MARINE ECOLOGY OF GULF OF MAINE ATLANTIC SALMON

SUMMARY DOCUMENT

from a 2008-2010 series of workshops

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I. INTRODUCTION

The number of Atlantic salmon (*Salmo salar*) returning to Maine rivers to spawn each year has declined over the last several centuries as human population and resource use have increased (Fay et al. 2006). By the turn of the twenty-first century, salmon populations had declined to record-lows, prompting endangered species listing and necessitating more aggressive research and recovery efforts.

Pacific salmon biologists have long held that four major factors are responsible for salmon declines: habitat degradation, hydroelectric and other dams, harvest practices, and fish hatcheries (collectively called the "four Hs;" Good et al. 2007). Although these factors are also important for Atlantic salmon, a fifth factor, low marine survival, has been an additional stressor, particularly during the past 15 years.

Cairns et al. (2001) reported that of the top 12 hypotheses for modern salmon declines (assembled by over 100 salmon scientists), 10 were marine- or estuarine-based. Three years later, the National Research Council (2004) indicated an urgent need to understand early marine survival of Atlantic salmon. Also in 2004, the North Atlantic Salmon Conservation Organization (NASCO) prioritized research on the migration and distribution of salmon at sea, in relation to feeding opportunities and predation. This international research program, called "Salmon at Sea" or SALSEA, investigates a comprehensive mix of freshwater, estuarine, and marine elements, thereby ensuring a thorough evaluation of the wide array of factors that may affect Atlantic salmon mortality. NASCO further encouraged partnering countries to identify areas where salmon losses occur and then determine the cause(s) of these mortalities.

Within Maine, NOAA National Marine Fisheries Service (NOAA Fisheries) primarily focuses on Atlantic salmon life stages in the estuarine and marine environments, while both the Maine Department of Marine Resources Bureau of Sea-Run Fisheries and Habitat and the US Fish and Wildlife Service focus on freshwater life stages and habitats. NOAA Fisheries also works closely with other federal agencies (particularly the US Geological Survey), the University of Maine System, and a wide range of state, academic, public and private partners, to "identify, quantify, and minimize threats to Atlantic salmon; conserve and enhance habitat; and evaluate progress toward recovery by assessing the viability of these populations at critical life history stages" (http://www.nefsc.noaa.gov/salmon/).

Building on these efforts, NOAA Fisheries and Maine Sea Grant hosted a series of workshops between 2008 and 2010 focused on the migratory and saltwater phases of Gulf of Maine Atlantic salmon populations. The goal of the workshops was to explore changes in marine survival of Gulf of Maine Atlantic salmon, and to generate an interdisciplinary synthesis of the universe in which salmon exist and factors affecting their marine survival. The workshops focused on the marine ecology of emigrating postsmolts from coastal Maine to Greenland, and on the return migration of adults.

This document briefly summarizes the status of Atlantic salmon in the Gulf of Maine, and prioritizes research questions about marine survival developed during the workshops.

Workshop agendas and participants are provided in Appendix A and Appendix B, respectively.

This summary document contains:
1) an overview of Gulf of Maine Atlantic salmon population declines and efforts to understand and address these declines;
2) background on marine-phase Atlantic salmon biology and physical habitat;
3) refined hypotheses, research activities, and approaches;
4) suggested management activities; and
5) data sets for examining research questions (Appendix C).

Our hope is that these findings and recommendations stimulate new and diverse research and management directions, and serve as a foundation for future research projects undertaken by NOAA Fisheries and by other agencies and investigators.

Gulf of Maine Atlantic Salmon Population Declines

Historically, the natural range of Atlantic salmon in the US extended from the Housatonic River in New York to the St. Croix River in Maine (Kendall 1935). However, by the early 1800s, Atlantic salmon runs in New England were severely depleted, greatly reducing the species' distribution in the southern half of its range. By the end of the 1880s, three of the five largest New England salmon populations (in the Connecticut, Merrimack, and Androscoggin rivers) had been extirpated, shifting the southern extent of the species approximately two degrees north in latitude and four degrees east in longitude (Fay et al. 2006).

Estimates of the peak number of adult salmon returning annually to US rivers range between 300,000 (Stolte 1981) and 500,000 (Beland 1984). The largest historical salmon runs were likely in the large river systems: Connecticut, Merrimack, Androscoggin, Kennebec, and Penobscot (DeRoche 1967; Baum 1983). Atkins and Foster (1867) estimated that the Penobscot alone held 100,000 adults annually. The Penobscot River continued to support a large population during the late 1800s, with a reported commercial catch of over 10,000 salmon in 1880 (Baum 1997). In subsequent years, a new artificial propagation program initiated in Maine influenced population abundance and distribution. However, the abundance of Atlantic salmon continued to decline; by the mid-1900s, the total adult run of Atlantic salmon in US rivers was only 500 to 2,000 fish, mostly in eastern Maine rivers (Baum 1983).

Under restoration efforts in the 1960s to 1980s, the number of returning adults increased from less than 800 in 1969 to nearly 5,700 in 1986. Most of this increase reflected the recovery of the Penobscot River hatchery-dependent population. Since 1998, fewer than 4,000 adults have returned annually to US rivers to spawn. Even if current hatchery supplementation efforts continue, the likelihood of extinction of Gulf of Maine Atlantic salmon within the next 100 years still ranges from 19% to 75% (Legault 2005). Further, if efforts to recover and enhance freshwater habitat succeed in restoring 80% of the species' historic range, populations are still unlikely to fully recover unless marine survival increases (Legault 2005).

Progress, Challenges, and Opportunities for an Enhanced Marine Focus

Previous efforts to summarize the various factors potentially influencing the decline of Atlantic salmon have found that while existing dams are responsible for a relatively stable level of mortality over the last century or more, variability in marine environmental conditions has emerged as the leading cause of the declining return rates of salmon in the last 25 years.

In 2000, the Department of Fisheries and Oceans Canada sponsored an international workshop to develop research strategies to determine the cause(s) of the decline in salmon abundance (O'Neil et al. 2000). The workshop affirmed higher mortality on emigrating fish as a population constraint, and generated a series of proposed research projects to address the principal hypotheses. As a follow-up to the workshop, Cairns (2001) prepared, ranked, and quantified a comprehensive list of 63 potential causes of salmon decline to identify "plausible" hypotheses.

Subsequent to the Endangered Species Act listing of Maine Atlantic salmon in 2000, the National Research Council also assessed the causes of decline and suggested strategies for rehabilitation (NRC 2004). This effort applied issues prominent with Pacific salmon science to Atlantic salmon, including the longstanding and well-known problems associated with the "four Hs"—hatcheries, habitat, hydropower, and harvest. The NRC report focused primarily on freshwater threats such as dams and pollution, and emphasized freshwater chemistry (pH) as a likely cause of poor early survival. However, the report also concluded, "…declining rates of returns of adult anadromous Atlantic salmon to Maine's rivers indicate increased mortality after the young salmon leave freshwater. While it is not possible to determine from return rates alone how much of the increased mortality occurs as smolts transition from freshwater to saltwater in the estuaries and how much occurs at sea, there are reasons to be concerned about both environments." The ocean was "a black box into which many salmon venture and few return" (NRC 2004).

Salmon in the Marine Environment: Gaining Insights into the Black Box

For decades, scientists considered the marine phase of Atlantic salmon a "black box." Young salmon (smolts) left rivers, entered the black box of the ocean, and a certain proportion then returned as adult spawners. Technological advances have enabled glimpses into the black box, but studying salmon in the ocean remains a challenge. In addition to a complicated life history that includes physiological transitions, multiple habitats, and dispersion, salmon make long migrations through remote regions of the ocean. Depending on the time of the year, marine-phase Atlantic salmon can occur anywhere from Maine estuaries to Disko Bay on the west coast of Greenland. In general, salmon are surface-dwelling fish that are difficult and expensive to survey. Even when highly abundant, salmon constitute only a minor component of the marine ecosystem and occur at relatively low densities at an ocean-wide scale.

Technological innovations have allowed scientists to measure salmon emigration and movement at sea (e.g., Lacroix and McCurdy 1996; Shelton et al. 1997; Voegeli et al. 1998; Holm et al. 2000). This work was previously limited to tagging studies (e.g., Saunders 1981) and scale imaging (e.g., Friedland et al. 2006). Ultrasonic telemetry and post-smolt trawls now allow in situ analysis of behavior and condition biometrics. Recent assessments of survival suggest that relatively high mortality rates occur during the marine transition and in the first weeks of marine life (LaCroix et al. 2005; Kocik et al. 2009; Dempson et al. 2011). Results from some Canadian rivers (Whoriskey et al. 2008) indicate consistently high freshwater survival, variable estuarine survival due to changes in predator-prey abundance, and downward trends in marine survival (as measured by adult returns). Kocik et al. (2009) reported that monthly mortality during emigration to offshore waters ranged between 53% and 64%, high relative to composite 30% to 42% monthly marine mortality estimates (WGNAS 2005). In inner Bay of Fundy stocks, initial marine mortality appears much lower, less than 10% (Lacroix et al. 2005). However, Whoriskey et al. (2008) found mortality rates in the northern New Brunswick Atlantic salmon stock to be comparable to those documented by Kocik et al. (2009). Dempson et al. (2011) found slightly higher survival but also more extended coastal residency. Because the telemetry technology used to generate these estimates is new, it is difficult to determine if these trends are low relative to the past, as all information has been obtained under the current low survival regime.

However, we do know that since 1986, salmon populations have declined consistently in the Northwest Atlantic region—even the Inner Bay of Fundy Designatable Unit, which does not migrate to Greenland, collapsed in 1990. In general, southern populations are much lower in abundance than northern populations. The identification of this “phase shift” suggests that marine survival has substantially changed in the last three decades, with no indication of future improvement (Chaput et al. 2005; see Figure 1).

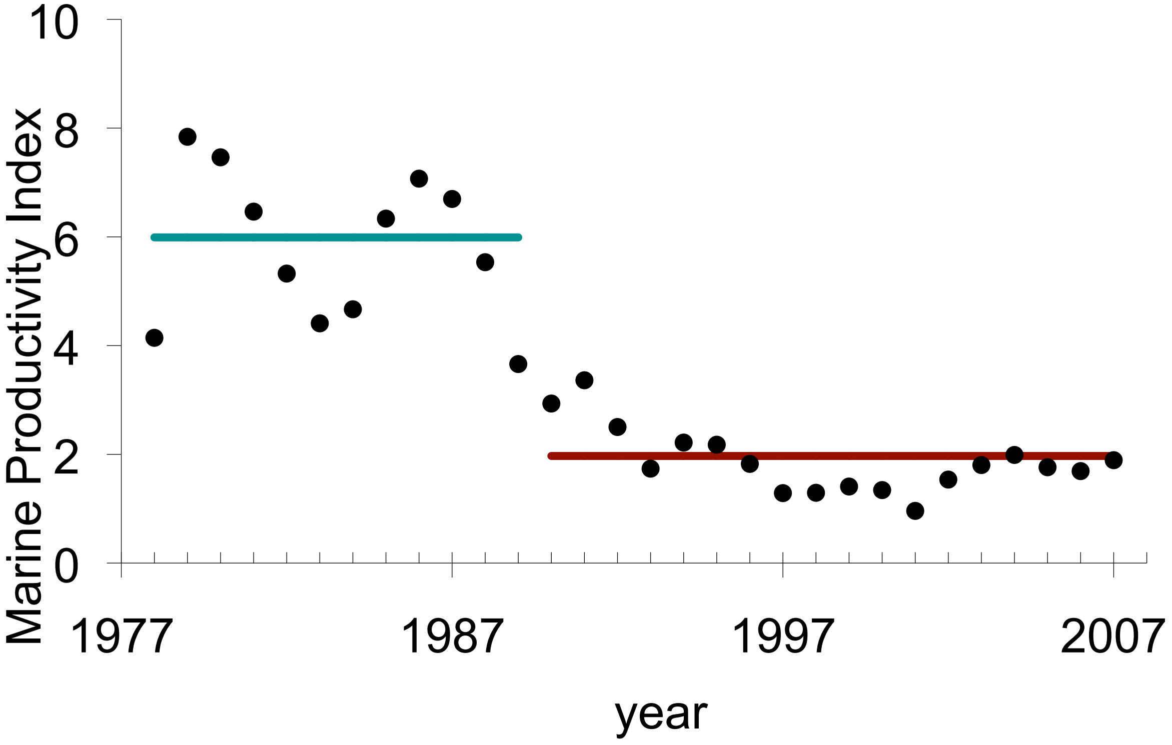

Figure 1. The Marine Productivity Index is obtained by dividing the pre-fishery abundance index by the lagged spawner number as first presented in ICES 2003, but updated with data presented by ICES 2009. This approach illustrates and identifies a phase shift suggesting that marine survival has substantially changed in the last three decades, with little indication of future improvement.

Population viability models offer an alternative perspective. Such models can illuminate the potential relative importance of freshwater and marine survival trends in overall population status (Legault 2005). Based on a summary of life-stage specific survival, it is possible to develop a replacement line relationship between marine and freshwater survival—which combinations result in population decline, stability, or growth (Figure 2). Both parameters are important. However, recent freshwater survival data contain observations that are high relative to ranges in published literature. Conversely, recent marine survival of Maine stocks is low relative to that presented by the literature. This suggests that small improvements in marine survival could improve stock status (Figure 3).

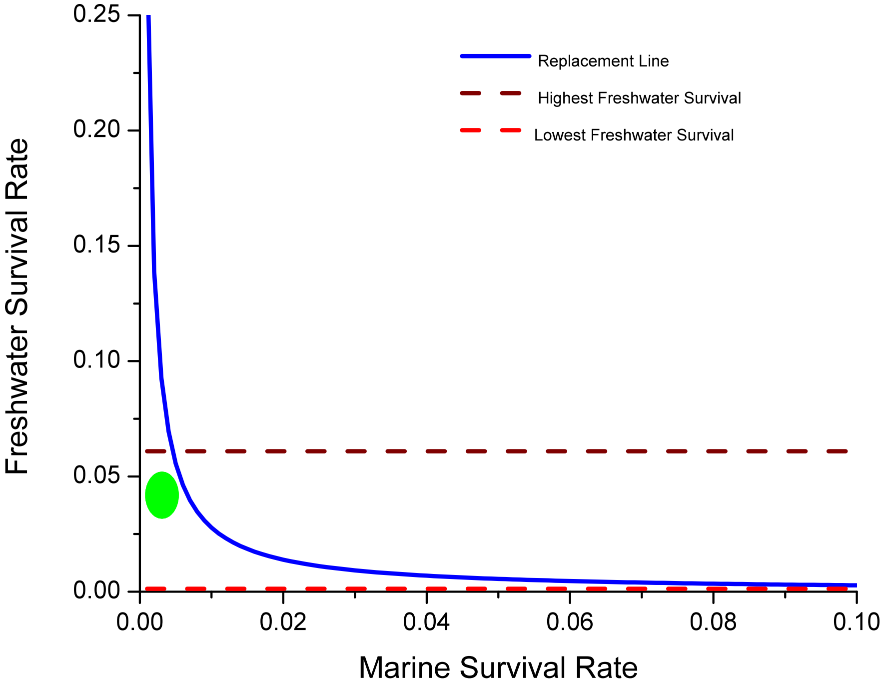

Figure 2. Relationship of marine and freshwater survival rates, with 1:1 replacement line (blue). Values above the line indicate a growing population; values below the line indicate declining populations. General trends from last 25 years for freshwater survival are bounded between 0.13% and 6.09% (red and maroon dashed lines) and values typical for recent years are within the green oval.

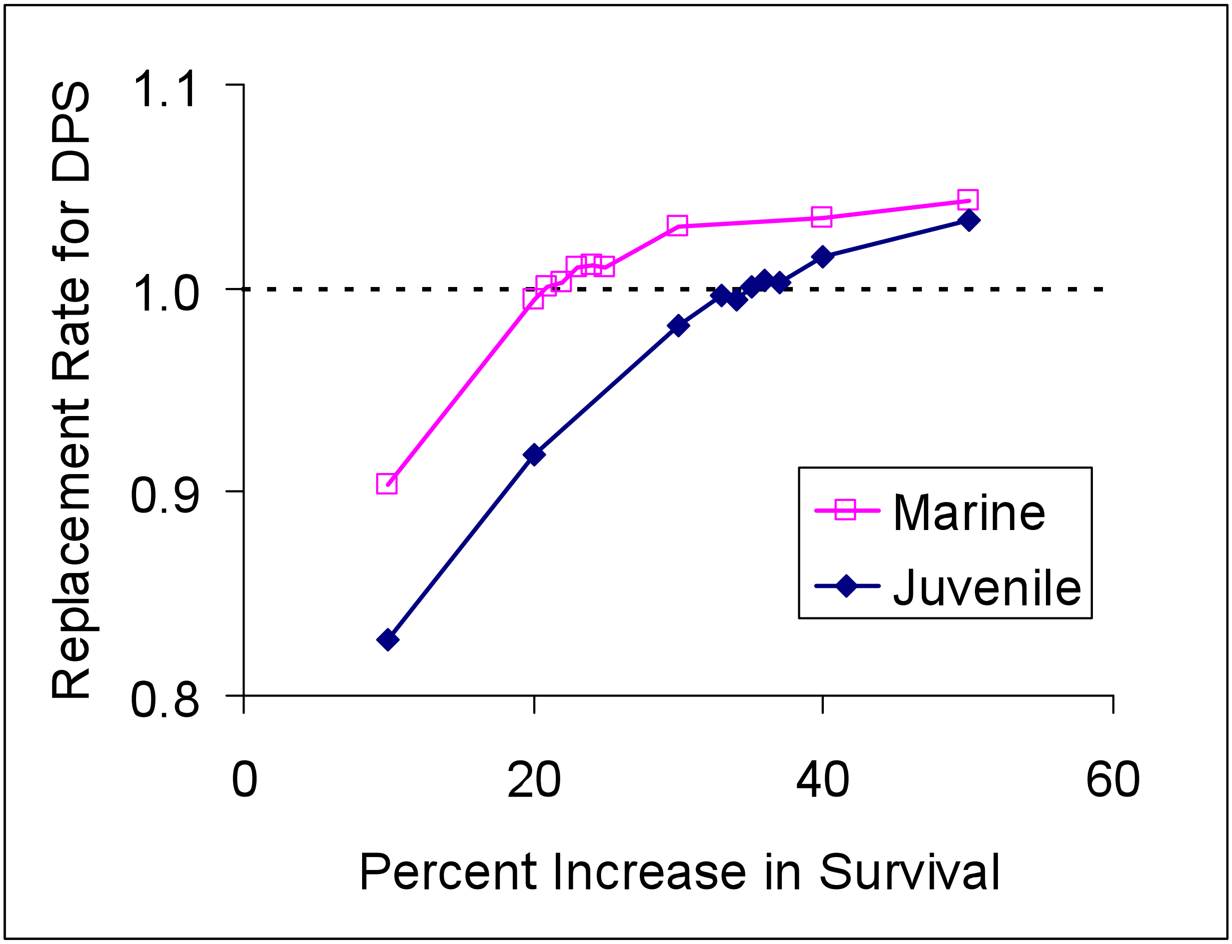

Figure 3. Legault (2005) modeled the viability of the Gulf of Maine Atlantic Salmon Distinct Population segment. This model allowed evaluation of an increase in vital rates (survival in freshwater or marine) needed to meet replacement level of 1 (population stability). This figure illustrates that a 20% increase in marine survival would result in a population increase, while a nearly 40% increase in freshwater production is needed to reach the same goal.

Defining the Biological Universe of Concern

Atlantic salmon go through several distinct phases in their life history, each identified by specific behavioral and physiological changes and also by changes in habitat use (Figure 4). General descriptions of the life history of Atlantic salmon are available in MacKenzie and Moring (1988), Bley and Moring (1988), Stanley and Trial (1995), Baum (1997), and Fay et al. (2006).

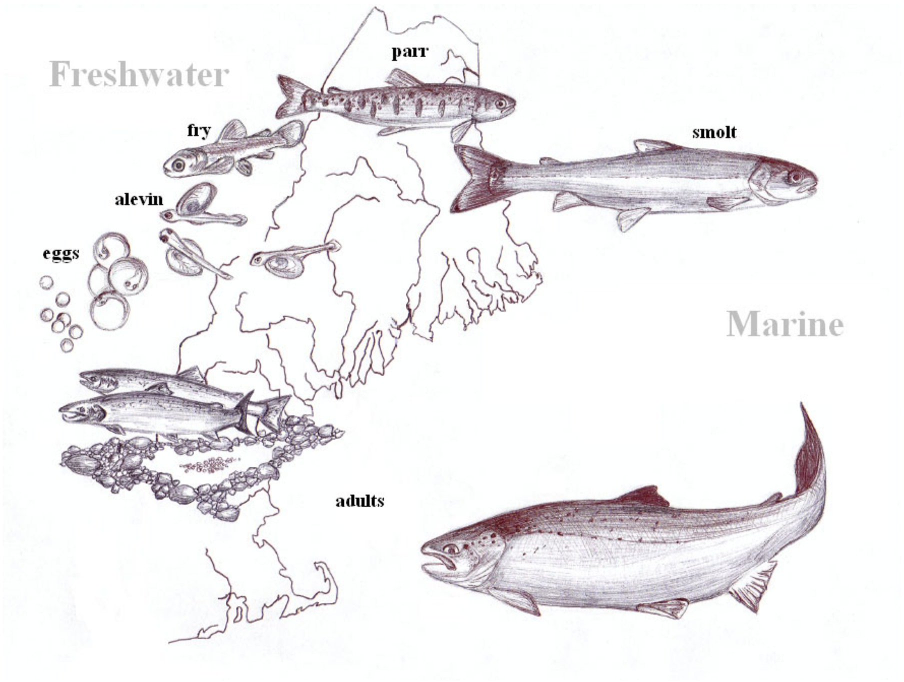

Figure 4. Atlantic salmon life cycle (illustration by Katrina Mueller).

The smolt stage is relatively short and marks the transition between the freshwater rearing habitat (where the fish are known as parr) and migration to the marine environment. In a salmon's second or third spring, when it has grown to a length of 13-23 centimeters, physiological changes result in visible morphological and behavioral changes. The juvenile fish loses its dark vertical banding (parr markings) and its body becomes streamlined and silvery with a more pronounced fork in the tail. Orientation in the water column changes from facing upstream to downstream. This process, called "smoltification," prepares the fish for the transition to saltwater (Hoar 1939; Farmer et al. 1977; Ruggles 1980; Bley 1987) and typically initiates in the fall preceding migration the following spring. To smolt or not to smolt is largely determined by an individual's size (length) and nutritional status during a critical period, defined by the annual photoperiod. For individuals that have initiated smoltification, local habitat conditions during the spring determine the actual timing of the migration. See McCormick et al. (1998) for a more complete description of the smoltification process.

As smolts emigrate from the rivers to the sea between April and June, they tend to travel near the water surface and must contend with changes in water temperature, salinity, pH, dissolved oxygen, pollution, and predation. Smolt movement in the fresher sections of estuaries is relatively passive, as the fish move seaward on ebb tides and remain neutral or move upstream on flood tides (Fried et al. 1978; Thorpe et al. 1981). As smolts enter the more saline portions of the estuary, their movements are more directed and less affected by tides. They move rapidly seaward at speeds averaging two body lengths per second (LaBar et al. 1978; 1.05 km/h in Kocik et al. 2009). Upon completing the physiological transition to salt water, the fish (now called post-smolts) grow to a length of 30-40 cm before the first winter at sea, a much larger size than most species of Pacific salmon at this stage. Post-smolts move in small schools and loose aggregations close to the surface (Dutil and Coutu 1988).

The marine life of Atlantic salmon of US origin is not as well understood as the river phase. Most of our knowledge has been gleaned from marking and tagging studies of fish stocked in the Connecticut, Merrimack, and Penobscot rivers. Over the history of the US program, marking has progressed from fin clipping (1942-present), to Carlin tags (1962-1992), and then to coded-wire tags (1982-1994) (Meister 1984; NOAA Fisheries unpublished data). Additional studies that have directly sampled Atlantic salmon in the ocean (e.g., Dutil and Coutu 1988; Reddin 1988; Ritter 1989; Reddin et al. 1991; Lacroix and Knox 2005) have provided insights about movements, exploitation, and population dynamics (Meister 1984; Friedland et al. 1993).

North American Atlantic salmon tend to move north and east in a seasonal pattern: spring migration through estuaries and the Gulf of Maine, and then along the Scotian Shelf (although some remain in the Bay of Fundy and Gulf of Maine to forage well into the summer). By early summer, post-smolts occur near Newfoundland, and by fall, the fish often congregate in a "post-smolt nursery area" in the southern Labrador Sea (Dutil and Coutu 1988). After their first winter, some fish travel north to Greenland while others remain in nursery areas or even revisit the coastal ocean (Friedland et al. 1999). A salmon swimming from Maine to southern Greenland could easily swim a one-way distance of 4,700 kilometers, or possibly 5,000 km if the fish migrated to Disko Bay, the northern end of the species' distribution at Greenland.

Gulf of Maine post-smolts become part of a mixture of Atlantic salmon stocks from US and Canadian rivers. Tagging data and scale growth analyses reveal that Maine post-smolts spend their first summer in the Bay of Fundy, Gulf of St. Lawrence, and along the Scotian Shelf (Meister 1984; Friedland et al. 1999). Tag recoveries from seabird colonies indicate that US post-smolts also occur in mid-summer off eastern Newfoundland (Montevecchi et al. 1988; Reddin and Short 1991). These findings complement older results that showed post-smolts moving very quickly and directly to the Labrador Sea, where the North American stock complex mixes with fish from Europe and Iceland. The US contribution to the stock complex has always been relatively low since production in US rivers accounts for a very small proportion of total Atlantic salmon production.

Most US-origin salmon spend two winters in the ocean (two sea winter or 2SW) before returning to natal streams to spawn. Some salmon, typically males, return after only one year at sea (1SW) at a smaller size, and are called grilse. Occasionally, a large 3SW salmon is found among returning adults. Adult salmon are thought to behave similarly to post-smolts, moving through the top six meters of the water column (Reddin 1985). Aggregations of adult Atlantic salmon can still occur after the first winter, but generally adults travel alone (Reddin 1985).

Homing to natal streams is facilitated using olfactory stimuli (Stasko et al. 1973). Adult Atlantic salmon ascend New England rivers from spring to fall, with a peak in June. Historically, the majority of adult Atlantic salmon in the Penobscot, Dennys, East Machias, Narraguagus, Kennebec, Androscoggin, and Saco rivers entered freshwater between May and mid-July and were called “early run,” whereas the majority of those returning to the St. Croix, Machias, and Ducktrap rivers entered freshwater after mid-July and were called “late run” (Baum 1997). Some rivers, such as the Sheepscot and Pleasant, had both early and late runs of Atlantic salmon (Baum 1997). Salmon returning early in the spring spend nearly five months in cool, deep pools before spawning in late October through November.

Diet and Predation

Marine-phase Atlantic salmon (post-smolts and adults) are opportunistic, generalist predators (Reddin 1988) that feed mainly near the surface but sometimes at depths (Hislop and Shelton 1993). The marine diet (Table 1) includes invertebrates and fish (Hislop and Youngson 1984; Jutila and Toivonen 1985; Fraser 1987; Hislop and Shelton 1993). As post-smolts grow, they feed increasingly on fish. Adult Atlantic salmon primarily eat fish, including capelin (*Mallotus villosus*), herring (*Clupea harengus*), and sand lance (*Ammodytes* spp.) (Hansen and Pethon 1985; Reddin 1985; Hislop and Shelton 1993).

Table 1. Marine Diets of Atlantic Salmon

	REGION	ATLANTIC SALMON PREY	REFERENCE
Post-smolt	Gulf of Maine	Atlantic herring, euphausiids (73%), polychaetes, copepods, isopods, amphipods, radiated shanny (*Ulvaria subbifurcata*), rock gunnel (*Pholis gunnellus*), sand lance, sea raven (*Hemitripterus americanus*), sculpin (*Myoxocephalus* spp.), wrymouth (*Cryptacanthodes maculatus*)	Renkawitz and Sheehan 2011 (see map)
	Bay of Fundy	amphipods, euphausiids (75%), sand lance, Atlantic herring, Atlantic cod (*Gadus morhua*), pollock (*Pollachius virens*)	Lacroix and Knox 2005
	Gulf of St. Lawrence	capelin, sand lance (89%), euphausiids, decapods, amphipods, surface insects	Dutil and Coutu 1988
	Labrador Sea	hyperiid amphipods (43%)	Reddin, unpublished
Adult	New Brunswick/ Newfoundland	capelin, Atlantic herring	Lear 1972
	Labrador Sea	barracudinas (Paralepididae), lanternfish (Myctophids), juvenile halibut (*Hypoglossus hypoglossus*), amphipods, euphausiids, shrimp, squid, octopus	Templeman 1967; Lear 1972; Lear 1980
	Grand Bank/Flemish Cap	Sand lance, capelin, squid, shrimp, lanternfish, amphipods, decapods	Templeman 1968; Reddin 1985
	Coastal West Greenland	Capelin, euphausiids, sand lance, amphipods, squid	Hansen 1965; Templeman 1968; Lear 1972; Lear 1980; NOAA Fisheries unpublished

Atlantic salmon post-smolts are preyed upon by cod, whiting (*Merluccius bilinearis*), cormorants, ducks, terns, gulls, and many other opportunistic predators (Hvidsten and Mokkelgjerd 1987; Gunnerod et al. 1988; Hvidsten and Lund 1988; Montevecchi et al. 1988; Hislop and Shelton 1993). Predation rates are difficult to estimate because of the wide spatial and temporal distribution of Atlantic salmon at low densities and the large variety of potential predators.

Young Atlantic salmon are one of several species of "little silvery fishes" that are prey for marine mammals and larger fish (Anthony 1994; Hammill 2000; Friedland et al. 2011a). Seals are important predators of returning salmon in Maine estuaries; 3-6% of adults at Penobscot traps show sign of marine mammal predation (J. Gilbert, personal communication). Historically, groundfish, particularly cod, were known to spawn in coastal waters in spring, and pre-spawning aggregations were thought to follow adult river herring (*Alosa* spp.) into river mouths (Ames 2004), potentially exposing emigrating smolts to predation. However, because young salmon travel near the water surface, deepwater, benthic predators such as cod could be less of a threat than surface-dwelling fish. Of potential predators, small (<24 cm) whiting, white hake (*Urophycis tenuis*) and dogfish (*Squalus* spp.) are most abundant in springtime inshore trawls, although smolts have not been found in stomach content analysis to date (S. Sherman, personal communication). In addition, climate-related shifts in species diversity influence the annual assemblage of these and other predators (Fisher et al. 2008, Friedland et al. 2011b).

Adult Atlantic salmon are less vulnerable to predation by the small piscivores (<24 cm silver and white hake) that feed upon post-smolts. Although most Atlantic salmon are caught near the surface, several benthic predators such as gadids, skates, and Greenland shark (*Somniosus microcephalus)* are known to prey on them at sea (Hislop and Shelton 1993). This information, and NOAA Fisheries acoustic depth tagging data, suggest that Atlantic salmon spend some time in deeper waters. However, much remains unknown about salmon predator-prey relationships.

Defining the Geophysical Universe of Concern

Large-scale geophysical processes such as oceanographic currents and climate have direct and indirect effects on salmon smolts, post-smolts, and adults at local to regional scales. Conditions in the Northwest Atlantic, including the Gulf of Maine, have been linked to large-scale climate phenomena. For example, variations in the relative strengths of atmospheric pressure systems (the Icelandic Low and Azores High) affect climate and weather, including patterns of temperature, precipitation, and wind over the continental US, the Gulf of Maine, and the Northwest Atlantic Ocean. The index of these systems, known as the North Atlantic Oscillation (NAO), is related to key oceanographic and ecological processes in the North Atlantic (Stenseth et al. 2002). The Atlantic Multi-decadal Oscillation (AMO) is a coherent pattern of variability in North Atlantic sea surface temperatures with a period of 60-80 years. Correlations between AMO and NAO anomalies and sea-surface temperatures are well developed (Hurrell and Dickson 2004).

In the North Atlantic/Gulf of Maine, changes in basin-scale atmospheric and oceanic conditions can impact all trophic levels of the marine ecosystem, including abundance, biomass, distribution, species assemblages, growth rates, and survival rates of phytoplankton, zooplankton, benthos, fish, marine diseases, whales, and seabirds (Drinkwater et al. 2003). Relationships linking climate variability and oceanographic responses in the Gulf of Maine remain unresolved, but understanding is increasing (Pershing et al. 2005; Friedland and Hare 2007; Nye et al. 2009). Although the Gulf of Maine water temperature record does not reflect Northern Hemisphere air temperatures, it does reflect changes in the Northwest Atlantic, such as weakening of the Gulf Stream and possible strengthening of the Labrador Current (Smith et al. 2001, Wanamaker 2007). Relationships with the NAO vary in direction and strength across the region and through time (Joyce 2002, Petrie 2007). For example, the NAO was correlated with deep water temperatures and copepod abundance in the Gulf of Maine from 1960-2000 (MERCINA 2001), but these relationships have become less prominent in the most recent decade (A. J. Pershing, *pers. comm.*).

The Gulf of Maine's sensitivity to climate variability was illustrated during the 1990s. In 1989, a pulse of cold, low-salinity water originating from melting Arctic ice caused shelf waters from the Labrador Sea to the Mid-Atlantic Bight to freshen significantly (Smith et al. 2001, Mountain 2003). This led to early stratification, early/larger winter phytoplankton blooms, and generated early production of smaller zooplankton (copepod) species in Gulf of Maine (Pershing et al. 2005; Greene and Pershing 2007, Kane 2007). Although the 1990s regime shift has been studied most closely in the Gulf of Maine, increasing evidence suggests that the changes observed in the Gulf of Maine (freshening, increased stratification, changes in zooplankton and phytoplankton) extend into the Newfoundland and Labrador region (de Young et al. 2004, Pershing et al. 2010). This raises the possibility that reduced survival of salmon during the 1990s was tied to climate-induced changes in the physical and biological conditions in their marine habitat.

II. RESEARCH PRIORITIES for Understanding Declining Marine Survival of Atlantic Salmon

Cairns (2001) reported four leading hypotheses of declining abundance of Atlantic salmon in estuarine-marine environments:

1) Post-fishery marine mortality is higher than presumed by fishery models.
2) Smolt survival is reduced due to fish predation in estuaries.
3) Bird and mammal predation reduces survival at sea.
4) Salmon have changed migration routes due to altered oceanographic conditions.

The 2008-2010 NOAA Fisheries Workshops were designed to reframe these existing North American Atlantic salmon mortality hypotheses and gain new perspectives. The deliberations focused on the migration of Atlantic salmon in the Gulf of Maine and did not address the freshwater life stages, except where effects may have affected marine phases (see http://www.seagrant.umaine.edu/extension/nmfs-salmon-ecology for a list of identified non-marine hypotheses). We placed emphasis on identifying parameters that could be managed at local or regional scales, and those with particular relevance to Gulf of Maine Atlantic salmon. Rather than a single, high-profile species approach, our interdisciplinary group felt that integration of climate, environmental, fisheries, and community ecology studies will foster an approach aimed at understanding and managing for the functional aspects and flexibility of the salmonid ecosystem. Six hypotheses emerged from the workshops as priority areas for research:

1. Climate change and variability have altered oceanic salmon habitat (temperature, productivity, physical oceanography), affecting marine survival of Gulf of Maine Atlantic salmon (see Cairns et al. 2001, hypotheses V.8.a and b).

2. Altered oceanographic conditions [meteorologically-driven shifts in current velocity and direction] have led to changes in migration routes/behavior resulting in reduced marine survival of Gulf of Maine Atlantic salmon (see Cairns et al. 2001, V.7.a),

3. Changes in Northeast Shelf marine communities have altered Atlantic salmon food webs, resulting in reduced marine survival of Gulf of Maine Atlantic salmon (see Cairns et al. 2001, V.7.b).

4. Populations of other diadromous species in the Gulf of Maine have declined, resulting in reduced marine survival of Gulf of Maine Atlantic salmon.

5. Climate change has disrupted the correspondence between freshwater and saltwater conditions, leading to greater mortality rates of smolts and affecting marine survival of Gulf of Maine Atlantic salmon.

6. A loss of genetic diversity has reduced life history diversity, including adult run timing and variability in marine migration routes, affecting marine survival of Gulf of Maine Atlantic salmon.

These are described in detail on the following pages, along with the rationale, a range of proposed research activities and approaches, and existing data sets (see Appendix C) that might be used in evaluating each hypothesis. The research activities range from the broad to the specific, from the ideal to the practical. The suggested studies also vary in length and timing. Some questions may require five studies over fifteen years, while others can be clarified within a few years. Where possible, management implications are highlighted.

1. Hypothesis: **Climate change and variability have altered oceanic habitat (temperature, productivity, physical oceanography), affecting marine survival of Gulf of Maine Atlantic salmon.**

During the 1990s, a regime shift occurred in the shelf ecosystems of the Northwest Atlantic, affecting both physical and biological processes (Chaput et al. 2005; Jacobson et al. 2009) and multiple species and trophic levels (Gao 2002; Pershing et al. 2005; see "Defining the Geophysical Universe"). This shift provides an opportunity to examine whether changes generated by climate variability altered the temporal and spatial distributions of preferred habitat for Atlantic salmon (Cairns 2001).

Climatic effects on Atlantic salmon can be physical (i.e., temperature and hydrography related) and biological (prey and predator related). For example, changes in temperature and ocean currents could alter the arrival time of salmon to feeding grounds (see Hypotheses 2 and 5). Shifts in oceanographic productivity could affect salmon prey or the spatial/temporal distribution of salmon predators (at one or more life stages) in nursery areas or on migration routes (see Hypotheses 2 and 3). The mismatch created by these altered patterns and dynamics might have a major influence on salmon survival.

Expanding analyses of salmon population dynamics in the marine environment to include multiple trophic levels (e.g., chlorophyll-a, plankton and/or forage fish, top predators) and abiotic conditions (temperature, salinity, mixing depths, current speeds, etc.) may help to identify the most influential ecological processes.

Key Initial Research Activities (see Appendix C for data set description and links)

1.1 Analyze the effects of climate variability and change (AMO, NAO, regime shift pattern) on salmon habitats in the Northwest Atlantic to identify and quantify specific mechanisms (e.g., bottom-up control via primary productivity and prey availability or top-down control via predation) and their relative influence on salmon survival.

1.2 Develop spatial/temporal niche models—using thermal preferences of salmon and their predators, prey, and competitors—to predict changes in salmon distribution and post-smolt migration pathways.

1.3 Apply results to General Circulation Models to predict potential climate change effects on salmon growth and survival.

Management Prescriptions

- Assess post-smolt populations for possible heritable differences in geographic distribution at sea; apply this knowledge in hatchery production to promote phenotypes that avoid potential stress areas while conserving migration pattern diversity.

- Identify spatial/temporal scales for conducting predator population studies.

- If top-down processes are identified as influential, apply ecosystem-based management principles to mitigate predation in the short-term (e.g., changes in fishing regulations, targeted predator control, increased stocking), while developing long-term solutions (restoration of estuarine species abundance, diversity, and habitat complexity).

2. Hypothesis: **Altered oceanographic conditions [meteorologically-driven shifts in current velocity and direction] have led to changes in migration routes/behavior resulting in reduced marine survival of Gulf of Maine Atlantic salmon.**

In late May when Atlantic salmon post-smolts travel through the Gulf of Maine, they swim near the surface and are thereby affected by winds and wind-driven currents. Limited evidence suggests that offshore conditions influence nearshore conditions, but not consistently due to heterogeneity in the Gulf of Maine. If changes in oceanographic conditions alter migration routes of salmon to areas with insufficient prey, reduced habitat, or increased predators, then survival of such fish would be reduced (Cairns 2001).

The spring-summer post-smolt migration occurs as current patterns in the Gulf of Maine develop based on the strength of the Eastern Maine Coastal Current (EMCC) and on the prevailing winds. Decadal-scale changes in spring wind patterns appear to be related to the survival patterns of Gulf of Maine Atlantic salmon (Friedland et al. 2011a). Typically, the EMCC flows from east to west along the Maine coast, and veers south (offshore) at Penobscot Bay toward the central Gulf of Maine as winds push surface water offshore. Salmon energetic migration costs might be expected to be lower (and salmon survival greater) during these conditions than in years when northeasterly storms push the EMCC to "flow through" to the west.

Sea surface temperature can vary seasonally depending on the location of fronts. Characterized by internal wave generation and breaking, water mass exchange, and wind-driven transient upwelling, fronts can be dynamic zones of energy transfer and high biological activity. North of Nantucket Shoals, tidal mixing fronts and fronts associated with the EMCC occur in summer. In winter, fronts occur over the inner and middle shelf from Cape Hatteras to the Bay of Fundy, and are characterized by cold sea surface temperatures on their landward (shallow) side resulting from surface cooling (Ullman et al. 1999). Do these differences in current flows and front position affect post-smolt survival?

From the 1980s to the 1990s, water inflow to the Gulf of Maine from the Scotian Shelf increased, affecting water properties and the zooplankton community in the Gulf region (Mountain and Kane 2010). With the greater southwesterly flow of water into the Gulf of Maine, northward migrating salmon in the 1990s may have encountered stronger opposing currents than existed in earlier decades and therefore experienced higher energetic migration costs.

Key Initial Research Activities

2.1 Analyze interannual variability in Gulf of Maine circulation and current patterns (EMCC strength and position, Penobscot River discharge, satellite sea surface temperature data) along theoretical salmon migration transects, and compare with post-smolt emigration and adult return rates.

2.2 Define salmon habitat spatially (examine hydrographic structure across the Scotian Shelf and Labrador shelf to identify extent of favorable conditions) and evaluate salmon energetic costs along migration routes.

2.3 Establish relationship of hydrography (eddy intensity and current structure) in Labrador Sea to salmon migration routes/marine survival, with appropriate cohort lag for returns.

2.4 Use satellite imagery to locate seasonal, daily, or “real-time” fronts and temperature anomalies, and compare to historical commercial salmon fishing data. Adapt smolt sampling and telemetry based on the results.

2.5 Compare the influence of a fixed migration pathway versus variable migration pathways on salmon arrival at post-smolt nurseries to evaluate whether local areas of reduced ocean productivity are limiting the return of fish from some stocks.

Management Prescriptions

- Match hatchery production to natural cycles based on documented and predicted environmental conditions and changes.

- Use improved forecasting to manage broodstock collections. Predict return rates based on marine habitat conditions in post-smolt nursery areas or transit pathways in the Labrador Sea, and use this information to optimize hatchery selection and salmon releases to marine conditions.

3. Hypothesis: **Changes in Northeast Shelf marine communities have altered Atlantic salmon food webs, resulting in reduced marine survival of Gulf of Maine Atlantic salmon.**

Maine salmon consume a range of marine pelagic and epibenthic fauna as they grow from post-smolts to adults. Could changes in prey fields, resulting from climate changes, cause declines in marine survival of Atlantic salmon? For example, capelin abundance in offshore Newfoundland and Labrador waters declined in the 1990s, despite predictions that abundance would increase due to fewer predators, especially cod (Carscadden et al. 2001; Frank et al. 2005). Two possible reasons for the reduced capelin abundance include (a) the early 1990s freshening and (b) the transport of cold-water shrimp and crabs from the sub-Arctic. Cod diet data (Sherwood et al. 2007) showed very little pelagic prey available in traditional capelin feeding areas, with cod feeding mostly on shrimp, which had increased in abundance (S. Sherman, personal communication). Scarcity of capelin (a lipid-rich prey source) has likely impeded cod recovery and may have negative impacts on other piscivorous predators, including Atlantic salmon.

Seabird diets can be used as a proxy for the prey field available to salmon. Gannet (*Morus bassanus*) diets reflect a dynamic food web in the North Atlantic, with dominant prey shifting between warm-water (mackerel [*Scomber scombrus*], squid) and cold-water (capelin) species (Davoren and Montevecchi 2003). Gannets and other seabirds also prey on salmon; however, positive correlations between bird diets and salmon returns suggest that gannets are not impacting salmon populations, and that the birds shift to other preferred prey when these are available (Montevecchi et al. 2002).

In the early 1990s, the regime changes in the Northwest Atlantic affected the entire shelf system from Labrador to Cape Hatteras (Hare and Able 2007; Friedland and Hare 2007; Nye et al. 2009). This change affected multiple trophic levels, from early/larger winter phytoplankton blooms and early production of smaller zooplankton (copepod) species in Gulf of Maine (Greene and Pershing 2003, Pershing et al. 2005, Greene and Pershing 2007, Greene et al. 2008) to a major shift in adult fish stocks (Link et al. 2002; Nye et al. 2009). Within the Gulf of Maine, these changes shifted the distributions of both southern and northern species. In addition, the strength of climate forcing via the North Atlantic Oscillation (NAO) is related to annual changes in local diversity of potential predators: 133 species showed at least a 20% difference in frequency of occurrence in years with opposing NAO states in the Northwest Atlantic (Fisher et al. 2008). Predators adjusted their distributions in the spring (from Massachusetts coast to Gulf of Maine) in response to warming temperatures; redfish (*Sebastes fasciatus*), cod, rosefish (*Helicolenus dactylopterus*), goosefish (*Lophius americanus*), hake, pollock, sea raven (*Hemitripterus americanus*), and dogfish became more abundant in the Gulf of Maine region.

Another recent analysis (Friedland et al. 2011a) found that six potential predator species have increased in abundance over most or part of the Gulf of Maine associated with post-smolt migrations. Increased abundance of whiting, red hake (*Urophycis chuss*), dogfish, goosefish, sea raven, and rosefish were negatively correlated with returns of 2SW salmon to the Penobscot River.

Key Initial Research Activities

3.1 Using data from post-smolt surface trawls with bottom trawls, acoustics, and observations of seabird and mammals, identify (e.g., with size spectrum analysis) the vertical structure, function, and within-year variability of the potential prey, predators, and competitors of Atlantic salmon under various spatial and temporal (including diurnal) conditions.

3.2 Estimate changes in abundance and distribution (horizontal and vertical) of key salmon prey, and evaluate the condition of salmon prey species via bioenergetic modeling to determine important linkages between environmental conditions (e.g., temperature) and salmon prey, and salmon growth and survival along the entire migration route.

3.3 Analyze historical food webs (e.g., stable isotope analysis of archived Atlantic salmon scale samples, zooplankton samples, and prey species) to examine possible shifts in salmon foraging (δ15N) and energy base/geography (δ13C; see Welch and Parsons 1993; Satterfield and Finney 2002; Kaeriyama et al. 2004). Perform food web experiments to validate isotope-diet relationships. Compare isotope results with historic growth and return rate data to evaluate food web processes on salmon survival at various life stages.

3.4 Monitor and characterize wounding rates on returning adults with methods designed to allow time-series comparisons.

Management Prescriptions

- Include salmon in any dialogue about conserving herring populations as forage base.

- Coordinate stocking experiments and research results dissemination with leadership from Maine Department of Marine Resources Bureau of Sea-Run Fisheries and Habitat to develop ecologically-based stocking products and release times.

4. Hypothesis: **Populations of other diadromous species in the Gulf of Maine have declined, resulting in reduced marine survival of Gulf of Maine Atlantic salmon.**

Historically, Atlantic salmon in the Gulf of Maine shared rivers and estuaries with at least 10 other species of diadromous fish; river herring (alewife, *Alosa pseudoharengus,* and blueback herring, *Alosa aestivalis*) and American shad (*Alosa sapidissima)* in particular were extremely abundant in many watersheds. This complex of species is thought to have provided benefits and services to Atlantic salmon and their habitat. For example:

- Prey buffering: Returning shad and river herring, which overlap spatially and temporally with emigrating salmon smolts and post-smolts, are similar in size to salmon but have a higher caloric content per individual (Schulze 1996). Historically, the abundance of these alosids was an order of magnitude greater than salmon (Smith 1894) and likely served as a robust alternative prey resource for predators that otherwise would have consumed salmon smolts, post-smolts, and adults (Mather 1998; USASAC 2004; Saunders et al. 2006).

- Habitat conditioning: In their late spring nest-building and spawning activity, sea lamprey (*Petromyzon marinus*) clean and loosen gravel streambeds, which Atlantic salmon could subsequently use in the fall for egg deposition.

- Marine derived nutrients: The millions of fish that once immigrated to Maine rivers transported significant quantities of nutrients (i.e., a marine subsidy) into upland watersheds, including juvenile salmon habitat.

- Adult forage: Immigrating small fish served as an important prey base for adult Atlantic salmon; for example, rainbow smelt (*Osmerus mordax*) in estuaries were consumed in large quantities by post-spawn kelts returning to sea (Hubley et al. 2008a).

However, many populations of these species have declined as a combined result of dams, pollution, and overfishing, reducing their potential functional roles in Atlantic salmon survival.

Key Initial Research Activities

4.1 Develop bioenergetics and foraging models of estuarine communities and salmon survival in river systems having different population sizes of river herring (complemented with marine surveys) to test whether adult river herring (and/or American shad) serve as predation buffers for emmigrating salmon smolts. If possible, conduct experimental manipulations of river herring and smolt abundance.

4.2 Quantify differences in the predator abundance and the encounter rates between predators and salmon. For example, quantify the presence of scars (mammal/avian predators) on returning adult Atlantic salmon in two river systems, with and without high American shad abundance, and if predation risk is a function of the geomorphology/structure of habitat.

4.3 Compare smolt production in streams with and without marine-derived nutrient additions and habitat conditioning (e.g., streams with and without spawning populations of sea lamprey) to evaluate if the addition of marine derived nutrients affects smolt production or migration timing.

4.4 Conduct a meta-analysis to determine if Atlantic salmon population status in Maine rivers is linked to the simultaneous presence of a full suite of native diadromous species. Conduct estuarine and coastal fish surveys to inform community composition and complexity evaluations.

Management Prescriptions

- Develop and implement a river herring/diadromous fish community monitoring program to generate good quality data on the timing and magnitude of runs in a variety of Maine's rivers.

- Support local efforts to enhance American shad and river herring runs in and around salmon rivers. Enhance fish passage and/or stock alewives into lakes (or blueback herring into river reaches) that are proximal to Atlantic salmon rearing habitat and where support for river herring restoration exists.

- Remove any artificial structures that increase predation rates in lower riverine and estuarine areas.

- Conduct predator deterrence programs: cormorant hazing, seal deterrent programs, striped bass (*Morone saxatilis*) removal, etc.

5. Hypothesis: **Climate change has disrupted the correspondence between freshwater and saltwater conditions, leading to greater mortality rates of smolts and affecting marine survival of Gulf of Maine Atlantic salmon.**

Atlantic salmon require specific habitat conditions for initiating smolt migration to ensure that smolts enter the ocean at an optimal time for survival (when marine waters provide adequate temperatures, food availability, and limited exposure to predators, etc.).

Water temperature of the freshwater rearing habitat is the primary “releasing factor” for migration. In Maine’s Atlantic salmon rivers, smolt migration generally begins when water temperatures exceed 5^{o}C (Whalen et al. 1999), and the migration intensifies as freshwater temperatures reach 8^{o}C to 12^{o}C. Other factors affecting the timing of the smolt migration include river discharge, water turbidity, and biotic interactions.

Atlantic salmon have survived climate change in the Gulf of Maine in the past. Historically, Gulf of Maine Atlantic salmon thrived during the low atmospheric temperatures of the Little Ice Age, but they also persisted in the middle Holocene when temperatures were likely higher than during recent times. Salmon identified at archaeological sites in Maine are associated with periods of higher lake levels and presumably higher flows in streams and rivers (Robinson and Jacobson 2009).

Climate-related changes, such as decreased snowpack, warmer spring temperatures, and even warmer fall water temperatures, alter local habitat conditions that influence smolt migration timing. Documented changes in the seasonal hydrology of Maine rivers include decreasing number of days with ice cover (Huntington et al. 2003; Hodgkins et al. 2005) and earlier peak (spring) runoff; increasing February flows over the last century; and decreasing May flows (Hodgkins et al. 2003; Huntington 2003; Dudley et al. 2008; Jacobson et al. 2009).

In the marine environment, correlations may have been identified between salmon mortality and several abiotic factors, particularly sea surface temperature (Scarnecchia 1984a, 1984b; Martin and Mitchell 1985; Scarnecchia et al. 1989; Friedland et al. 1993; Todd et al. 2008). Between 1982 and 2008, the area of intermediate habitat between 5°C and 15°C—the thermal universe for salmon—decreased (Ecosystem Assessment Program 2009). Variations in the water masses inhabited by post-smolts during their first months at sea have been associated with the recruitment pattern of the North American stock complex in the Gulf of St. Lawrence (Friedland et al. 2003a; 2003b) and the Gulf of Maine (Friedland et al. in press). These results indicate that freshwater and marine habitat changes have been asynchronous; postsmolts now emigrate into an increasingly warmer ocean and encounter elevated mortality risks associated with higher water temperatures.

Earlier onset of warmer water temperatures has influenced shifts in the spatial and temporal distributions of many marine species. Friedland et al. (2009) suggest that North American salmon recruitment is governed by a predator-mediated mechanism that is independent of post-smolt growth. Given the influx of warmer water species now entering Maine’s bays, salmon smolts face a new survival challenge, confronting predation pressure from unfamiliar, “warm-water” piscivores.

Key Initial Research Activities

5.1 Examine the effect of changes in smolt migration timing on survival using tagging studies and hatchery manipulations. Determine if run timing variation is heritable.

5.2 Correlate smolt migration timing with environmental conditions in the estuarine-marine transition zone for salmon post-smolts, including vertical profiles of oceanographic parameters (temperature, salinity, chlorophyll, turbidity, alkalinity, pH). Correlate migration timing with spring bloom/productivity conditions of the open ocean to evaluate whether smolt migration timing affects survival.

5.3 Continue to test the phenological mismatch between smolt migration and predator fields associated with higher seawater temperature.

Management Prescriptions

- Account for salmon post-smolt mortality in ecosystem-based fishery management, by quantifying the impact of predators on salmon post-smolts.

- Support the comprehensive monitoring of water temperature, salinity, chlorophyll-a, vertical zonation, etc., and form alliances with ocean observing groups.

6. Hypothesis: **A loss of genetic diversity has reduced life history diversity, including adult run timing and variability in marine migration routes, affecting marine survival of Gulf of Maine Atlantic salmon.**

Life history diversity allows a population to persist in a variable environment, as different phenotypes have varying levels of fitness in response to changing conditions. Diverse populations maintain the capacity to adapt to changing environmental conditions, for example, by the expression of physiological tolerances or behaviors in response to "bottlenecks." Small or declining populations generally have less genetic and phenotypic diversity, and therefore a reduced capacity to effectively respond to new environmental conditions (ICES 2004; see also Ebersol et al. 1997).

Small or declining populations frequently exhibit compensatory responses to reduced abundance, such as maturation at a younger age. In US Atlantic salmon, almost all sea-run 1SW grilse are males. Some freshwater resident juvenile males mature as precocious parr and successfully spawn (Moran et al. 1996). Females older than 2SW have always been uncommon but now are even more rare. Younger age-at-maturation can lead to higher population reproductive effort by reducing generation time. Conversely, it can also have negative consequences because older/larger females have higher egg numbers (with better egg quality), provide better parental care (i.e., dig deeper redds; Van den Berghe and Gross 1984), and have a greater probability of repeat spawning. The interaction of these differences in age and location of maturity provides a limited scope for adaptation that is complicated by gender differences.

In several Canadian Atlantic salmon stocks, fish are growing faster and altering their migration strategy: populations migrating through the Bay of Fundy/Scotian Shelf are not doing as well as northerly populations where post-smolts migrate directly to Greenland (Gibson 2006; Hubley et al. 2008b; LaCroix 2008; Byron in preparation). Groups of closely related fish appear to migrate together through oceanographic "choke points." For example, based on circulation patterns in the Gulf of St. Lawrence, migrating fish are predicted to exit via the Cabot Strait, yet tracking data show fish converging and traveling north through the Strait of Belle Isle (even fish whose natal rivers, such as the Margaree, are much closer to Cabot Strait). Similarly, kelts exiting the Miramichi River in 2008-2009 showed synchronous movement with smolts: the adults left four weeks earlier but seemed to pause somewhere in the Gulf of St. Lawrence (F. Whoriskey, unpublished data). Is it possible that this adult staging and migratory delay facilitates the adults waiting to "teach" the juveniles the migration route? If so, is this social transmission weakened or decoupled by a low adult abundance, as observed in other species (Brown and Laland 2003; Cooke et al. 2008)? Returning adults take a different route; perhaps both adults and juveniles simultaneously wait for particular conditions/mechanisms to trigger synchronous movement.

Key Initial Research Activities

6.1 Perform a quantitative assessment of the losses associated with small population size, testing factors such as influence of 3SW and repeat spawners. Sample returning adults to identify differences (e.g., genetic, fitness) between early and late arriving individuals (requires long-term sampling, as failure for early returns might reflect poor marine survival *not* local failure of reconditioned adults, and phenotypic diversity may change as marine survival changes).

6.2 Reconstruct historic run timing, age at maturity, sex-linked differences in maturity, and range in freshwater and saltwater residency, and other related variables to compare past and present diversity (geographic, genetic, phenotypic) to characterize the current adaptive scope of Maine Atlantic salmon populations.

6.3 Assess the frequency of precocious development or other means of cross-generational mating, and compare with high integrity (pristine) populations; i.e., use three to five "out groups" to generate a cline of expected conditions; deviation of Gulf of Maine fish would reflect a significant change.

6.4 Determine the existence of inter-generational communication via chemical signaling, with consequences for route finding by outgoing smolts or returning adults.

6.5 Evaluate population-specific thermal optima and tolerances.

Management Prescriptions

- Assess fitness of reconditioned spawned adults to increase frequency of repeat spawners.

- Explore utility of inter-basin transfers (i.e., stocking). Would this be a positive addition of new genetic material (i.e., moving fish from the south to the north to introduce warmer temperature thermal optima) or a negative due to loss of local adaptation? Focus hatchery and stocking efforts on those populations likely to tolerate warmer waters.

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APPENDIX A: THE WORKSHOPS

Workshops were organized based on salmon life stage/habitat, spanning the freshwater-saltwater smolt transition to adult migration. Steering committee members identified expertise in relevant disciplines and invited panel members to present their latest research within the context of Atlantic salmon life stage/habitat. Facilitated discussions after each panel were used to identify research questions, approaches, and relevant available data. Agendas and abstracts are listed in Appendix A, participants in Appendix B, and an inventory of data sets in Appendix C.

Workshop 1 in July 2008 highlighted the need for a contemporary analysis of data sets of river flows, precipitation (seasonal variability), temperatures, contaminants (including pH), and oceanographic water quality within the context of salmon declines (although the lack of long term data sets of implicated variables at the applicable spatial scale makes this approach difficult). Workshop 1 also identified several hypotheses for the recent decline in Atlantic salmon survival in the riverine/estuarine zone, including the relationship of salmon within a co-evolved diadromous species complex, and potential changes in the food web structure affecting feeding and predation.

The second workshop, held in January 2009, focused on the outer bays, and the Gulf of Maine/Gulf of St. Lawrence regions. Workshop participants identified a disconnect between data availability, models, and actual environmental conditions in the individual bays, gulfs, and the ocean. Differences in migration timing and behavior among populations exist within a context of heterogeneous environmental conditions. Because population declines are widespread, region-wide factors appear to override local factors. Discerning these effects requires the overlap of oceanographic and coastal fisheries research, and linking Atlantic Ocean models with coastal shelf/Gulf of Maine models.

The third workshop, in January 2010, focused on food web changes and changes in the predator/prey structure for Atlantic salmon. In the second half of the workshop, the project steering committee examined all hypotheses proposed to date, with particular emphasis on the marine-related research questions and suggested approaches and available data sets.

Marine Ecology of Gulf of Maine Atlantic Salmon
Sponsored by NOAA Fisheries and Maine Sea Grant

Workshop #1: Freshwater and Estuarine
July 22-23, 2008
Gulf of Maine Research Institute, Portland, Maine

Tuesday, July 22, 2008

12:30 – 1:00pm	Welcome presentation (John Kocik and Tim Sheehan, NOAA Fisheries)
1:00 – 3:00pm	Focus Area Panel #1: Freshwater Flows and Temperature Trends
3:00 – 3:30pm	Break
3:30 – 5:30pm	Focus Area Panel #2: Freshwater Quality
5:30pm	Wrap-up and adjourn (dinner on your own)

Wednesday, July 23, 2008

8:00 – 8:30am	continental breakfast (provided)
8:30 – 10:30am	Focus Area Panel #3: Estuarine Dynamics and Water/Sediment Quality
10:30 – 10:45am	Break
10:45 –12:30pm	Focus Area Panel #4: Predator-Prey Interactions
1:00 – 2:00pm	Lunch (provided)
2:00 – 3:00pm	Synthesis and wrap-up

Marine Ecology of Gulf of Maine Atlantic Salmon
Sponsored by NOAA Fisheries and Maine Sea Grant

Workshop #2: Bays and the Gulf of Maine

January 27-28, 2009
Eastland Park Hotel, Portland, Maine

Tuesday, January 27, 2009

9:30 – 10:00am	Welcome and logistics (Paul Anderson, John Kocik and Tim Sheehan, NOAA Fisheries)
10:00 – 12:00am	Kevin Friedland Recruitment of Atlantic Salmon
12:00 – 12:30pm	Lunch (provided)
12:30 – 2:30pm	Focus Area Panel #1: Climate forcing Moderator: Andy Pershing Panelists: Lew Incze, David Mountain, Rubao Ji, Jonathan Fisher
2:30 – 3:00pm	Break
3:00 – 5:00pm	Focus Area Panel #2: Post-smolt migration and distribution Moderator: Andrew Thomas Panelists: Jim Manning, Neal Pettigrew, Huijie Xue
5:00 - 5:30pm	Discussion and synthesis of hypotheses, adjourn (dinner on your own)

Wednesday, January 28, 2009

8:00 – 8:30am	Continental breakfast (provided)
8:30 – 10:30am	Focus Area Panel #3: Post-smolt growth Moderator: Mike Cooperman Panelists: Jamie Gibson, Pete Jumars, Jeff Runge
10:30 – 11:00am	Break
11:00 –1:00pm	Focus Area Panel #4: Predation on postsmolts Moderator: Jason Stockwell Panelists: Scott Hall, John Sowles
1:00 – 1:30pm	Lunch (provided)
1:30 – 3:00pm	Synthesis and wrap-up

Marine Ecology of Gulf of Maine Atlantic Salmon
Sponsored by NOAA Fisheries and Maine Sea Grant

Workshop #3: Prey and Predation in the Gulf of Maine
January 27-28, 2010
Regency Hotel, Portland, Maine

Wednesday, January 27, 2010

12:00 – 12:30pm	Lunch (provided)
12:30 – 1:00pm	Welcome and logistics (Paul Anderson, John Kocik)
1:00 – 4:00pm	Focus Area Panel: Prey and Predation in the Gulf of Maine Andrew Pershing (moderator) Graham Sherwood, Sally Sherman, Bill Montevecchi, Andrew Gilbert
4:00 – 5:00pm	Report Status (Catherine Schmitt) and process for tomorrow Dinner on your own

Thursday, January 28, 2010

8:30 - 10:30am	Report writing: Steering committee breakout sessions
10:30 – 11:00am	Break
11:00 – 12:00pm	Convene and review revised text, next steps and adjourn.

APPENDIX B: WORKSHOP PARTICIPANTS

Paul Anderson, Maine Sea Grant (SC)
Matthew Cieri, Maine Department of Marine Resources
Mary Colligan, NOAA Fisheries (SC)
Michael Cooperman, NOAA Fisheries
David Courtemanch, Maine Department of Environmental Protection
Rob Dudley, US Geological Survey
Adria Elskus, USGS Conte Laboratory
Jonathan Fisher, Queens University
Kevin Friedland, NOAA Fisheries
James Gibson, Bedford Institute of Oceanography
Andrew Gilbert, USGS Patuxent Wildlife Research Center
James Gilbert, University of Maine
Tom Hawley, National Weather Service
Thomas Huntington, US Geological Survey
Lew Incze, University of Southern Maine and Gulf of Maine Reearch Institute
Rubao Ji, Woods Hole Oceanographic Institution
Peter Jumars, University of Maine
John Kocik, NOAA Fisheries (SC)
Peter Larsen, Bigelow Laboratory
Jason Link, NOAA Northeast Fisheries Science Center
Martha Mather, Massachusetts Fish & Wildlife Unit
Steve McCormick, USGS Conte Laboratory
Steve Mierzykowski, US Fish & Wildlife Service
James Manning, NOAA Northeast Fisheries Science Center
William Montevecchi, Memorial University of Newfoundland
David Mountain
Andrew Pershing, University of Maine and Gulf of Maine Research Institute (SC)
Neal Pettigrew, University of Maine
Collin Roesler, University of Maine
Jeff Runge, University of Maine and Gulf of Maine Research Institute
Lauren Sahl, Maine Maritime Academy
Rory Saunders, NOAA Fisheries (SC)
Catherine Schmitt, Maine Sea Grant (SC)
Timothy Sheehan, NOAA Fisheries (SC)
Sally Sherman, Maine Department of Marine Resources
Graham Sherwood, Gulf of Maine Research Institute
John Sowles, Maine Department of Marine Resources
Jason Stockwell, Gulf of Maine Research Institute (SC)
Andrew Thomas, University of Maine (SC)
David Vallee, National Weather Service
Adam Vashon, USDA APHIS
Fred Whoriskey, Atlantic Salmon Federation (SC)

Theo Willis, University of Southern Maine
Karen Wilson, University of Southern Maine
Huijie Xue, University of Maine
Joseph Zydlewski, USGS Maine Cooperative Fish and Wildlife Research Unit

(SC): Steering Committee

APPENDIX C: DATA SETS

Physical/Oceanographic

Climate Modeling from IPCC
http://www.ipcc-data.org/

Climate Indices (NAO, AMO) NCAR
http://www.cgd.ucar.edu/cas/catalog/climind/

National Climatic Data Center
http://www.ncdc.noaa.gov/oa/ncdc.html

Atmospheric forcing model forecast data for the Gulf of Maine (2001-)
http://fvcom.smast.umassd.edu/research_projects/GB/mm5/index.html

NOAA Operational Model Archive and Distribution System (NOMADS) air-sea fluxes (wind, heat flux, fw flux), rivers, tides, and predicted open ocean conditions. Archived data available via OPeNDAP.
http://nomads.ncdc.noaa.gov/nomads.php

Bedford Institute of Oceanography Climate Database (1920-present)
http://www.bio.gc.ca/science/data-donnees/base/index-eng.php

Fisheries and Oceans Canada Hydrographic Climate Database
http://www.bio.gc.ca/science/data-donnees/base/climate-climat-eng.php

Water mass inventories in Gulf of Maine (UMaine Physical Oceanography Group)
http://gyre.umeoce.maine.edu

Ocean circulation & currents

Unstructured Grid Finite Volume Coastal Ocean Model, UMass Dartmouth
http://fvcom.smast.umassd.edu/FVCOM/index.html

Gulf of Maine/Princeton Ocean Model, UMaine Ocean Modeling Group
http://www.umeoce.maine.edu/Gulf-of-Maine/gom.htm

RAFOS floats and remote sensing of Gulf Stream and North Atlantic Current
http://www.po.gso.uri.edu/rafos/

Ocean Surface Topography from Space (NASA TOPEX)
http://sealevel.jpl.nasa.gov/

For Labrador Sea, see *Journal of Physical Oceanography* Vol. 32 No. 2, 2002.

Buoy data

GoMOOS data buoys, University of Maine
http://www.gomoos.org

World Ocean Database
http://www.nodc.noaa.gov/OC5/indprod.html

Integrated Ocean Observing System
http://ioos.gov/

Sea Surface Temperature

Extended Reconstruction Sea Surface Temperatures, NOAA
http://www.ncdc.noaa.gov/ersst/

Satellite Oceanography Data Lab, UMaine
http://www.seasurface.umaine.edu

Bottom Temperature, salinity, current velocity

Environmental Monitors on Lobster Traps (119 sites, 2001-present)
http://www.nefsc.noaa.gov/epd/ocean/MainPage/emolt.html

Gulf of Maine Nutrient and Hydrographic Database
http://grampus.umeoce.maine.edu/nutrients/

River discharge data, US Geological Survey
http://me.water.usgs.gov/

Biological data

Continuous plankton recorders (1960-present)

Gulf of Maine, NMFS
http://na.nefsc.noaa.gov/ecosystem.html

Canadian Shelf/North Atlantic, Sir Alister Hardy Foundation for Ocean Science
http://www.sahfos.ac.uk/

Satellite chlorophyll

NASA (1998-present)

oceancolor.gsfc.nasa.gov

Satellite Oceanography Data Lab (UMaine)
http://www.seasurface.umaine.edu

Damariscotta River Phytoplankton and Optics Sampling
http://perrylab.umeoce.maine.edu/mjperry.php

Monthly zooplankton data from western Gulf of Maine
http://www.st.nmfs.noaa.gov/plankton/data/ecomonsoopgom/index.html

Atlantic salmon, modern

Carlin tag data

SALTAG

NOAA Northeast Salmon Team post-smolt trawl surveys
http://www.nefsc.noaa.gov/salmon/Finalpost-smolttrawl.html

NOAA Northeast Salmon Team telemetry arrays
http://www.nefsc.noaa.gov/salmon/Finaltelemetry.html

SALSEA genetics and tracking data
http://www.nasco.int/sas/salseaamerica.htm

Atlantic salmon, historic

Report of ICES Workshop on the Development and Use of Historical Salmon Tagging Information from Oceanic Areas
http://www.nasco.int/sas/pdf/reports/misc/WKDUHSTI07.pdf

Retrospective Funk Island tag data (juvenile migration), Memorial University
http://play.psych.mun.ca/~mont/discovery.html

Trap counts (adult returns), state and provincial data sets
http://www.maine.gov/dmr/searunfish/trapcounts.htm

Broodstock collection (adult returns), Craig Brook National Fish Hatchery
http://www.fws.gov/northeast/craigbrook/

Traditional ecological knowledge

Maritime Aboriginal Aquatic Resources Secretariate
http://mapcmaars.ca/

Penobscot Indian Nation
http://www.penobscotnation.org/

Genetics

Genomics Research on Atlantic Salmon Project (GRASP), University of Victoria
http://www.genomebc.ca/portfolio/projects/fisheries-projects/

Genetics technical assistance
http://www.lsc.usgs.gov/?q=cafb-genetics-tools

Population Viability Analysis
(See Legault 2005)

Community structure (other fish/predators/prey)

Maine-New Hampshire inshore trawl survey (2000)
http://www.maine.gov/dmr/rm/trawl/index.htm

NMFS bottom trawl survey (1963-)
http://www.gulfofmaine-census.org/data-mapping/visualizations/nmfs-nefsc-bottom-trawl-survey-by-year/

Canadian Science Advisory Secretariat, Status reports for stocks, ecosystem, habitat
http://www.dfo-mpo.gc.ca/csas-sccs/process-processus/sar-as/index-eng.htm

FishBase
http://fishbase.org/

Future of Marine Animal Populations, Census of Marine Life
http://www.gulfofmaine-census.org/

American shad and alewife abundance, Maine DMR
http://www.maine.gov/dmr/searunfish/programs/index.htm

Striped bass stock assessment, ASMFC
http://www.asmfc.org/

Community Aquatic Monitoring Program
http://www.glf.dfo-mpo.gc.ca/e0006182

New Brunswick Aquatic data warehouse
http://www.unb.ca/research/institutes/cri/nbaquatic/

Atlantic Canada conservation data set
http://www.accdc.com

Canadian Aquatic Biomonitoring Network
http://cabin.cciw.ca

Committee on the Status of Endangered Wildlife in Canada
http://www.cosewic.gc.ca/

Global invasive species database
http://www.issg.org/database/welcome/

Seabird distribution modeling for the western Atlantic, USGS
http://www.pwrc.usgs.gov/resshow/windpower/oconnell_seabird_dist.cfm

Cormorant nesting data
www.fws.gov/migratorybirds/CurrentBirdIssues/Management/cormorant/cormorant.html