to the situation that unfolded in Newfoundland two decades ago (see sidebar). The stock is faring poorly, and fishing alone cannot account for its reduced performance. Successfully weathering the current storm and emerging with a healthy stock and sustainable fishery will require a concerted effort to understand the factors driving the poor stock performance and to evaluate options for enhancing the management and profitability of the fishery. We have organized these efforts around four assertions:

1. **Understanding Environmental Change:** Shifts in the Gulf of Maine ecosystem have impacted cod and the cod fishery. Understanding these past events is necessary to sustain this population in a changing climate.
2. **Diagnosing Stock Structure and Movement:** Cod stock structure, behavior, and diet are more complex than previously appreciated. Building knowledge about these topics will support more effective fishery management in an ecosystem context.
3. **Improving Stock Assessments and Management:** Advances in stock assessment and innovation in fishery management are necessary to sustain the Gulf of Maine cod population.
4. **Increasing Profitability:** The limited availability of cod will challenge the industry. Novel marketing strategies and innovative application of gear and information technology will support an economically and ecologically sustainable fishery.

Although our discussion is restricted to cod, the challenges and solutions we outline are relevant to most fisheries as they struggle to adapt to a world of increasing climate and economic changes.

1. Understanding Environmental Change

Cod, like other fish species, are affected by and respond to environmental conditions they experience throughout their life. Larval survival is strongly influenced by environmental conditions such as

Lessons from Newfoundland

Changing ocean conditions. Changing centers of distribution. Overfishing. Declining cod. Have we not seen these challenges before elsewhere? In the Gulf of Maine, cod have gone through a rocky couple of decades. Overfishing led to declines in Gulf of Maine groundfish abundance in the 1990s, including cod, which set off a series of management actions aimed at curbing effort and mortality. These restrictions appeared to be working up until 2008, when the cod assessment indicated that rebuilding was underway. However, due to problems with the 2008 assessment (identified in the 2011 assessment), it is now known that the Gulf of Maine cod stock was not in as good shape as was previously believed.

Newfoundland endured similar experiences with its cod fishery in the early 1990s. What can we learn from the experience in Newfoundland that will help us understand and adapt to the current Gulf of Maine cod decline? First of all, the initial overcapitalization and then high exploitation of Gulf of Maine cod, following establishment of a 200-mile EEZ, mirrors the pattern observed for the northern cod stock in Newfoundland. At the same time that the northern cod were being heavily exploited, capelin, the primary prey of the northern cod, moved southward during an unusually cold period. This prey range shift, in combination with declining abundance, led to northern cod being much more aggregated near the southern end of the stock range and more vulnerable to further overfishing by the highly efficient offshore fleet.

Has a similar "hyper-aggregation" (Rose et al. 2002) occurred in the Gulf of Maine? Comparable to the case in Newfoundland, Gulf of Maine cod appear to have shifted their distribution from throughout the Gulf of Maine to primarily the western Gulf of Maine (Figure 1). Hyper-aggregation assumes a single population (within the stock) and a range contraction due to declining abundance and other environmental shifts. On the other hand, Ames (2004) described distinct sub-populations within the Gulf of Maine which, if real, would argue against hyper-aggregation and rather support the idea of local depletion of cod within sub-regions (i.e., eastern Maine). And while the Gulf of Maine is warming, the eastern portion remains the coolest and therefore would likely serve as a thermal refuge, not an abandoned habitat, with all else being equal. As such, there is perhaps cause for even greater concern, given the possibility that the only

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winds and currents (Churchill et al. 2011), along with plankton abundance (Mountain and Kane 2010). Food availability, especially the abundance of lipid-rich forage fish, is also an important external driver of cod production (Sherwood et al. 2007). A combination of these factors, along with a recent warming trend, could explain the poor performance of the stock in recent years.

Temperature has a strong influence on fish throughout their life, affecting growth, reproduction, distribution, migration, and recruitment (Drinkwater 2005). Cod is a subpolar species and the Gulf of Maine is near the southern limit of its range in the western Atlantic. Any increase in temperature can be expected to adversely impact this stock (Drinkwater 2005, Fogarty et al. 2008), and examining how the population has responded to past changes in temperature can provide some insight into where the stock may be headed.

The Gulf of Maine is now warmer than it has ever been; however, temperatures only recently exceeded those experienced during the late 1940s and early 1950s (*Figure 3*). In 1950, the northwest Atlantic was 0.5-1°C warmer than the 1982-2011 average. However, the rest of the global ocean was, on average, 0.5-1°C cooler. The abrupt decline in landings in 1950 (*Figure 2*) coincided with this warming period, although it is unclear whether the decline was due to reduced abundance, changes in the fishery, or to under-reporting of landings.

The recent warming began in 1999 and accelerated in 2010, reaching record levels in 2012. Although annual mean temperatures have only recently exceeded the mid-century values, the recent warming has a different character than the earlier period. During the 1945-55 period, the warming was strongest during the winter, leading to increased annual minimum temperatures. With the exception of the very warm 2011/2012 winter, recent winter temperatures have been normal, and the observed warming is due to elevated summer temperatures (Friedland and Hare, 2007). This means that species in the Gulf of Maine are encountering maximum temperatures outside their historical experience.

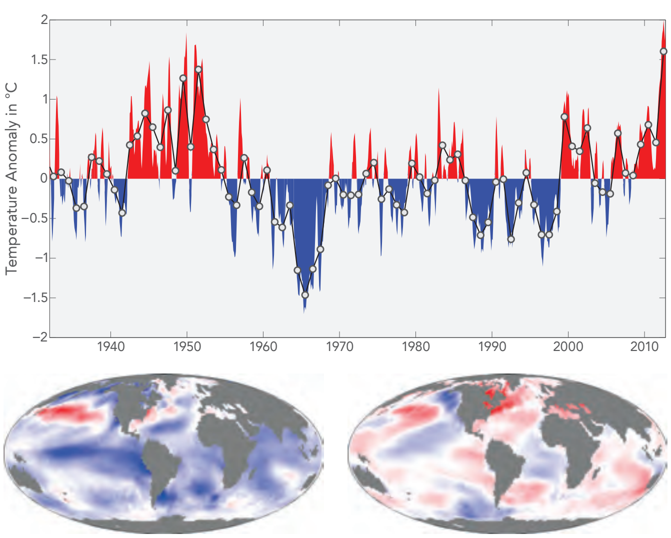

Figure 3. Monthly (shaded region) and yearly (circles) sea surface temperature anomalies for the Gulf of Maine. The anomalies were computing using ERSST data referenced to the 1982-2011 climatology. The maps are the global anomalies for the years 1950 (left) and 2012 (right), with red and blue colors indicating above and below normal temperatures, respectively.

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remaining sub-population in the Gulf of Maine coincides with the area of highest temperature.

Another valuable lesson from the Newfoundland experience is that, despite an all-out moratorium on cod fishing, it took nearly two decades for a recovery to take hold in the northern stock. Initial estimates following the establishment of the moratorium put the rebuilding time frame at just a few years. Clearly other factors were at play that held the northern cod at low abundance for many years and then allowed a sudden recovery in 2006 (DFO 2011). This recent recovery of northern cod is likely related to an increase in the abundance of capelin. Without capelin, Newfoundland cod grow poorly, lack energy reserves and spawn less frequently (Sherwood et al. 2007). What does this mean for Gulf of Maine cod? Perhaps cod in eastern Maine are also limited by a shortage of forage fish such as river herring and inshore Atlantic herring (Ames 2004). It remains to be seen whether dam removals, which are likely to lead to reestablishment of river herring runs, and restrictions on nearshore mid-water trawling for Atlantic herring will result in greater forage fish availability and a recovery of cod in eastern Maine, which has been inexplicably devoid of cod for nearly two decades.

Water temperature impacts on Atlantic cod biology and ecology are well documented (Drinkwater 2005). For example, shifts in the distribution of cod to cooler, deeper water have been identified on Georges Bank when bottom temperatures exceed 10°C (Serchuk 1994). Temperature is also an important factor determining growth rates of cod across life stages, with maximum growth rates for juvenile and adult cod occurring between 10-15°C (Drinkwater 2005). Additionally, cod age-at-maturity has been shown to decrease with increasing water temperature (Brander 1995). Fogarty et al. (2008) explored the potential impacts of increasing water temperature associated with climate change on cod in US waters. Modeling revealed that increasing temperature reduced the survival of young cod but increased their growth rates, with the combined impact of reduced cod production in the Gulf of Maine (Fogarty et al. 2008). Warming in the Gulf of Maine is also altering the composition of the entire groundfish community as southerly species move northward (Nye et al. 2009; Lucey and Nye 2010). The influence of these potential prey, competitors, and predators of cod is unknown.

Body size has important implications for marine fish populations and ecosystems, and changes in size have the potential to impact both the performance of the stock and the assessment. For example, larger fish require less food to maintain each gram of tissue (Brown et al. 2004) and larger females produce more and higher quality eggs (Berkeley et al. 2004). Thus, populations with many large individuals can withstand poor environmental conditions and recover more rapidly when conditions improve (Chesson and Warner 1981, Field and Francis 2000). Substantial declines in the mean body size of several fish species have been reported for the Newfoundland-Labrador Shelf, Scotian Shelf, and Gulf of Maine-Georges Bank region of the Northeast Shelf during the late 1980s and early 1990s (Fisher et al. 2010, Mills 2010, Shackell et al. 2010), suggesting that large-scale environmental changes are likely driving the declines in size.

Declines in cod body size in the Gulf of Maine may be related to a change in growth at the stock level. Generally, fish in colder waters, such as the eastern Gulf of Maine, grow more slowly but reach larger body sizes at older ages than fish in warmer waters, such as the western Gulf of Maine and Georges Bank (Tallack et al. 2009). As cod abundance has declined in the eastern Gulf of Maine, faster growing but smaller western Gulf of Maine fish represent a larger contingent of the population. However, changing environmental conditions may also play a role, as the timing of the declines in cod size coincides with major shifts in physical conditions and community composition in the Gulf of Maine ecosystem that may affect feeding opportunities for cod (Greene and Pershing, 2007; Lucey and Nye 2010). The shift towards smaller body sizes could have important implications for cod and for their management within an ecosystem context. The 2011 stock assessment found that the age at maturity has not changed, which suggests that cod are maturing at smaller sizes, and as such, may be producing fewer or lower quality eggs. A decline in fecundity and recruitment potential may constrain recovery of the cod population.

While temperature can influence growth and fecundity in fish, it is only one side of the equation. Robust growth and high fecundity require abundant food, and there is growing evidence that changes in food availability can constrain cod. Cod have been described as ecological generalists (Garrison 2000), but the relative importance of different prey changes as cod grow. By the time cod reach reproductive age, they likely target high-lipid forage fish such as sand lance and herring, including Atlantic herring and river herring (Ames 2004, Sherwood et al. 2007). For example, in Newfoundland, in the absence of capelin, medium-sized cod grow slowly and are less likely to spawn (Sherwood et al. 2007). Older, larger cod, which have a disproportionate impact on egg production (Martinsdottir and Steinarsson 1998), seem to thrive on being top predators and even cannibals. That is, they may have moved beyond needing forage fish.

However, without forage fish to provide the "stepping stone" to top predator status, cod can get caught in an energetic bottleneck and never reach large sizes and their full reproductive potential, or even reproduce at all (Sherwood et al. 2007).

Although Atlantic herring, the primary forage fish in the region, are currently abundant in the Gulf of Maine (TRAC 2009), forage fish limitation may still be negatively affecting Gulf of Maine cod. In the past, spawning aggregations of cod were found all along the coast of Maine in locations and seasons corresponding to runs of river herring (Ames 2004). Declines in river herring in Maine rivers due to habitat alterations (i.e., dams; Moring 2005) and possibly bycatch in the Atlantic herring fishery (Cournane et al. 2013), may be making it harder for cod to grow and reproduce, particularly in eastern Maine (Ames 2004).

Developing relationships between environmental drivers, including changes in prey abundance and distribution, and aspects of cod biology, such as recruitment and growth, will provide a mechanistic understanding of cod population dynamics. These mechanistic relationships will be critical to forecast the response of cod to environmental variability as well as climate change.

RECOMMENDATIONS

- ***1a. Develop a deeper knowledge of how temperature impacts the distribution, growth, and fecundity of cod***
- ***1b. Understand the influence of age and size structure on population resiliency***
- ***1c. Quantify the impact of herring and other forage fish on cod growth and reproduction.***

2. Understanding Stock Structure and Movement

For assessment and management, cod in US waters are divided into Gulf of Maine and a Georges Bank management units. This distinction was based on based upon traditional fishing areas and early studies of movement, growth, and spawning from the 1960s. Since then, a range of studies using tagging, genetics, and circulation modeling indicate that stock structure may be different and more complex. Modeling exercises have shown that management units that are composed of multiple biological populations can be difficult to assess with accuracy (Frank and Brickman 2000, Fu and Fanning 2004, Kerr et al. 2010). This is an area that requires further research to determine the most appropriate management units for cod.

Recent genetic analysis of Atlantic cod (Lage et al. 2004, Wirgen et al. 2007, Kovach et al 2010) revealed stock complexity at both spatial and temporal scales that raised questions about the appropriateness of the current distinction between Gulf of Maine and Georges Bank cod. Using genetic markers, Kovach et al. (2010) identified significant (statistically and biologically) genetic differentiation among three spawning complexes (*Figure 4*):

1. A northern spawning complex, which spawns in inshore Gulf of Maine waters (off western Maine to Massachusetts Bay) in the spring;
2. A southern spawning complex, which primarily spawns in inshore Gulf of Maine waters (from Ipswich Bay to southern New England, including the Great South Channel) in the winter; and
3. A population that spawns offshore on the northeast peak of Georges Bank in the early spring.

Interestingly, the strongest genetic differentiation was identified between spawning groups in the Gulf of Maine that overlap spatially but spawn in different seasons (Kovach et al. 2010). This distinction is important to understanding recruitment patterns in the Gulf of Maine stock. Both spawning groups share nursery habitat in Massachusetts Bay. However, recruitment to the northern spawning complex, centered in Ipswich Bay, depends on winds and plankton availability in May-June, whereas the southern spawning complex depends on the winds and plankton availability in December-February; hence they utilize the nursery habitat in different