Atlantic States Marine Fisheries Commission

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MEMORANDUM

TO: American Lobster Management Board

FROM: American Lobster Technical Committee

DATE: January 12, 2017

SUBJECT: Report on the GOM/GBK Stock

At their May 2016 meeting, the American Lobster Management Board (Board) charged the American Lobster Technical Committee (TC) with a series of tasks to investigate stock conditions in the Gulf of Maine and Georges Bank (GOM/GBK). This was prompted by the 2015 stock assessment which found that, while the GOM/GBK is at record high abundance, there has been a decline in settlement in recent years. This could be a sign of poor recruitment in the future.

To more fully understand potential changes occurring in the GOM/GBK stock, the Board tasked the TC with: describing ocean currents and larval supply patterns; investigating stock connectivity; identifying changes in the size distribution of egg-bearing females; plotting a stock recruit relationship; investigating the potential standardization of biological management measures; develop a traffic light analysis; and identifying research holes and data gaps. The TC also investigated habitat availability for recruitment.

The TC met via conference call on September 7th, November 29th, and January 6th as well as in-person on September 27th and 28th. Below is the TC's analysis on the tasks requested by the Board. An executive summary is presented on pages 2-3 followed by the full report.

The TC would like to start by noting that current reference abundance and SSB are at all-time highs according to the 2015 stock assessment. While YOY indices have declined, the trends in total abundance and SSB suggest that egg production is not the cause behind the observed declines in young-of-year (YOY) settlement.

Executive Summary

Ocean currents play a critical role in the life history of lobsters as studies suggest there is a strong connectivity between the life stages of lobster that rely on physical oceanography. Lobster larvae in the GOM are primarily transported by the Gulf of Maine Coastal Current (GMCC) which moves counter-clockwise and is comprised of two major branches including the Eastern Maine Coastal Current, which flows intensely along the shore from the Bay of Fundy to Penobscot Bay, and the Western Maine Coastal Current, which is weaker and flows southwest along the coast west of Penobscot Bay. Potential changes in the Gulf of Maine oceanography, including changes in temperature, stratification, phytoplankton species composition, and wind forcing advection patterns could all impact lobster settlement and recruitment.

Based on tagging data, lobster movement appears to be quite complex with long distance movements between some areas, but limited evidence of exchange in other areas. Although there is tag data suggesting some movement of lobsters between GOM and GBK, the impacts of this movement cannot be determined with the existing tagging data. Using historic tagging data alone to determine stock **connectivity** is inconclusive and requires some additional research. In an effort address this question, the TC intends to further analyze a historic tagging study that was recently brought to their attention and continue to collect/analyze data on a recent tagging effort on GBK. Larval connectivity, as well as the location of larval sinks, is dependent on the GMCC. Typically the GMCC operates in a “gate ajar” scenario, causing water to be deflected offshore at Penobscot Bay with some leaking into the WMCC; however, the GMCC can flow in a “gate open” scenario, which causes greater water flow along the coast strengthening WMCC, or a “gate closed” scenario when the current is completely deflected offshore at Penobscot Bay.

Commercial trap sampling data provides evidence of **decreased size-at-maturity**. Increases in the proportion of egg-bearing females in the 76-80 mm CL size range are evident in all statistical areas but most prominent in the southern portion of GOM. Importantly, while spawning stock biomass is at an all-time high and larval indices show increases in the abundance of Stage I larvae, there has been a noticeable decrease in the abundance of stage IV larvae. This could be the result of changes in wind patterns (advection), food availability, or timing of hatch. There is evidence that zooplankton populations have decreased in recent years and that eggs are hatching earlier in the season.

In an effort to look at the **habitat available for recruitment**, analysis was undertaken to examine the quantity of habitat by depth for the GOM. The results show that incremental increases in depths suitable as recruitment habitat would likely result in incremental increases in total recruitment habitat. This suggests that the decrease seen in settlement cannot be explained solely by increases in the habitat available for recruitment. More work is needed to assess the importance of, and potential changes in, temperature and increased bottom complexity with depth.

The **stock-recruit relationship** for the GOM/GBK shows increases in recruitment through the time series. The relationship between recruitment and SSB is generally linear from 1981-2002, suggesting that recruitment per unit of spawning biomass was stable. In contrast, recruitment between 2002 and 2007 increased while spawning biomass remained relatively stable, suggesting that recruits per unit of spawning biomass increased over these years. In contrast, spawning biomass in SNE has remained stable since 2003 while recruitment has decreased, suggesting a decline in recruitment per unit of spawning biomass.

Biological management measures, namely gauge size changes, were explored as a way to improve resiliency of the stock. Analysis shows that increasing the minimum size is predicted to increase total catch in the fishery by weight but decrease catch by number. Furthermore, increases in the minimum gauge size could result in dramatic increases in the number of mature lobsters and SSB, potentially adding resilience to the fishery. An important caveat regarding this analysis is that, given lobster abundance in the GOM is already at record levels, it is unclear whether the ecosystem can support large increases in the amount of lobster biomass.

The development of a **Traffic Light Analysis (TLA)** was explored as a method to maintain high catch rates in the GOM/GBK; however, several concerns were noted with this method. Primarily, concerns were expressed that a TLA is designed for data-poor species and that color coded model-free indicators are already created as a part of the stock assessment, and can be used for annual updates to monitor stock conditions. Recognizing the Board's desire to be proactive, the TC recommends the Board monitor the ventless trap surveys for decreases in recruitment as this would confirm changing stock conditions. Further, it is recommended that management action be triggered at the 50th percentile, rather than the 25th percentile. Finally, the TC could develop an environmental indicator based on water temperature, should the Board desire this analysis.

Given the effects of water temperature of lobster life history, **research** is critically needed to update the maturity and growth information used in the stock assessment. Studies are also needed to examine age- or length-varying natural mortality and post-larval settlement dynamics given changes in the distribution of spawning females.

1. Ocean Currents in GOM

Circulation changes in the Gulf of Maine may have implications for future recruitment and spawning stock of American lobster through population connectivity. Recent genetic work indicates lobsters north of Nova Scotia and in the Gulf of St. Lawrence may be genetically different than the GOM/GBK and SNE stocks; however, lobsters within the U.S. managed stocks appear to be genetically indistinguishable, suggesting possible stock mixing (Benestan et al., 2015). Synchrony between settlement densities and models that predict larval transport suggests there is strong connectivity between these life stages that rely on physical oceanography (Incze et al., 2010). Given the apparent significance of circulation on recruitment, Gulf of Maine current systems are summarized to evaluate prospective future challenges under a changing environment.

The Gulf of Maine is a semi-enclosed system with an overall counterclockwise circulation (Figure 1). The majority of deep water entering the Gulf of Maine is through the Northeast Channel, located between Georges Bank and Browns Bank (Figure 2). Water masses entering deep through the Northeast Channel are largely influenced by current systems north and south of the domain and are reflective of the slope water outside of the Gulf (Townsend et al. 2004). The slope water conditions vary based on the predominance of two types of slope water: the Labrador Sea Slope Water (LSSW) and the Warm Slope Water (WSW) (MERCINA, 2001; Townsend et al., 2010). The LSSW originates from the Labrador Current, moves south around the Grand Banks towards the Northeast Channel, and is characterized as cold, fresh, and low in nitrate. The WSW originates from the Gulf Stream, moving north/northeast, and is typically warmer, saltier, and higher in nitrate than the LSSW. Prevalence of either water mass on the slope and that enters the Gulf of Maine typically depends on the strength of the Labrador Current and/or Gulf Stream. The strength of these current systems are linked to the atmospheric pressure system over the North Atlantic, represented as the North Atlantic Oscillation (MERCINA, 2001, Pershing et al., 2005). NAO phase shifts and changes in slope water temperatures have implications for water column mixing, primary productivity, and zooplankton abundances in the Gulf of Maine (MERCINA et al. 2001, 2004). With strong tidal mixing and progressive counter-clockwise circulation in the northern Gulf of Maine, deep water entering via the Northeast Channel is vertically mixed with surface waters. At the surface, these waters move counterclockwise in the Gulf of Maine and eventually exit through the Great South Channel between Georges Bank and Nantucket Shoals, or the Northeast Channel.

Fresh, less dense surface water enters the Gulf of Maine from the Scotian Shelf (Brown and Beardsley, 1978; Pettigrew et al. 1998; Ji et al. 2010). It is this northern portion of the Gulf of Maine, near the mouth of the Bay of Fundy, where the Gulf of Maine's coastal current system begins, known as the Gulf of Maine Coastal Current (GMCC). The GMCC is a pressure gradient current driven by freshwater inflows to the Gulf of Maine (Pettigrew et al. 2005). GMCC surface waters flow south as part of two major branches. The Eastern Maine Coastal Current (EMCC) is characteristic of a cold band that extends southwestward from the Bay of Fundy towards Penobscot Bay. At this juncture, the EMCC bifurcates (Figure 2). One pathway includes water moving offshore to the center of the Gulf, contributing to the cyclonic circulation around Jordan Basin (Pettigrew et al. 1998). The other branch continues along the coast to what becomes the Western Maine Coastal Current (WMCC) (Brooks, 1985; Pettigrew et al., 2005). The WMCC is a buoyant, wind-driven current which accumulates plume water from several Maine rivers (e.g. Kennebec, Androscoggin, Penobscot, Merrimack and St. John Rivers) as it flows southwest (Geyer et al., 2004; Janzen et al., 2005). Plume thickness within the WMCC can be 20m in depth up to 100m, suggesting the WMCC can be stratified over the water column depending on the amount of freshwater (Geyer et al. 2004). Once around Cape Ann, the WMCC either enters northern Massachusetts Bay or moves offshore along the eastern edge of Stellwagen Bank towards Georges Bank, depending on the wind conditions (Lynch et al., 1997; Jiang et al., 2007).

The physical structure of the GMCC and its two branches (EMCC, WMCC) can change from year to year. Pettigrew et al. (2005) described the three GMCC summer scenarios at the interface of the EMCC and the weaker WMCC. The typical condition of the GMCC is "gate ajar" where most of the EMCC deflects offshore at Penobscot Bay, though there is some spillover in the nearshore into the WMCC. The two other scenarios are when the EMCC is connected to the WMCC increasing the western flow and connectivity as a "gate open" condition or the "gate closed" condition where the EMCC does not flow west of Penobscot Bay and is deflected offshore. *Section 3B: Larval Connectivity* describes how these three scenarios can impact larval settlement.

The GMCC strength and water properties have implications for downstream nutrient and particulate loading (Balch et al., 2012), phytoplankton species composition (Jiang et al. 2014) harmful algal bloom prevalence (Franks and Anderson 1992), primary productivity (McManus et al., 2014), and larval fish transport and survival (Churchill et al. 2016). Particularly for the clockwise gyre circulating around Georges Bank, phytoplankton biomass produced in GMCC can support biological productivity on the Bank (Hannah et al., 1998).

As such, lobster settlement in coastal Maine may be influenced by the transport and the habitat structure of the GMCC. Physical transport, behavioral responses to changing environments, and reduced survival are all mechanisms that the GMCC may have on lobsters from hatch to settlement. Annis et al. (2013) found that while larval lobster abundances did not vary across different bottom temperature regions in coastal Gulf of Maine, settlement abundances were higher in the warmer (>12ºC), coastal areas. Barret et al. (2016) also identified temperature as critical in dictating larval survival, settlement behavior, and post larval energetics. The authors found that thermoclines in the water column reduce settlement (Barret et al. 2016), thus prospective stratification in the GMCC could impact recruitment for the GOM/GBK stock. Differences in the EMCC and WMCC systems may transcend to spatial differences in lobster recruitment patterns along the coastal Gulf of Maine. Chang et al. (2016) found that stock-recruitment relationships, both fitness, form, and parameter estimates, varied between eastern and western Gulf of Maine. Further, the authors note that data aggregation and analyses at a medium scale were best in identifying stock-recruitment relationships. Thus, while it is known that fine-scale oceanographic processes are important to larval settlement, there is not a good understanding of how to scale this fine-scale information up to the population level.

Future changes in Gulf of Maine oceanography and the GMCC may have implications for larval transport and settlement locations. Given lobster larval transport relies heavily on the GMCC and varies with strength of the GMCC and prevailing winds (Xue et al. 2008), long term changes in stratification, river runoff, and temperature may influence mortality rates through thermal tolerance, larval drift offshore and food supply. Sea surface temperatures and days above thermal thresholds in coastal Gulf of Maine have increased since the 1980s (Figure 3). The northwest Atlantic is projected to further increase in temperature in the coming decades (Saba et al., 2016), which could increase Gulf of Maine temperature and stratification, as well as alter the water masses circulating in the Gulf of Maine.

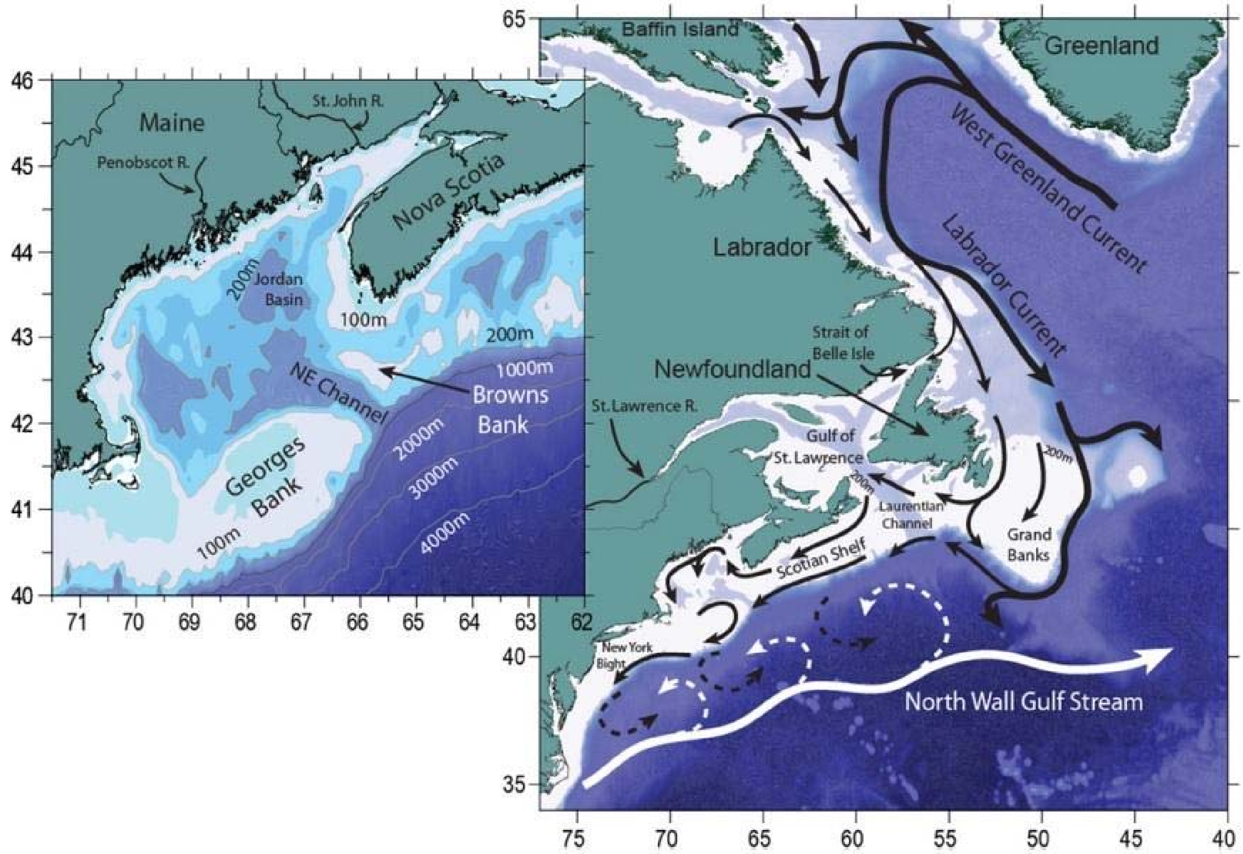

Figure 1. Maps of Gulf of Maine and Georges Banks (left) and larger northwest Atlantic current paths (Townsend et al., 2010).

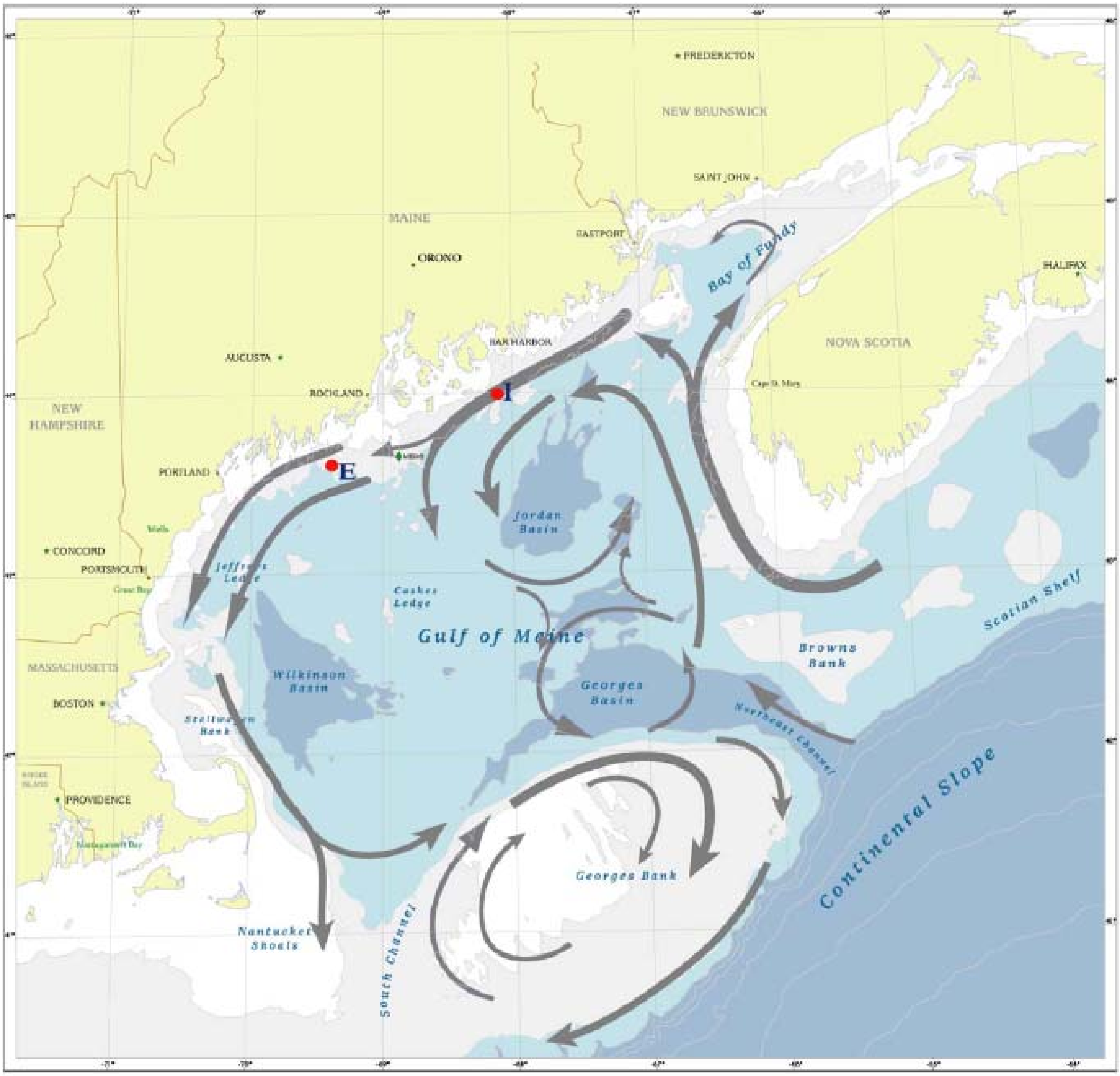

Figure 2. Finer scale circulation of Georges Bank and the Gulf of Maine. The EMCC and WMCC are delineated with the bifurcation near Penobscot Bay (Pettigrew et al. 2005).

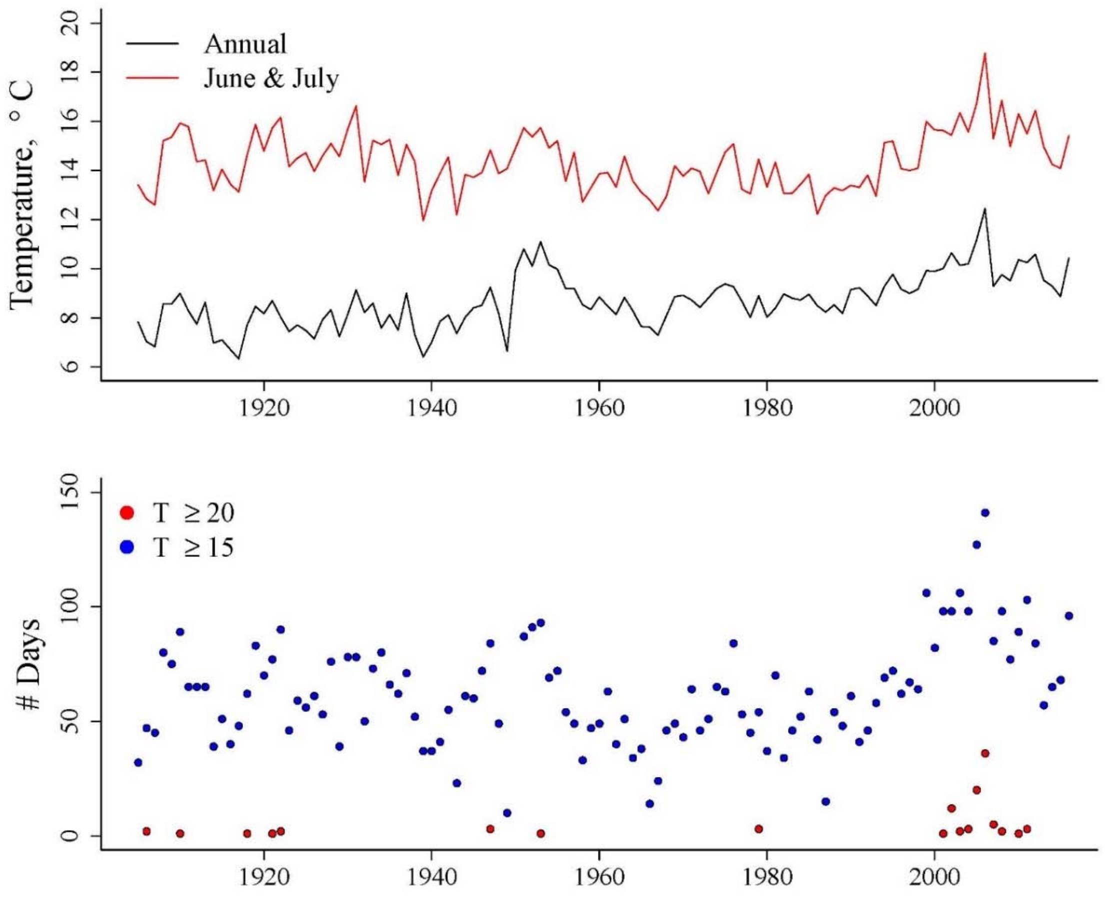

Figure 3. Long-term Boothbay Harbor, ME average sea surface temperatures (top) annually (black) and May-June only (red). Number of days per year ≥ 15 (blue) and 20ºC (red) from the same data are also presented (bottom).

2. Connectivity Between GOM, GBK, and Canada

A. Tagging Studies Show Some Migration Over Stock Boundaries

American lobster movement has been studied dating back to 1898, when Herman Bumpus released approximately 500 mature females near Woods Hole, Massachusetts (reviewed in Krouse, 1980). This tagging study, as well as others that followed through 1950 showed that lobster movement was limited to <18km. It wasn't until 1957-59 when Robert Dow tagged 162 non-legal lobsters (i.e. sublegals, ovigerous, v-notch and oversize) on the coast of Maine that it was discovered lobsters can take on extensive movements (Dow, 1974). One lobster in Dow's study traveled 138 miles in 7 months.

Since the early tagging studies conducted from 1898-1960, it's easy to get lost in the volumes of information available with regards to lobster movement. To date there have been well over 40 studies conducted with some form of active or passive tagging device. There are certain patterns that tend to hold true for lobster movement throughout the range and there are also some discrepancies and questions that remain unanswered.

It's well established in literature that smaller lobsters, in particular, early benthic phase lobsters are cryptic and move little from areas which provide shelter from predators (Wahle and Steneck, 1992). Larger immature lobsters show limited movement whereas movement increases as individuals reach sexual maturity (Morrissey, 1971; Dow, 1974; Krouse, 1980; Campbell and Stasko, 1985; Campbell and Stasko, 1986, Campbell, 1989). Several research papers have shown that sexually mature lobsters tend to exhibit seasonal patterns of movement towards deep waters in the colder months and towards shoal waters in the warmer months (Cooper and Uzmann, 1971; Campbell and Stasko, 1986; Campbell et al., 1984; Krouse, 1980; Campbell and Stasko, 1986; Campbell, 1986). Authors of these papers have hypothesized that these directed movements are to obtain sufficient heat units for egg development. Furthermore, Aiken and Waddy (1992 and 1995) suggested that temperatures must decline to less than 8˚C in the winter for proper synchronization of the molt/reproduction cycle. There's a strong association between lobsters and temperature and it has been demonstrated they will behaviorally thermoregulate (Crossin et al., 1998) and can detect very small changes in temperature (Jury and Watson, 2000).

The abovementioned patterns are well documented and there's a general consensus on these topics among the scientific community. In contrast, attempting to use these past tagging studies to assess impacts of movement on stock structure has proven quite difficult. Tagging conducted in Canada near Grand Manan and on Browns Bank has shown some movement of animals throughout the Gulf of Maine and Georges Bank (Campbell and Stasko, 1985 & Campbell and Stasko, 1986). Furthermore, preliminary results from a tagging study conducted in the 1980s that was recently brought to the attention of the TC indicates that some lobsters tagged in offshore GOM moved both to GBK and to inshore GOM. The rate of exchange between these areas is still unclear, but further analyses will be pursued by TC members once this dataset is located (NMFS, unpublished).

Another approach to determining mixing between the stocks is to tag lobsters on Georges Bank and assess movement from tags recaptured inshore. Past tagging studies using this method have shown limited movement between the stocks (Cooper and Uzmann, 1971; Campbell et al., 1984). Between 1968 and 1973, a total of 5,500 lobsters were tagged on GBK and Browns Bank and none were recaptured inshore north of Cape Cod.

In an attempt to better determine movement between GBK and GOM; AOLA and NH Fish and Game were awarded a grant to tag ~4,000 lobsters on Georges Bank in 2015. Tag returns from this project are still being reported and final results will be available in 2019. Of the 3,500 tags deployed during the duration of this study, thus far, 100 have been recaptured. A large majority of these recaptures were from GBK; however, one lobster was reported "inshore" in Gulf of Maine and three returns were reported from Canada. Tag returns from this project will continue to be collected and updates will be provided to the Board. In addition, TC members from both Maine and New Hampshire are working with AOLA to secure funding to continue tagging on GBK and in the deep water of the GOM.

There are limitations associated with this type of tagging method, mainly that the days-at-large for many of these studies are on the order of weeks and spatiotemporal patterns of fishing effort can create biased patterns in tag-return rates. Empirical data from the most recent assessment suggests movement between stocks based on NMFS trawl survey data as there are high catches of females in the fall which are not present in the spring (ASMFC, 2016).

In conclusion, inshore tagging studies in the GOM have shown movement throughout inshore Gulf of Maine and to the OCC, but no movement to Georges Bank proper. Additionally, lobsters tagged on GBK have shown minimal movement to the Gulf of Maine; however, preliminary results from a newly re-discovered tagging dataset indicate that lobsters tagged in offshore GOM have been reported to move to both GBK and to inshore GOM. Lobster movement appears to be quite complex with long distance movements between some areas, but little to no evidence of it in other areas. Although there appears to be some movement between GOM and GBK, the impacts of this movement on population structure, looking solely at tagging studies, cannot be determined at this time based. In an effort to better understand stock structure, the TC will further pursue analysis of the offshore GOM dataset that was recently brought to our attention and continue to analyze data from the 2015 GBK tagging effort.

B. Larval Connectivity

Coupled biophysical models have been used to describe the connectivity for larval lobsters in the Gulf of Maine system with different scales and parameters considered (Incze et al., 2010 and Xue et al., 2008). The management areas considered were a combination of Canadian regions, Maine Lobster Zones, and southern GOM areas in New Hampshire and Massachusetts (Figure 4). They found that source and sink larval dynamics are complex and likely a combination of self-recruitment in local areas, adjacent areas, and distant sources. Larval connectivity in the GOM depends on egg production, hatching location, hatch timing, larval development times, coastal current transport, drift by wind forcing, and the location and size of the receiving management zones (Incze et al., 2010 and Xue et al., 2008). Some of these parameters can be difficult to model, especially if the annual trends vary in strength and direction, like wind forcing (Xue et al., 2008).

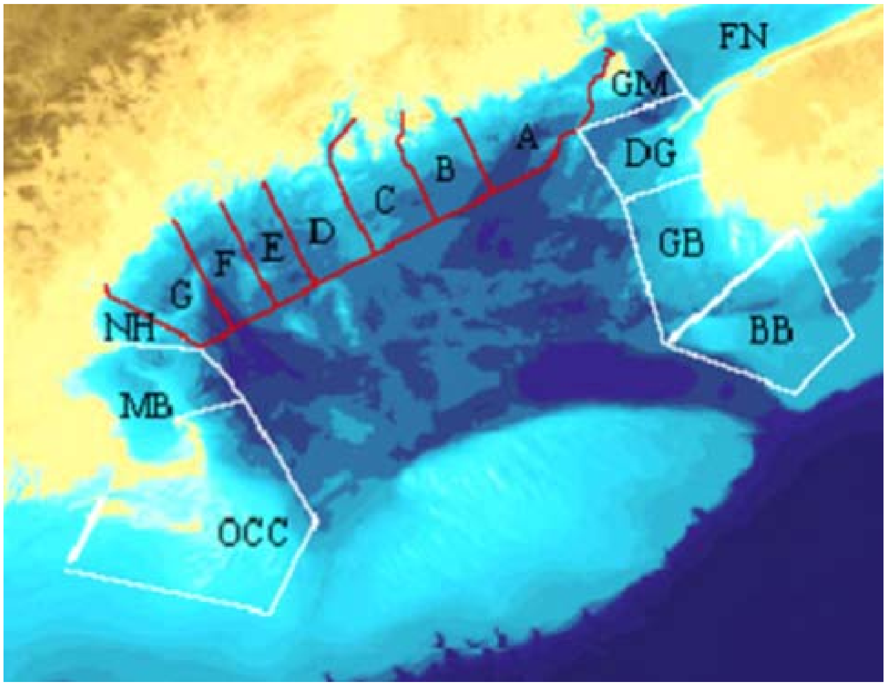

Figure 4. Management areas considered by modeling of small particles as proxy for larval connectivity. Red polygons A–G are Maine's Lobster Management Zones; others are: BB (Browns Bank); GB (German Bank); DG (Digby Neck); FN (Bay of Fundy); GM (Grand Manan); NH (New Hampshire); MB (Massachusetts Bay) and OCC (Outer Cape Cod). (Xue et al., 2008.)

As discussed in the first section, the prevailing direction of larval transport in GOM is via the GMCC in a counterclockwise cyclonic direction along the coast; however, the degree of the larval sink dynamics for each inshore management area can depend on the inter-annual variability of sea surface temperatures as well as the strength and interaction of subsections of the nearshore current, offshore wind forcing, and eddies. Incze et al. found that post-larvae in a management area

(Figure 4) were hatched in the same, adjacent, or nearby zones in the prevailing upstream direction, but it was also common that the sources could be diverse and distant (Incze et al, 2010). The predicted distance of travel depended on assumptions about larval mortality in addition to currents. There was less accumulation in the eastern regions and greater accumulation in western management areas, but overall Xue et al. found that 20-40% of the modeled particles remained in a local area. Eastern GOM, consisting of the Bay of Fundy and eastern Maine management zones, were primary sources for settlers for downstream areas with higher levels of egg production and the strong EMCC carrying the larvae downstream (Incze et al., 2010). Western Maine, especially just west of Penobscot Bay in Zones D and E, acted as sink areas. Based on field survey data from 1989-2001, there were more post-larvae in western Maine than there were in eastern areas confirming these patterns (Annis, 2004).

Also discussed in the first section are the three summer scenarios for the physical structure of the EMCC and WMCC (gate ajar, gate open, gate closed). Incze at al. (2010) determined these three scenarios impacted larval transport, especially for the zones at the interface of the two branches of the GMCC. When the gate was ajar or open, more larvae were predicted to travel to western zones while the gate closed scenario allowed for more offshore transport during the early to mid-summer months (Incze et al., 2010). Additional eastward drift from wind forcing primarily impacted the post-larvae along the coast because biologically they were most likely to be at the surface and subject to Ekman transport by the prevailing southwesterly summer winds (Xue et al., 2008). The modeled scenarios also tested the fate of larvae which hatch later in the season when the prevailing winds change direction, and predicted less eastward advection of larvae and therefore less offshore supply from US areas to the Canadian areas of Browns Bank and German Bank (Xue et al., 2008).

There continues to be uncertainty about the connectivity with offshore areas, especially as a source of larvae. Some preliminary modeling by Quinn et al. (in prep but not peer reviewed), expanded Incze and Xue's GOM models to the offshore banks, Nova Scotia and Gulf of St. Lawrence. Quinn's initial model predictions confirmed the limited connectivity between Gulf of Saint Lawrence and GOM and those regional population assemblages determined by genetic studies (Benestan et al., 2015). Quinn et al.'s model also implied that Georges Bank could be a partial sink for larval supply coming from southern Maine, New Hampshire, and Massachusetts. Harding et al. (2005) suggested that the exact source for post-larvae found near the offshore banks likely varies annually and depends on the strength and location of wind fields near and offshore. As noted above, Xue et al. confirmed this idea of inter-annual variability. There is evidence of additional high self-recruitment from the preliminary model predictions (Quinn et al., in prep), but post-larvae have been observed over Brown's and Georges Bank at the same time as the resident ovigerous females are hatching so there was no credible development period for those observed post-larvae to be locally recruited (Harding et al, 2005).

The connectivity of the inshore lobster population in the Gulf of Maine is high and depends on inter-annual environmental variability, hatching location, larval development, mortality, larval dispersion rates, relative egg production among zones, and transport pathways impacting losses and gains. There is modeled evidence for variable larval connectivity to the offshore banks, including Georges Bank. The role of each area as a sink or source may have specific consequences and implications with future environmental and management changes. While larval connectivity is very important, ocean currents and temperatures alone cannot control changes in all recognized connectivity and, it is important to also consider the biological process of growth, maturity, and adult lobster movement.

3. Size Distribution of Egg-Bearing Females

A. Evidence of Decreased Size At Maturity

While specific studies to update size-at-maturity have not been conducted recently, evidence from various states' commercial trap sampling programs indicates that there has been a downward shift in size-at-maturity. This coincides with multiple reports from fishermen stating they have been seeing smaller females with eggs than in the past. The TC examined the commercial trap sampling data for Maine (NMFS Areas 511, 512, and 513), New Hampshire (NMFS Area 513), and Massachusetts (NMFS Area 514) for changes in the proportion of females in 5 mm size bins that were egg-bearing. We used only those sizes that have always been below minimum legal size, to avoid any influence in changes in gauge size on the proportion egg-bearing. Each state and statistical area was analyzed separately, to examine geographic differences.

Increases in the proportion of females bearing eggs in the 76-80 mm CL size range are evident in all statistical areas, but are most dramatic in the more southern SAs, representing the southern portion of GOM (Figure 5a-e). In MA, which had the longest data set available for this analysis, increases in proportion egg-bearing in the 76-80 mm size bin started in the early 1990s, and over the time series have gone from 0.02 (2%) to around 0.14 (14%) (Figure 5e). Increases in the proportion of females bearing eggs are also evident in the 71-75 mm size class in the more southern SAs, specifically 513 and 514 (Figure 5c,d,e).

These data indicate that lobsters in the southern GOM, in particular, are maturing at smaller sizes. This suggests that spawning stock biomass estimates from the 2015 stock assessment may be slightly underestimated, since they were based on old maturity data. Other studies have documented similar changes in size at maturity (Landers et al. 2001, DNC 2013, Pugh et al. 2013, Gaudette et al. 2014). We strongly suggest that a standardized study to update maturity indices be funded and undertaken in all portions of the stock, to confirm this fishery-dependent based analysis.

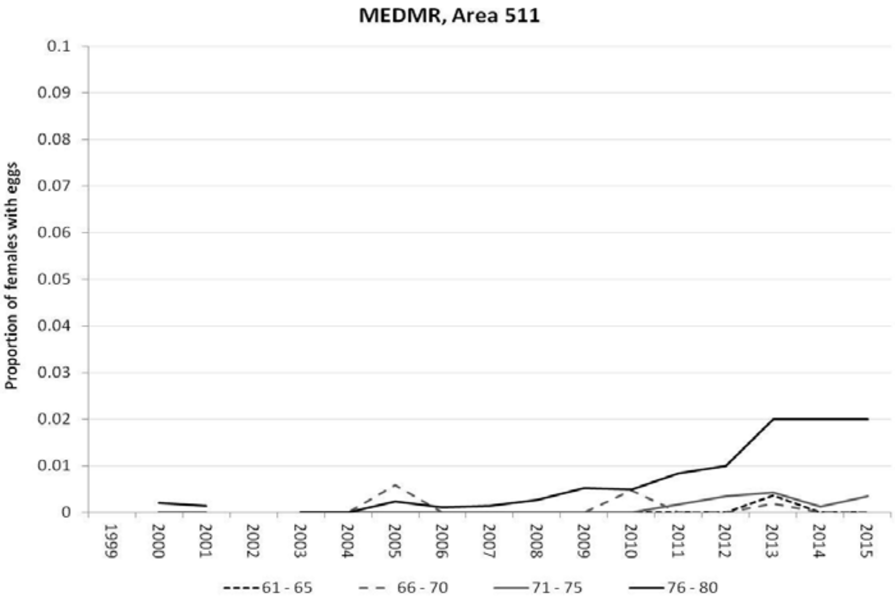

Figure 5a. Annual proportion of females that were bearing eggs in each 5 mm size bin (61 – 65 mm CL, 66 – 70 mm CL, 71 – 75 mm CL, 76 – 80 mm CL) for NOAA Statistical Area 511. Data from ME commercial trap sampling program, May – November, by NMFS Statistical Area.

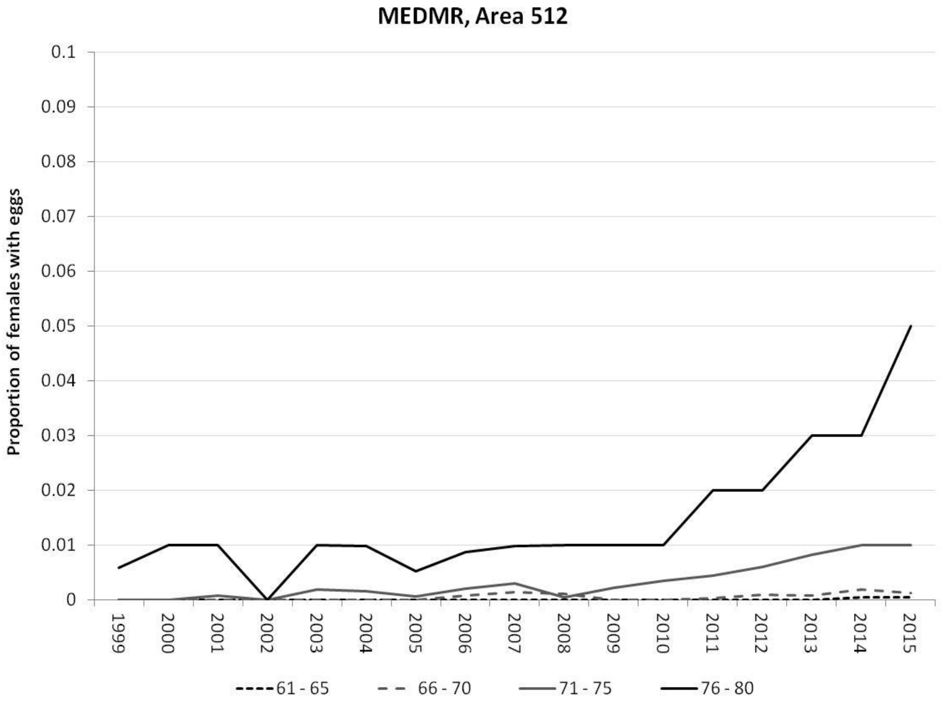

Figure 5b. Annual proportion of females that were bearing eggs in each 5 mm size bin (61 – 65 mm CL, 66 – 70 mm CL, 71 – 75 mm CL, 76 – 80 mm CL) for NOAA Statistical Area 512. Data from ME commercial trap sampling program, May – November, by NMFS Statistical Area.

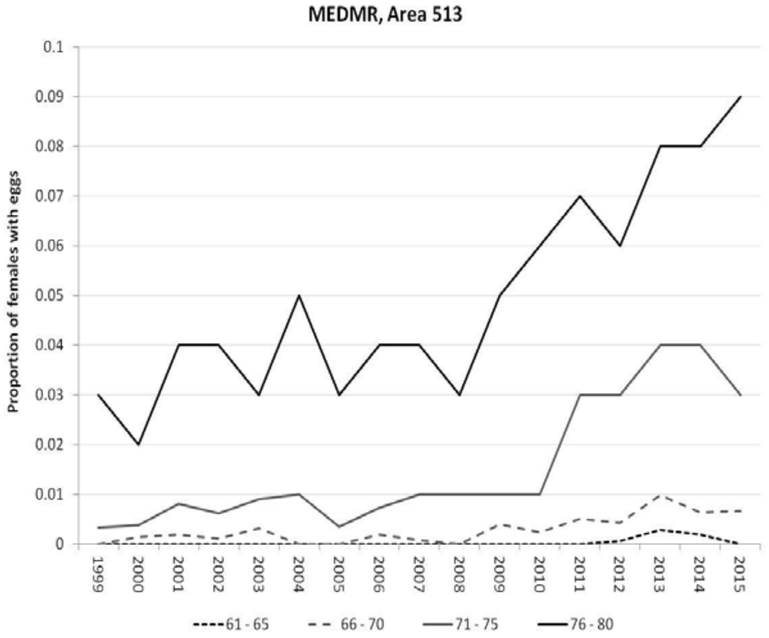

Figure 5c. Annual proportion of females that were bearing eggs in each 5 mm size bin (61 – 65 mm CL, 66 – 70 mm CL, 71 – 75 mm CL, 76 – 80 mm CL) for NOAA Statistical Area 513. Data from ME commercial trap sampling program, May – November, by NMFS Statistical Area.

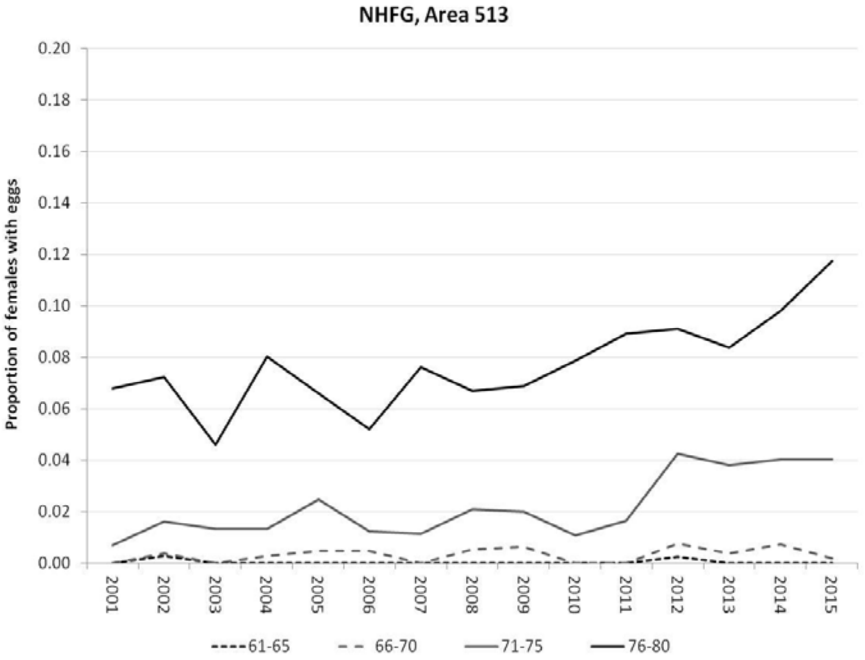

Figure 5d. Annual proportion of females that were bearing eggs in each 5 mm size bin (61 – 65 mm CL, 66 – 70 mm CL, 71 – 75 mm CL, 76 – 80 mm CL) for NOAA Statistical Area 513. Data from NH commercial trap sampling program, May – November, by NMFS Statistical Area.

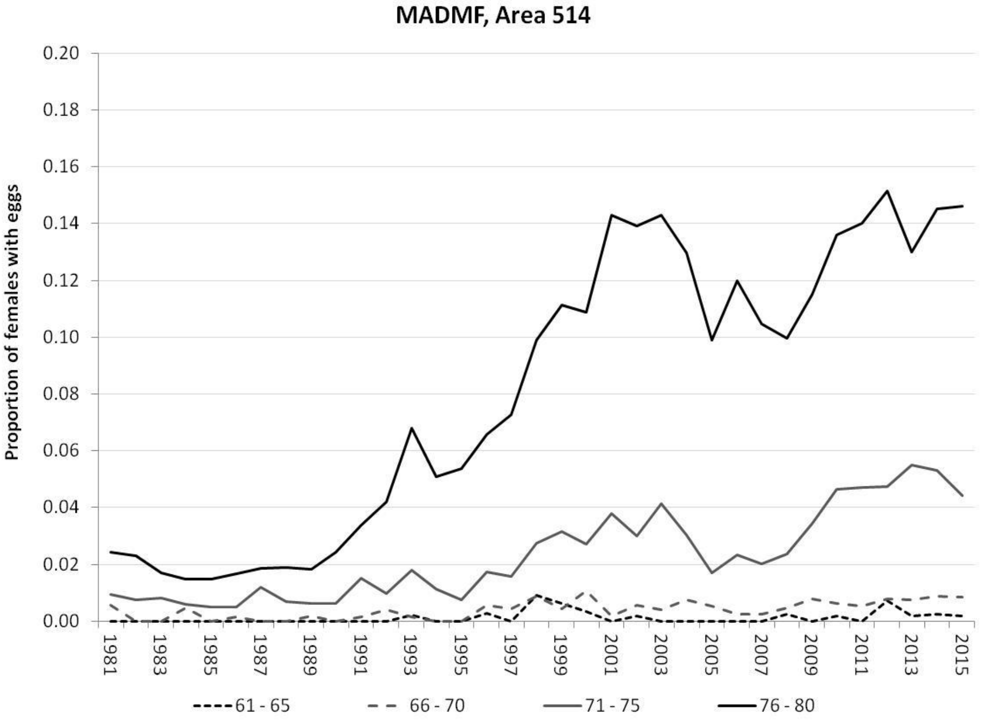

Figure 5e. Annual proportion of females that were bearing eggs in each 5 mm size bin (61 – 65 mm CL, 66 – 70 mm CL, 71 – 75 mm CL, 76 – 80 mm CL) for NOAA Statistical Area 514. Data from MA commercial trap sampling program, May – November, by NMFS Statistical Area.

B. Larval Studies Show Decreasing Trend of Stage IV Lobsters

Monitoring of indigenous populations of fish, shellfish and wildlife has been ongoing since the late 1970s at Seabrook Nuclear Power Station on the coast of New Hampshire. Normandeau Associates Inc. (NAI) has been contracted for this work by Nextera Energy and data from this environmental monitoring were generously provided to New Hampshire Fish and Game and the ASMFC Technical Committee to conduct the following analyses. As part of this environmental monitoring American lobster larvae have been sampled via neuston nets collected once a week from single tows at three locations. Collections were consistently taken from all locations starting in 1988. Additionally, both temperature and zooplankton populations have been monitored consistently along the coast of New Hampshire during the same time period.

Spawning stock biomass (SSB) in the Gulf of Maine (GOM) is at time series highs (ASMFC 2015). Additionally, Lobster Sea Sampling Programs for ME, NH and MA have recorded an increase in the proportion of female catch bearing eggs over the past 15 years in the southern SA's of 513 and 514 (Figure 6). This suggests high levels of egg production, which should presumably lead to increased larval abundance. Based upon neuston sampling from Seabrook Station Environmental Monitoring (SSEM), this high abundance of egg bearing lobsters has translated into a high abundance of stage I larvae in the water column (Figure 7). This time series shows a significant upward trend (Mann Kendall, $p<0.05$) and current levels are at or near time series highs. Additionally, the past seven years are above the time series median. In contrast, the time series for stage IV from SSEM neuston sampling shows a significant downward trend (Mann Kendall $p <0.05$) and the past four years have been below the time series median (Figure 8). The time series (1988-2015) for stage IV from SSEM shows a similar trend to the American Lobster Settlement Index (ALSI) from mid-coast Maine and the two surveys show a moderate to strong relationship (Figure 9, $r^2=0.6$, df=25, $p<0.05$, excluding 1990). The relationship between the stage IV sampled via neuston and YOY sampled via SCUBA based surveys is improved when limiting analysis to the most recent 15 years ($r^2=0.69$, df=14, $p<0.05$).

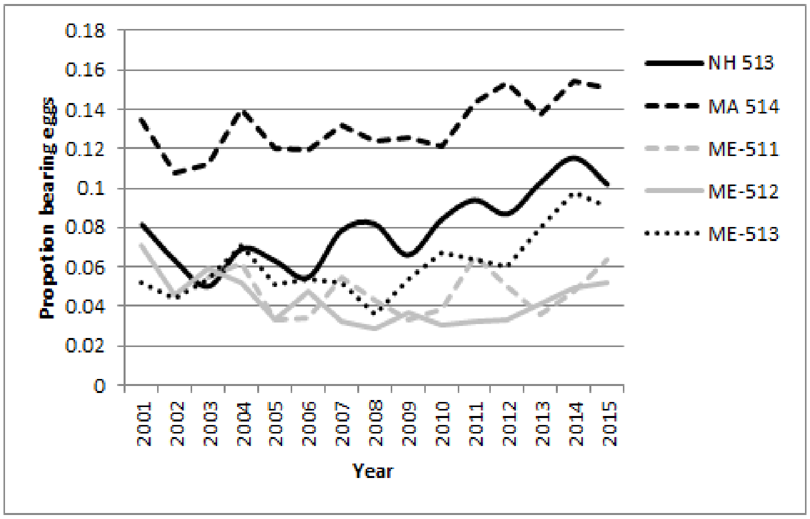

Figure 6. Proportion of female catch bearing eggs observed in Lobster Sea Sampling programs in ME, NH and MA.

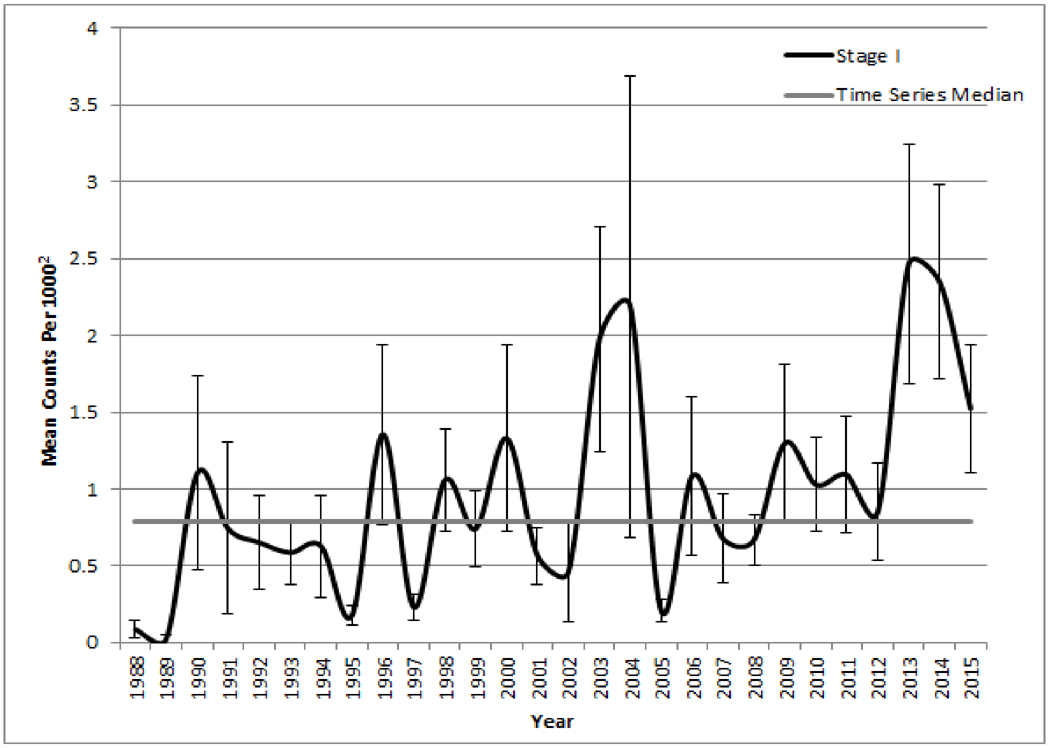

Figure 7. Mean count of stage I larvae collected from neuston tows on the coast of NH during SSEM.

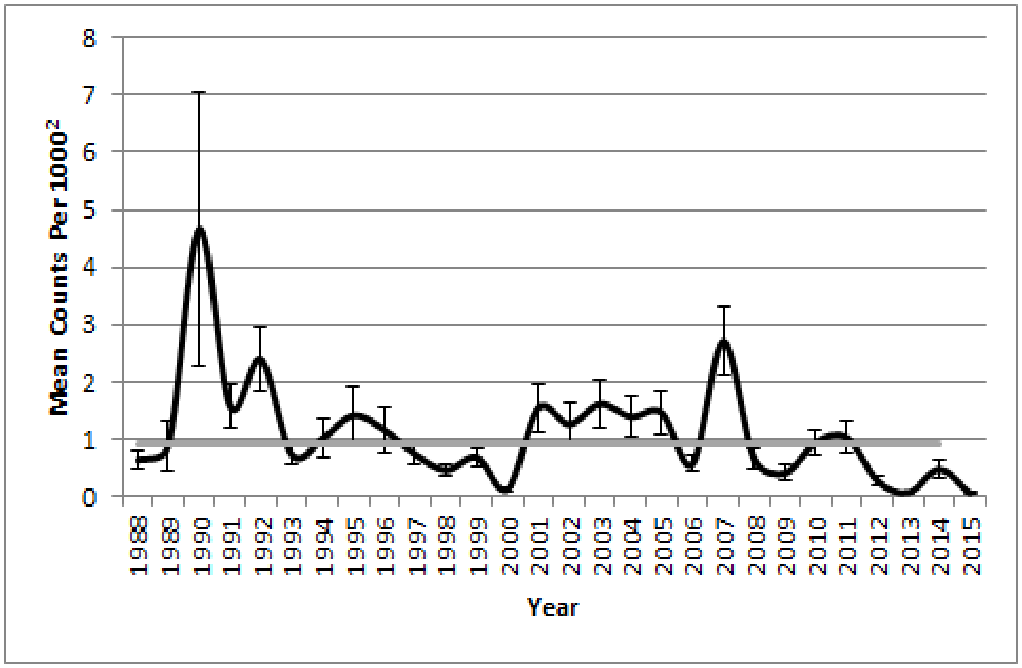

Figure 8. Mean count of stage IV larvae collected from neuston tows on the coast of NH during SSEM.

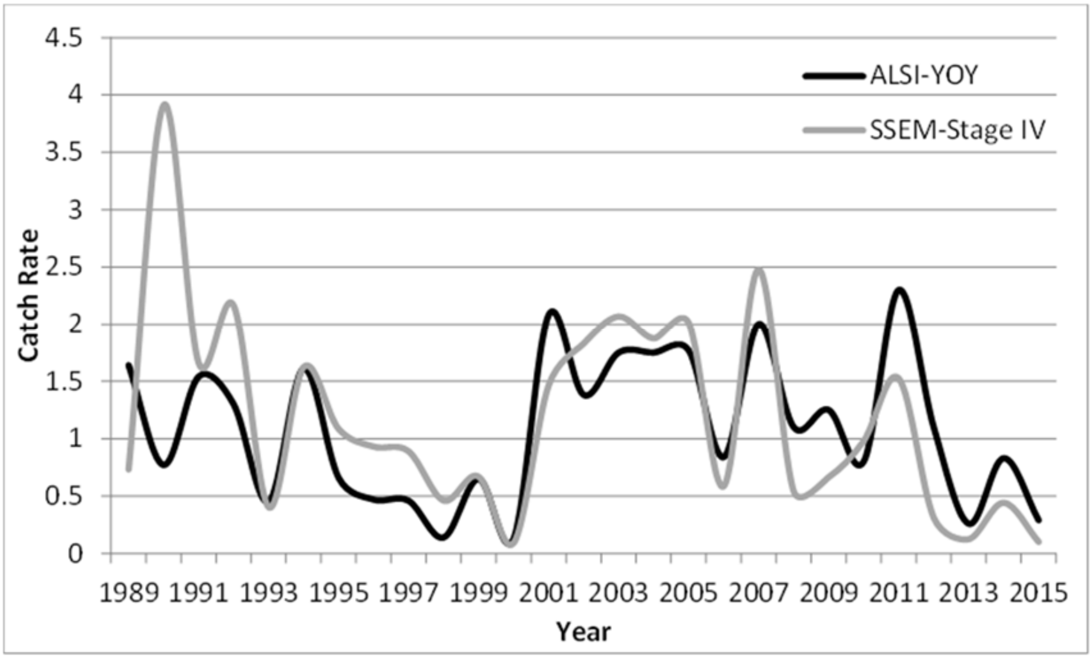

Figure 9. Time series of SSEM neuston sampling of stage IV larvae compared to YOY lobster index from ALSI (midcoast Maine).

Based on the available data, it is clear there is a record high abundance of SSB in the GOM and a higher than average abundance of stage I larvae along the coast of NH; however, this does not appear to be translating into stage IV and newly settled lobsters within the areas being sampled. There are obviously many factors at play and the possible explanations for this are certainly complex and numerous. For instance, changes in wind patterns or currents over the time series could be advecting the later stage larva to areas not being sampled by SSEM or ALSI (Hudon & Fradette, 1993). Two of the other factors that could be responsible for this disconnect are temperature and food availability which are discussed below.

SSEM takes both surface and bottom water temperatures during neuston sampling and monthly mean temperatures are presented in Figure 10. Although there does appear to be a modest increase in surface temperatures in the months of June and July throughout the time series, monthly mean temperatures do not exceed temperatures that would suggest an increase in mortality. In fact, total cumulative survival to stage V has been shown to be highest at 18 C (Mackenzie, 1988). Based on literature the temperatures recorded during sampling are in the optimal range for lobster larvae. These data suggest that temperature is not a major factor responsible for mortality within the sample area. Warmer water temperatures could lead to accelerated transition time from stage I to stage IV, or to changes in location of larvae in the water column leading to a change in catchability of the neuston net (Annis, 2005). However, the fact that the time series for stage IV from SSEM and YOY from ALSI correlate well, and the ALSI time series is at low levels as well, suggest catchability of the neuston net is not a major factor in estimating stage IV larvae in the water column.

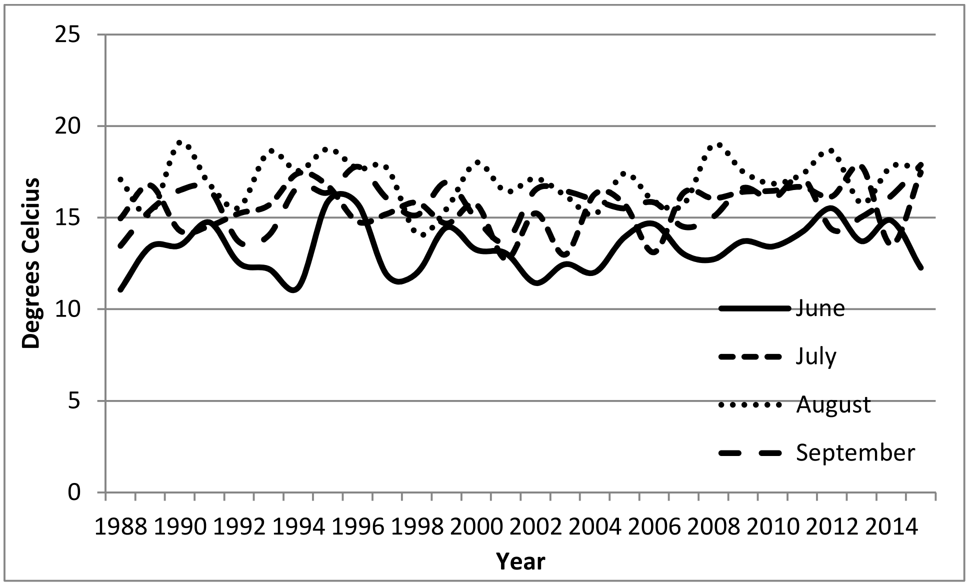

Figure 10. Mean monthly water temperature collected during neuston tows on the coast of NH during SSEM.

There is the potential that the food supply for larvae is limited throughout the inshore GOM. Lobster larvae feed on both phytoplankton and zooplankton. With record high SSB and record high stage I larvae in the water column, food availability could be a limiting factor in the development of larvae. Survival and rate of development to fourth stage are correlated positively with food quality; high survival requires that first stage larvae encounter an abundance of food (Eagles et al. 1986). Furthermore, research shows that reducing the food (copepods) provided by half reduces lobster survival to the post-larval stage from 60% to 20% and increases the time required to reach post-larval stage from 25-30 days to 50-55 days (Templeman, 1936). When decreasing the food by another half, few larvae reach stage II and none reach stage III. With this information in mind, it’s plausible that larval food supply is a limiting factor in the development of larvae from stage I to stage IV. This theory is supported by data collected from SSEM on zooplankton populations. Several species of both holoplankton and meroplankton populations are decreasing throughout the SSEM sample area (NAI 2015). Trends from SSEM have been corroborated by larger scale trends of zooplankton in the Gulf of Maine where zooplankton size structure has decreased since the mid-2000s (Morse et al. 2016; Pershing et al., 2005).

The following populations of zooplankton have been declining in recent years: *Cance*r spp., *Calanus finmarchicus*, C. *typicus*, *Crangon septemspinosa*, *Temora longicornis, Centropages hamatus* (NAI, 2015). Additionally, some offshore species of zooplankton have been showing up in samples in recent years and in 2015, Lion’s Mane Jellyfish were abundant on the coast, a time with abnormally low zooplankton in SSEM samples (NAI 2015). Lobsters are known to feed on a variety of phytoplankton and zooplankton species and once they reach stage III are known to prefer larger zooplankton species (Juinio and Cobb, 1992). Lobster larva are omnivorous, opportunistic feeders and diet will depend on geographic location and food availability. No natural diet studies are available for this local area, but in Rhode Island lobster post-larvae primarily feed on larvae of decapod crustaceans and copepods (Juinio and Cobb, 1992). Appendix I shows the time series of selected zooplankton species sampled by SSEM. One of the most common zooplankton species available locally is *Calanus finmarchicus*. There appears to be a relationship between the decline in *Calanus finmarchicus* and YOY from ALSI sampled during the time period of 2001-2015 (r^2=0.55,

$p<0.05$, excluding 2011). This is just one of many zooplankton populations that appear to be declining within the study area and this regression is meant to illustrate potential relationships.

There has also been a concern that the timing of egg hatch could be changing with warming water in the Gulf of Maine. This could potentially lead to changes in the success of settlement in any given year due to the mismatch theory, in which hatch time does not match up with food availability (Cushing, 1990). Data from SSEM show a higher proportion of larvae in the water column earlier in the season in recent years. Between 2001 and 2015, the proportion of total larvae sampled for the year that were in the water column in June has shown a significant upward trend (Figure 11, Mann Kendall, $p < 0.05$). Furthermore, though not significant, the proportion of total larvae sampled in July shows a general upward trend and both August and September show a general downward trend. This shift in phenology is corroborated by Sea Sampling programs conducted in ME and NH. In Maine, there appears to be a higher proportion of eggs hatching early in the season in the 2009-2015 time period compared to the 2001-2008 time period (Figures 12, 13 & 14). Furthermore, sea sampling from NH shows there's a significant upward trend in the proportion of females sampled with eggs in the process of hatching or with signs of eggs that have recently hatched in July (Figure 15, Mann Kendall, $p<0.05$). The availability of food matching up with the time of hatch could also be a factor responsible for the lack of stage IV and newly settled lobster in the GOM in recent years.

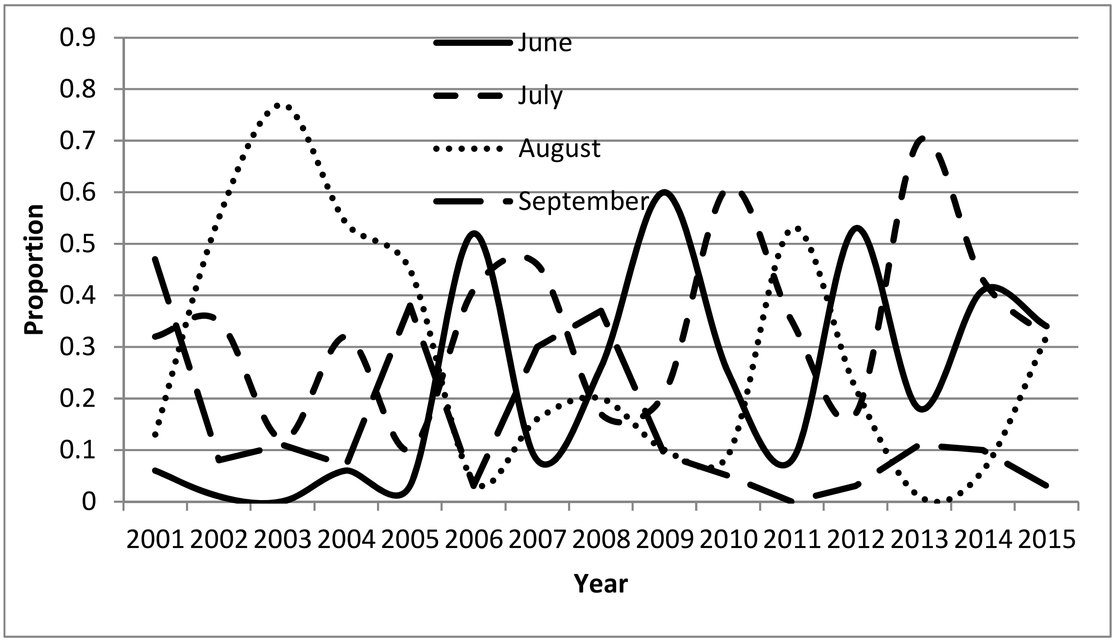

Figure 11. Monthly proportion of total annual larvae sampled during SSEM.

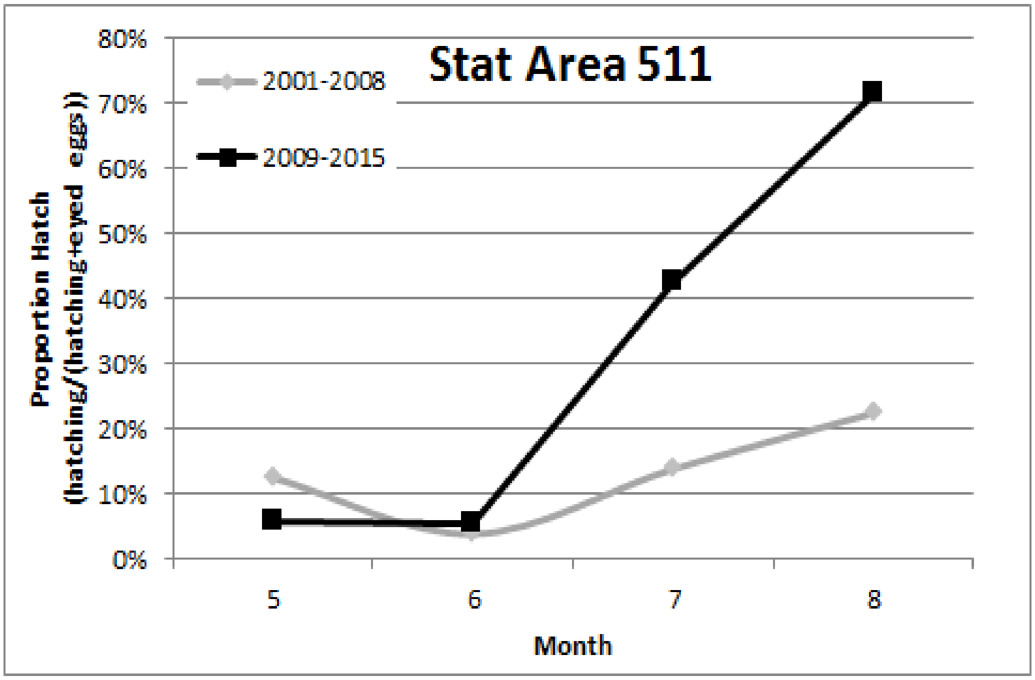

Figure 12. Proportion of eggs hatching by month for two different time periods in SA 511.

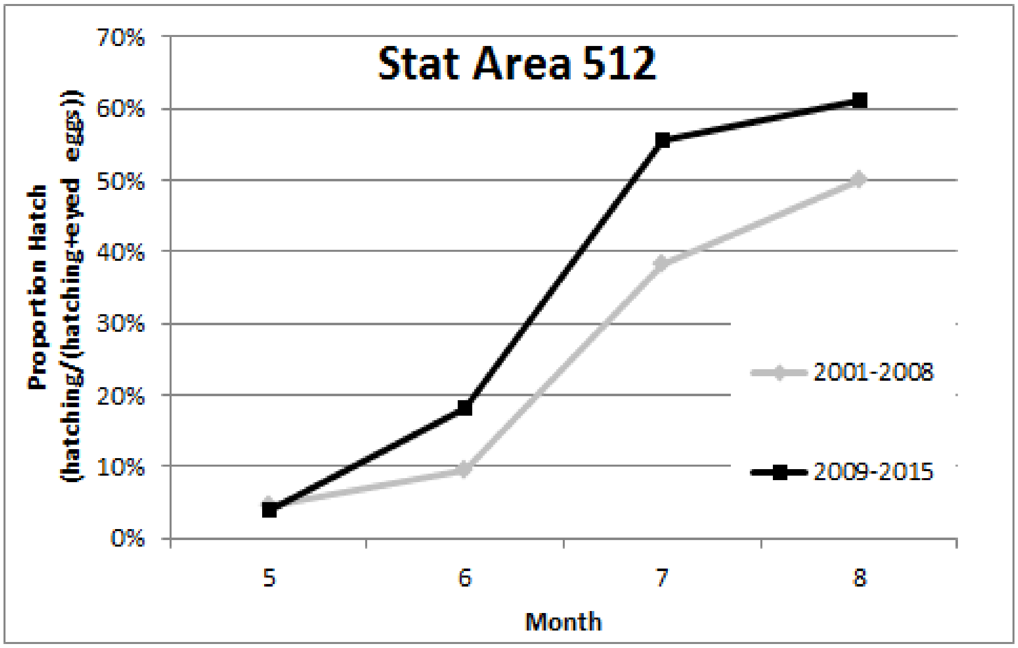

Figure 13**.** Proportion of eggs hatching by month for two time different periods in SA 512.

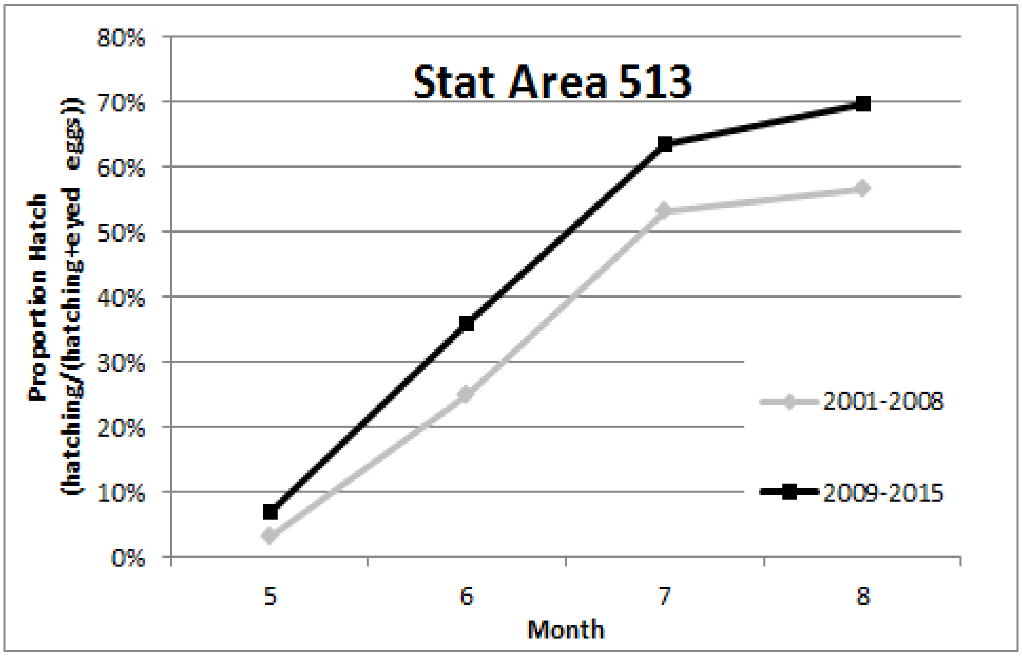

Figure 14. Proportion of eggs hatching by month for two different time periods in SA 513.

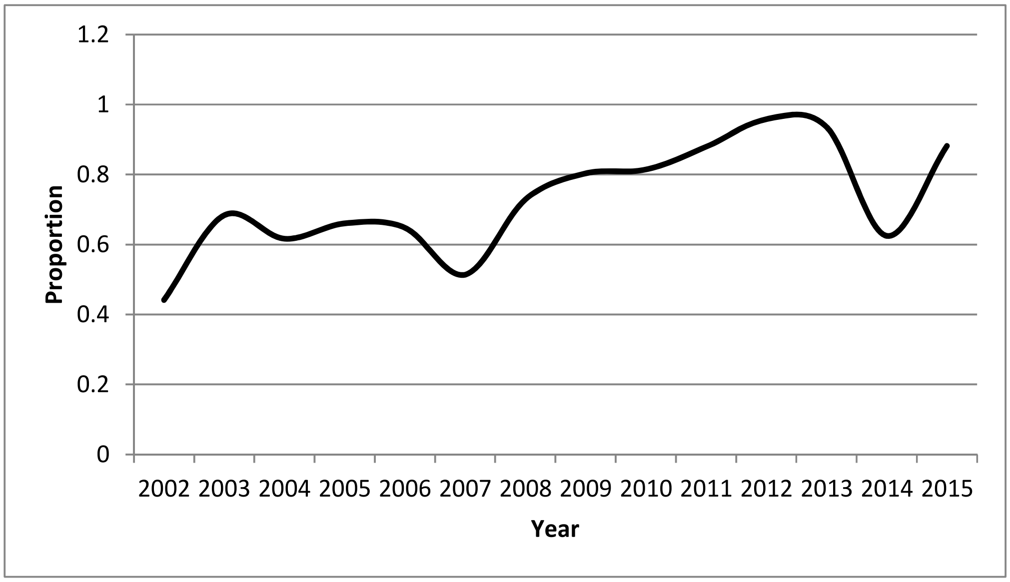

Figure 15. Proportion of total egg bearing lobsters with signs of eggs hatching or recently hatched in the month of July from NH Lobster Sea Sampling Program.

As stated above, there are several possibilities for why the ALSI has shown low numbers over the past four years. Water temperatures have increased in the Gulf of Maine and there's evidence that thermal habitat suitable for lobster settlement may be expanding (see *Section 4. Habitat Availability for Recruitment*). With a warming climate a myriad of changes may be taking place that affect the lobster population, including, but not limited to changes in wind/current patterns and predation by finfish. As with all natural systems, many factors are at play, but the above analysis does suggest that larval food supply may be one of the factors responsible for the recent declines in settlement in the Gulf of Maine.

4. Habitat Availability for Recruitment

The TC was interested in examining the relative abundance of coastal habitat to see how available benthic habitat might increase if coastal waters warmed to greater depths. If lobster recruits are constrained to shallow water due to sensitivity to cold water and there is an abundance of habitat marginally deeper than what has historically been recruitment habitat, then warming of this deeper habitat could be spreading recruitment across a greater area, resulting in declining densities in shallow habitat and a perceived drop in recruitment.

This analysis is preliminary and only examines the distribution or quantity of habitat by depth for the Gulf of Maine. It does not examine any analysis on the quality of habitat at greater depths or empirical evidence for changing bottom water temperatures or the extent of recruitment habitat.

To quantify the amount of bottom habitat with depth, we used the NGDC Coastal Relief Model bathymetry and cropped it to NMFS statistical areas 511 – 514. We then totaled the number of raster cells by bottom depth for each statistical area, converted to approximate square kilometers and calculated cumulative area with depth. Finally, we used total habitat less than 10 m depth (approximate habitat sampled by ALSI) for a baseline recruitment habitat and converted total habitat-at-depth to values relative to the 10m baseline.

Figure 16 shows the quantity of habitat (area in km^2) for each depth bin by statistical area. For interpretation, a generally flat profile would suggest consistently sloping bottoms with increased distance from shore while peaks in these profiles correspond to depths where habitats are comparatively abundant due to the presence of basins or flat-topped banks. Such “peaks” can be identified as various ocean floor features. For example the peak in habitat around 170m depth in statistical area 513 corresponds to the presence of Platt’s Basin and the northern end of Wilkinson Basin in this statistical area, while the multiple small peaks between 30 and 80m in stat area 514 correspond to Stellwagen Bank and Jeffrey’s Ledge. If waters warm sufficiently to include depths exhibiting such “peaks”, the amount of available recruitment habitat could increase rapidly.

The majority of the benthic habitat in the Gulf of Maine is at depths between 150 and 250 meters. Shallower habitat (<50m) is generally constrained to the coastline with the exception of waters adjacent to islands along the central and eastern Maine coast and a couple of the shallower offshore banks in Massachusetts (Figure 17).

In general, stat areas 512 (mid-coast Maine) and 514 (MA) have the most shallow habitat while downeast Maine (511) has the least. Large “peaks” in habitat are lacking in shallow waters with only some moderate “peaks” shallower than 60m evident in stat areas 512 and 514. As a result, the cumulative amount of habitat in any given stat area increases almost linearly with increasing depth without evidence that incremental increases in depth will create sudden increases in available habitat.

Relative increases in potentially suitable habitat quantity vary across statistical areas (Figure 18). Relative to the total habitat <10m, available habitat doubles around 18 – 20m depth for stat areas 512, 513, and 514 but wouldn’t double until around 27 m depth for stat area 511.

This preliminary analysis suggests that incremental increases in depths suitable as recruitment habitat would most probably result in similarly incremental increases in total recruitment habitat and small observed decreases in recruit densities in shallow water. If observed recruitment densities in shallow water decreased substantially, say by 50%, then the depths available to recruitment would have to approximately double to get no net change in total recruitment. Moreover, in order for the diffusion of post-larvae over a larger area to be an explanation for the observed decreases in YOY indices, the available area over which they diffused would have to be more than double the original area available. This suggests that increased availability of habitat is not sufficient to solely explain decreases seen in the YOY indices.

These results are only preliminary and, as mentioned above, do not account for the quality of habitat at depth (for example, substrate type or complexity) or include data on the structure-of or changes-in water temperature profiles. A more in-depth analysis is certainly warranted.

A more comprehensive analysis of changes in recruitment thermal habitat in coastal Gulf of Maine is currently being conducted at the University of Maine in Damian Brady’s and Rick Wahle's laboratories, supported by the NSF Coastal SEES, NOAA-FATE, and the UMaine Research Reinvestment programs. This study is combining local American Lobster Settlement Indices (ALSI) and bottom temperatures from ocean circulation model output to examine if the availability of thermal habitat has changed over recent years, explore the range of depths that may currently supply appropriate recruitment habitat, and if such changes can partially explain recent dynamics in the ALSI. An update on this research is expected within a year.

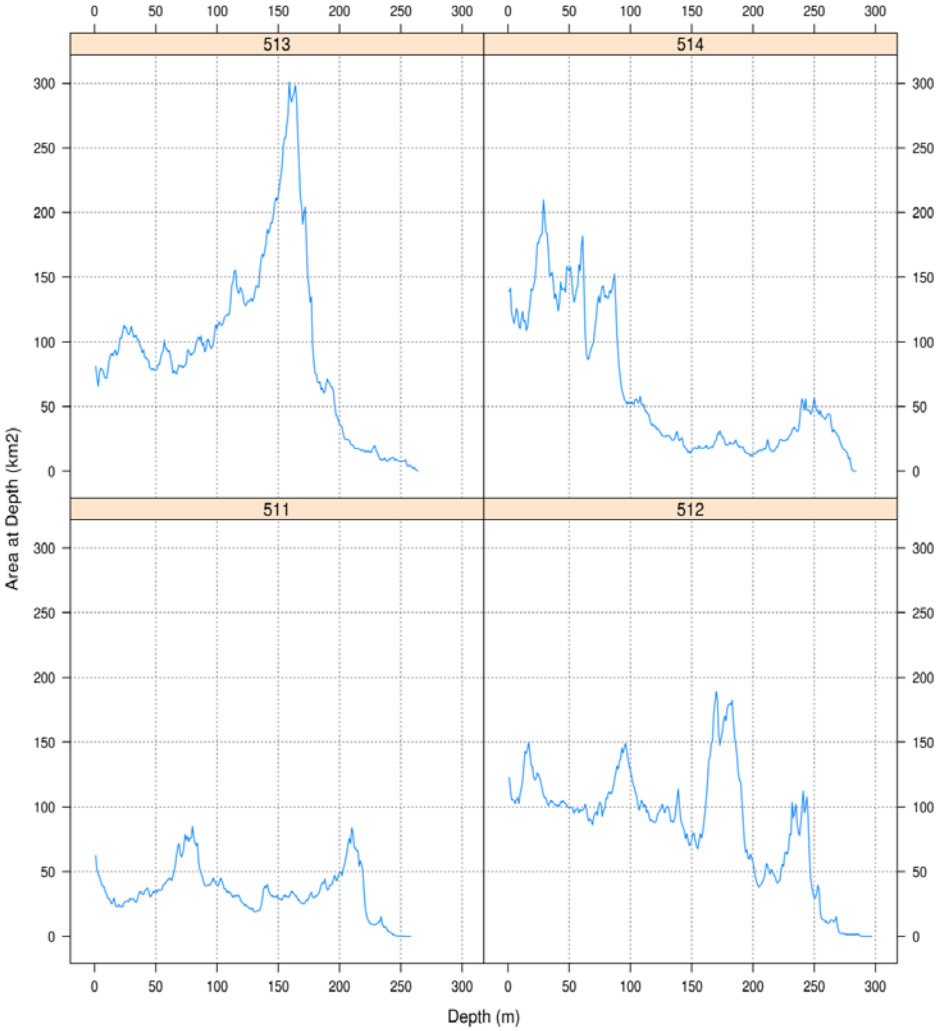

Figure 16. Area at depth (i.e. square kilometers of habitat for each 1m depth increment) by statistical area.

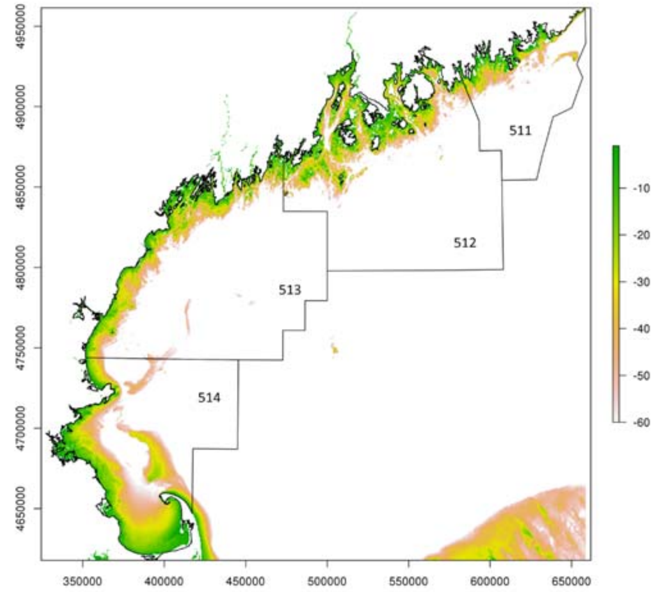

Figure 17. Coastal bathymetry (m) constrained to <60m.

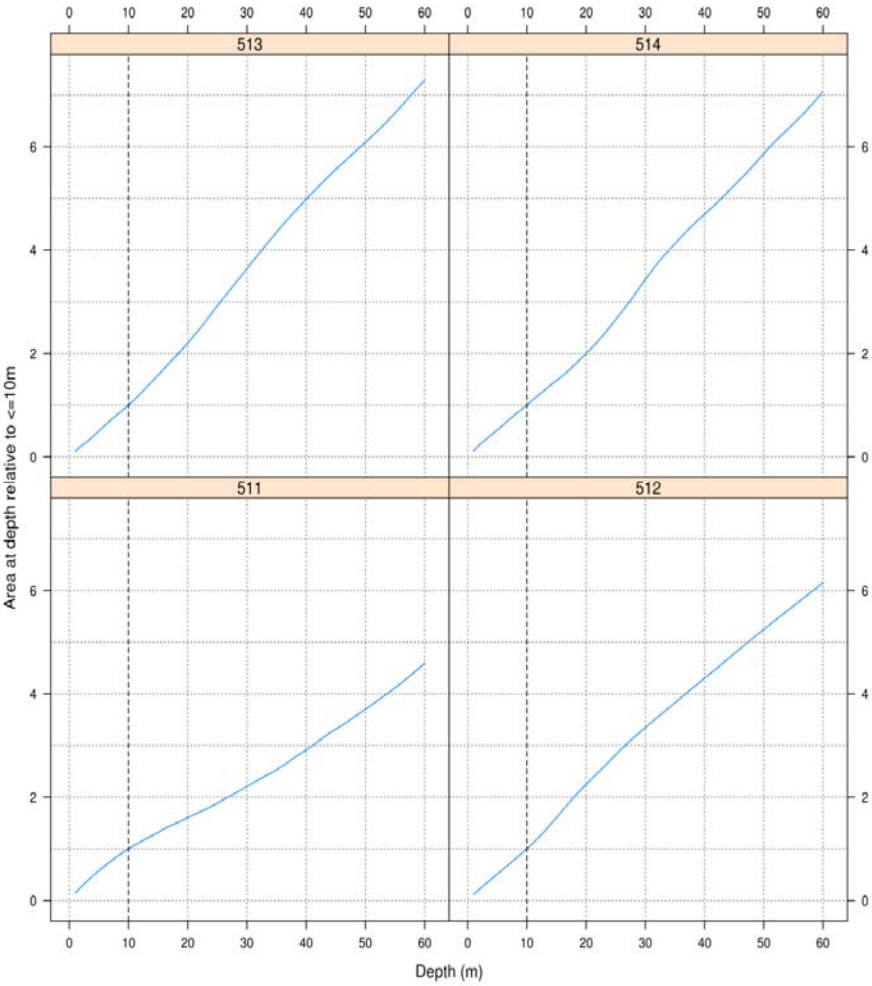

Figure 18. Cumulative area at depth, relative to total area <-10m. The vertical dashed line at 10m demarks the baseline shallow habitat that other depths are compared to. I.e. in Area 511, total habitat < ~27m is double the habitat <10m.

5. Stock-Recruit Relationship

The TC was tasked with presenting the trajectory of stock-recruit estimates for the GOM/GBK stock. A similar analysis was previously presented for the Southern New England (SNE) stock, which proved to be a useful tool for understanding underlying recruitment processes and identifying potential regime shifts in reproductive success. Such analysis for both stocks is presented below for comparison of the dynamics occurring in the different regions.

Information for this analysis comes from model outputs from the respective basecase 2015 assessment model. Recruitment numbers are model estimates for the number of lobsters that were needed to enter the model population in a given year to fit the observed data (landings, survey indices, and fishery and survey length compositions). Similarly, Spawning Stock Biomass (SSB) is derived from the numbers of female lobsters at-size in any given year as estimated by the model from the data-fitting process. It should be highlighted that these are model estimates and do not represent empirical data. As a result, changing the assumptions or tuning of the model will yield different results, though the general trajectories should be robust. It is also worth noting that there is no stock-recruit relationship included in the basecase models, so there was no constraint on the model for recruitment to be related to SSB. Thus, care should be used in interpreting these plots.

Since lobsters “recruit” to the assessment model at a minimum size of 53mm, it is necessary to lag recruitment estimates back a number of years to match them with the approximate year they were spawned. Due to different growth rates between stocks, the GOM/GBK recruits were lagged back five years (i.e. recruitment estimates for 2014 were matched to SSB estimates for 2009), while the SNE recruits were lagged four years. As a result of this biological lag, the most recent years are not included in this analysis because recruits spawned in recent years have not yet grown into the sizes tracked by the assessment model. Lag years are approximate based on growth studies but, again, general trajectories are robust to small changes in this assumption.

For both the recruit and SSB estimates, both the raw model estimates and smoothed time series are presented. The smoothed time series are included because raw model estimates can be erratic due to interannual variability, errors in model data input (i.e. sampling error, etc.), or model specification. The smoothed time series are intended to remove this variability to capture only the longer-term trends. Smoothed time series were calculated using a loess smoothing function with span of 0.4 or 40% of the time series. This span was visually selected for removing inter-annual variability that is probably “noise” while conserving the general dynamics. While both the raw model estimates and smoothed series are presented, only the smoothed series are discussed.

For GOM/GBK, recruitment increases throughout the time series (Figure 19), with the exception of 2008 and 2009 (discussed below). The relation between recruitment and SSB is nearly linear from 1981 – 2002, suggesting that recruitment per unit spawning biomass was stable over these years at a level favorable for increasing the abundance of lobsters. Between 2002 and 2007, spawning biomass remained relatively stable but recruitment continued to increase, suggesting that recruits per spawner increased over these years. This change in pattern likely indicates an external influence on recruitment success, such as an environmental driver. Recruit estimates decline marginally but remain high in 2008 and 2009. However, these two years are based on recruitment estimates from the terminal years of the model (2013 and 2014) and are, therefore, unstable and should be interpreted carefully.

The stock-recruit trajectory for SNE is complex, suggesting the potential for multiple shifts in reproductive processes. Recruits/spawner increase from 1979 to 1991 as both recruitment and SSB increase. From 1991 to 1996, recruitment declines despite increasing SSB as the recruitments from 1990 – 1992 grow and reach maturity. Between 1997 and ~2003 spawning biomass drops precipitously, though recruitment remains remarkably stable. Recruitment per spawner was considerably lower in this time period than in the 1980's. After 2003, spawning biomass remains fairly stable but recruitment begins an incremental decline, suggesting that recruitment per spawner and stock productivity are declining rapidly over these years.

Thus, there are contrasting dynamics between the two stocks. Since 2002, both GOM and SNE spawning stock biomass has remained fairly stable, with GOM at time-series highs and SNE near time-series lows; however, recruitment rates from these spawning stock have trended in opposite directions. This suggests that factors other than spawning stock biomass itself are strongly influencing recruitment processes. Possible accessory factors would include, but are not limited to, shifts in where lobsters are hatching-out, changing water circulation patterns that affect larval retention, and changing environmental conditions that affect larval and juvenile survival rates. Regardless, this decoupling of recruitment from SSB presents difficulties to management.

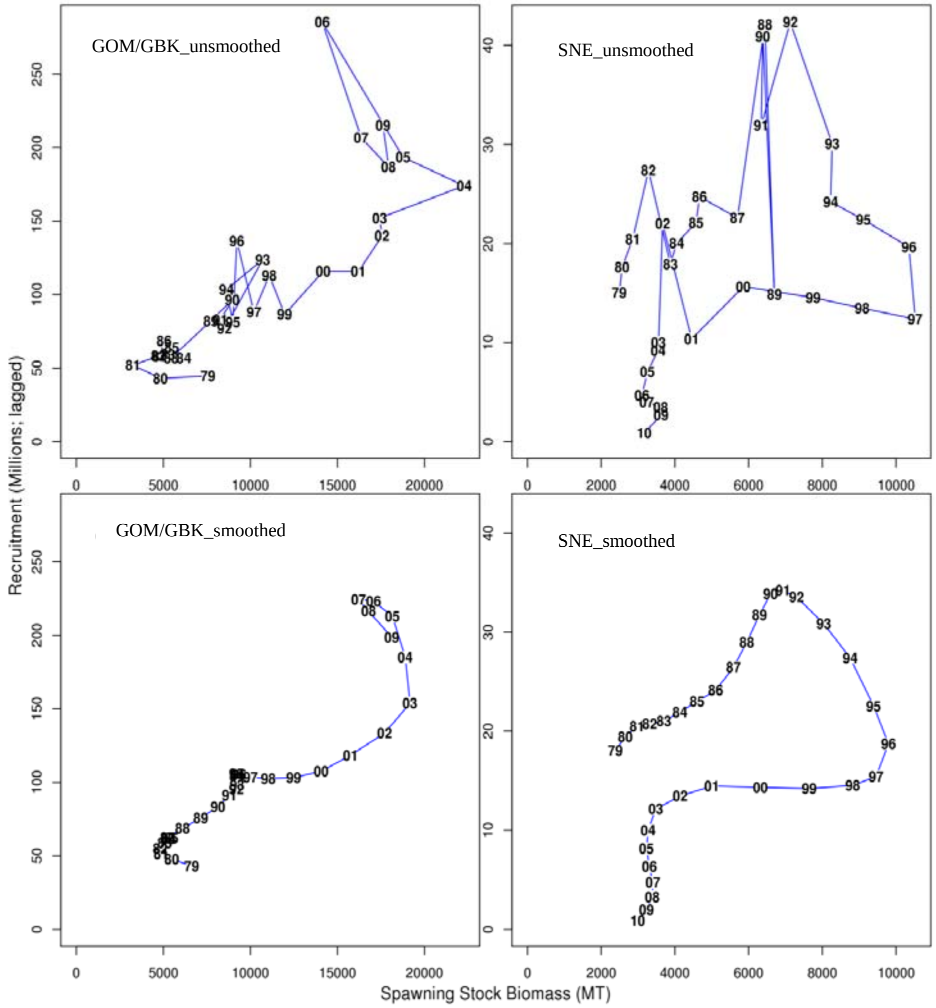

Figure 19. Model-estimated SSB and Recruitment trajectories for the GOM/GBK (left) and SNE (right), from the 2015 stock assessment. Both Raw (top) and smoothed (bottom) time series are shown. Recruitment estimates are lagged back to match the approximate year they were spawned. Numbers in the plots represent the last two digits of spawning year.

6. Biological Management Measures

Though the Gulf of Maine lobster fishery is currently at record abundances, some data suggest that young-of-year (YOY) recruitment has decreased in recent years, in which case landings may decrease in coming years. Out of a concern for this possibility, the Board asked the TC to provide advice on management measures that could be implemented to make the lobster population more robust to decreasing recruitment. Existing regulations protect egg-bearing and v-notched females, which helps protect the spawning stock. Thus, another reasonable management measure to consider is if lobsters are being fished optimally based on legal size regulations. In particular, if lobsters are being harvested at too small of a size, it may be possible to realize similar harvest in total pounds, by deferring harvest to a larger size.

An increase in the minimum legal size may have biological benefits that will increase the resiliency of the population to environmental changes and fishing pressure. This action would ensure that a higher proportion of lobsters are sexually mature before they are vulnerable to harvest. This may also increase the proportion of females who produce more than one clutch prior to harvest, which might be beneficial to larval fitness as some (albeit limited) information suggests that larger females produce larger larvae (Ouellet and Plante 2004) and may better manage the thermal environment to which their eggs are exposed (Cowan et al 2007).

Models that examine how a change in legal size affects population size, length composition, spawning biomass, and commercial harvest are necessarily dependent on, and sensitive to, life history parameters including natural mortality, probability of molting, and probable molt increment. Thus, it is important to understand how life history parameters are used in these calculations and how errors in these parameters affect the conclusions.

For a simplified example, one can examine the difference between harvesting an 82mm male lobster in a given year versus leaving that lobster in the population for an additional year. For lobster modeling in the Gulf of Maine, we generally assume a natural mortality (M) of 0.15. So the probability of losing a lobster to natural mortality in a given year is $1 - e^{(-0.15)} = 0.139$ or 13.9%. If a lobster survives to the next year, the lobster may or may not molt. Based on existing tagging studies and similar data sets, the probability of molting is 86.5% with 13.5% not molting. The probability of survival is combined with the probability of molting or not molting to estimate that 11.6% survive and don't molt and 74.5% survive and do molt. If that lobster does molt, it will on average grow ~11mm to 93mm CL, again based on data from tagging and growth studies. From available length-weight data, an 82mm CL male lobster weighs 0.97 pounds while a 93mm CL male weighs 1.44 pounds. We then combine these calculations to determine what the projected harvest would be if the lobster was caught in the next year (Table 1).

Based on the above assumptions, leaving the lobster in the population for an additional year and accounting for molt and mortality would yield ~1.19 lbs while harvesting the lobster immediately would yield ~0.97 lbs. Changing any of the above assumptions necessarily changes the outcome; increasing natural mortality, or decreasing the molt probability or molt increment would all decrease the projected next-year yield.

Table 1. Simplified example calculations for leaving an 82mm CL male lobster in the population for an extra year.

Scenario	Probability of Scenario	CL next year (mm)	Weight at size (lbs.)	Harvest (Probability * Weight)
Lost to Natural Mortality	13.9%	NA	NA	0
Survived, didn't molt	11.6%	82	0.97	0.11
Survived and molted	74.5%	93	1.44	1.07
			Projected Harvest (lbs.)	1.19

We used a population simulation model to examine the effects of different minimum legal sizes on projected lobster populations and fishery catch. The structure of the model is based on the assessment model and uses the same natural mortality, growth model (molt probability and increment), and estimated fishing mortality as the accepted GOM/GBK assessment model run from the 2015 benchmark. The calculations in the model are similar to the above example but marginally more complex as the model applies natural mortality, growth, and fishing mortality at quarterly intervals. Unlike the above example, lobsters are only available to the fishery when they reach the minimum legal size, rather than delaying fishing mortality for a set period of time. Finally, the fishing mortality rate, estimated from the assessment model, results in a portion of legal lobsters surviving for additional years. The same simulation model has been used over the past year for examining management options for the SNE stock.

Population Model Configuration

Most model inputs were based on inputs or outputs from the GOM/GBK assessment model, including:

- Size at maturity
- Recruitment length composition
- Recruitment seasonality
- Quarterly growth transition matrices
- Weight-at-length relationships by size
- Natural mortality assumed to be 0.15

Quarterly fishing mortality rates (F) were calculated from the average estimated F from the assessment model for 2011 – 2013 where estimates of F were stable.

Separate model runs were conducted for legal minimum carapace length (MCL) ranging from 72 to 95mm in 1mm increments. This range was chosen to provide contrast between model runs but to not greatly exceed the domain under which we understand lobster biology. Some proportion of the population above legal size is also not available to the fishery due to differences in minimum and maximum legal sizes between inshore and offshore LMA's, as well as the proportion of females at size that are egg-bearing or v-notched. For these simulations, proportion of legal lobsters at-size above minimum legal size were the same as the inputs for the assessment model and were calculated based on biosample data and the spatial distribution of landings.

Because we explored some minimum legal sizes that are smaller than the currently assumed trap selectivity, we removed gear selectivity for all model runs, which makes all lobsters equally available to the fishery. This only has notable effects for model runs where MCL was smaller than the current minimum.

All model runs started with no population and had constant recruitment of one million individuals per year. This model initiation and recruitment was selected so that any differences between different legal size scenarios could be attributed only to the difference in MCL. Otherwise, starting with an assumed existing population abundance and size composition can create transient behavior in model projections, complicating interpretation of results. Model results like catch and population abundance are directly proportional to the assumed recruitment rate. As a result of using a convenient but arbitrary recruitment rate for the simulations, results are only valid for comparison among different projection scenarios.

Models were allowed to run for 25 years and the output examined to ensure that the populations had reached equilibrium abundance and size composition. Simulation model and analysis code are archived on NEFSC servers at:
/net/work4/LobsterGroup/Management/GOM_PostAssessment2015/LegalSizeAnalysis/script
LegalSize_FixedR_FixedM_FnoF.R

Results

Note that data series in Figures 20, 21, 26, 27, and 28 exhibit a regular “wavy” pattern at 5mm intervals within the general trend. This is an artifact from changing MCL at finer scales than the projection model can fully resolve, as the model bins all lobsters at 5mm intervals. Thus, such fine-scale irregularities should not be interpreted.

Across the range of MCL examined (72 – 95mm), increasing the minimum size is predicted to increase total catch of the fishery by weight but decrease catch by number (Figure 20). Reducing the MCL to 72mm would decrease catch weight by ~25% but increase catch number by ~15%. In contrast, increasing legal size to 90mm is projected to increase catch weight by ~20% but decrease catch number by ~10%. Catch weight and number by sex are similar for males and females at smaller MCL but diverge at larger MCL with males exhibiting larger catch numbers and weights than females, presumably because female growth slows once they become reproductively mature and are more likely to be egg-bearing (Figure 21).

The length composition of the catch shifts with increasing MCL with larger size classes representing a larger portion of the catch at higher MCL (Figures 22 and 23). For at the current MCL of 82mm, the model estimated median catch size is 87mm (50% of catch between 83 and 91mm) and median weight is 538g (1.18 lbs). For a MCL of 90mm, median catch size is projected to be 95mm (50% of catch between 92 and 100mm) and median weight would be 703g (1.54 lbs).

As MCL increases, the number of lobsters at-size in the population also increases (Figure 24). If we apply the expected proportion of lobsters that are mature at-size to this population, we get an estimate of the mature population at-size (Figure 25). Because the current MCL is near the size that lobsters are expected to mature, increasing the minimum legal size results in dramatic increases in the number of mature lobsters (Figure 25) and SSB (Figure 26). Additionally, the biomass of the population as a whole (>53 mm) will also increase as a result of changing MCL (Figure 27).

Population exploitation is calculated as the proportion of lobsters above a fixed size (78mm in this case) that are removed from the population by fishing within a year. Because changing the MCL directly changes the portion of the population that is available to the fishery, increasing MCL is expected to decrease exploitations rates (Figure 28). Projections suggest that an MCL between 85 and 86mm would achieve a 20% decrease in exploitation while an MCL of 90mm would result in a 40% reduction in exploitation.

Discussion

These simulation calculations suggest that increasing the minimum carapace length has the potential to produce similar total landings by weight, with a smaller number of lobsters but at larger sizes. However, because lobsters would survive longer before capture, such changes in MCL could results in a significant increase in the numbers of mature lobsters and SSB, potentially adding resilience to the lobster population. It is important to note that there is no stock-recruit relationship included in the current model configuration, so any benefits in recruitment and population abundance resulting from increasing SSB is not accounted for in this analysis.

These results are preliminary and would only be the first step in the research that would be necessary before any recommended changes to management would be appropriate. As mentioned in the methods, all results presented here are based on assumed growth rates, molt increments and natural mortality rates. Though the growth model was updated to include all available growth data for the 2015 assessment, much of the data are dated and may not be accurate for current lobster populations in the GOM. Also, relatively little growth data exist for larger sized lobsters, so projection results that are strongly influenced by the abundance of large lobsters are more uncertain.

The assumed rate of natural mortality (M) also needs further examination and validation. The current natural mortality rate is one of the major sources of uncertainty for similar analysis recently conducted for SNE. Targeted research and diagnostic analysis of the stock assessment model for SNE indicate an increase in M in recent decades but it is hard to determine what values are currently appropriate or how this value may change in the near future. This is less of a problem for the GOM as there is no strong evidence that M has changed markedly or is expected to change in the near future. However, the assumed value of M for the GOM, along with the assumption that M is the same for lobster of all size in the model, should be carefully examined.

The assumed rate of maturation is very influential on calculations for numbers of mature lobsters (Figure 25) and particularly changes in SSB (Figure 26). The TC generally agrees that the maturation rate used in the stock assessment needs updating and suspects that lobster are actually maturing at a smaller size than the maturity schedule used in these calculations. Shifting the maturity schedule to smaller sizes would increase the number of mature lobsters at smaller sizes for all MCL scenarios in Figure 25 and decrease the relative changes in SSB with increasing MCL in Figure 26.

Given the above concerns, this or similar analyses would benefit greatly from a closer examination and potentially updating the major parameters that determine the results. In the absence of additional data, meetings could be held with experts from industry, management, and research to agree on appropriate ranges for input parameters and sensitivity analysis could be conducted across these ranges.

Additionally, it would be good to externally validate the results against another population model. We initially tested this population model against the projection model written into the stock assessment model and confirmed that both models produced the same results. However, it would still be potentially useful to validate model calculations from this model against a different model framework, like an Individual Based Model (IBM). Such an IBM has been developed in Yong Chen's laboratory at the University of Maine and is currently being used to examine different management actions. A formal comparison of results from the two models would be appropriate.

In addition to the concerns listed above, there are additional ecological assumptions that are not captured in the model and need to be examined. Primarily, the model assumes no resource limitations that would constrain the size of the lobster population. With the lobster population currently at record high numbers, it is unclear if the GOM ecosystem could actually support the 50% increase in lobster biomass projected for a 90mm MCL (Figure 27) or if habitat, food, or other resources would become limiting. It is also difficult to understand how these large-scale projections would scale down to local dynamics. If this increase in biomass could not be supported, it would be important to understand the factors that limit the carrying capacity of the lobster population to accurately project the effects of different management actions or appropriate scales for management.

Beyond the validity of the model projection and biological constraints, it is critical to consider the impacts that changing the MCL would have on the economics of the lobster fishery and fleet dynamics for a fishery as valuable and important as the GOM. While the above analysis suggests that landings of a similar biomass may be possible with a larger MCL, it does not address how changing MCL would actually impact the total revenue of the fishery. With a large enough increase in minimum size, entire market categories would disappear with landings being be pushed into larger market categories. Extensive economic analyses should be conducted before any major management action is implemented. Similarly, increasing MCL may serve to further push the fishery to deeper waters at greater distances from shore, complicating fishing operations for operators of smaller vessels.

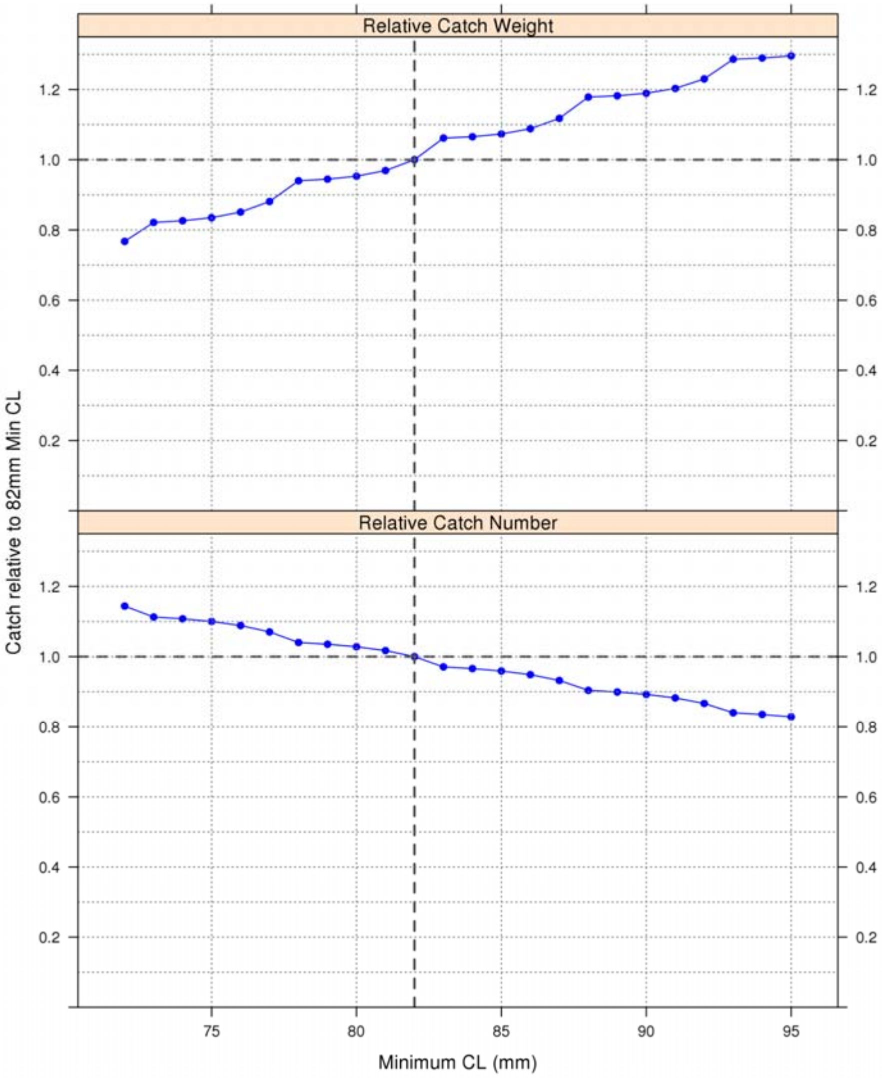

Figure 20. Projected changes in annual catch weight and catch number for different minimum sizes. Values are relative to an 82mm minimum size, so a value of 0.8 represents a 20% reduction, etc.

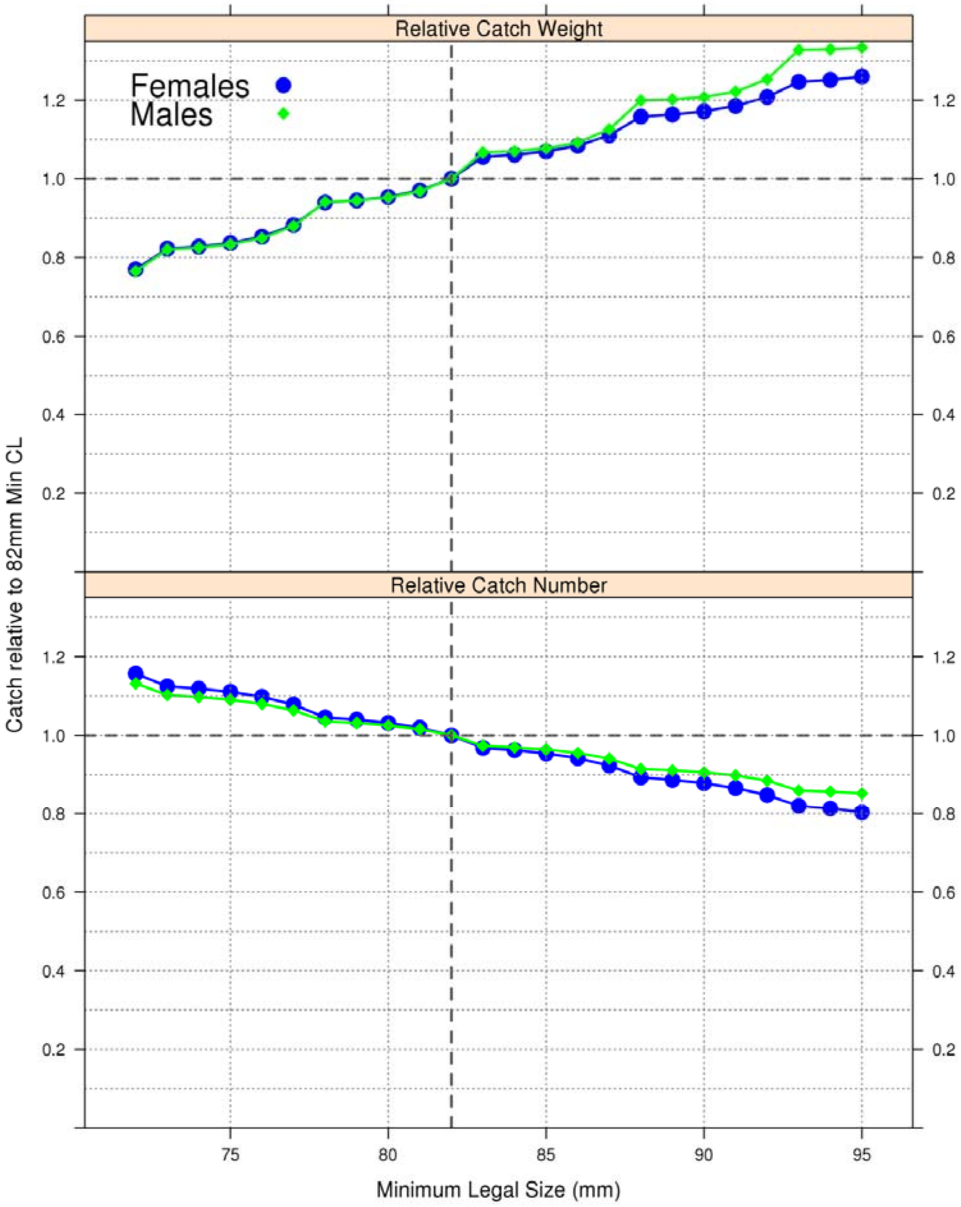

Figure 21. Projected changes in annual catch weight and catch number by sex for different minimum sizes. Values are relative to an 82mm minimum size, so a value of 0.8 represents a 20% reduction, etc.

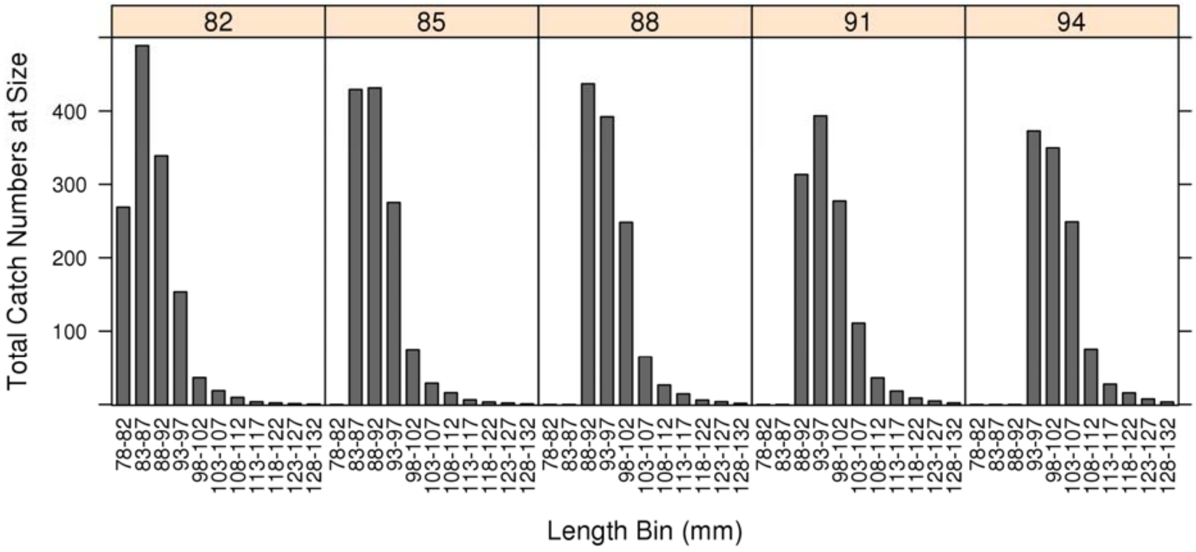

Figure 22. Projected size composition of catch under five different minimum legal size scenarios.

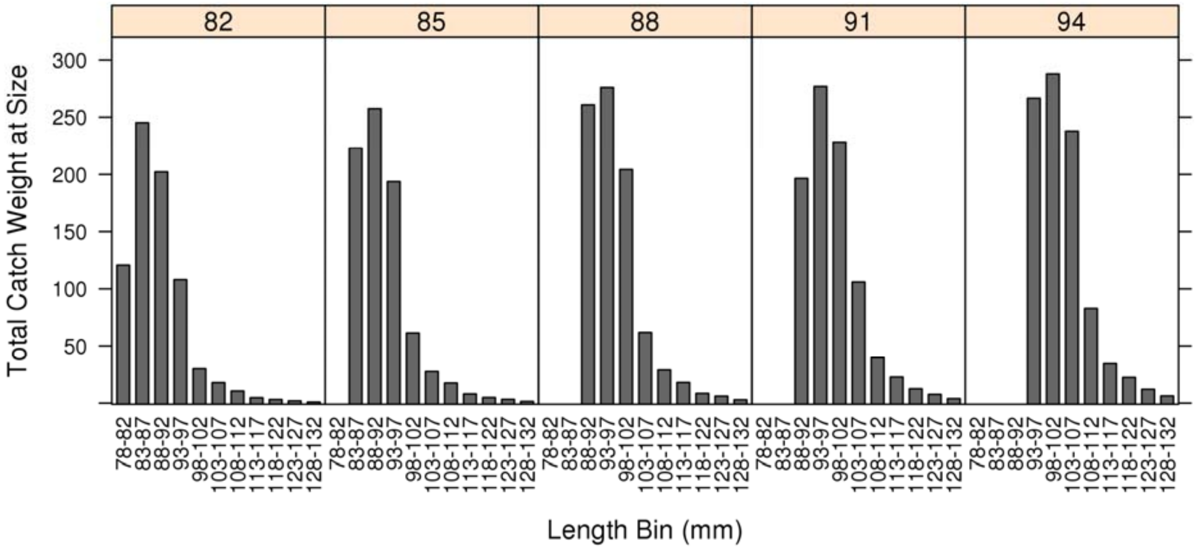

Figure 23. Projected weight composition of catch under five different minimum legal size scenarios.

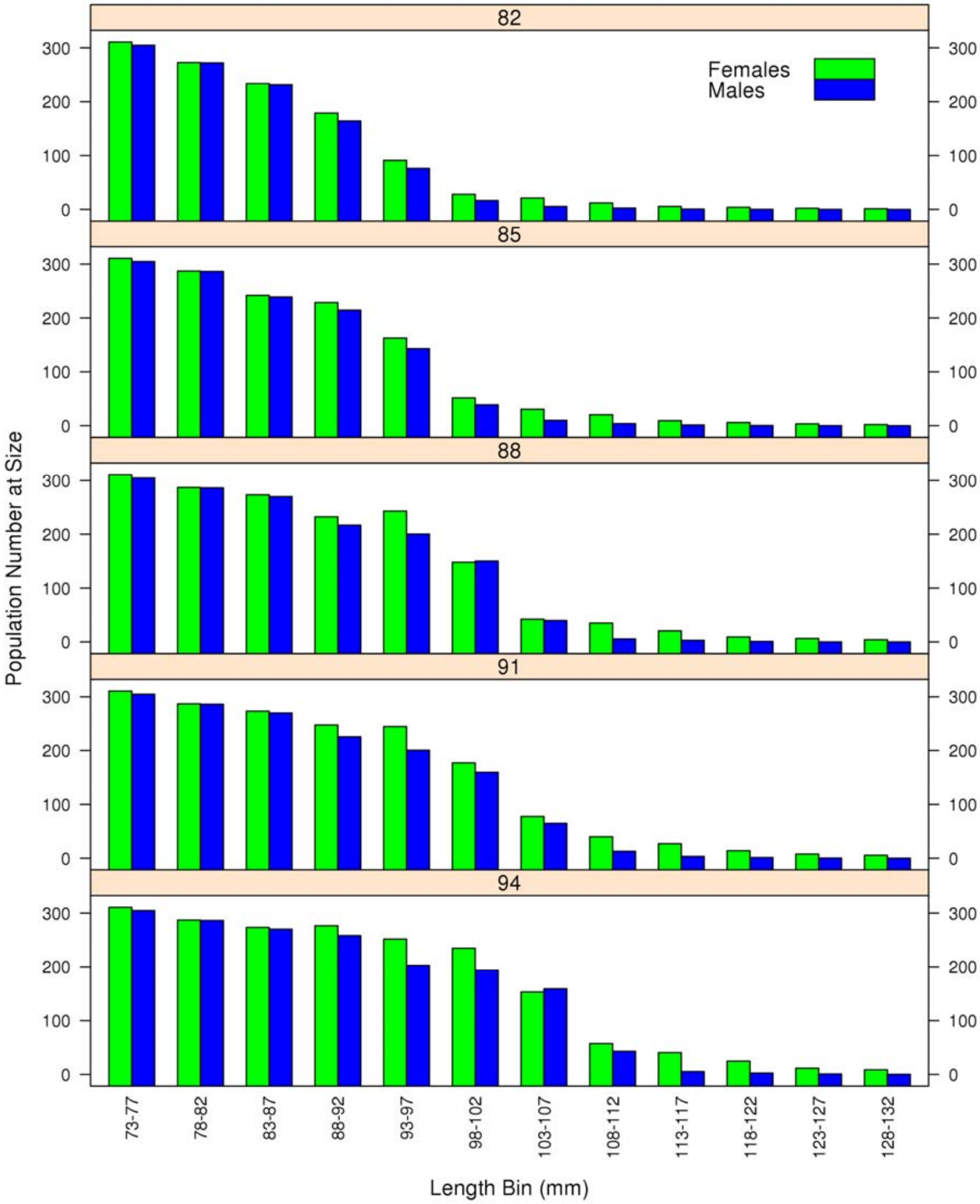

Figure 24. Projected population size composition by sex for five minimum legal size scenarios at equilibrium at the end of the Spring quarter.

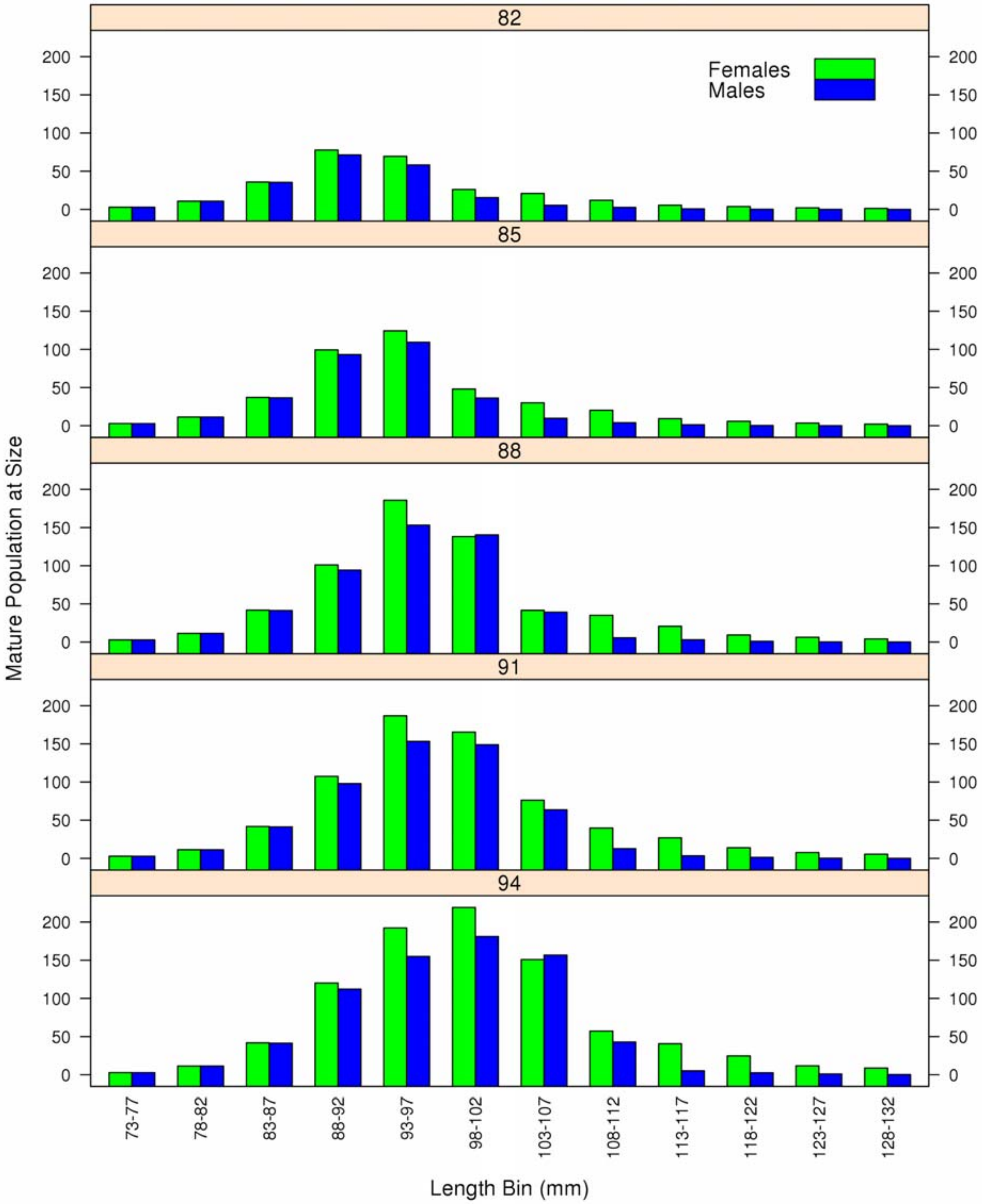

Figure 25. Projected population size and abundance of mature lobsters, by sex at equilibrium at the end of the Spring quarter for different minimum legal size scenarios.

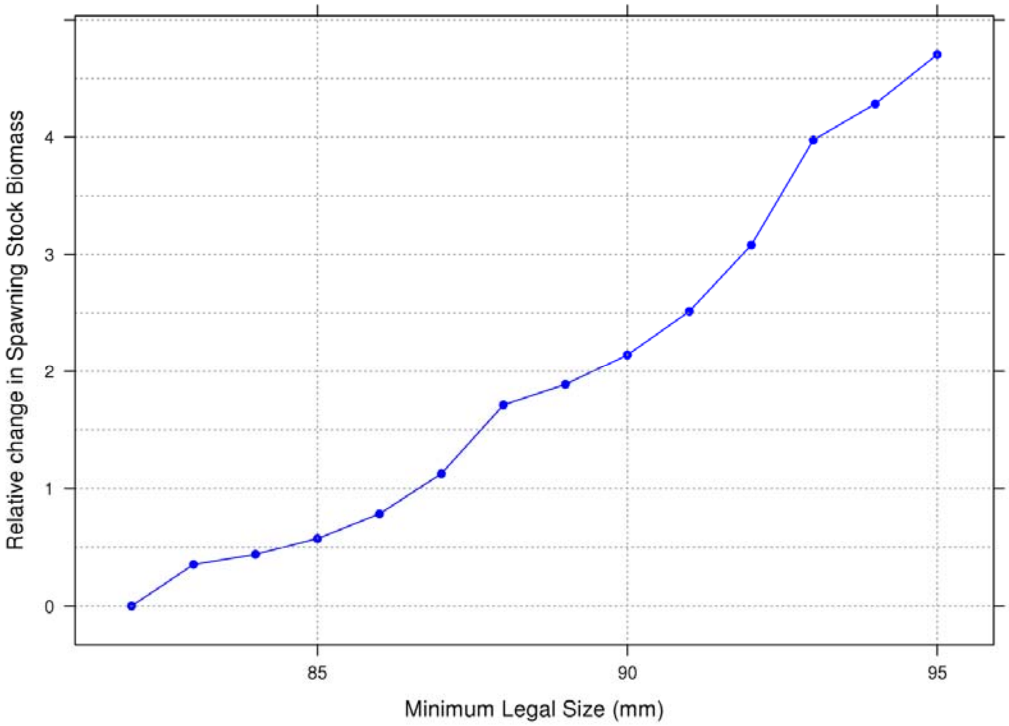

Figure 26. Projected changes in Spawning Stock Biomass at equilibrium at the end of the Spring quarter under different legal size scenarios. Values are relative to an 82mm minimum size, so a value of 1 represents a 100% increase.

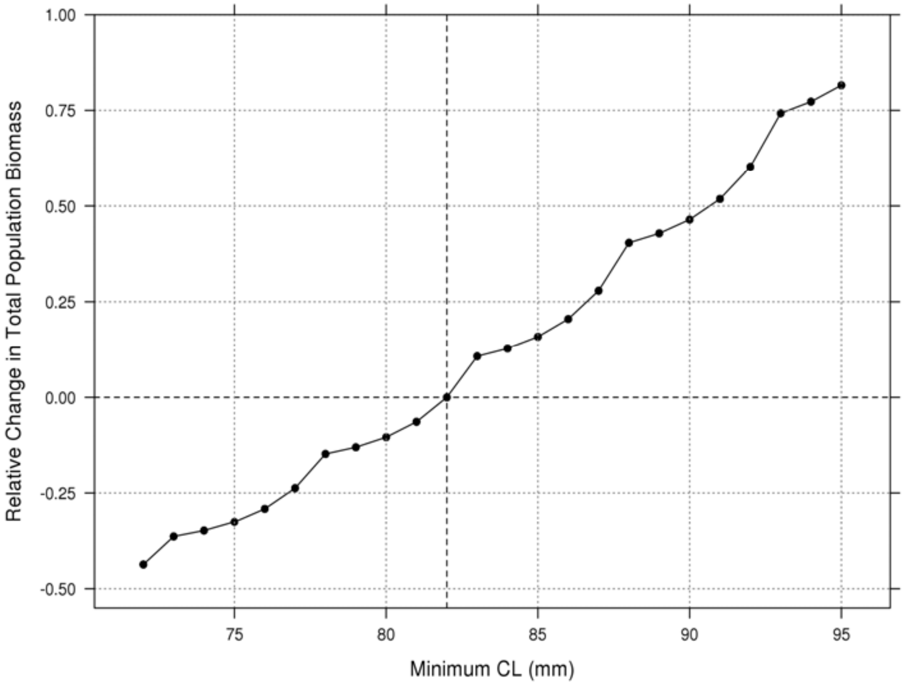

Figure 27. Relative total population biomass at equilibrium at the end of the Spring quarter for all lobsters >=53mm CL. Values are relative to the current minimum legal size of 82mm so a value of 0.5 represents a 50% increase in lobster population biomass.

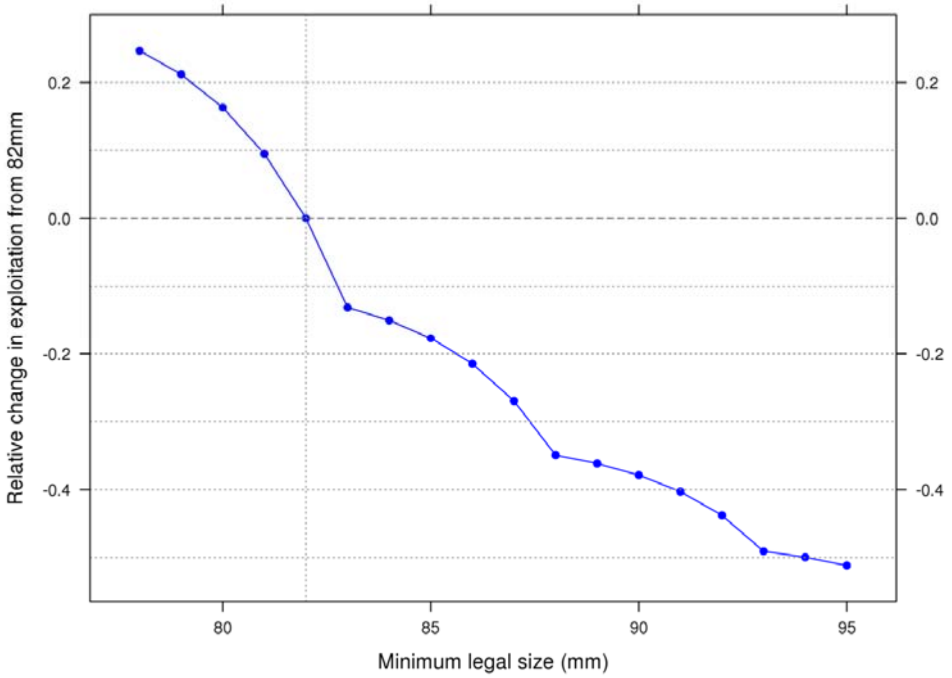

Figure 28. Projected changes in annual population exploitation under different minimum legal sizes. Values are relative to an 82mm minimum size so -0.2 represents a 20% reduction in exploitation.

7. Traffic Light Analysis

Given the desire to maintain high catch rates in the GOM/GBK, the Board asked the TC to develop a control rule, such as a Traffic Light Analysis (TLA), to trigger management action before the stock is overfished or overfishing is occurring. TLAs are currently used in the management of other Commission species, such as Atlantic croaker and spot. In both cases the TLA monitors the stock in between stock assessments and provides a simple metric to understand the condition of the population.

The TC discussed the potential application of a TLA to the GOM/GBK lobster stock and several concerns were raised by the group. The first concern was that the TLA was originally developed as a precautionary management tool for data-poor species. Given that significant data exist on the lobster population and sophisticated models have been developed to determine the stock's status, the TC raised concerns that a TLA could over-simplify and dilute the work already done to model the stock. Furthermore, the TC noted that model-free indicators have already been developed for the GOM/GBK stock which provide color-coded information on spawning stock biomass, recruit abundance, young-of-year indices, revenue, and landings. Noting the Board's desire to maintain high catch rates seen in the last 10 years, the TC also considered developing reference points based on a more recent time period. However, the TC discussed that periods of high reference abundance can occur even when recruitment is low. As a result, truncating the reference time period can be deceiving as the stock could be achieving the reference abundance target but experiencing poor recruitment. This scenario occurred in SNE where low YOY indices were seen in the early to mid-1990's when landings were at their highest.

Recognizing the Board's desire to be proactive in the management of the GOM/GBK stock, the TC has two recommendations which could inform the Board of changing conditions and enhance resiliency of the stock. The first recommendation is to closely monitor the Ventless Trap Surveys (VTS) and Inshore Trawl Surveys (ITS) from Maine, New Hampshire, and Massachusetts. Currently, the young-of-year (YOY) indices are showing declines which could foreshadow poor recruitment in the stock. However, there may be other reasons, besides deteriorating stock conditions, which could be causing declines in the YOY indices. One reason could be changes in the distribution of newly settled lobsters. Given the YOY surveys are fixed site surveys, they may not be able to discern changes in the distribution of lobsters from decreases in settlement. As a result, the TC highlights the importance of monitoring results of the VTS and ITS, which can detect the abundance of sub-legal lobsters. Should the decline in the YOY indices indeed reflect a decline in settlement, this change will next be seen in the VTS and the ITS. The TC expects to see declines in the VTS 5-7 years after the declines the YOY survey. Distinct changes in the trajectory of abundance indices from the VTS and/or ITS would help confirm changing stock conditions and poor recruitment in the GOM/GBK stock.

Another recommendation is to modify the abundance reference threshold for GOM/GBK. In an April 2010 memo to the Board, the TC recommended that, when stock abundance falls below the 50th percentile, action be taken to increase the spawning stock and reducing fishing mortality.[1] Currently, reference abundance in the GOM/GBK can decline to the 25th percentile before management action is triggered to rebuild the stock. The TC again recommends that management action be triggered at the 50th percentile to increase resiliency in the stock.

While writing up this report, the TC also discussed adding an environmental indicator to the model-free indicators that are a part of the benchmark stock assessments. One of the clear conclusions of the 2015 stock assessment is that environmental factors, primarily water temperature, are impacting the lobster stock. Sea surface temperatures from Boothbay Harbor, ME show that the number of days in the optimal temperature range of 12-18°C has increased since the early 2000's (ASMFC 2015). In contrast, the number of days above 20°C, a number considered to be an important temperature threshold for lobsters, has increased in Woods Hole, MA and Long Island Sound, CT (ASMFC 2015). Given this information, the TC discussed creating a water temperature indicator for SNE and GOM/GBK to help illuminate these trends. Specifically, the indicator could look at anomalies from the mean number of days above 20°C. While there was not enough time to complete this analysis for this report, the TC is willing to continue work on this indicator should the Board feel this is a worthy exercise.

As the Board considers potential control rules in the GOM/GBK, the TC cautions the Board against creating a biological trigger for an economic problem. Recent landings in the GOM/GBK have been unprecedented and are likely a result, in part, of ideal environmental conditions (including water temperatures) for egg production and settlement. The Board may not be able to manage the stock to maintain these record high abundance rates, especially as conditions in the Gulf of Maine continue to change. Furthermore, the TC notes that there may be declines in the population and the stock might still be considered healthy given its historical abundance levels.

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[1] American Lobster Technical Committee memo to American Lobster Board, RE: American Lobster Reference Points. April 23, 2010. M010-034.

8. Research Holes and Data Gaps

In an attempt to highlight data gaps as well as on-going research in the Gulf of Maine, the TC discussed remaining questions regarding the biology and recruitment of lobsters, especially in regards to changing habitat conditions, and compiled information regarding on-going projections. This section is split into three parts: A) Research Needs; B) Assessment Model Development; and C) On-Going Research.

A. Research Needs

Maturity, Growth, and Age

Increases in water temperatures over the past several decades have likely resulted in changes to size at maturity and growth patterns. Maturity data used in the 2015 assessment are more than 20 years old, making it likely that available maturity and growth information are not representative of present rates. Evidence of decreased female size at maturity exists for both the GOM/GBK stock (Pugh et al. 2013) and the SNE stock (DNC 2013, Landers et al. 2001). Changes in sizes at maturity will subsequently affect growth, since female molting frequency decreases after reaching sexual maturity. Such phenomena have been documented for the SNE stock, as increased molt frequency and decreased molt increments have occurred (DNC 2013). Additionally, female maturity and growth are directly linked to reproduction, as females do not molt if they are carrying eggs. It is critical to collect updated information on maturity and growth in order to appropriately assign molt probabilities to lobsters in the U. Maine length-based model. When females mature at smaller sizes, their growth slows down earlier than what the existing transition matrices predict. This research would also inform age-length relationships, which may also have changed with increased temperatures. Future research should aim to confirm the transition matrices used in the University of Maine model and improve the current assessment, particularly at older ages/sizes.

Natural Mortality

Research is needed to examine new methods for determining age- or length-varying natural mortality, as well as looking at more rigorous ways of determining time-varying natural mortality for lobster. The former is of critical significance given the probable overestimation of natural mortality in older individuals. The latter is also critical given climatic shifts and changing predator fields. Additionally, interplay between natural mortality and the potential for under-reported harvest should be examined to determine how these factors may impact assessment outcomes. Quantifying differences in natural mortality with and without shell disease must be investigated as disease prevalence continues to be significant in certain areas of SNE and may be spreading northward.

Environmental Influence on Lobster Life History

As noted above, environmental conditions, particularly temperature, significantly influence lobster life history. Research should continue exploring relationships between environmental drivers and lobster population dynamics (maturity schedules, growth, mortality, recruitment, and movement). With oceanographic projections, relationships should look at how lobster life history may change with future climate change, particularly habitat suitability.

Post-larval settlement dynamics should be examined in relation to movement or re-distribution of a spawning stock and the habitat required for post-settling lobsters (e.g. temperature, substrate, water column structure, light, prey, predators).

Mating and Reproductive Success

Due to continued observations of female-skewed sex ratios in the GOM/GBK stock, questions regarding the reproductive capacity of these large females should be considered. Recent laboratory work showed that females who mated with smaller males, or who mated under female-skewed sex ratios, did not have completely filled seminal receptacles, and may have been sperm-limited (Pugh 2014). As such, information regarding the location and timing of the female molt (and thus mating) would be required to determine whether the skewed sex ratios and larger female size structure might impact female reproductive output. Additionally, sampling of the large females to determine whether they have mated would also be informative with regard to reproductive activity, as preliminary data indicated some large females had not mated (Goldstein et al. 2014).

Stock Connectivity

There is need for a comprehensive large scale tagging study to examine stock connectivity between GOM and GBK, as well as GBK and SNE. Historical tagging studies demonstrated movement from the inshore GOM to locations east of Cape Cod in the inshore portions of GBK, from the Scotian Shelf to GBK, and from inshore areas east of Cape Cod to inshore GOM (ASMFC 2015). What is lacking is a tagging study of lobsters in the fall/winter on Georges Bank proper, prior to seasonal migrations which occur in the spring. This information would be extremely valuable to strengthen data used to justify the merged GOM/GBK stock.

Tagging information provides insight into movement of ovigerous females that can be used to understand stock connectivity via larval transport. Hydrodynamic modeling of the GBK and SNE outer shelf areas, with particles assigned lobster larval behaviors, would add valuable insight to the possibility that northern stocks may provide a source of larvae ultimately recruiting to the SNE stock. See Ongoing Research VII below.

Tagging studies are often used to assess stock connectivity; however, information on the reporting rates of tagging studies is still unclear. A study which had both high and low reward tags would help elucidate fishermen behavior and expected tag returns rates in the fishery.

Fishery-Dependent Information

Analysis of fishing effort compared to economic indicators would be valuable in understanding the contributions of resource availability (e.g. SSB) and U.S. economic status on industry and recorded landings.

Accurate and comparable landings are the principal data needed to assess the impact of fishing on lobster populations. The quality of landings data has not been consistent spatially or temporally. Limited funding, and in some cases elimination of sea sampling and port sampling programs, have negatively affected the accuracy of catch and conservation discard assessment. This lack of accuracy then limits the ability of the model to accurately describe landings and stock conditions. It is imperative that funding for critical monitoring programs continues, and increased monitoring efforts for offshore areas are necessary, particularly those from which a large portion of landings originate. These types of programs are essential for accurate lobster assessments and must have dedicated funding.

There are some indications that lobster harvest were under-reported and this under-reporting was significant for extended time frames. Impacts of under-reporting should be investigated via simulation testing. One particular area that should be examined is the period prior to the implementation of the 100/500 possession rule for non-pot gear, as landings by non-pot gear may have been a significant source of under-reporting.

A thorough investigation of methods for determining optimal biological sampling intensity based on variability in catch and spatial/temporal landings information should be undertaken. This investigation should explore other metrics that may be more variable than length composition (i.e. conservation discards, sex ratio, legal proportions), as well as an examination of the importance of data from different Statistical Areas to the assessment and the interplay with various levels of sampling from each Area.

B. Assessment Model Development

Natural Mortality

Incorporate varying natural mortality rates to produce scenarios of healthy vs. shell diseased populations of lobsters, and incorporate environmentally-explicit model between climate (e.g. temperature), shell disease prevalence, and mortality for forecasting SSB and catches.

Survey Data Aggregation

Examine the use of a hierarchical modeling technique (Conn, 2010) to aggregate survey information for the different stock areas as an alternative to internally weighting indices in the model or using area-swept information.

Settlement-YOY Survey

Incorporate settlement-YOY survey into the assessment to construct abundance indices for early age classes and understand mortality rates in the first few years of life.

Stock-Recruitment Relationship

Identify appropriate stock-recruitment functions, both traditional and environmentally explicit, to more accurately understand the feedbacks between spawning adults and recruitment, particularly under recent dynamics of recruit/spawner rates (i.e. SNE recruitment failure and GOM/GBK recruit/spawner increase).

Assessment Model Language

A priority that was emphasized by the Review Panel during recent SASC presentations and discussions was the rigidity of the UM model that is written in Advanced Differential Model Builder (ADMB, Fournier *et al.* 2012) and difficulty of reconfiguration. We recommend re-writing the UM model in a more flexible and efficient configuration, using either the ADMB or Template Model Builder (TMB, Kristensen et al. 2016) software platforms.

C. On-Going Research

I) In 2013 the Maine Department of Marine Resources contracted with the University of Maine for a five year $250,000 project designed to apply Kilada et al.'s (2012) approach to ageing for lobster. This work focuses on lobsters ranging in size from newly settled lobsters to fully recruited sizes. Regional temperature regimes will be tested as well as differences between laboratory and field scenarios. Anticipated deliverables should be directly applicable to future assessment and will include size-at-age estimates, molt increments and molt frequency.

II) The Maine Department of Marine Resources conducted a three-year study (2010-2013) where settlement was measured in randomly selected sites, based on depth and substrate, and compared to standardized sentinel locations in Mid-Coast Maine. Mid-Coast Maine is the region with the longest time series for settlement, dating back to 1989. For this reason, it was important to investigate the patterns of settlement from fixed and randomly selected sites. Initial results indicate fixed and random stations have similar magnitude and trend with respect to settlement density for this region.

In other regions in Maine, there is evidence that thermal conditions may have changed, providing additional habitat for settlement. Annis et al. (2013) suggest that small differences in water temperature may shape settlement patterns through either behavioral avoidance of colder settlement sites or elevated post-settlement mortality of post-larvae settling at colder sites. Wahle et al. (2013) observed young-of-year lobsters as deep as 80 m. If available substrate has increased in eastern/northern Maine, simply as a result of increasing water temperatures, then fixed sentinel sites in shallow water may miss a broader pattern of settlement in the region. Researchers (Rick Wahle) at the University of Maine, Orono and NOAA have received funding from the University of Maine Research Reinvestment Program to study changing depth distributions of lobster recruitment. The study is using collectors to determine if lobsters are settling at greater depths than have historically been monitored. This research may provide insight into recent trends observed in the American Lobster Settlement Index. Work has also been funded through NOAA's Northeast Regional Sea Grant Consortium to research the genetic and phenotypic response of larval American lobster to ocean warming and acidification across New England's steep thermal gradient (Rick Wahle, Umaine; David Fields, Bigelow Laboratory for Ocean Sciences; and Spencer Greenwood, University of PEI). A number of projects have been funded to enhance and expand forecasting lobster fishery recruitment using the American Lobster Settlement Index (Rick Wahle, UMaine; A. Pershing, GMRI; L. Jacobson, NEFSC; D. Brady, UMaine; B. Beal, UMaine Machias; B. Shank, NEFSC).

III) Kathy Castro of the University of Rhode Island is currently assessing the impact of various vent sizes on retaining lobsters entering traps. Traps were stocked with lobsters of known sizes and sexes and released for 5 night soaks to see the degree of escapement.

IV) Researchers from VIMS (John Hoenig, Jeff Shields, Maya Groner) are currently working on environmentally explicit models to describe size-specific mortality rates for shell-diseased lobsters. These relationships will be evaluated for inclusion in the currently used projection model to understand future lobster population dynamics under diseased and non-diseased scenarios.

V) Researchers from Davidson Laboratory at the Stevens Institute, CT DEEP, and NOAA have recently evaluated habitat restrictions for lobster using high resolution climate change model for Long Island Sound. Future habitat work should draw on these techniques for other SNE states (RI and MA) as well as the GOM/GBK stock.

VI) Massachusetts Division of Marine Fisheries is currently conducting research into the sub-lethal effects of shell disease, specifically in relation to reproductive capacity. The research, funded by NOAA's Saltonstall-Kennedy grant, will examine male and female lobster reproductive capabilities relative to presence or absence of shell disease. Female mating success, initial fecundity (number and quality of eggs spawned) and realized fecundity (number of eggs expected to hatch) will be determined. Male spermatophore quality will be determined relative to disease status. Mating behaviors of diseased males and females will be examined, and compared to that of non-diseased lobsters. The results are intended to help understand the potential for rebuilding the SNE stock based on reproductive capacity, and to identify potential consequences of increased incidence of shell disease in the GOM stock.

VII) Researchers from Woods Hole Oceanographic, University of Massachusetts, Dartmouth, Mass DMF and NOAA are currently investigating the impact of climate change on larval connectivity, larval dispersal patterns and recruitment of lobster in Southern New England (SNE). This project, funded by the NOAA Saltonstall-Kennedy Program will help determine how changing spatial distributions of the spawning stock are impacting larval supply to SNE nursery habitats and provide management advice on measures that may help mediate recruitment failure.

VIII New Hampshire Fish and Game and AOLA were awarded funds to conduct a T-bar tagging study on Georges Bank in 2015. Recaptures from this study are still being reported by fishermen and information from this research is being shared with the ASMFC Lobster TC to assist in their ongoing stock connectivity analysis. Tagging proposals for future funding covering expanded spatial regions have been submitted.

IX) Researchers from Virginia Institute of Marine Science and Cornell University (Jeff Shields and Jeff Maynard) received SK funding to develop a predictive model integrating sea surface temperature and shell disease incidence in the Gulf of Maine. They plan to validate predicted shell disease incidence rates with data from state commercial at sea sampling programs.

X) Over the last few years, Dr. Heather Hamlin, Dr. Robert Bayer and Deborah Bouchard (University of Maine and Lobster Institute) have been engaged in lobster health research addressing the effects of a changing ocean ecosystem on lobster health in the context of rising water temperatures and ocean acidification. Focus has been on how these changes may directly impact lobster biology in regards to reproductive development and susceptibility to disease. A parallel component of these projects moving forward is to develop the ability and sensibility within Maine's lobster industry that early reporting and diagnosis of presumed diseased or deformed lobsters is critical to gauging the population's susceptibility to new and emerging pathogens. Funding for this work has been obtained from the Saltonstall-Kennedy Program (NOAA Fisheries), the University of Maine Research Re-investment Fund and the Lobster RED Board (State of Maine, Department of Marine Resource).

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Appendix 1: Figures from SSEM of zooplankton time series.

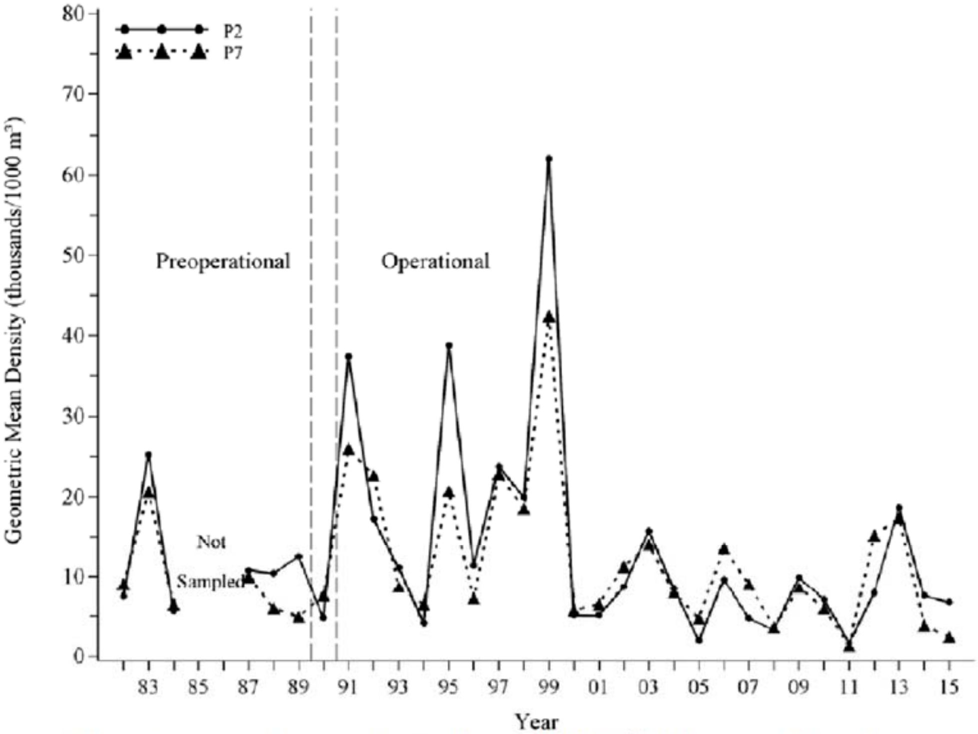

Figure 6-10. Annual geometric mean density (thousands/1000 m^3) of *Cancer* spp. larvae from 1982-2015 (data between dashed lines excluded from the ANOVA model). Seabrook Operational Report, 2015.

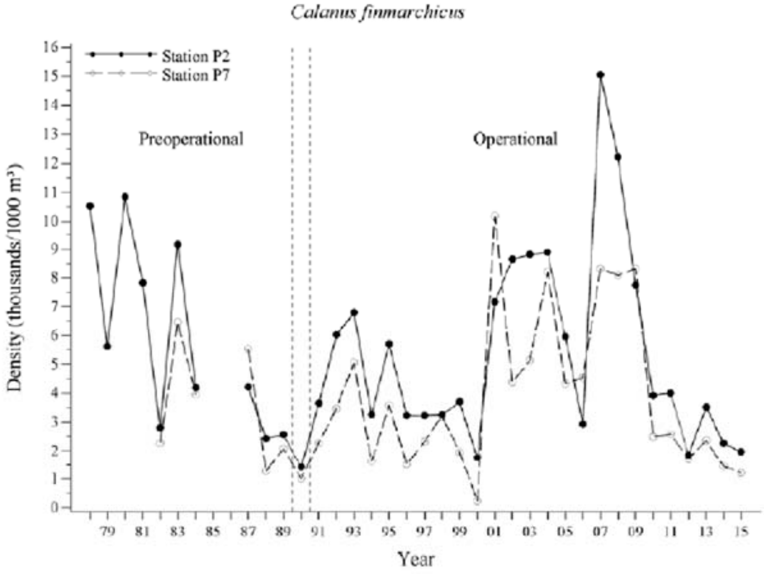

Figure 3-8. Annual geometric mean density of *Calanus finmarchicus* at Stations P2 and P7 from 1978 to 2015. Seabrook Operational Report, 2015.