly and have been reported to form large swarms in the Northwest Atlantic Ocean during summer (Wiebe *et al.*, 1979; Madin *et al.*, 2006). Salps were the third most abundant (16 587/100m^3) taxon captured in nets towed through MAB waters during July–August survey cruises. Though there is no record of salps directly feeding on *Pseudocalanus* spp., these filter feeders ingest a wide size range of particulate matter and can substantially reduce the quantities of phytoplankton, bacteria, and microzooplankton that other mesozooplankton use for food (Paffenhofer, 1994; Vargas and Madin, 2004, Bernard *et al.*, 2012). Several studies have proposed that high predation rates by salps indirectly limit the growth of copepod populations (Dubischar and Bathmann, 1997; Halsband-Lenk *et al.*, 2001; Everett *et al.*, 2011). This study has found that salps and *Pseudocalanus* spp. population levels were tightly coupled during the time series, suggesting that salp predation is responsible for the copepod's sharp summer decline. However, since our surveys do not measure phytoplankton size structure, we

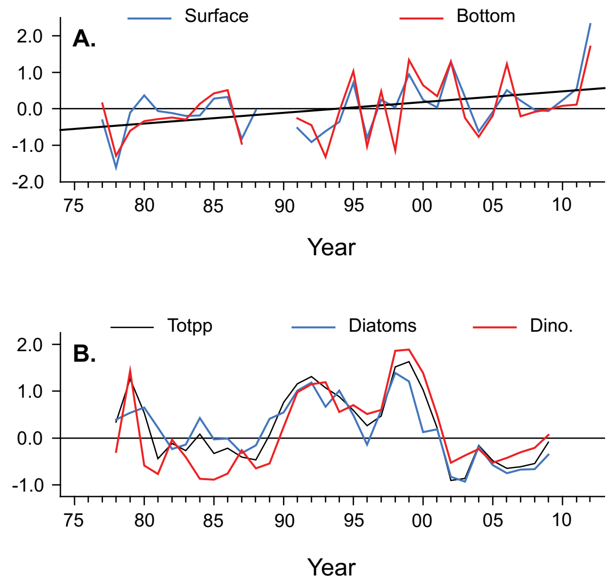

Fig. 8. **A**) Annual anomalies (1977–2012) of surface and bottom water temperatures (°C) in the Southern New England region with values fit with a linear trend line. **B**) Annual abundance (#m3) anomalies (1978–2009) of total phytoplankton (Totpp), diatoms, and dinoflagellates (Dino.) captured along the Gulf of Maine CPR transect.

could not test if the correlation was caused by factors that created feeding conditions favorable for salps and detrimental for *Pseudocalanus* spp. production.

During the past century, water temperature has been gradually rising in the North Atlantic Ocean (Beaugrand, 2009). If ocean temperatures continue to warm at rates predicted by general circulation models, it is projected that mortality of *Pseudocalanus* spp. will increase in warmer waters and substantially reduce population abundance in shelf areas south of 45°N (Stegert *et al.*, 2010). Spatially, the authors predict that the copepods population center will shift northwards during the 21st century. Have these transitions already begun in the southernmost region of the ecosystem? Distribution maps of *Pseudocalanus* spp. in March–April show that an area of high abundance present in the MAB region during the initial decade of sampling has been slowly retreating northward during the time series, drastically depressing seasonal mean abundance. One possibility may be that warmer summer temperatures have depressed the size of the overwintering population, reducing the following year's spring maximum. However, survey data do not support this hypothesis. Correlation analysis between abundance anomalies in autumn and spring of the following year produced coefficients that were low and insignificant. Thus far, it seems unlikely that the modest temperature increases in the 2000s directly affected MAB *Pseudocalanus* spp. production in early spring. The exact mechanism remains elusive, but it is probably related to the decadal low phytoplankton food stocks.

Global circulation models have projected that the earth will continue to warm under higher levels of greenhouse gases (IPCC, 2007). As ocean temperatures rise, recruitment success of higher trophic levels will be affected because it depends on the synchronization of primary and secondary production. For example, warming of the North Sea has already been correlated with changes in the zooplankton community, resulting in low food levels for cod larvae that have led to a decline in overall recruitment (Beaugrand *et al.*, 2003). Evidence was found that adult cod stocks in the North Atlantic have been unable to rebuild because climate change has altered the distribution of temperatures, causing low levels of zooplankton prey for larval stages (Friedland *et al.*, 2013). The present study has found that increasing temperatures in the 2000s has depressed phytoplankton food stocks and the abundance of the dominant copepod *Pseudocalanus* spp., a major prey item of larval fish.

Extending our time series into the future will be necessary to measure the response of lower trophic levels to the projected anthropogenic and natural oscillations that may impact the ecosystem. However, the exact mechanisms responsible for the observed patterns will be difficult to determine from our surveys which provide only bimonthly snap-shots of ecosystem conditions. Complex numerical models and dedicated process orientated studies will be needed to define the complex of factors that intertwine to determine how warming seas affect primary and secondary production. Understanding the effects of climate change on the transfer of resources through trophic levels will be central to predict future alterations to the ecosystem's food web.

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Impact of maximum sustainable yield-based fisheries management frameworks on rebuilding North Atlantic cod stocks

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Abstract

Fisheries management frameworks based on maximum sustainable yield reference points have been put forward by all agencies and organizations responsible for providing scientific advice for the management of 22 major North Atlantic cod stocks. These frameworks provide a structure for rebuilding depleted cod stocks and for future sustainable fishing. Unfortunately, in most cases these frameworks have not been fully implemented. Although information is lacking for some stocks, it would appear that a large proportion of North Atlantic cod stocks are either experiencing a fishing mortality rate that exceeds that required to achieve maximum sustainable yield, are at a biomass level far below that which provides maximum sustainable yield, or have both occurring. Despite this general failure, there are some notable successes, which have led to stock rebuilding and substantial fisheries, providing an incentive for striving to achieve rebuilding and sustainable management objectives for other Atlantic cod stocks. Management frameworks based on harvest control rules that result in fishing mortality rates below those associated with maximum sustainable yield are essential when stock size is low in order to rebuild to levels capable of producing maximum sustainable yield.

Keywords: Atlantic cod, depleted fish stocks, stock rebuilding, overfishing, MSY-based management frameworks, rebuilding plans, management plans, feedback harvest control rules.

Introduction

The need to adopt a Precautionary Approach to fisheries management in order to avoid serious harm to fish stocks was firmly established by the UN Fish Stock Agreement (UNFSA; UN, 1995). This led to a focus on estimating and avoiding Limit Reference Points for spawning stock biomass (*SSB*) and fishing mortality (*F*). Following UNFSA, rebuilding already depleted fish stocks and the sustainable management of healthy stocks received emphasis at the World Summit on Sustainable Development (WSSD) in Johannesburg (UN, 2002). The accord calls for actions to "Maintain or restore stocks to levels that can produce the maximum sustainable yield with the aim of achieving these goals for depleted stocks on an urgent basis and where possible not later than 2015". The focus thus shifted from avoiding limits under UNFSA to achieving maximum sustainable yield (MSY) targets under WSSD. Although 2015 is proving an ambitious goal for rebuilding to the *SSB* associated with maximum sustainable yield (SSB_{msy}), the WSSD continues to influence approaches to fisheries management in a number of positive ways.

In Europe, the decision by the European Commission to implement the maximum sustainable yield (MSY) principle led ICES to introduce a new MSY-based approach for providing advice in 2009 (Lassen *et al*., 2013). In the US, the 2006 Reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) emphasized an MSY-based approach that requires overfishing to stop and for depleted stocks to be rebuilt (NOAA, 2007). In Canada, new MSY-based fisheries policies were developed under the Sustainable Fisheries Framework (SFF; DFO, 2009a). In 2008 the Northwest Atlantic Fisheries Organization expanded its Convention to include MSY-based objectives (NAFO, 2008).

These policy changes are beginning to have a positive effect, although, in the case of several important Atlantic cod (*Gadus morhua*) stocks, full development of MSY-based frameworks including harvest control rules, and effective implementation, is lagging policy development. In this paper MSY-based fisheries frameworks are compared across advisory bodies (International Council for Exploration of the Sea (ICES), Canadian Department of Fisheries and Oceans (DFO), Northwest Atlantic Fisheries Organization (NAFO), US National Oceanic and Atmospheric Administration National Marine Fisheries Service (NOAA-NMFS)). A summary is provided on progress in completing these frameworks and applying them to rebuild Atlantic cod stocks. Conclusions are drawn regarding what needs to be done to make these frameworks fully operational and to achieve success in rebuilding cod stocks.

Comparison of MSY-based advisory frameworks

There are a number of similarities across MSY-based advisory frameworks applied by the various bodies providing scientific advice for the management of fisheries on Atlantic cod stocks, but there are also some important differences. The ICES MSY-based framework (Fig. 1) is designed to promote recovery of a stock to the normal range of stock sizes associated with MSY when *SSB* is below this range, *i.e.* when it is below $SSB_{trigger}$ (Lassen *et al*., 2013). Below $SSB_{trigger}$, the advised fishing mortality (F) is reduced from the fishing mortality that gives MSY (F_{msy}) by a linear function. When the stock size is so low that recruitment failure is a concern, *e.g.* at or below an *SSB* limit reference point SSB_{lim}, as estimated for a Precautionary Approach (PA), additional conservation measures may be invoked to prevent a further decline. It should be noted that under the ICES approach, F_{msy} is currently considered a target exploitation rate but once this is achieved for most stocks, ICES may consider whether the fishing mortality target should be adjusted to be less than F_{msy} (Lassen *et al*., 2013).

The Canadian MSY-based framework (Fig. 2) recognizes three *SSB* zones, Healthy, Cautious and Critical (DFO, 2009a). In the Healthy Zone fishing morality may be set at a level of F_{msy} or lower. Once *SSB* falls below the lower boundary of the Healthy Zone, termed the Upper Stock Reference Point, and enters the Cautious Zone, fishing mortality must be reduced to return the stock to the Healthy Zone. If *SSB* falls below the Limit Reference Point and enters the Critical Zone, fishing mortality from all sources must be kept to an absolute minimum. A provisional harvest control rule (HCR) based on this is approach defines the Upper Stock Reference Point to be 80%SSB_{msy}, the Limit Reference Point to be 40%SSB_{msy} and the decrease in fishing mortality to be linear, reaching zero at 40%SSB_{msy} (DFO, 2009a). The

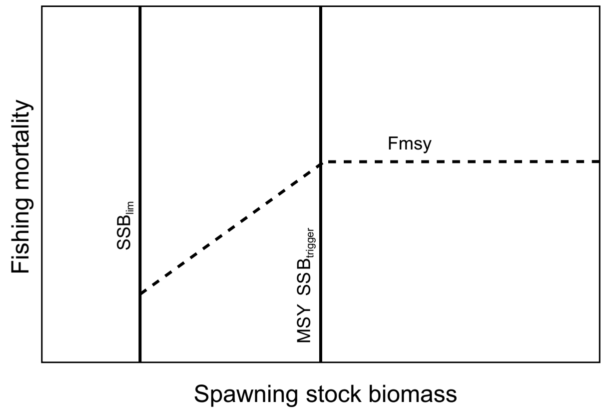

Fig. 1. MSY-based framework adopted by ICES for providing scientific advice. The broken line indicates the fishing mortality rate that would be advised depending on the spawning stock biomass. Below SSB_{lim} additional conservation measures may be invoked based on the Precautionary Approach.

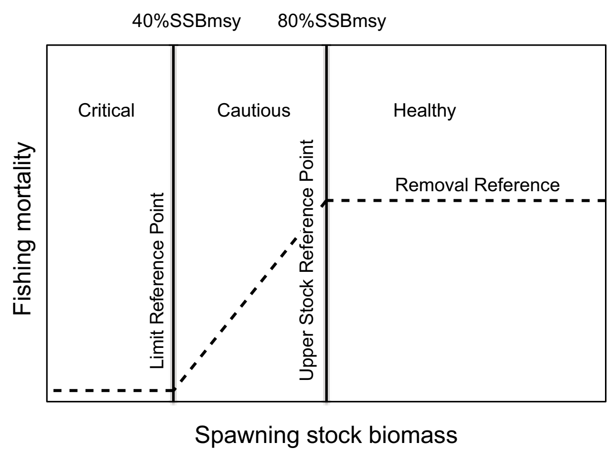

Fig. 2. MSY-based framework adopted by Canada for providing advice on Canadian fish stocks. Vertical lines demarcate spawning stock biomass zones. The broken line indicates the fishing mortality to be advised. In the Healthy Zone the removal reference mortality rate can be set at F_{msy} or lower.

Canadian framework is ambiguous with regard to whether F_{msy} should be considered a target or a limit since fishing mortality can be set as high as F_{msy} in the Healthy Zone.

The NAFO Precautionary Approach Framework (NAFO, 2004a), augmented by the 2008 NAFO Resolution on the Interpretation and Implementation of the Convention on the Future Multilateral Cooperation in the Northwest Atlantic Fisheries (NAFO, 2008), provides an MSY-based context for scientific advice. The 2008 Resolution requires that NAFO adopt measures based on the best scientific evidence available to ensure that fishery resources are maintained at, or restored to, levels capable of producing MSY. The NAFO PA framework recognizes five zones based on *SSB* and *F*: Safe, Overfishing, Cautionary *F*, Danger and Collapse (Fig. 3). In the Safe Zone, *i.e.* when $SSB > SSB_{buf}$, *F* must be selected to have a low probability (<20%) of exceeding a fishing mortality limit reference point F_{lim}, which is defined by NAFO as F_{msy}, and a very low (<10%) probability of being below SSB_{lim} which has a default value of 30%SSB_{msy} unless defined on some other basis in order to take into account specific stock-recruit considerations (NAFO, 2004b). In the Overfishing Zone *F* needs to be set below a fishing mortality "buffer" level, F_{buf}. F_{buf} should be specified by managers and should satisfy the requirement that there is a low probability (<20%) that any fishing mortality rate estimated to be below F_{buf} will actually be above F_{lim}. In the Cautionary *F* Zone, the closer *SSB* is to SSB_{lim}, the lower *F* should be below F_{buf} to ensure that there is a very low (<10%) probability that biomass will decline below SSB_{lim} within 5–10 years. The NAFO framework allows for buffer reference points to be superseded by computations of the risk of being below SSB_{lim} or above F_{lim} and for managers to set risk tolerances other than the default values specified above.

Under the US MSFCMA MSY-based framework, four zones are recognized (NOAA, 2007; Fig. 4): (i) Overfishing is not occurring, stock is not Overfished; (ii) Overfishing is occurring, stock is not Overfished; (iii) Overfishing is occurring, stock is Overfished; (iv) Overfishing is not occurring, stock is Overfished. Overfishing is defined as $F \geq F_{msy}$ and Overfished as $SSB <$ 50%SSB_{msy}. If a stock is identified as being Overfished, Overfishing has to end within two years. Further, Overfished stocks are required to be subject to a rebuilding plan that will rebuild the stock to SSB_{msy} within a specified period of time, typically not exceeding 10 years, by reducing *F*. Further, *F* is required to be adjusted to prevent Overfishing from occurring whenever a stock is identified to be approaching an Overfished condition. Given that Overfishing is considered to be $F \geq F_{msy}$, the US MSY-based approach considers F_{msy} as a limit.

It is clear from this comparison of MSY-based approaches currently being applied to Atlantic cod stocks that the interpretation of F_{msy} in terms of whether it constitutes a limit or a target varies, although none of the approaches support deliberately setting $F > F_{msy}$. It should be noted that if F_{msy} is considered to be a limit to be avoided with a probability >50%, then there is an apparent contradiction in simultaneously considering SSB_{msy} to be a target with the consequent expectation that it would be achieved with

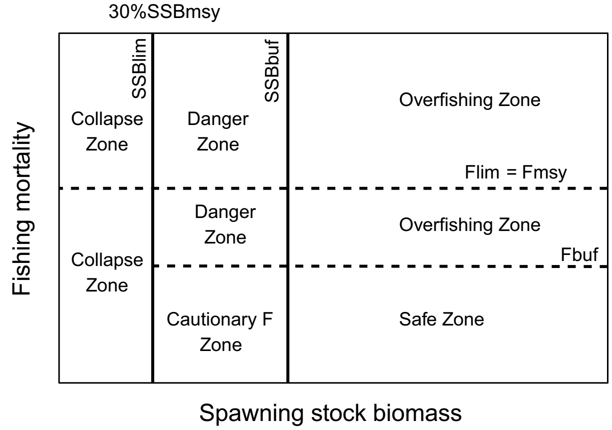

Fig. 3. MSY-based framework adopted by NAFO for advising on stocks in the NAFO Regulatory Area. Vertical solid lines demarcate spawning stock biomass zones whereas broken horizontal lines demarcate fishing mortality zones.

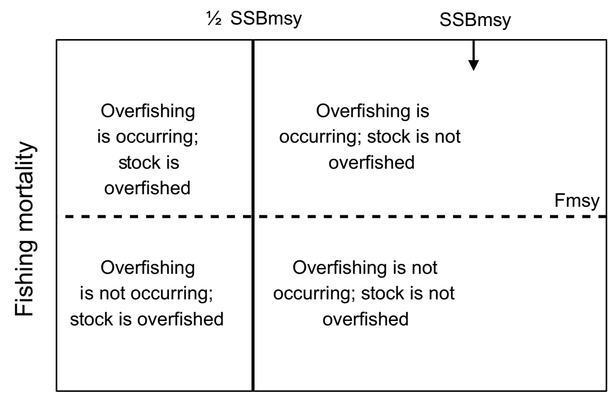

Fig. 4. MSY-based framework adopted by the US National Marine Fisheries Service for providing scientific advice under the MSFCMA. The vertical solid line demarcates spawning stock biomass zones whereas the horizontal broken line shows F_{msy}.

a 50% probability (*i.e.* a risk-neutral desired outcome in keeping with the definition of a target).

All the MSY-based frameworks require *F* to be reduced below F_{msy} to rebuild the stock should biomass fall below an *SSB* level specified in the framework, denoted generically as SSB_{ref} in this paper. The actual derivation of SSB_{ref} varies across frameworks and is discussed further below. The Canadian framework proposes a specific provisional HCR for achieving the reduction in *F* below SSB_{ref}. The NAFO framework emphasizes risk tolerances that need to be met with respect to avoiding limit reference points when adjusting *F* in each zone. The US framework emphasizes rapid cessation of Overfishing through F reduction below F_{msy} to achieve a 10 year or less time period for rebuilding to SSB_{msy}. The ICES framework typically advises a linear reduction in F as SSB decreases below SSB_{ref}.

Application of MSY-based frameworks to Atlantic cod stocks

Information on the scientific assessments and advice for 22 major Atlantic cod stocks are readily available from the websites of the advisory bodies of the responsible organizations (Table 1). ICES provides advice for 11 of these cod stocks, Canada (DFO) for 7, while NAFO and the US (NOAA – NMFS) provide advice for 2 stocks each.

A state-space assessment model (SAM; unpublished; Anders Nielsen, DTU AQUA, National Institute of Aquatic Resources, Section for Marine Living Resources, Technical University of Denmark, Charlottenlund Slot Jægersborg Allé 1, 2920 Charlottenlund, Denmark), is currently applied to 5 of the 11 Atlantic cod stocks for which ICES provides advice. Methods used on other cod stocks include Extended Survivors Analysis (XSA; Darby and Flatman, 1994; Shepherd, 1999), Sequential Population Analysis (ADAPT version; Gavaris, 1988), Statistical Catch at Age (SCAA; Fournier and Archibald, 1982), Survey Based Analysis (SURBA; Beare *et al*., 2005), Time Series Analysis (TSA; Gudmundsson, 1994) and Age Structured Assessment Program (ASAP; NEFSC, 2013b). Two stocks are assessed qualitatively while two stocks have no method applied because of low abundance. Although a comparison of the strengths of these assessment approaches is beyond the scope of this paper, it should be noted that the SURBA approach uses only survey data and therefore has limited value in terms of MSY-based TAC (total allowable catch) management.

The SSB level below which F should be reduced, SSB_{ref}, (for example MSY $SSB_{trigger}$ under ICES) is undefined for all Canadian and NAFO stocks, as well as for three ICES stocks. SSB_{ref} is not required under NAFO when risk with respect to limit reference points can be reliably estimated. For five of the ICES stocks, SSB_{ref} is based on the precautionary SSB, B_{pa}, which is computed as $1.4{*}SSB_{lim}$ for three of the stocks and as the level below which recruitment is impaired for two stocks. For Barents Sea cod SSB_{ref} is denoted as the lowest SSB estimate having >90% probability of being above SSB_{lim}. A similar approach is applied to West of Scotland cod.

The approach for determining TAC advice to achieve an F reduction when the stock declines below SSB_{ref} varies across advisory bodies and cod stocks. In some cases the change in F is governed by a feedback harvest control rule (HCR), which alters F in response to the estimated SSB from the stock assessment relative to the estimated SSB_{ref}, for example $SSB_{trigger}$. Examples include advice from ICES on Barents Sea cod and Icelandic cod (ICES, 2013). A feedback HCR is also encompassed in the DFO management framework (DFO, 2009a) although implementation in providing advice on Canadian cod stocks has not yet materialized. NAFO advice is not based on a prescribed HCR and instead outcomes from a range of F options are provided (see for example 3M cod advice; NAFO, 2013). DFO advice for 3Ps cod is also based on providing the outcome of F options to managers (DFO, 2012a). The Northeast Fisheries Science Center of the US National Marine Fisheries Service (NEFSC) advice for the depleted Gulf of Maine and Georges Bank cod stocks are based on $75\%F_{msy}$ with the expectation from model projections that this will rebuild stocks to SSB_{msy} within the requisite 10 year time period (NEFSC, 2013a). In some cases where F is currently well above F_{msy}, step-wise reductions in F towards F_{msy} have been instituted (*e.g.* Baltic cod stocks).

Although there is uncertainty in the assessed state of the stock and in the estimates of MSY reference points, advice for Atlantic cod stocks tends to be based on the point estimate or median estimate of SSB from the current assessment relative to the best estimate of SSB_{ref}. In some cases, such as Icelandic cod, the HCR within the Management Plan has been evaluated with respect to uncertainty through simulation testing by applying management strategy evaluation (MSE; De Oliveira *et al*., 2008), and found to conform with the ICES MSY approach (ICES, 2009). The Canadian provisional HCR based on an SSB_{ref} of $80\%SSB_{msy}$ and SSB_{lim} of $40\%SSB_{msy}$ has yet to be subject to an evaluation of robustness to uncertainty through simulation testing.

All organizations providing scientific advice on Atlantic cod stocks develop that advice through a consensus-forming approach. This has recently become an issue in the US advisory system with regard to a contested assessment for Gulf of Maine cod where industry-hired consultants presented an alternative, more optimistic analysis for consideration as part of the NMFS process for developing scientific advice for managers (Butterworth and Rademeyer, 2008a, MS 2008b). While contested assessments are not necessarily bad (see for example Starr *et al*., 1998), they create a more complex dynamic and create a dilemma if consensus cannot be reached. In most cases stock assessments are based on a prior benchmark review to establish the best assessment model, which is then applied to new data on an annual basis to provide scientific advice, until a better assessment model is

Table 1. Summary of stock assessment and scientific advice for 22 Atlantic cod stocks for which information is readily available.

	Stock	Area	Advice	Method	SSBref	F≥Fmsy	B<SSBref	Advice	Reference
1	Barents Sea	I and II	ICES	XSA	P wrt Blim	N	N	HCR	ICES, 2013
2	Kattegat	IIIa east	ICES	SAM	Undefined	U	U	No fishing	ICES, 2013
3	East Baltic	Subdiv 25-32	ICES	SAM	Bpa=1.4*Blim	N	N	F step to Fmsy	ICES, 2013
4	West Baltic	Subdiv 22-24	ICES	SAM	Bpa=1.4*Blim	Y	N	F step to Fmsy	ICES, 2013
5	North Sea	IV, VIId and IIIa	ICES	SAM	Bpa≈imparied R	Y	Y	HCR	ICES, 2013
6	Irish Sea	VIIa	ICES	SAM	Bpa≈imparied R	Y	Y	HCR	ICES, 2013
7	Celtic Sea	VIIe-k	ICES	XSA	Bpa=1.4*Blim	Y	N	Fmsy	ICES, 2013
8	West of Scotland	VIa	ICES	TSA	P wrt Blim	Y	Y	HCR	ICES, 2013
9	Rockall Plateau	VIb	ICES	Qual	Undefined	U	U	Qual	ICES, 2013
10	Iceland	Va	ICES	SCAA	Defined by managers	N	N	HCR	ICES, 2013
11	West Greenland	NAFO SA1	ICES	Qual	Undefined	U	U	Qual	ICES, 2013
12	Northern Labrador	2GH	Canada	None	Undefined	U	U	None	No recent assessment
13	Northern	2J3KL	Canada	SURBA	Undefined	U	U	F options	DFO, 2013
14	Flemish Cap	3M	NAFO	XSA	Undefined	Y	U	F options ≤ Fmax	NAFO, 2013
15	Southern Grand Bank	3NO	NAFO	SPA	Undefined	N	U	Lowest possible F	NAFO, 2013
16	St. Pierre Bank	3Ps	Canada	SURBA	Undefined	U	U	F options	DFO, 2012a
17	Northern Gulf of St Lawrence	4RS3Pn	Canada	SPA	Undefined	U	U	Lowest possible F	DFO, 2012b
18	Southern Gulf of St Lawrence	4Tvn	Canada	SPA	Undefined	U	U	Lowest possible F	DFO, 2009b
19	Eastern Scotian Shelf	4VsW	Canada	None	Undefined	U	U	None	No recent assessment
20	Southern Scotian Shelf - Bay of Fundy	4X	Canada	SPA	Undefined	U	U	Lowest possible F	DFO, 2009c
21	Georges Bank	5Z	USA	ASAP	50%SSBmsy	Y	Y	0.75*Fmsy	NEFC, 2013a
22	Gulf of Maine	5Y	USA	ASAP	50%SSBmsy	Y	Y	0.75*Fmsy	NEFC, 2013a

XSA = Extended Survivors Analysis, SAM = State Space Assessment Model, Qual = qualitative assessment, SCAA = Statistical Catch At Age Analysis, SURBA = Survey Based Assessment, SPA = Sequential Population Analysis, ASAP = Age Structured Assessment Program, SPA = Sequential Population Analysis, P wrt Blim = probability with respect to SSB_{lim}, Y = yes, N = no, U = undefined.

proposed and accepted. Contested assessments generally introduce changes to the current assessment model, for example a domed shaped selectivity function rather than a flat-topped function (Butterworth and Rademeyer, 2008a, MS 2008b), requiring a new benchmark review. If the review cannot resolve the best model to apply, then this may result in two different sets of advice being provided to managers, which may be confusing. Model uncertainty is important if it leads to substantially different estimates of MSY reference points and the status of the stock relative to these reference points, and therefore shouldn't be ignored. If there is no consensus on the best model, an alternative to model-averaging or integrating over the risk estimated by both models, is to evaluate the robustness of a feedback HCR to both models through MSE, to ensure that the objectives are achieved irrespective of which model is closer to reality (De Oliveira *et al.*, 2008).

Response of Atlantic cod stocks to MSY-based management

Total landings of Atlantic cod from all stocks peaked at around 4 million tons in the late 1960s, declined steadily during the 1970s, 1980s and early 1990s, stabilized below one million tons in the 2000s, and then increased slightly in the most recent years (FAO, 2013; Fig. 5). Trajectories were similar for the North East Atlantic stocks and the North West Atlantic stocks up until 1990 after which the North West Atlantic cod fisheries collapsed and subsequently failed to rebuild. In comparison, North East Atlantic cod landings leveled off during the 2000s and since 2008 have shown a modest increase, which may be related to implementation of HCRs based on MSY

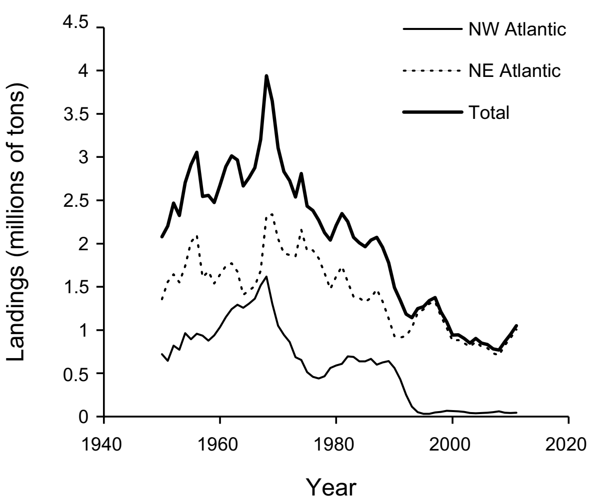

Fig. 5. Total landings of cod from the North Atlantic and for the North East and North West Atlantic separately. Data are from the 2013 edition of FAO Fishery Statistical Collections Global Capture Production.

frameworks. The recent trends in North East Atlantic cod are driven mainly by the Barents Sea and Iceland stocks, which historically did not suffer the same level of depletion from overfishing as many other cod stocks, particularly those in the North West Atlantic.

Information on 22 major Atlantic cod stocks summarized in Table 1 can be used to determine whether or not an SSB_{ref} value has been set for the stock and whether or not an HCR is in place to adjust F when SSB falls below SSB_{ref}. Adopting terms used in the US under the MSFCMA, for those stocks for which the required information is available, one can evaluate whether Overfishing is taking place ($F \geq F_{msy}$) or whether the stock is Overfished ($SSB<SSB_{ref}$). For 10 of the 22 stocks (45%), Overfishing could not be evaluated because there is no recent assessment, no estimate of current F, or no estimate of F_{msy}. Of the remaining 12 stocks, 8 (66%) have Overfishing taking place. With regard to being Overfished, this could be determined for 10 of the 22 stocks (45%). For four of these (40%) the stocks are Overfished and also have Overfishing taking place. If it is assumed that for all stocks for which Overfished status is unknown, the stock is in fact Overfished, with the exception of Flemish Cap cod for which SSB is currently estimated to be high relative to historic values (NAFO, 2013), then the percentage of Overfished cod stocks rises to 64%. Only 5 of the 22 stocks (23%) are known not to have Overfishing taking place.

For 12 of the 22 stocks (55%) SSB_{ref} has not yet been determined. Full feedback HCRs are developed for only 5 of the 22 stocks (23%). For 12 other stocks a range of F-based advice is provided that does not involve adjusting the level of F based on current SSB relative to SSB_{ref}. Only three cod stocks are known to be neither Overfished nor subject to Overfishing – Barents Sea cod, Icelandic cod and East Baltic cod. Assessments for these stocks are carried out in ICES scientific working groups and advice is provided through the ICES advisory process (ICES, 2013). A common factor for these three stocks has been a steady decrease in F over the last decade or more. In the case of Barents Sea and Icelandic cod, feedback HCRs have been implemented that set F_{msy} as a target fishing mortality and reduce F below F_{msy} when the stock falls below $SSB_{trigger}$ (ICES, 2013).

Discussion

Although conceptual MSY-based frameworks are now in place for all Atlantic cod stocks, the parameterization of these frameworks (determination of all required reference points and the explicit mathematical form of the feedback HCR), as well as actual implementation on the fishery, is lagging in a number of cases. Consequently it may be premature to expect positive effects from MSY-based frameworks for many of these stocks. This is particularly true for North West Atlantic cod stocks, where little or no recovery has taken place since the adoption of MSY-based approaches as indicated by the consistently low total landings trend. Most cod stocks assessed by Canada and NAFO lack estimates of F_{msy} and SSB_{ref}. Two of the stocks assessed by Canada, Northern cod and St. Pierre Bank cod, are assessed using only survey data because commercial and recreational catch statistics are considered unreliable (DFO, 2012a, 2013). Consequently application of the MSY-based approach on these stocks is not possible.

Two cod stocks assessed by Canada have no recent assessments because of ongoing low stock size. Only one cod fishery managed by either Canada or NAFO is known not to have Overfishing taking place (Southern Grand Bank cod), although this stock is Overfished because *SSB* is below B_{lim} (NAFO, 2013). In the recent past it was concluded that bycatch mortality was a major factor delaying recovery of this stock (Shelton and Morgan, 2005). Only two North West Atlantic cod stocks have significant directed commercial fisheries at present, St. Pierre Bank cod and Flemish Cap cod. If the *F* that gives maximum yield per recruit, F_{max}, is taken as a proxy for F_{msy} then with current F>2*F_{max} (NAFO, 2013), the Flemish Cap cod stock has Overfishing taking place. The SURBA-based assessment of St. Pierre Bank cod indicates high total mortality rates on this stock but there is no estimate of SSB_{ref} (DFO, 2012a). Consequently, neither St. Pierre Bank cod fishery nor Flemish Cap cod fishery can currently be considered sustainably managed at the present time (not Overfished, Overfishing not taking place) under their respective MSY-based frameworks.

Flemish Cap cod is unique among North West Atlantic cod stocks in that it has had a recent rapid and substantial increase in *SSB* (González-Troncoso *et al*., MS 2013). This stock was placed under a fishing moratorium between 1999 and 2009 following stock collapse. *SSB* increased after 2006 as a result of good recruitment and low fishing mortality, reaching highest recorded *SSB* levels since the start of the series in 1972 by 2012, well above SSB_{lim}. However, the absence of a fully parameterized MSY-based framework and implementation error with respect to the current scientific advice has resulted in *F* once again increasing and the stock is currently subject to Overfishing (NAFO, 2013). Consequently the expectation is that this stock will decline and that ongoing sustainable management of the fishery will not be achieved.

The failure of most Canadian and NAFO managed cod stocks to rebuild can be attributed in large part to ongoing fisheries, either directed or bycatch, removing all or nearly all the surplus production (Shelton *et al*., 2006). Directed fishing is allowed on several Canadian stocks despite *SSB* being well below SSB_{lim}, resulting in levels of *F* that are not conducive to stock recovery. There is no explicit rebuilding plan in place for most of these stocks, providing targets and timelines, and fisheries management decisions are made largely on an *ad hoc* basis. In some cases surplus production is very low or negative, leading to pessimistic prognoses regarding possible rebuilding even in the absence of fishing (*e.g* Southern Gulf Cod; Swain and Chouinard, 2008).

Although US fisheries policy has been considerably strengthened through the reauthorization of the MSFCMA in 2006, the Gulf of Maine and Georges Bank cod fisheries remain Overfished and have Overfishing taking place (NEFSC, 2013a). In comparison there has been more success with regard to rebuilding other US fish stocks. Of the 85 fish stocks or stock complexes declared Overfished under the MSFCMA, rebuilding plans were implemented for 79, of which 25 were classified as rebuilt to SSB_{msy} by September 2012 (five additional stocks were rebuilt before a plan was implemented; NRC, 2013). For those US stocks assessed using analytical methods, fishing mortality under rebuilding plans has generally been reduced and stock biomass has generally increased following the introduction of the MSFCMA and the associated MSY-based management framework (NRC, 2013).

The 2008 SPA-based assessment of the Gulf of Maine cod stock estimated that the biomass was increasing and that the stock was no longer Overfished although Overfishing was still occurring (NEFSC, 2008; Pershing *et al*., 2013). A 2008 independent assessment by industry consultants using SCAA was even more optimistic, estimating that *SSB* was 1.4*SSB_{msy} and that *F* was 0.4*F_{msy} (Butterworth and Rademeyer, MS 2008b). The 2011 NEFSC assessment of Gulf of Maine cod, which was based on ASAP and a new treatment of discard data, gave a much more pessimistic outcome, finding that the stock was still Overfished and that the biomass was much lower than the 2008 assessment estimate (NEFSC, 2012). Although substantial TAC reductions are required under the adopted 75%F_{msy} HCR to achieve rebuilding of Gulf of Maine cod within 10 years, full implementation of this HCR has been delayed by social, economic and political considerations. The adjacent Georges Bank cod stock was estimated to be at is only 7% of SSB_{msy} in 2011 with fishing mortality more than twice F_{msy} (NEFC, 2013a), suggesting difficulty in implementing the 75% F_{msy} HCR on this stock as well, and therefore poor prospects for rebuilding in the near future.

In comparison with the North West Atlantic, the North East Atlantic cod landings have been maintained around one million tons from 2000 onwards and have even increased slightly since 2007 following the implementation of MSY-based management frameworks. The major contributors are the Barents Sea Cod and the Icelandic cod. These two stocks are the only inarguably sustainably managed Atlantic cod fisheries – Overfishing is not occurring, they are not Overfished, and they have management plans currently being implemented that include feedback HCRs to moderate F below F_{msy} when SSB falls below SSB_{ref}. These management plans have been evaluated by ICES and found to meet MSY and PA objectives. They serve as examples of the potential to rebuild and sustainably manage Atlantic cod stocks under MSY-based frameworks, although with the caveat that the historic levels of depletion of these two stocks was less severe than for a number of other Atlantic cod stocks that currently remain depleted.

Fishing mortality on Celtic Sea cod has been declining since 2005 and is now at F_{msy} and SSB has recently increased to well above SSB_{ref} (MSY $B_{trigger}$). A management plan including an HCR is under development for this stock. Management of four other European cod stocks was recently reviewed by Kraak *et al*. (2013): Kattegat, North Sea, Irish Sea and West of Scotland cod. Three of these stocks (North Sea, Irish Sea and West of Scotland) are Overfished and Overfishing is taking place. The current status of Kattegat cod is uncertain and ICES advice is that there be no fishing under the assumption that it is severely depleted. These four stocks have HCRs in place and these have been evaluated through MSE. Inadequate implementation and enforcement of the management plans appear to be major problems in current efforts to reduce fishing mortality and rebuild these stocks (Kraak *et al*., 2013). Problems include basing the HCR on landings and not catch including discards, and ongoing bycatch of cod in mixed species fisheries. Kraak *et al*. (2013) argue that it is not sufficient to simply put an HCR in place based on MSY reference points and expect the stock to recover, particularly in the case of mixed species fisheries. Socio-economic considerations need to be taken into account and innovative approaches need to be found that encourage stakeholders to find ways of achieving the reductions in fishing mortality required to rebuild cod stocks.

The East Baltic and West Baltic cod stocks are both above their SSB_{ref} levels and therefore not Overfished and step-wise reductions in F have led to a cessation in Overfishing in the case of East Baltic cod but not West Baltic cod. Recovery of the East Baltic cod is attributed to a combination of a substantial reduction in F by ensuring that the TAC corresponds to fishery removals and not only landings, and strong year-classes entering the fishery (Eero *et al*., 2012). In contrast there has not been a similar improvement in recruitment in West Baltic cod.

Strong year-classes in combination with a reduction in F under an HCR are important ingredients associated with successful rebuilding. Strong recruitment is more likely for cod stocks that have not been depleted to very low SSB levels.

A major EU-funded project, aimed at producing a rational scientific basis for developing recovery strategies, undertaken between 2006 and 2010 (UNCOVER), identified a number of predictors for successful rebuilding (Hammer *et al*., 2010a). These include a rapid reduction in fishing mortality when depletion is first detected, favorable environmental conditions for recruitment, growth and survival during the recovery period, life-history characteristics conducive to stock rebuilding (*e.g.* size-at-maturity, maximum size, longevity, growth rate, and natural mortality), and effective management. Although the likelihood of these positive factors co-occurring may be less than desired, an international symposium marking the conclusion of the UNCOVER project jointly sponsored by ICES, PISCES and NAFO brought forward overwhelming evidence from Europe and around the world that collapsed and severely depleted fish stocks can recover and be rebuilt if fishing mortality is rapidly and substantially reduced (Hammer *et al*., 2010b; Murawski, 2010). However, the recovery process might be slower than predicted, especially if evolutionary changes in fish populations and ecosystem shifts have taken place that are not adequately accounted for in the assessment models (Hammer *et al*., 2010b). In retrospect the WSSD resolution may have been more realistic and effective had it called for an end to Overfishing by 2015 rather than setting recovery to SSB_{msy} as the goal.

It is widely recognized that current MSY-based frameworks are not the last word in sustainable fisheries management because they ignore important ecosystem dynamics and environmental processes that result in variable production in the target stock (Morgan *et al*., 2014; Haltuch *et al*., 2009; Walters *et al*., 2005). Nevertheless, for many stocks Overfishing is the paramount reason for depletion and continuing lack of recovery, and reducing fishing mortality has to be a management priority. Getting F down to the long-term F_{msy} level expressed in MSY-based frameworks would be a major achievement for many of these Overfished stocks where Overfishing is continuing to occur. However, it may not be sufficient. Changes in the productivity of fish stocks caused by variability in the environment and ecosystem processes suggest it may be more desirable to consider the long-term F_{msy} as a limit not to be exceeded by some chosen probability level rather than treating F_{msy} as a target to be achieved with a 50% probability. For MSY-based management frameworks to be internally consistent, it would follow that SSB_{msy} should, on average, be exceeded by a probability >50%.

Consideration should also be given to rapidly reducing *F* if a stock has fallen below SSB_{msy}, rather than waiting for the stock to fall to an even lower biomass corresponding to SSB_{ref} before initiating a reduction in *F*. This may be particularly important in TAC-based management systems where there is an excess in fishing capacity, uncertainty in the assessment and a lag between the latest assessment of the status of the stock and the implementation in a reduction in *F*.

Atlantic cod fisheries are historically among the most important in the world. While existing MSY-based management frameworks that are universally proposed for the provision of scientific advice and management of Atlantic cod stocks may not be perfect, and may not be able to fully meet the aspirations of an ecosystem approach to fisheries management, the failure to complete these frameworks and successfully implement them in the actual management of cod fisheries, represents a major shortcoming in achieving sustainable fisheries management objectives.

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An evaluation of an inshore bottom trawl survey design for American lobster (*Homarus americanus*) using computer simulations

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Abstract

This paper evaluates the performance of six possible sampling designs to estimate the population abundance index for American lobster using computer simulations. These designs include simple random sampling (SRS), systematic sampling (SYS) and stratified random sampling with four stratification schemes (*i.e.*, based on region, depth, sediment and region × depth). For the stratified random design with region and depth being used for stratification, we evaluated the performances of different strategies for allocating sampling efforts. Simulations were implemented on the "true" populations which were estimated annually from 2002 to 2008 for both spring and fall based on a general additive model model developed in a separate study. Relative Estimation Error (REE), Relative Bias (RB) and design effect were used to measure the precision, accuracy and efficiency of mean estimation for different designs. On average, SYS tended to yield the most precise and efficient estimate of mean with specified sample size. However, its estimates tended to be biased and its performance varied with sample sizes and realizations of "true" population, thus changed with lobster distribution. Appropriate stratification, such as using depth to determine strata, significantly improved the precision and efficiency over SRS. Sediment, which is related to lobster distribution, was found to have little contribution to the improvement of the performance over SRS when it is used to determine strata. Also, allocating samples to each stratum based on variance or mean of previous year improved precision and efficiency. This study suggests that current design (*i.e.*, region-depth stratified design) used in the survey had stable performance across years and seasons.

Keywords: Survey design, computer simulation, precision, accuracy, and design effect

Introduction

Sampling is an essential process for studying a fish population. Scientific sampling designs help scientists to have a representative view of target population with limited efforts. In fisheries, because of different characteristics of target species (*e.g.*, spatial structure) and objectives of sampling (*e.g.*, estimators), different sampling designs are required to gain maximal efficiency (Liu *et al*., 2009; Simmonds and Fryer, 1996; Wang *et al*., 2009). Of the sampling designs, simple random sample without replacement (SRS) is more commonly used as a null design for comparing the efficiency (relative variance) of different sampling schemes than as an optimal practical fishery survey design (Pooler and Smith, 2005; Skibo *et al*., 2008).

Stratified random sampling approaches are commonly adopted in periodic fishery-independent surveys for tracking the temporal trend of abundance and estimating the total abundance at the defined spatial scale (Gavaris and Smith, 1987). Stratified designs can spread the sampling effort over the study area to improve the precision of estimates especially when there are heterogeneities between strata and homogeneities within a stratum (Lohr, 2009). Systematic sampling (SYS) tends to be more precise when there are spatial correlations between observations (Cochran 2007, Rivoirard *et al*., 2000). Stratified random designs allow for estimating the precision of the estimates of total abundance whereas the SYS does not. Other sampling schemes can also be designed for specific cases. For example, adaptive cluster sampling strategies were designed for use in cases of rare or highly aggregated populations (Skibo *et al*., 2008; Thompson 1990).

An ideal sampling scheme is always constrained by budget and logistics (Lohr, 2009). Therefore, it is important and necessary to optimize the sampling design and maximize the information output from limited sampling efforts. Computer simulations are commonly used for evaluating and comparing different sampling designs in identifying optimal sampling design (Liu *et al*., 2009; Simmonds and Fryer, 1996). The sampling process of proposed designs is simulated on hypothetical "true" populations. Performance indices of different sampling strategies can be calculated based on defined criteria associated with sampling objectives. In general performance indices include measures of accuracy, which reflects the closeness to the true value; precision, which shows the extent to which repeated measurements or calculations gain the same or similar results (Taylor, 1997); and design effect, which measures the improvement in sampling efficiency of a particular sampling design over the SRS. The design effect is often calculated as the ratio of the estimator's variance that would be obtained from SRS to the variance obtained from an alternative sampling design with the same total sample size (Kish, 1965).

Estimating population abundance index or total abundance is usually the primary objective for periodic fishery-independent surveys which are critical to fish stock assessment and management (Smith and Lundy, 2006). The precision of these estimates is important in influencing uncertainty associated with stock assessment and subsequent development of decision rules of fisheries management (Smith and Lundy, 2006). Improving the precision of survey estimates can lead to reduced uncertainty in assessment model estimates of stock size and improve fisheries management.

For a stratified random designed survey, many studies revealed that optimizing either sample allocation schemes or stratification schemes could lead to an increased precision of survey means or total estimates (Folmer and Pennington, 2000; Gavaris and Smith, 1987; Smith and Tremblay, 2003). There are many methods for allocating samples among strata, the most common being to allocate samples in proportion to strata area/size. The Neyman allocation rule allocates samples in proportion to strata variance (Lohr, 2009) although it is difficult to know the variance before a survey is conducted. Typically the variance estimates from previous years' surveys are used as estimates (Cochran, 2007). Recently, adaptive allocation methods have been developed to increase the precision of estimates from stratified surveys (Smith and Lundy, 2006).

The American lobster, *Homarus americanus*, are distributed in the northwest Atlantic from Newfoundland, Canada to offshore North Carolina, USA (Lawton and Lavalli, 1995) and support one of the most valuable commercial fishery in the United States, with an ex-vessel value over 500 million dollars in 2013. Multiple fishery-independent surveys with differed spatial coverage were conducted to monitor this important economic species along the northeast American coast. The Maine-New Hampshire inshore trawl survey evaluated in this study yields an abundance index of inshore component of lobster population in the Gulf of Maine (GOM) (Chen *et al*., 2006), which contributes the majority of commercial catch in the US. This abundance index has been used to calibrate the stock assessment model for the lobster population in the GOM (ASMFC, 2009), thus providing critical information for the management. However, this survey is designed for groundfish monitoring and its performance for capturing the dynamics of lobster population is unknown and needs to be evaluated.

The objectives of this study are: (1) to evaluate the performance of current design (*i.e.*, stratified random sampling) in terms of its accuracy, precision and efficiency by comparing with other possible sampling strategies; (2) to compare alternative allocations of sampling efforts for current stratified sampling design used in the survey; (3) to evaluate the robustness of evaluated sampling schemes over time in order to understand the impacts of lobster spatial dynamics resulting from possible environment changes on sampling strategies. A study such as this one is important to understand the overall performance of the current survey design for monitoring lobster and it could also provide knowledge for designing a fishery-independent survey.

Materials and methods

Maine-New Hampshire Inshore Trawl Survey

The Maine-New Hampshire inshore trawl survey evaluated in this study is a biannual multiple-species fishery-independent survey conducted by the Maine Department of Marine Resources (DMR) each spring and fall since fall of 2000. It follows a stratified random design with four depth strata (9–37 m, 37−64 m, 64−100 m, and >100 m with 12 km offshore limit) and five longitudinal regions based on oceanographic and geological features (Fig. 1). A target of 115 sampling stations was designed for each survey and the number of sample size per stratum was apportioned according to its total area. Groundfish species are the main target species of this survey in its design. However, an estimate of abundance index for American

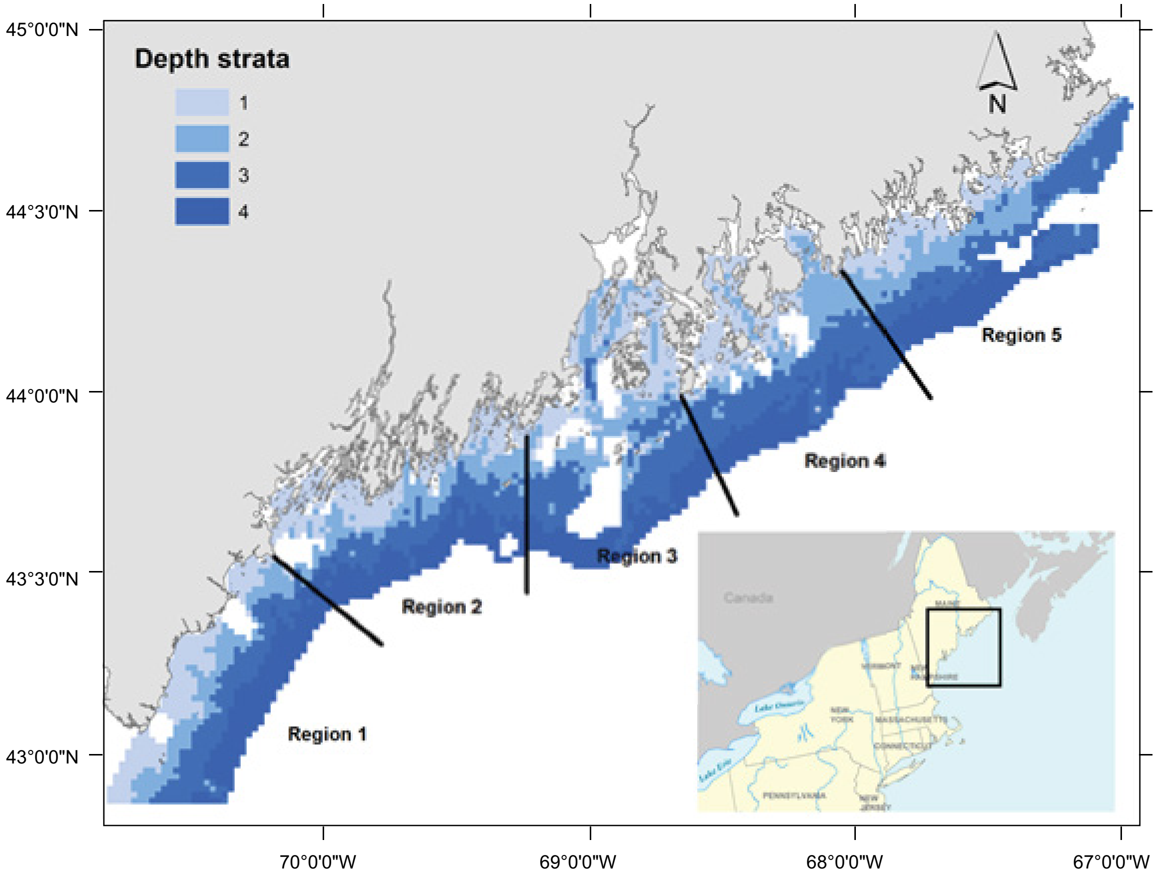

Fig. 1. Region and depth strata for the Maine-New Hampshire inshore trawl survey (white areas are the areas that could not be towed)

lobster is also a primary sampling objective (Chen *et al.*, 2006). The net is a modified version of shrimp net design used in Maine waters and designed to fish for a variety of near-bottom dwelling species without targeting any specific component.

Simulation of a "true" population

The spatial distribution of American lobster is influenced by many factors such as temperature (Aiken and Waddy, 1986), salinity (Jury *et al.*, 1994), and shelter availability (Wahle and Steneck 1991) and it differs greatly by season, sex, and size class (Chen *et al.*, 2006). Chang *et al.*, (2010) developed a habitat modeling approach for quantifying season-, size-, and sex-specific lobster distribution in the Gulf of Maine. They used a 2-stage general additive model (GAM), with a stage 1 GAM to estimate the probability of presence of lobsters and stage 2 GAM to estimate the lobster density and multiplied the 2 stage model results to estimate the comprehensive lobster density. The model results suggested that lobster distribution was strongly associated with temperature and depth and different seasonally by sex and size classes, which are consistent with the ecology of the American lobster. In this study, the GAM models with bottom temperature, bottom salinity, latitude, longitude, depth, distance offshore, and two substratum features as the explanatory variables were used to estimate the season-, size-, and sex-specific lobster density distribution from 2002 to 2008. The model predictions were summed over size and sex to produce the spatial distribution of total lobster density (per tow) for spring and fall of each year from 2002 to 2008. We considered these time-series spatial distributions as "true" populations in evaluating alternative sampling designs. These "true" populations changed over time with respect to changes in temperature and salinity variables (see details in Chang *et al.*, 2010). The temperature and salinity information for 2002 to 2008 was produced by the Gulf of Maine Ocean Observing System circulation nowcast/forecast system (Xue *et al.*, 2005).

Survey designs

The 3698 potential sampling stations generated by overlaying 1 nautical mile (NM) × 1(NM) grids over the survey area were considered as the sampling frame of this study. Areas that could not be towed were excluded (Fig. 1). Three types of sampling designs were considered:

- SRS: *n* stations of the potential 3698 sites were randomly selected and sampled;
- Stratified random sampling: four stratification schemes were defined, including four depths, five regions, seven sediments (*i.e.*, gravel, gravel-sand, sand, clay-silt/sand, sand-clay/silt, clay, and sand/silt/clay), and four depths × five regions, and *n* stations were allocated proportionally to the size of the strata. The stratified mean $\bar{y}_{str}$ was estimated by taking the weighted mean over all strata (Lohr 2009):

$$\bar{y}_{\text{str}} = \sum_{h=1}^{H} \frac{N_h}{N} \sum_{h=1}^{n_h} \frac{y_{hi}}{n_h} \quad (1)$$

where n_h is the number of stations sampled in

- stratum $h, n = \sum_{h=1}^{H} n_h$ is the total number of stations sampled, N_h is the total number of possible stations in stratum h, H is the number of strata, $N = \sum_{h=1}^{H} N_h$ is the total number of possible stations in the survey area, and y_{hi} is the number of lobster density in station i of stratum h.
- SYS: the first station was randomly selected from the total of 3698 grids and the remaining stations $n - 1$ were evenly spaced in the survey area.

Based on the above three designs, a total of six survey designs were evaluated in this study (Table 1).

For the stratified survey design currently used by Maine DMR, Neyman allocation scheme was used to evaluate if such an approach can improve the precision of estimates. Neyman allocation is the special case of optimal allocation when the costs in the strata are approximately equal (Lohr, 2009). The sample size in the stratum, n_h, is proportional to $N_h S_h$, where S_h is the variance of stratum *h* (Lohr, 2009). S_h was assumed to be equal to the population variance of the previous year in stratum *h* which is estimated based on habitat model. In this case, we allocated more sample to highly variable strata and large strata of the previous year. Also we considered the case that n_h is just proportional to S_h which means we just allocate more samples to highly variable strata forecasted by previous year. In most fisheries surveys, mean and variance are related (Smith and Lundy, 2006). Therefore, we also investigated the two allocation schemes with mean substituted for variance. Thus we considered four scenarios of sample allocations for the survey design currently used by the Maine DMR:

- Scenario one: allocating samples based on variances of strata weighted by area
- Scenario two: allocating samples just based on variances of strata
- Scenario three: allocating samples based on means of strata weighted by area
- Scenario four: allocating samples just based on means of strata

Evaluating survey designs

Three indices were used to measure the performance (*e.g.*, accuracy, precision and efficiency) of each sampling scheme. Relative Estimation Error (REE) was used to quantify the accuracy and precision of estimated mean (Chen 1996):

$$REE = \frac{1}{y^{true}} \sqrt{\sum_{i=1}^{N} (y_i^{est} - y^{true})^2 \cdot \frac{1}{N}} \quad (2)$$

We also calculated Relative Bias (RB) for the estimated mean as (Paloheimo and Chen 1996):

$$RB = \frac{1}{y^{true}} \left(\frac{\sum_{i=1}^{N} y_i^{est} - N y^{true}}{N} \right) \quad (3)$$

where $Y_i^{estimated}$ is the estimated mean in the i[th] simulated

Table 1. List of sampling designs

Design I	Design II	Design III	Design IV	Design V	Design VI
Simple random design	Systematic design	Stratified design with 5 regions strata	Stratified design with 4 depths strata	Stratified design with 7 sediments strata	Stratified design with 20 strata (4 depths × 5 regions)

survey, Y^{true} is the true mean, N is the number of simulation times. The REE and RB values reflect both bias and variation in the estimation, and a smaller REE or RB value suggests a better performance (Chen, 1996). The RB value could also indicate whether the sampling design tends to underestimate or overestimate the population mean.

The variance of sample mean of each sampling strategy was calculated from the distribution of sample mean generated by repeating the sampling process on the "true" population. Such a variance reflects the variability of sample mean. In theory, the sampling designs considered in this study produce unbiased estimates of population mean. However the unbiasedness does not mean that estimate of mean for a particular simulation run would be equal to the true population mean. Rather, the unbiased estimators have variability; sometimes they would be too low or too high. If the estimates of mean are too variable based on certain design, it would be considered of low precision and less efficient. Design effect, $deff(\overline{m})$ was used to quantify the difference of sample-to-sample variability between a specified sampling design and SRS:

$$deff(\overline{m}) = \frac{V(k,\overline{m})}{V(SRS,\overline{m})} \quad (4)$$

where $\overline{m}$ is the sample mean, $V(k,\overline{m})$ is the variance of sample mean under the k^{th} sampling design, $V(SRS,\overline{m})$ is the variance of sample mean under the SRS design.

Simulation procedure

The sampling process was simulated for each design by spring and fall from 2002 to 2008 based on the "true populations". For Design I to Design VI (Table 1), three sample sizes were considered (87, 115, 144) in order to test the impacts of sample size. Simulations could be divided into two steps for each sampling design: (1) draw samples according to a particular design from the "true" population for 1000 times and calculate each performance index; and (2) repeat step 1 for 100 times to capture variability in the simulation and get the distribution of performance indices.

Results

Simulated populations

The predicted spatial pattern of lobster distribution was stable over time for both spring and fall from 2002 to 2008, therefore, only the distributions of 2006 were shown as an example (Fig. 2). In general, lobster density was predicted to be higher in inshore waters. The hot spots were located

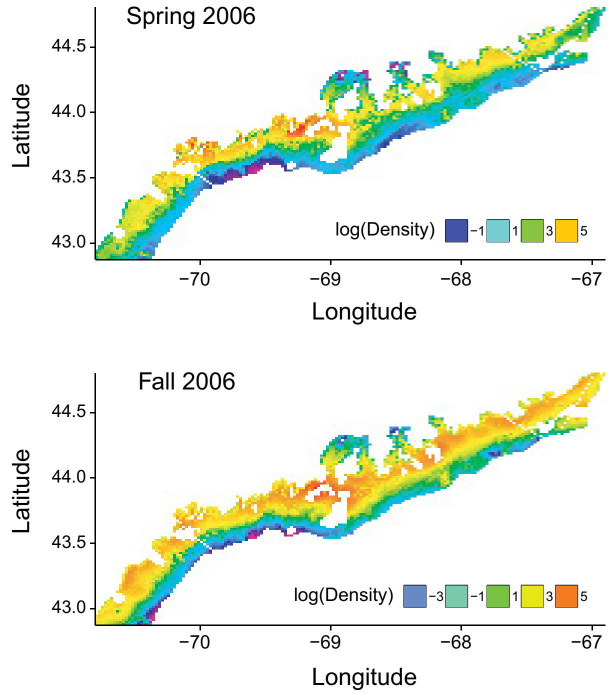

Fig. 2. Simulated 'true' population distribution of American lobster in the Gulf of Maine for 2006

in the mid-coast region. Those patterns were similar for both spring and fall.

Survey designs

The values of REE and design effect showed consistently that the performance (*i.e.*, efficiency and precision) of the six survey designs had the following ranking (from best to worst): Design II > Design VI > Design IV > Design V > Design III > Design I. This performance ranking was the same for both spring and fall populations, for different sample sizes (*i.e.*, 87, 115 and 144; Table 2, Fig. 3), and for different years (*i.e.*, from 2002 to 2008; Table 2, Fig. 4). The same pattern in these two indices was apparent for the spring population (not illustrated).

SYS yielded the most precise and efficient estimates of population mean. However, its performance indices (*e.g.*, REE and design effect) showed large variation with the change of sample size (Table 2, Fig. 3). For example, the annual average REE for fall population decreased from 7.11% to 4.92% when sample size increased from 87 to 115. However it increased from 4.92% to 6.49% when sample size increased from 115 to 144. The annual average design effect showed the same pattern. Thus, increased sample size might lead to decreased performances for SYS. Such variation in the design effects and REE also existed in the spring population. In addition, the design

Table 2. The design effects estimated in simulation for seven years with small, medium and large sample size

		Design / spring						Design / fall					
Sample size	Year	I	II	III	IV	V	VI	I	II	III	IV	V	VI
87	2002	1	0.341	0.964	0.689	0.807	0.604	1	0.244	0.993	0.662	0.915	0.582
	2003	1	0.349	0.964	0.674	0.807	0.600	1	0.244	0.991	0.662	0.914	0.581
	2004	1	0.409	0.983	0.690	0.847	0.614	1	0.260	0.993	0.636	0.907	0.578
	2005	1	0.375	0.973	0.688	0.825	0.612	1	0.261	0.994	0.656	0.930	0.593
	2006	1	0.552	0.940	0.699	0.871	0.579	1	0.265	0.998	0.637	0.930	0.584
	2007	1	0.358	0.973	0.700	0.820	0.620	1	0.249	0.996	0.641	0.923	0.575
	2008	1	0.425	0.975	0.712	0.875	0.611	1	0.249	1.000	0.664	0.938	0.588
115	2002	1	0.120	0.959	0.690	0.810	0.605	1	0.170	0.985	0.646	0.915	0.577
	2003	1	0.118	0.971	0.662	0.823	0.576	1	0.168	0.988	0.642	0.920	0.586
	2004	1	0.129	0.968	0.678	0.836	0.600	1	0.161	0.985	0.624	0.913	0.574
	2005	1	0.125	0.964	0.682	0.817	0.600	1	0.160	1.001	0.633	0.937	0.583
	2006	1	0.198	0.924	0.698	0.865	0.556	1	0.157	0.990	0.625	0.922	0.579
	2007	1	0.123	0.956	0.683	0.816	0.593	1	0.155	0.998	0.628	0.919	0.571
	2008	1	0.155	0.949	0.682	0.853	0.576	1	0.159	0.979	0.633	0.920	0.584
144	2002	1	0.419	0.942	0.697	0.802	0.600	1	0.312	0.983	0.666	0.919	0.589
	2003	1	0.470	0.954	0.685	0.823	0.591	1	0.294	0.971	0.667	0.921	0.597
	2004	1	0.458	0.953	0.691	0.835	0.605	1	0.330	0.975	0.645	0.921	0.587
	2005	1	0.488	0.944	0.697	0.831	0.610	1	0.329	0.978	0.644	0.925	0.598
	2006	1	0.499	0.921	0.714	0.865	0.563	1	0.333	0.976	0.644	0.928	0.592
	2007	1	0.484	0.950	0.710	0.813	0.606	1	0.329	0.987	0.649	0.927	0.587
	2008	1	0.501	0.934	0.707	0.856	0.586	1	0.346	0.966	0.658	0.932	0.589

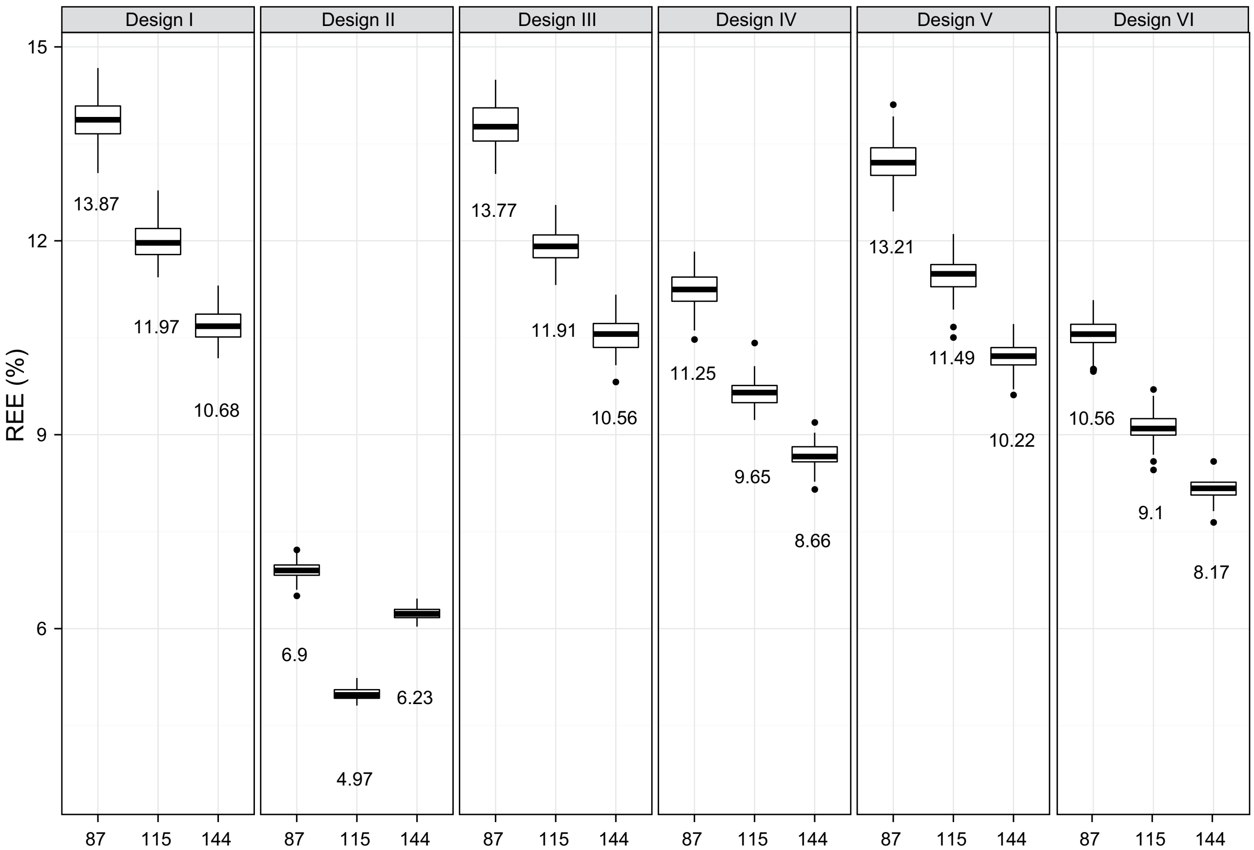

Fig. 3. Comparison of index REE yielded by five evaluated sampling designs with small (87), medium (115) and large (144) sample sizes for fall population of 2002 (values in the plot are medians)

effect of SYS differed for spring and fall population with the same sample size, suggesting SYS is likely to be sensitive to different realization of population spatial distribution (Table 2).

The current region-depth stratified design used by DMR performed slightly better in annual average design effect and REE compared to the depth-stratified design alone, when the same sample size was the used. Stratification by regions only contributes a little to the improvement of the efficiency since it just resulted in less than 10% improvement in design effect. Most of the improved efficiency due to the current depth-region-based 20-strata design came from the depth component of the stratification scheme. Sediment-stratified design had the similar efficiency as region-based design. However, its performance differed by season (Table 2). The REE and design effect obtained by region-stratified design and sediment-stratified design were close (Table 2, Fig. 3). The annual average REE values of stratified designs for the estimation of both spring and fall populations decreased as the sample size became larger (Fig. 3). Such a decrease was gained by increasing sample size from 87 to 115 and was larger than the decrease resulting from increasing sample size from 115 to 144. The improvement of precision by increasing the sample size varied with different designs.

The RB values of all the designs except for Design II were distributed evenly around zero (*e.g.*, annual means were less than 0.1%) for any given sample size and population which indicates that the biases of these designs have no tendency to be either negative or positive (Fig.5). However, for SYS biases tended to be positive consistently across all the years for both spring and fall populations when sample size was 87 and tended to be negative when sample size increased (Fig. 5). The annual average RB values of SYS had relatively large variation with the change of sample size. The SYS might yield overestimated or underestimated population mean compared to the other sampling designs.

The variations of REE and RB between different years are shown in Figs. 4 and 6. The patterns of REE across the years associated with six sampling designs are almost the same and variations are relative small (Fig. 4). The values

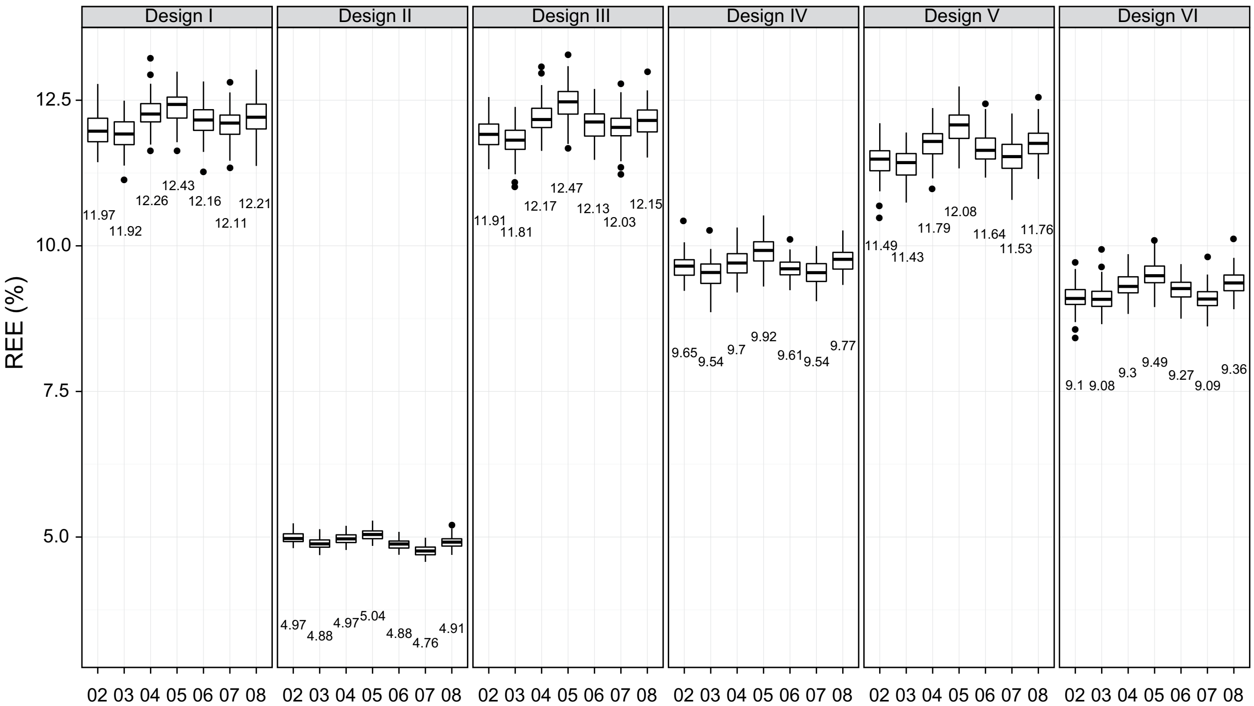

Fig. 4. Performance index (*i.e.*, REE) of five evaluated sampling designs with sample size being 115 across years (*i.e.*, 2002–2008) for fall population (values in the plot are medians)

of RB across years are stable and show no bias on average for all the sampling designs except SYS (Fig. 6), indicating that different realizations of population distribution in the simulation might not exert a large influence on the performance of those sampling designs.

In conclusion, SYS gave the most precise and efficient estimates of population mean; however, these estimates were biased. Its precision differed by season and its bias varied across years. Stratified design produced unbiased estimates and its precision and efficiency depends on the stratification strategy. All the stratification strategies evaluated had stable performance across years and seasons except sediment-stratified design whose performance varied with season. However, season-specific performance of sediment-stratified strategy was stable across years.

Sample allocations

The results of reallocating samples for Design VI showed that REE of four scenarios reduced by about 2%, suggesting that reallocating samples based on variance or mean of previous year only improved precision slightly. The design effects of the four scenarios decreased by 20% for the years from 2003 to 2008 of both fall and spring populations, suggesting that reallocating samples improved efficiency by about 20%. The RB values were so small (less than 0.1%) that they could be ignored. The performances of the four scenarios are shown in Table 3. Scenario one and two performed best for both spring and fall population through all the years and the performance indices of those two scenarios are very close.

For the fall population, Scenario two performed best for the years of 2003, 2005 and 2008 in which both the REE and design effect were smallest (Table 3). For the year of 2006 the performance of Scenarios three was the best. For the year of 2004 and 2007 Scenario one had the highest precision and efficiency. For the spring population, best scenarios were not consistently suggested by the values of REE and design effect. However the values of those two indices were very close (Table 3). Scenario four did not perform well in any given scenario for both spring and fall populations. Scenario three only performed best in the year of 2006 for the fall population. Variance or weighted variance of immediately previous year was a better indicator for allocating samples to each stratum than the mean.

Discussion

The performance of several sampling designs and different sample sizes in their ability of estimating abundance indices in fishery-independent surveys especially for

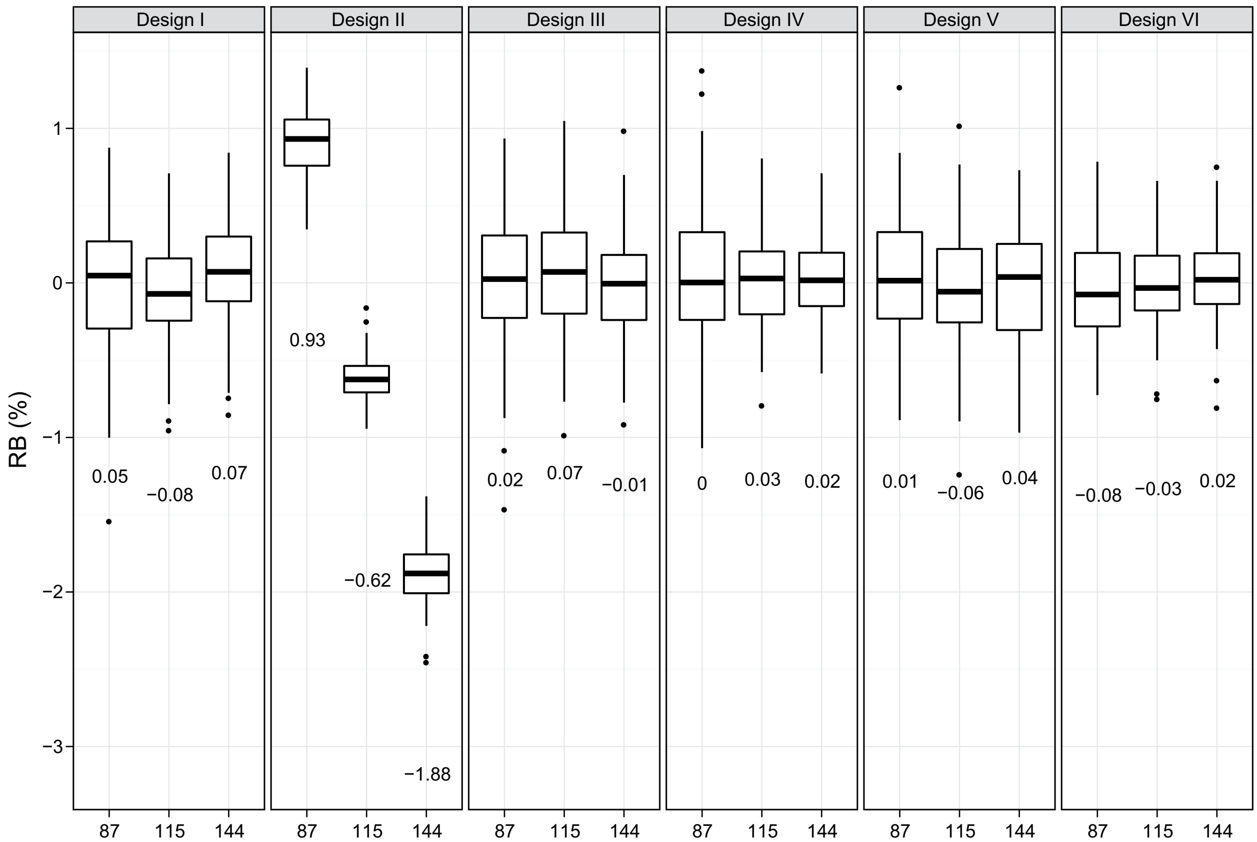

Fig. 5. Comparison of index RB yielded by five evaluated sampling designs with small (87), medium (115) and large (144) sample sizes for fall population of 2002 (values in the plot are medians)

benthic invertebrate species was examined in several studies (Cabral and Murta, 2004; Smith and Lundy, 2006; Smith and Tremblay, 2003). Although these studies generated insights about performance of various survey designs and sample size, either the number of designs involved or the number of "true" spatial distributions was limited. In this study, the bias relative to the "true" population value and precision and efficiency relative to the variance obtained by SRS, stratified random sampling and SYS were compared, and alternative sampling effort allocation schemes were explored and evaluated using computer simulation based on 14 "true" populations (*e.g.*, spring and fall population each year from 2002 to 2008).

The currently used stratified random sampling design was on average less precise and efficient for estimating population mean than SYS for both spring and fall surveys in all the years investigated. This is consistent with previous studies which suggest that SYS tends to be more accurate than stratified random design (Cochran, 2007; Ripley, 2004). The desirable properties of SYS generally embodies in providing better support for kriging methods which aim to obtain estimates of spatial distribution (Liu *et al*., 2009). In this study, SYS was demonstrated to out-perform random and stratified random designs for estimating the population mean in terms of precision and efficiency. However, given that RB is non zero for SYS on average, this suggests that the sampling design either over- or under-estimates 'true' population mean. Another striking feature of SYS in this study is that precision and design effect are not always improved with increased sample sizes. For example, increasing the sample size by 25% from 115 to 144 would not reduce sampling errors, rather would actually increase the REE and design effect by 32% and 100%, respectively. REE and variance of sample mean did decrease when the sample size approached the entire population globally (Fig. 7). However, local behaviors of REE and variance were complex. There are some major peaks and a lot of small fluctuations in the curves of REE and variance versus sample size (Fig. 7). Therefore, it is difficult to select a specific sample size to reach a specified performance for a SYS design.

Table 3. The performance indices for four scenarios of sample allocation based on stratified design with 20 strata. The smallest REE and design effect for each scenario are emboldened.

		REE (%)				RB (%)				Design effect			
	Year	1	2	3	4	1	2	3	4	1	2	3	4
FALL	2002	10.067	9.562	10.101	10.107	-0.019	-0.009	0.021	0.024	0.551	0.496	0.552	0.549
	2003	8.099	**7.943**	8.254	8.460	-0.014	-0.002	0.000	0.012	0.388	**0.372**	0.406	0.420
	2004	**8.426**	8.433	8.647	9.044	-0.012	-0.057	-0.022	0.015	**0.393**	0.394	0.416	0.451
	2005	8.849	**8.688**	8.947	9.131	0.057	-0.040	0.023	0.059	0.401	**0.383**	0.407	0.419
	2006	8.822	8.715	**8.663**	8.728	-0.039	0.033	-0.039	0.007	0.401	0.396	**0.388**	0.393
	2007	**7.930**	8.096	8.013	8.431	-0.023	-0.004	0.042	0.025	**0.356**	0.371	0.364	0.402
	2008	8.054	**7.977**	8.549	8.715	-0.034	0.031	-0.008	-0.027	0.360	**0.354**	0.407	0.419
SPRING	2002	10.277	10.359	10.333	10.332	0.002	-0.023	-0.010	-0.010	0.589	0.600	0.597	0.597
	2003	**7.973**	7.993	8.219	8.414	0.030	-0.023	-0.011	-0.019	**0.377**	0.378	0.398	0.421
	2004	8.106	**8.071**	8.510	8.693	-0.003	0.014	0.027	-0.047	**0.386**	0.387	0.431	0.446
	2005	8.584	**8.425**	8.532	8.935	-0.018	0.010	0.019	0.009	0.391	**0.375**	0.390	0.422
	2006	8.237	**8.236**	8.500	8.707	-0.046	0.018	0.065	0.017	**0.333**	0.334	0.359	0.373
	2007	**8.347**	8.367	8.637	8.916	-0.014	0.001	-0.008	0.017	**0.367**	0.369	0.394	0.423
	2008	8.368	**8.317**	8.621	8.792	0.007	0.025	0.015	0.019	0.370	**0.363**	0.389	0.407

Stratified random design can spread out the samples and often improve the precision and efficiency of survey means compared to SRS (Lohr, 2009). However, this study demonstrates that stratification, if determined inappropriately, such as only using regions to determine strata, makes little contribution to the improvement of precision and efficiency. It is critical to select suitable variables to determine strata. Variables that may greatly influence spatial distribution and population structure of target species are considered to be good choices because the strata determined by such variables tend to make homogeneity within a stratum and heterogeneity between stratum. For example, the stratification based on depth in this study improved the efficiency and precision greatly over SRS. Previous studies revealed that lobster distribution and size composition vary with water depth (Chen *et al*., 2006; Wahle and Steneck, 1991). However, the stratification based on sediment, which is another variable used in the GAM model for generating the 'true' population, did not improve the performance over SRS as much as depth-stratified design did. Although studies have revealed that high lobster density occurs in substrates with boulders (Cooper and Uzmann, 1980) and rocks (Steneck, 2006). Due to the limitation of gear type used in this trawl survey such substrates had limited coverage the trawl survey. Also, variable sediment is not as significant as variable depth in the GAM developed by Chang *et al*., (2010). This study suggests that no all variables that may influence spatial distribution of lobster are suitable for survey stratficiation.

Reallocating samples among strata can significantly improve the ability of estimating population mean. A reduction of 20% samples from the current sample size (115) could obtain similar precision and efficiency for estimating population mean by reallocating the sampling efforts based on the variances estimated in the previous year. The four scenarios considered in this study yield improvement in efficiency and precision, indicating that variance and mean might be correlated. However, variance tends to be better than mean as an indicator of allocating samples among the strata. The difference between scenario one and scenario two is that variance used in scenario one is weighted by area. The impact of area weight to variance was related to how well the variance of previous year predicting the next's. For the years that scenario one outweighs scenario two, the reason is that the weighted variances of previous year are more approaching the true variances than those un-weighted.

The current stratified sampling design was found to be robust to different realizations of lobster population, and its performance was stable between seasons and among years. This suggests that the change in temporal and spatial distributions driven by environmental factors such as bottom temperature and salinity has no effect on the

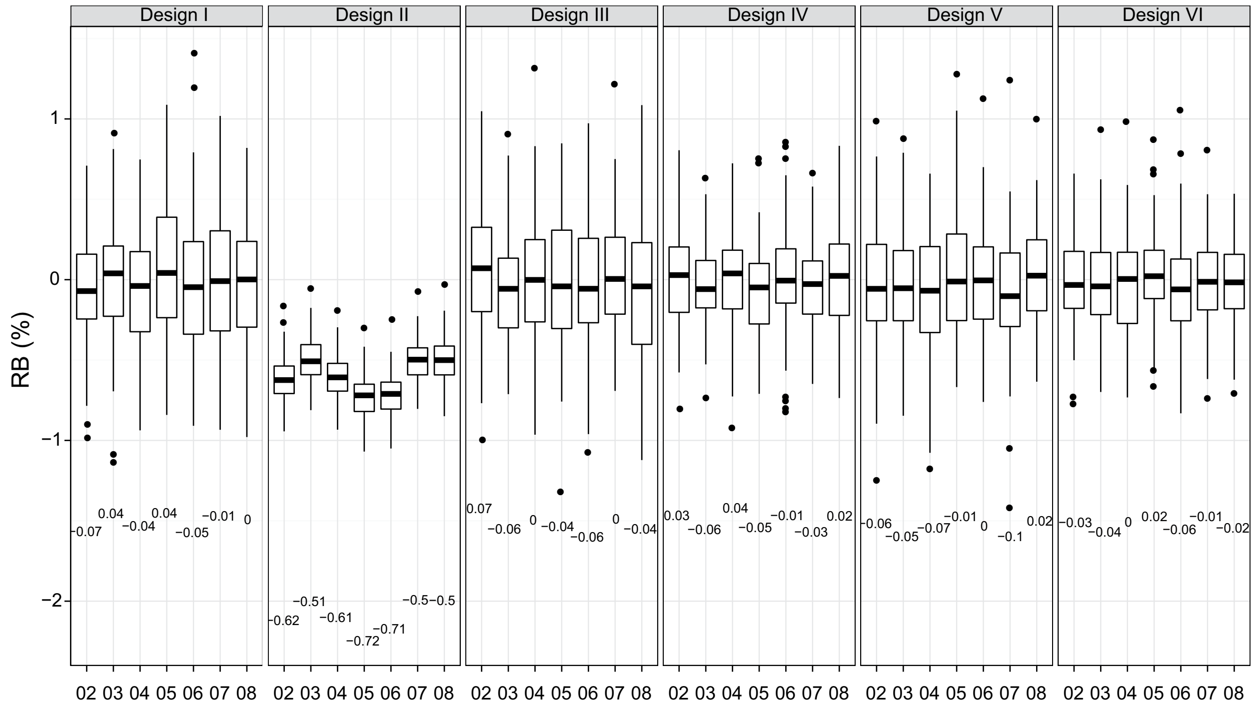

Fig. 6. Performance index *(i.e.*, RB) of five evaluated sampling designs with sample size being 115 across years (*i.e.*, 2002–2008) for fall population (values in the plot are medians)

ability of appropriate stratified sampling design to estimate the mean. Smith (1996) simulated two very different populations (with and without spatial structure) to show that the underlying distribution and spatial structure of population have no effect on the performance of stratified sampling design in estimating mean and its standard error. Our study is consistent with his study. Such a result indicates that the relative abundance trend of lobster could be well tracked based on the current design without any standardization.

For a fishery independent survey targeting multiple species as the one evaluated in this study stratified random design is more appropriate. Because different species tend to have different spatial distributions, SYS may perform well on one or some, but not all. Additionally, it's hard to decide a particular sample size for SYS since its performance could dramatically fluctuate with small change of sample size. However appropriate stratified random design is robust to different distributions. Given the variability in fish population distribution over time and space and nature of targeting multispecies in a fishery-independent survey program, stratified random survey design is more desirable for a fishery-independent survey. Defining the sampling frame is a critical issue in a fishery-independent survey. For example, the size of sampling unit can influence the performance of certain sampling designs (Pennington and Volstad 1991). In this study the sampling unit was defined as 1NM × 1NM and some potential sampling units were excluded due to the operability of gear type. Studies may be needed to evaluate the impacts of sampling frame on the inshore bottom trawl survey for the American lobster.

This study suggests that stratified random survey design used in the Maine bottom trawl survey can yield abundance index estimates that can reliably capture spatial and temporal variability of American lobster population along the coast of Maine covered by the survey program.

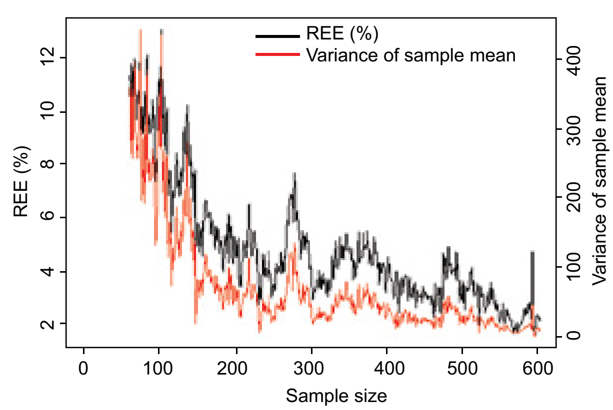

Fig. 7. Change of REE and variance of sample mean yielded by Systematic design with sample size

The use of the abundance index in the lobster stock assessment (ASMFC, 2009) is thus desirable. Similar approach used in this study can also be used for other fish species to evaluate the reliability of abundance index derived from a fishery-independent survey program in capturing fish stock dynamics in stock assessment.

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ÁVILA DE MELO, A. M., D. POWER, and R. ALPOIM. MS 2005. An assessment of the status of the redfish in NAFO Division 3LN, *NAFO SCR Doc.*, No. 52, Serial No. N5138, 19 p.

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