Gulf of Maine Council on the Marine Environment
Climate Change Network

Identifying the Possible Effects of Climate Change on Invasive Species in the Gulf of Maine – a Background Report

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Introduction

The Gulf of Maine Council on the Marine Environment (GoMC) was established in 1989 by the Governments of Nova Scotia, New Brunswick, Maine, New Hampshire, and Massachusetts to foster cooperative actions within the Gulf watershed.[1] The Council consists of committees falling under the headings of habitats, maritime activities, services, and cross cutting. Under these general headings there are several sub committees, such as habitat monitoring and IT and mapping initiatives.

The two cross cutting committees consist of the Ecosystem Indicator Partnership (ESIP) and the Climate Change Network. ESIP's activities focus on convening regional practitioners in six indicator areas: coastal development, contaminants and pathogens, eutrophication, aquatic habitat, fisheries and aquaculture, and climate change. ESIP is developing indicators for the Gulf of Maine (GoM) and integrating regional data for a new web-based reporting system for marine ecosystem monitoring. The Climate Change Network strives to bring the latest climate change science, impacts, and adaptation information to the Gulf of Maine community.[2]

The Climate Change Network is currently working toward completion of three sections of the 2007-2012 Action Plan (GoMC 2007) under Goal 1. These include:

1.6 Compile and disseminate information on coastal habitats and watersheds at risk due to climate change;

1.17 Conduct risk analysis and prioritize the vectors of invasive species and understand the effects of climate change;

1.18 Convene stakeholder workshops to identify and promote mitigative and adaptive strategies for dealing with sea-level rise and changes in water quality related to climate change.

This is the second of three documents addressing the background of the information available on climate change. The purpose of this document is to identify available research on climate change and the effect this may have on invasive species in the Gulf of Maine. The research primarily includes studies on invasive species, habitats, oceanography, and the indicators of climate change. The focus is to bring together the available information in publications and maps and to begin to identify where gaps may exist. Recommendations for further work are subsequently suggested.

[1] http://www.gulfofmaine.org/

[2] http://www.gulfofmaine.org/council/committees/

The Gulf of Maine Overview

The Gulf of Maine is roughly rectangular in shape with approximately 21 basins, the deepest of which include Georges, Wilkinson and Jordan basins (300-400 m). The Gulf, which has an area covering approximately 93 000 km^2 (36 000 mi^2) of ocean, 12 000 km (7 500 mi) of coastline, and a watershed of 179 000 km^2 (69 000 mi^2) is of significant importance to many species of marine, estuarine, freshwater and terrestrial origin. Many of the habitats found in this region are sensitive to environmental change and are constantly under threat from human activities both direct, such as point source pollution (e.g. sewage effluent) and human development (coastal barriers); and indirect, such as non-point source pollution (e.g. acid rain) and climate change impacts (e.g. sea-level rise). One growing threat to ecosystems across the globe is that of invasive or non-native species. This is becoming a great concern both ecologically and economically as the frequency and volume of transport between various areas of the world is increasing.

The Gulf of Maine and its watershed has a diversity of environments, which give rise to many habitats both terrestrial and aquatic. In order to study the effect of invasive species and the impacts climate change may have on these, the environments they inhabit can be grouped into three main categories: terrestrial, freshwater, and marine. These are by no means ecosystems in isolation. All activities of one area have consequences on each of the other, and many species will reside in more than one system during their life cycle. An example would be anadromous fish (e.g. salmon) for which the combined effect of invasive species and climate change could be devastating.

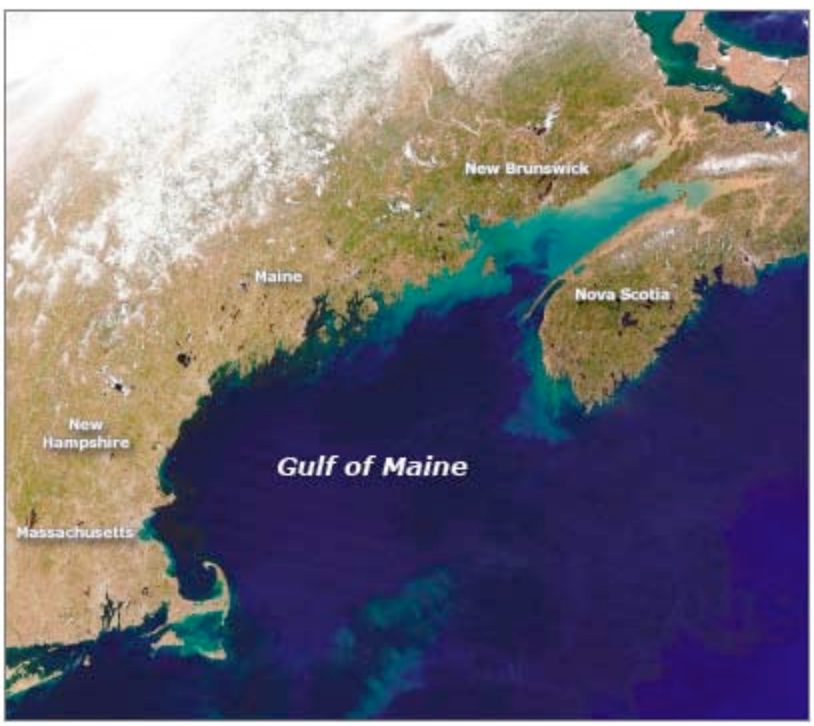

Figure 1: the Gulf of Maine

The Environments

The distinctive topography of peaks and plateaus of the Appalachian Mountains and the rocky coastlines give hints of the icy past. Glaciers cut valleys and shaped coastlines, scouring rock from one areas and depositing in others. This created a mosaic of forest types, numerous swamp and lake water basins and an undersea shelf as diverse as any on earth. The mountains and plateaus are underlain by granite and metamorphic rocks and are often thinly mantled by glacial till.

The climate is characterized by warm, moist summers and cold, snowy winters. Maritime air masses moderate the extremes and bring precipitation to the area year round and evenly distributed in the forms of either rain or snow with a mean annual rate of 1000-1600mm. This increases towards the Atlantic coast and at higher elevations. Inclusive of areas slightly inland and to the west of the Gulf watershed mean annual temperatures range from 3°C to 6.5°C, rising in the east, and mean summer temperature is 14.5°C. Mean winter temperature within this region ranges considerably, from -7.5°C in the northern New Brunswick Uplands to -1.5°C along the Atlantic coast of Nova Scotia.[3]

Figure 2: Fundy National Park, N.B. (photo by S. Leslie)

Terrestrial Environment

The terrestrial environment in the GoM consists mostly of temperate deciduous forests in the New England States changing to mixed deciduous and coniferous forests in northern Maine, New Brunswick and Nova Scotia. Forested areas make up some

[3] http://www.nationalgeographic.com/wildworld/profiles/terrestrial/na/na0410.html

91 700 square miles (237 600 square kilometres) and cover about 75% of land.

The World Wildlife Fund and National Geographic have divided the world into 'ecoregions'. The GoM comprises two of these regions: the Northeastern coastal forests and the New England-Acadian forests. The Northeast coastal forests range from Maryland to Southern Maine. These forests are dominated by oak and have lost almost all native American Chestnut trees to a parasite (*Endothia parasitica*) brought in by Chinese chestnuts in 1904. Invasive species are still a major threat to this forest system.[4]

The second forest type can be described as a transition zone between the boreal spruce-fir forest to the north and the deciduous forest to the south, with the Atlantic Ocean strongly influencing vegetation dynamics of the ecoregion, especially in coastal areas. Along the Fundy Coast, high winds, cooler summers and strongly broken topography with many areas of shallow soil result in a greater occurrence of conifer-dominated forests. Introduced species are also a threat here. "During the last few decades certain introduced shrubs, vines, and trees such as Japanese honeysuckle (*Lonicera japonica*), Oriental bitterwseet (*Celastrus orbiculatus*), shrub honeysuckle (*Lonicera* spp.), multiflora rose (*Rosa multiflora*), autumn olive (*Elaeagnus umbellata*) and Norway maple (*Acer platanoides*) have become serious competitors in many post-agricultural and forest communities in New England".[4]

Urban areas comprise a few densely populated cities such as Boston, Portland, and Saint John with smaller towns and villages dotted along the coast and interior. Compared to other provinces and states, this part of Canada and the US is sparsely populated.

Swathes of agricultural land that support seasonal crops and livestock can be found throughout the region. In Nova Scotia the main agricultural area is partly at sea level behind levees in the Dykelands along the Bay of Fundy and in the Annapolis Valley. Elsewhere in the GoM farming is generally within easy reach of major transport routes and freshwater sources. This itself has impacts on the watershed habitats as alterations to land for drainage or irrigation disturb ecosystems and chemicals such as pesticides and fertilizers indiscriminately kill non-harmful species and cause eutrophication. Invasive species have been a part of terrestrial environments for centuries and forestry and agriculture have been subsequent victims.

[4] http://www.worldwildlife.org/wildworld/profiles/terrestrial/na/na0411_full.html

Figure 3: Atlantic salmon in Maine river (photo by USFWS)[5]

[illegible]

Freshwater is in abundance in the GoM. The many rivers, lakes and coastal wetlands in the Gulf of Maine watershed provide productive nurseries for many marine fish, riverine pathways for historically abundant populations of anadromous fish, important habitat for breeding, migratory and wintering waterbirds and neotropical migrants, and vital habitat for nationally threatened and endangered species.[6] The watershed area encompasses much of Nova Scotia, New Brunswick, Maine, New Hampshire and Massachusetts, and a small portion of Quebec. The total land area of this watershed is 69 115 square miles, or 179 008 square kilometres.[7] Figure 4 shows the Gulf of Maine Watershed including major river basins.

More than sixty rivers with thousands of tributaries make their way through the watershed and drain around 250 billion gallons into the Gulf basin each year. The drainage network comprises 176 699 km^2 (69 115mi^2). Found within are the riparian zones, a vital and often overlooked area of the freshwater environment. Riparian areas form the transition zones where land meets water. They are vegetated habitats such as forests, which fringe the shores of rivers, lakes ponds and coastlines and are vital to the ecosystem as they filter water, control flooding, maintain water quality conditions, such as cool water temperatures and are an important food source for aquatic invertebrates.[8] These invertebrates in turn support ecologically diverse food web including 12 of the 87 known diadromous fish species in the world.

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[5] http://www.maine.gov/ifw/wildlife/species/endangered_species/atlantic_salmon/

[6] http://www.beginningwithhabitat.org/about_bwh/index.html

[7] http://www.gulfofmaine.org/knowledgebase/aboutthegulf/aseabesidethesea.php

[8] http://www.gulfofmaine.org/times/fall2002/science_insights.html

Figure 4: watershed of the Gulf of Maine and its major tributaries[9]

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The marine environment is the largest and argumentatively the most important habitat in the GoM. A variety of seascapes and coastal habitats make up the marine ecosystem. The GoMC Knowledgebase[10] habitat type website breaks the marine habitats into six groups plus tidal action. From the Knowledgebase:

- ***Barrier banks and deep channel -*** Georges and Brown Banks define the seaward edge of the Gulf of Maine, forming a barrier to the North Atlantic. Glacial erosion created the deeper western region of the Gulf of Maine. This higher barrier marks the southern extent of the glaciers during the Ice Age. The deep, cold nutrient-rich water reaches up from the deep ocean, mixes, and washes over this shelf-edge structure, contributing to the Gulf's high biological productivity. Feeding on this ‘soup’ are floating communities of microscopic plants, tiny shrimp-like animals, and jellyfish that concentrate on Georges Bank. This community of ani-

[9] http://www.gulfofmaine.org/knowledgebase/aboutthegulf/maps/mapsandphotos.php

[10] http://references.pearl.maine.edu/kb/search.asp

mals once sustained abundant populations of Atlantic cod and other ground fish until they were depleted by overfishing during the past 30 years. Between the banks is the Northeast Channel, a deep water conduit that brings dense, high-salinity, nutrient-rich water from the North Atlantic into the Gulf, where it settles into Jordan, Wilkinson, and Georges Basins.

• ***Banks and ledges*** - Stellwagen Bank and Cashes Ledge are two highly productive undersea islands within the Gulf of Maine. Covered with a layer of sand and gravel, their bedrock resisted glacial scouring that eroded and deepened adjacent basins. Probably nowhere in the Gulf are so many different habitats in such proximity as in the Stellwagen Bank National Marine Sanctuary. From hardy anemone-like cerianthids nestled in the muddy sands along its flanks to juvenile cod hiding among its boulder fields, Stellwagen Bank and nearby Jeffreys Ledge exemplify marine biodiversity in northern waters. The multitudes of sand lance and herring on and around these undersea islands attract groundfish, bluefin tuna, and the mighty whales, making the Sanctuary one of the top whale watching spots in the world. Cashes Ledge is a mountain within the Gulf whose summit is capped by a unique kelp bed and whose clear waters support one of the deepest cold-water seaweed communities in the world. Its fields of anemones and varied sponge communities produce a singularly colourful and fascinating marine landscape.

• ***Coastal habitats -*** In the Gulf of Maine, the coastal zones of Maine and Nova Scotia have a high density of marine organisms and highest productivity.... Most lobsters, sea urchins, clams, scallops, shrimp, and mussels are harvested from the coastal zone, which extends three miles from land. This zone also has the most diverse habitats of the Gulf of Maine. The habitat diversity- a patchwork of rock, mud, sand, and gravel deposits scattered across the seafloor - is a consequence of sea-level changes that accompanied the Ice Age. As the glaciers melted away, they left a mixture of materials underwater. These materials were washed by waves and currents as the sea fell about 10000 years ago, and washed again as it rose to the present shoreline. This diversity of bottom habitats contributes to the variety of species found in the Gulf of Maine.

• ***Deep basins -*** Jordan, Wilkinson and Georges Basins, each more than 600 feet (200 metres) deep, are the deepest habitats within the Gulf of Maine. Their great depths resulted from glacial erosion of relatively soft rocks. In the summer, the water of these basins becomes layered into warm, nutrient-poor surface water; cold, nutrient-rich intermediate water; and cool high-salinity bottom water. On the seafloor of these basins live unique marine communities, such as fields of ‘pens’, primitive relatives of soft corals.

• ***The Gulf's currents -*** Currents flowing through the Gulf of Maine influence the underwater landscapes. Currents bring well-mixed, nutrient-rich water to the shores of the Gulf, where it supplies food to filter-feeding creatures, fertilizes kelp, and acts as a larval superhighway for species such as lobsters. Surface water completely circles the Gulf of Maine in three months, travelling approximately seven nautical miles a day. Driven by a cold current off the Nova Scotia coast- which enters the Gulf of Maine over Brown Bank and through the Northeast Channel — the Gulf's surface waters move in a counterclockwise pattern. This giant 'gyre' gains momentum from the world's most powerful tidal surges released from the Bay of Fundy, and from the fresh water that flows into the Gulf from the major rivers of its watershed.

- ***Sheltered bays –*** ...for the past 350 years Boston Harbor has served as a center for shipping and international trade. Expanding population and industrial growth had its price, however, with sewage and industrial discharges and urban runoff causing tremendous pollution problems. By the late 1970s, most of Boston Harbor was closed to shellfishing, fishing, and swimming. Beginning in the 1980s, a massive sewage treatment project, along with industrial toxics and urban runoff programs, has led to a true success story. Today, beaches are consistently safe for swimming; shellfish beds are reopened; and porpoises, seals, and striped bass are returning to their old haunts in Boston Harbor and Massachusetts Bay.

- ***Tidal action -*** With a tidal range of nearly 15 metres, the Bay of Fundy has the highest tides in the world. Twice a day, vast areas of the seafloor are uncovered at low tide, revealing large sand bars, mud flats, and even ancient forests drowned by the rise of the sea. Tidal action mixes the ocean water and makes the entire nearshore system highly productive. As a result, whales- including the endangered North Atlantic right whale- migrate to feed on the bounty of zooplankton in the mouth of the Bay. In the upper reaches of the Bay of Fundy at low tide, many species of migratory birds 'up' prior to their long southerly migrations by consuming large quantities of tidal-flat animals, like sea fleas and mud shrimp. The cool, nutrient rich, tidally-mixed water then flows from the bay along the Maine coast, creating a unique, foggy microclimate and increasing fertility of waters to the southwest.

Physical Oceanography

The water in the Gulf of Maine is primarily dominated by the presence of the frigid waters of the Labrador Current. These enter through the Northeast Channel at the southern tip of Nova Scotia then circle counterclockwise northeast to southwest for three months. These waters finally exit at the Great South Channel near Cape Cod and mix with the Gulf Stream. See Figure 6. Occasionally the Gulf Stream will enter the Gulf bringing with it warmer waters and subtropical organisms.

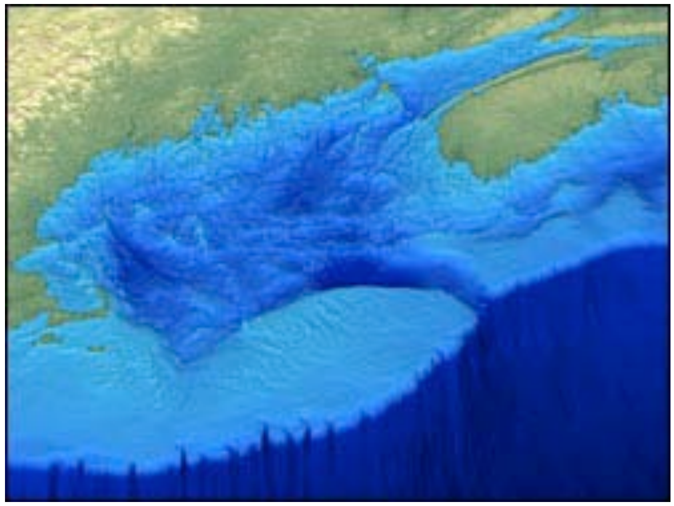

Figure 5: bathymetry map of the Gulf of Maine

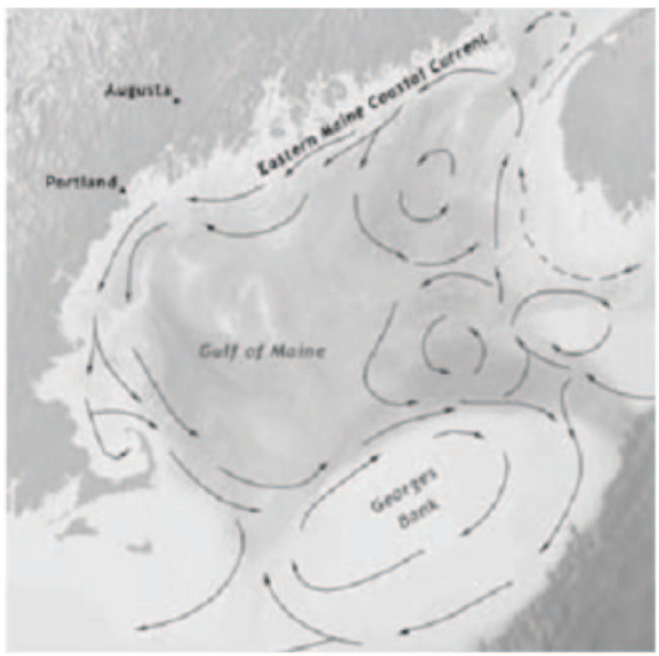

Figure 6: direction of ocean currents in the Gulf of Maine (map by Chris Brehme. redrawn from map by Neal R. Pettigrew)

[illegible]

Our understanding of the impacts of climate change on the marine environment is somewhat less certain and detailed than what we know about the land and the air, and even the freshwater environment. The extent of these climate change impacts will depend, in large degree, on the interaction between the oceans and atmosphere. Much work is being done to understand this relationship, and the latest assessment by the Intergovernmental Panel on Climate Change (IPCC, 2007) extrapolates our current understanding to implications for climate change. For example, Nicholls et al. (2007) concluded that sea surface temperature may increase 1.5-2.6°C on average globally by the end of the century. This may result in changes to circulation, increased stratification, and increased dissolved CO_2. The latter may lead to increased ocean acidity (Nicholls et al., 2007).

Fluctuations in the Gulf Stream, Labrador Current, and the North Atlantic Decadal Oscillation bring predictable changes in temperature and mixing in the Gulf of Maine. Future climate change impacts on these are not well understood and may bring changes to the Gulf outside of its normal range of variation.

Indicators of Past and Future Climate Change

Understanding climate change is not limited to computer-based and other scientific models. Many of the impacts can be readily detected over time, through deliberate observations of current events or data mining of past records. Making such observations and understanding their relationship to climate change can result in the development of climate change indicators. Once identified, these indicators can tell us which aspects of a local system are sensitive to climate change and thus should be monitored into the future to better understand how climate change is driving changes in the local ecosystems.

In the Gulf of Maine region several efforts to develop climate change indicators have taken place in recent years. Clean Air - Cool Planet and Wake (2005) looked at indicators in the North-eastern U.S., and Wake et al. (2006) built upon that effort by expanding the area to include the Maritime Provinces. The mostly terrestrial indicators included timing and magnitude of meteorological, hydrological, and phenological events over the last 100 years and generally indicated a trend toward a warmer, wetter climate for the region. Both sea-level rise and sea surface temperature, the two marine-specific indicators chosen, showed upward trends.

Subsequent climate change indicator work for the Gulf of Maine is underway by ESIP [11] (McKenzie et al., 2008). Using a pressure-state response framework, the committee has chosen four initial priority climate change indicators: air temperature change, precipitation anomalies, sea-level rise, and sea surface temperature change.[12]

Sea surface temperature is one of the easier climate impacted marine variables to measure and speculate on. Researchers such as Chmura et al.[13] have attempted to extrapolate modelled future surface temperatures to depth to offer some insight on future impacts on marine species in the Gulf of Maine.

[11] http://www.gulfofmaine.org/esip/

[12] G. Lines, personal communication, 2009

[13] http://www.geog.mcgill.ca/climatechange/

Marine Species and Climate Change

Climate is traditionally a limiting factor to the spread and success of invasive species, and the marine environment is no exception. Species that arrive during the milder seasons often cannot survive the winter, but with warmer winter water, the chance of survival of invasive species increases, regardless of their vector of arrival. Greater success rates of alien pests and diseases can weaken indigenous ecosystems, leaving them more vulnerable to the higher order invasives. Changes to salinity, turbidity, temperature, light, acidity, nutrients, and even depth brought on by climate change can also negatively impact existing species and ecosystems, thus facilitating the invasion of alien species.

Invasive Species

The movement of species into new areas is a natural phenomenon that has occurred throughout evolutionary history. In modern times however, the movement of species has been augmented by humans operating in a progressively globalized world (Tinner and Lotter, 2001). Some introduced species become invasive. Invasive species means an alien species or non-native species whose introduction may cause environmental harm, or does cause harm to the host ecosystem, economy, or human health. Invasive species thrive in the absence of their native predators and have the potential to drastically alter the habitat they invade. Effects on aquatic ecosystems include modified water tables; changes in run-off dynamics and fire frequency; introduction of toxins; and decline in light or nutrient availability. Such alterations render ecosystems inhospitable for native species resulting in decreased native populations and are now the second leading cause of species extinction and loss of biodiversity in aquatic environments worldwide.[14] It is estimated that the cost of control of invasive species equals five percent of the world's economy.[15]

The U.S. Environmental Protection Agency (EPA, 2009) uses the working definitions:

- Non-indigenous (non-native) species: with respect to a particular ecosystem, any species that is not found in that ecosystem. Species introduced or spread from one region of the US to another outside their normal range are non-indigenous, as are species introduced from other continents.

- Invasive species: a species whose presence in the environment causes economic or environmental harm or harm to human health. Native species or non-native species may show invasive traits, although this is rare for native species and relatively common for non-native species. EPA (2008) actually uses the term invasive species to mean invasive non-native species.

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[14] http://www.dfo-mpo.gc.ca/science/enviro/ais-eae/index-eng.htm

[15] http://www.nature.org/initiatives/invasivespecies/about/

- Not all non-indigenous species survive their release into a new environment. The EPA Watershed Academy web uses the “Ten Percent Rule”. This says that only about 10% of all non native species introduced into an area will survive, and of those survivors only about 10% become invasive. This means about 1% of the original number of species introduced into a new ecosystem become harmful.[16]

Traits of Invasive Species

Normally populations are prevented from extending past the carrying capacity of an area by environmental resistance factors both biotic and abiotic. Biotic factors include: predation or herbivory, limitation of food, intraspecific and interspecific competition for resources, diseases (density dependent), etc. Physical or abiotic factors also prevent population explosions by limiting the amount of space, sunlight, nutrient sources, pressure, availability of water or moisture, ambient temperature, and diseases (density independent), etc. If these factors change and certain populations have ideal or more suitable conditions, then those populations will be at a competitive advantage leading to a loss of biodiversity in an area. When alien species are introduced to an area that has a missing preventative measure the species may become invasive. To determine which traits define a species as invasive a number of criteria may be used. The EPA Watershed Academy uses nine criteria:

- capable of doing significant harm to ecosystems, economy or public health;
- capable of spreading without apparent natural controls (natural predators, disease);
- population levels that are unchecked;
- causing major change faster than native ecosystems can accommodate;
- changing major ecological processes (nutrient cycling, hydrology, fire regime, energy);
- destabilizing environmental (physical or community) structure;
- forming undesirable monotypic stands of vegetation that replace diverse communities;
- reducing biodiversity/integrity, causing extirpations and extinctions;
- reducing or eliminating a natural product, ecological service or other valued attribute.[17]

The United States Geological Survey (USGS) has collected data and created graphical representation to show the extent of invasive species both nationally and at a State level. These data only show species found within the United States’ borders so an

[16] http://www.epa.gov/watertrain/invasive2.html

[17] http://www.epa.gov/watertrain/invasive4.html

extrapolation for the Canadian waters of the Gulf of Maine would need to be produced for a more accurate view. These graphs represent all introduced species with no clear division as to the number that has become invasive. However, the graphs show the stark reality of the non-native species problem. If conditions become favourable, then the percentage of benign introduced species turning into harmful invasives may soar exponentially.

Surprisingly the number of introductions of freshwater to marine in both Maine and Massachusetts is high. The following graph shows the majority of species introduced has been in freshwater. As most of Maine contains watershed for the GoM, this is no small input. The Massachusetts and New Hampshire graphs, not shown here, look nearly identical. It is worthy to note that the USGS is graphing data it has available. This does not show the extent of marine introductions as the marine data were limited.

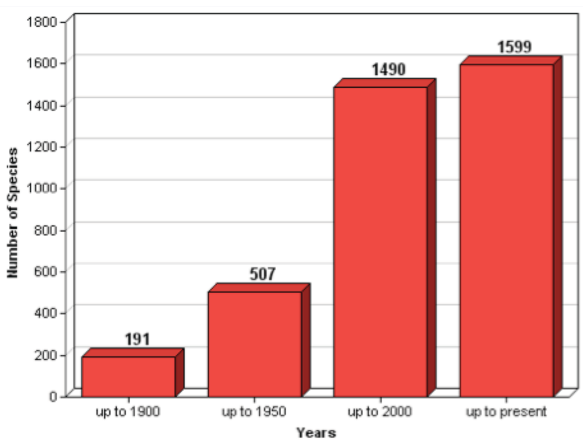

Figure 7: introduced species in the United States. This analysis includes all species introduced into either freshwater or marine areas, including those that did not become established. Most brackish species are included as marine. (graph created 2/19/2009 by the United States Geological Survey)[18]

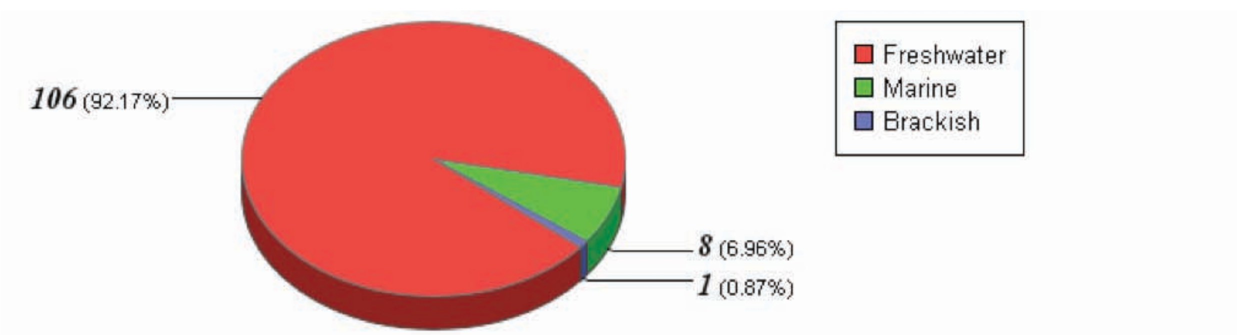

Figure 8: marine versus freshwater introductions. This analysis includes all species introduced into either freshwater or marine areas, including those that did not become established. Most

[18] http://nas.er.usgs.gov/graphs/All.asp, retrieved 26-02-09 (used with permission)

brackish species are included as marine. (graph created: 2/19/2009 by the United States Geological Survey)[18]

Vectors

To begin to include additive ecological stressors such as climate change and formulate management plans, the vectors of the exotic species first need to be understood. Vectors are the mechanisms by which species are transported from their original habitat into the new ecosystem. There are many pathways of invasive species introduction and depending on the host environment, can occurs in a variety of ways.

Terrestrial species have been monitored and combated more thoroughly in the past than aquatic; perhaps as the effects of these have been more widely observed. Historically many of these non-native species were brought into North America purposely by settlers and became part of the agricultural industry or domestic gardens, or as pets. There is still an ongoing battle to eradicate some particularly aggressive species but generally much of the land has already been influenced to some degree and precautions are generally in place.

In the aquatic environment, non-indigenous species have been introduced for the same length of time but the effects have been less noticed by the general public. In some areas no action had taken place until the situation became a major commercial problem. The Great Lakes for example are probably the area of primary focus for Canada and a very high priority in the US. There is now a concerted effort to control the problem of some phenomenally successful invaders such as the Zebra Mussel (*Dreissena polymorpha*). This species has been introduced as the direct result of the primary cause of introductions: international shipping. Molner et al. (2008) in their review paper *Assessing the Global Threat to Marine Diversity*, identify international shipping, followed by aquaculture as the two leading causes. These have also been identified as 'key' pathways by Fisheries and Oceans Canada (DFO) and the United States Environmental Protection Agency (EPA). Shipping, in particular the intake and subsequent emptying of ballast water, accounts for the majority of introductions (Figure 9).[19]

[19] http://www.eoearth.org/article/Aquatic_invasive_species

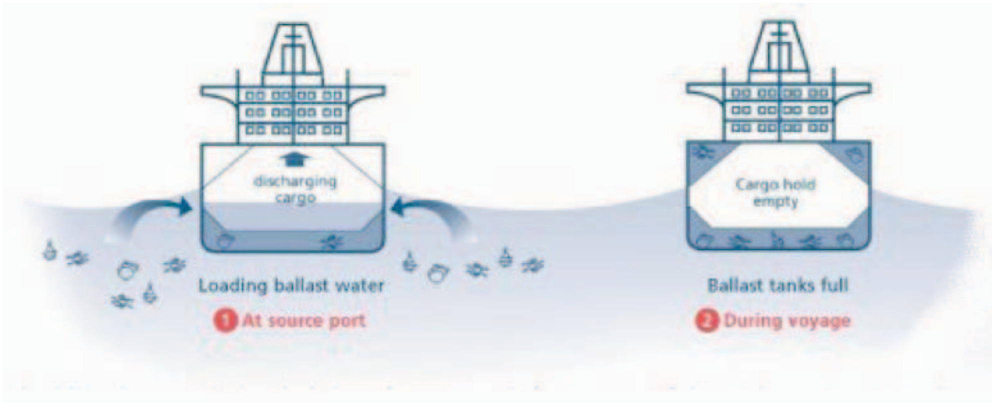

Figure 9: Ballast water being loaded in native port. Species taken on board with seawater.(Roman and McClary, 2008)

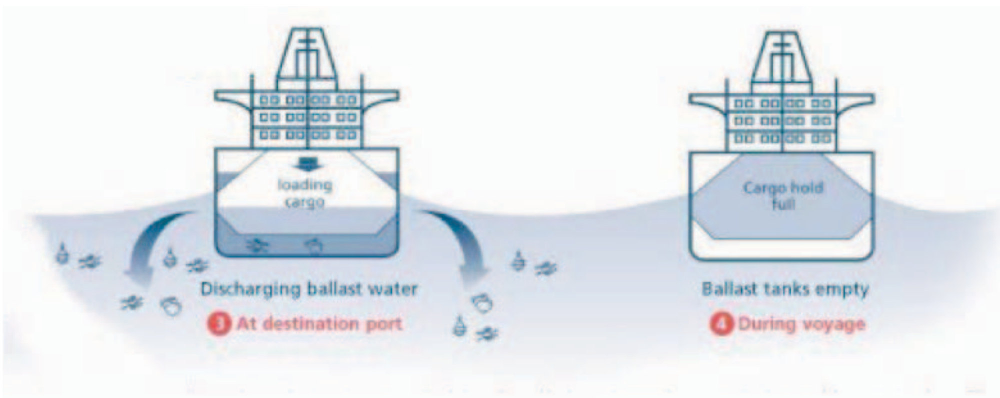

Figure 10: Ballast water being discharged in foreign port. Species introduced to host environment. (Roman and McClary, 2008)

Post-transport ballast water contains high densities of holoplankton, organisms such as dinoflagellates and jellyfish that spend their entire life as plankton and meroplankton, the temporary larval stages of crustaceans worms, and fish. Because ballast tanks may hold millions of litres of water, numerous individuals can be introduced in a single event.[20] The United States now require ships to flush out ballast tanks at sea, thus reducing the possibility that foreign bodies will make it to coastal waters.[21] Canada however, has no such restrictions and operates on a voluntary basis.[22] The Great Lakes fall under the US regulations. It is unclear whether the GoM has such stringent regulations.

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[20] http://www.eoearth.org/article/Aquatic_invasive_species

[21] http://www.gulfofmaine.org/times/summer2008/profile2.php

[22] http://www.dfo-mpo.gc.ca/science/enviro/ais-eae/plan/plan-eng.htm#key_pathways_ introduction_spread

The United States has taken an active role in containment and eradication of nuisance species. Many of the states combating current problems stress that a large part of the solution is prevention of further introductions. There is much literature on the pathways of introduced species and management practices. The EPA has published a list of common pathways under the Oceans, Coasts and Estuaries section (refer to Appendix A for the complete list) and DFO has highlighted seven key pathways (refer to Appendix B for abridged list). Aside from ballast water and aquaculture, fouling on recreational boats, stocking of lakes and rivers, creation of new waterways, live foodfish, live bait, seafood packaging and waste disposal, and species introduced by government programmes (to control other problem species) are other common pathways.

The Invasive Species

Ascidians

Fouling is a major problem in the GoM. Fouling communities are assemblages of sessile suspension feeders that inhabit vertical and shaded surfaces on natural and anthropogenic substrates (Dijkstra, 2007). Fouling communities clog water intake pipes, attach to fishing gear, boats, and docks, and cover other organisms. Tunicates, or ‘sea squirts’, such as *Didemnum* sp., *Botrylloides violaceus* and *Diplosoma listerianum* (colonial ascidians) grow in colonies and spread on bottom areas, competing with indigenous organisms such as juvenile fish and scallops for settling habitat and food (Thayer and Stahlnecker, 2006). *Didemnum* is a particularly aggressive species which will quickly take advantage of any disturbed areas as well as progressively convert biodiverse habitats into singularly dominated communities. *B violaceous* currently ranges from Virginia to Maine. Another tunicate of concern is the 'clubbed' tunicate *Styela clava*, a native of the western Pacific. It too is a major problem for aquaculture, fouling gear and competing with young oysters and mussels for food and space.

Bryozoans

Encrusting bryozoans such as *Membranipora membranacea* from the northeast Atlantic is an epiphyte of kelp. Since its introduction it has become the dominant encrustment on *Laminaria* spp. The *Membranipora* settle on kelp blades after a period of up to two months as larvae in the water column and reproduce by asexual reproduction. The kelp blades become brittle and more susceptible to breakage by waves.

Algaes

Codium fragile, also known as ‘Dead Man's Finger’ or ‘Oyster Thief’ is a green alga that is native to Japan. It attaches to rock surfaces and mollusc shells, and it is one of the most invasive seaweeds in the world. This alga was first reported in Long Island New York in 1957 then in Boothbay Harbor in the 1960s. It is thought to have come through aquaculture. Since then it has been spreading northward and is found in both sheltered and wave-exposed environments, in intertidal pools and in the subtidal zone as deep as fifteen metres. In some areas it is now the dominant algae above seven metres deep

(Tyrrell, 2005). It is opportunistic and will quickly colonize kelp beds damaged by bryozoans.

Parasites and Diseases

An introduced virus called Orthomyxovirus was first reported in the mid 1980s in New Brunswick. This virus attacks Atlantic salmon causing mortality and in 2001 was diagnosed in Maine and caused the slaughter of all fish in affected farming cages.

The parasite *Haplosporidium nelsoni* was introduced from Asia to the Chesapeake Bay area in the late 1950s. This parasite attacks native oysters.

Crustaceans

In July 2001, it was reported that the Asian shore crab *Hemigrapsus sanguineus* had been sighted for the first time in Maine, in South Portland and Scarborough. This is an aggressive crab, which may eat other crabs as well as out competing them for resources (Thayer and Stahlnecker, 2006). Asian shore crabs are omnivores that feed on algae, small molluscs, and barnacles. Young shellfish are vulnerable to predation but the small claws of the crab render them fairly harmless to large molluscs.[23]

Carcinus maenus, otherwise known as the European Green Crab has been a long-term invader in the GoM. Since its arrival from Europe and North Africa in the 1800s via ballast water from the Baltic and North Seas, it has gained the reputation of being one of the world's hundred most invasive species. Its success is down to its ability to withstand a large temperature range and high and low salinity. The populations are only seen to slow down during exceedingly cold winters.

Plants

Phragmites australis or Common reed is a perennial grass that grows along riverbanks, lakes, and other freshwater or low salinity aquatic environment. *Phragmites* have flourished in areas of disturbance where tidal restrictions or high freshwater run-off has occurred. These invasives can dominate an area and ostensibly create a monoculture. Success of this species is in part due to reproductive means such as wind blown dispersal of seeds and expansion through underground rhizomes.

Climate Change Impacts and Invasive Species

The effects of climate change on invasive species and their combined effects on ecosystems are not well understood, and these changes vary regionally with climate and species traits. As well as changes in the physical environment, climate change is altering ecosystems and species' life cycles. In some instances climate change may

[23] http://www.gulfofmaine.org/times/fall2001/gulf_log.html

create additional opportunities for invasion or create conditions unsuitable for certain invasive species. Consequently, the magnitude of ecological, economic, and human-health impacts of invasive species may increase, decrease, or remain the same (EPA 2008).

Theory predicts that systems that are more diverse should be more resistant to exotic species. In experimental communities of sessile marine invertebrates, increased species richness significantly decreased invasion success, possibly because species-rich communities use available space and limit the resources for invasives in the system (Stachowicz et al., 1999). It has been found that the organisms most vulnerable to climate change in an ecosystem are those with narrow tolerance ranges and specific habitat requirements.[24] Therefore species with wide tolerance ranges such as *Codium fragile* or *Carcinus maenus* may easily out compete native species intolerant of the temperature or substrate changes.

Changes in atmospheric temperature and particularly sea surface temperature can lead to phenological changes in species. Phenology, the study of annually recurring life cycle events such as the timing of migrations and reproduction, can provide particularly sensitive indicators of climate change. Temperate marine environments such as the GoM may be particularly vulnerable to these changes because the recruitment success of higher trophic levels is highly dependent on synchronization with pulsed planktonic production. A study by Edwards and Richardson (2004) showed that the magnitude of changes in phenology reported in marine environments are greater than those from previous studies on terrestrial communities and indicate that marine pelagic communities are particularly sensitive to climate change. Large phenological shifts were observed to have occurred during the study period (1958–2002) with an increase in SST of 0.90°C (Edwards and Richardson, 2004). Any further increase may create an opportunity for earlier developing invasive species and allow establishment and use of available resources. Climate change will influence the likelihood of new species becoming established by reducing periods of cold temperatures in which die back occurs or winter hypoxia that currently prevent survival (McCauley and Beitinger, 1992). This may be very influential to species in the tidal mudflats, salt marsh, and freshwater environments.

A stark example of changes in phenology in the GoM watershed terrestrial environment can be seen in the difference between two photographs taken at the same time (on the last Monday) in May in Massachusetts. One photograph was taken in 1868, the other in 2005 (*Figure 11*).

[24] http://www.landscope.org/explore/threats/climate/Climate%20Change%20101/02/

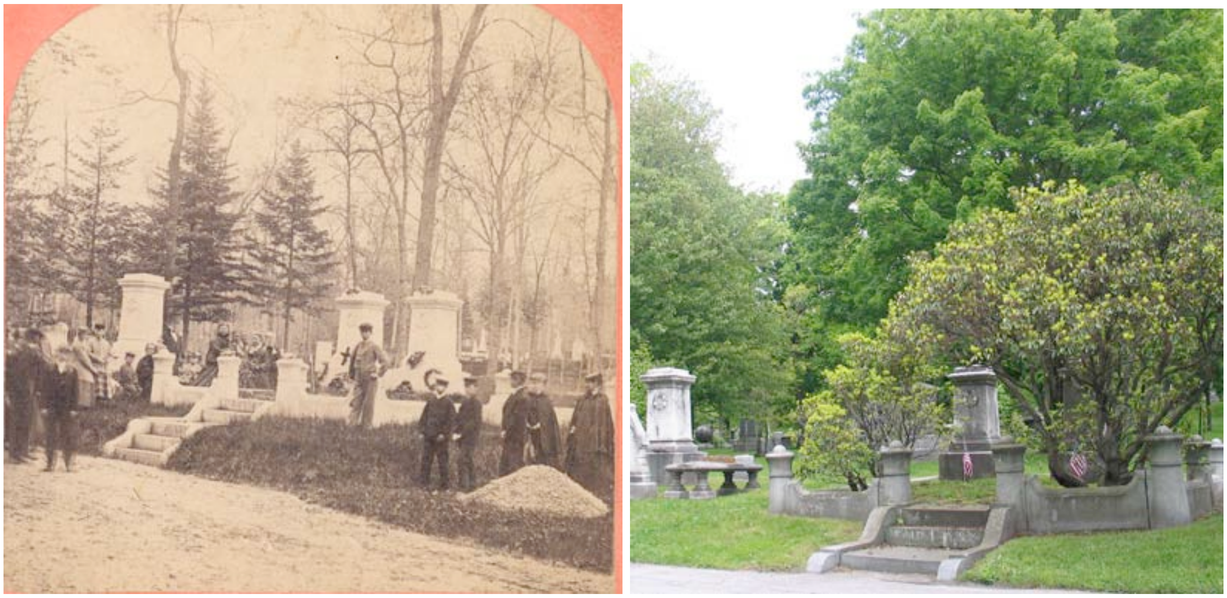

Figure 11: Memorial Day 1868 (left) and Memorial Day 2005 (right), Lowell Cemetery in Lowell, MA (Courtesy of Richard Primack)

Water temperatures may not only increase, as a general impact of climate change, but indirectly may be affected by current changes already in place. In periods of a positive North Atlantic Oscillation phase (a climate variability indicator that is indicative of changes to Atlantic storm strength and track), the Gulf Stream may enter the GoM. The warmer waters cause milder winters and reduction in the nutrient availability due to changes in the vertical mixing of the water column. An impact of climate change may be a more frequent cycle of positive to negative phases of the NAO. If this occurs then the food web will be affected on a more frequent basis and may not have adequate time to recover between cycles. Impacts of the Gulf Stream deflection include effects on producer species such as phytoplankton, which depend on the upwelling of nutrients from cold bottom waters. These may not be as numerous and higher trophic levels may see large decreases in numbers or general loss of biodiversity within all levels of the food web.

Changes in seasonality can affect succession of species. There is much evidence in the invasive-species literature that ecosystem disturbances encourage pioneer species, and many invasive species are pioneers (Byers, 2002). This concurs with results found by Dijkstra (2007). In this investigation studies conducted on three colonial ascidians (tunicates) and one bryozoan between 1979-1982 and 2003-2006 showed a 33% change in the species composition between the two time periods. In the initial study succession was directional and led to a stable climax community, whereas the later period showed the ascidians and bryozoan to have become part of the fouling community and show invasive traits. In the 2003-2006 study it was found that the succession was directional only for the first two years then species diversity was not maintained; this being due to the seasonal nature of the invasives. In the 1979-1982 study a four-season development was observed and in the 2003-2006 study only a three-season development. “The smaller number of seasons was linked to a rise in temperature that facilitated the longevity and dominance of the warmer water species” (Dijkstra, 2007). An increase in water temperature could further facilitate changes in succession and increase fouling.

Wind or storm damage due to increases in frequency or ferocity may create areas of bare substrate that allow secondary succession. If combined with other climate change factors such as increased temperature then a synergistic effect occurs and a competitive advantage is given to species with rapid reproduction such as ascidians. The effects of climate change on ecosystems already stressed by non-native species may have ramifications that in turn further degrade the system. An example would be the impact of invading lacy crust bryozoan, *Membranipora membranacea*, on kelp, *Laminaria saccharina*. Kelp blades that have become encrusted with *M. membranacea* become brittle and more susceptible to breakage by waves. If wave energy increases, then vast kelp beds may be damaged and, in turn, destroy valuable habitat for other organisms such as native green sea urchins that graze in kelp forests (Warren and Gough, 2005). This may then provide a spatial resource for other invasive species such as *Codium* to inhabit (Thayer and Stahlnecker, 2006). A damaged ecosystem will not always be able to regenerate itself to its previous state and is therefore more susceptible to subsequent invasion.

Changes in precipitation due to climate change may affect AIS (aquatic invasive species) establishment and dispersal. Increased rainfall may allow for greater dispersal of upstream invasive species to downstream habitats. As wetland invasive plant species are often dispersed by water this makes wetlands highly vulnerable to invasions as rainfall and flooding increase.

Despite a long-term trend toward a warmer climate, the Gulf of Maine region might experience a period of cooling in coming decades. Scientists believe that the Gulf Stream might weaken or shift its course due to melting of arctic sea ice, possibly leading to a rapid cooling period with longer and harsher winters.[25] This may contain the population numbers of those species sensitive to cold temperatures. Even at current temperatures the GoM is thought to be fairly resilient in its ability to fend off introduced species that have come from ballast water. Maine’s near shore marine waters are relatively cold. If there is a further temperature decrease then potential invaders originating from temperate or tropical regions introduced in Maine coastal waters would be less likely to survive (Thayer and Stahlnecker, 2006).

Not all combinations of invasive species and climate change have a negative effect. There are examples of species having a negative effect in one location and a positive effect in another. One such organism is the Asiatic clam (*Corbicula fluminea*). In the late 1970s it invaded a tidal marsh in the Potomac River and increased clarity of the water to

[25] http://www.eoearth.org/article/Aquatic_invasive_species

the point where previously lost vegetation reappeared and aquatic birds returned. In other areas this species has altered habitats and fouled water pipes (EPA, 2008). The efficiency of a filter feeder such as this clam may help offset increased turbidity as a result of run-off from precipitation or sediments disturbed by increased storm activity. This clam may not have reached the GoM but if ambient and sea temperatures increase, the invasive species now inhabiting the coast to the south of Massachusetts may move northward in Gulf waters.

An organism already in situ in the GoM that may have an unexpected beneficial effect is the Common reed *Phragmite australis*. As air temperature increases, production increases. It is possible that due to the very nature of its reproductive success, its high productivity, lack of export of litter, slow decay rates, carbon storage and rapid accumulation of sediments it may offset the impacts of climate change such as sea level rise and increased atmospheric carbon dioxide (Tyrrell, 2005).

Gap Analysis

As was mentioned in the document Coastal Habitats at Risk of Climate Change (Horton and McKenzie, 2009) there are a number or organizations studying and reporting on various aspects related to the Gulf of Maine environment. Some of the issues, such as access to information remain the same for all research topics. The more specific nature of invasive species has made the search field narrower, however, there are still several topic specific gaps.

1. Scientific Study: Research Polarization

The literature available for climate change and invasive species is limited. There is an abundance of research on invasive species and there is an equal amount on climate change. Rarely however are the two disciplines brought together. Literature for invasive species and climate change in the Gulf of Maine is even more restricted. There are very few studies conducted in relation to species currently exhibiting changes as a result of climate change or extrapolations of possible effects of climate change.

The United States has taken the lead in North America for collating publications, identifying gaps, and giving guidance to policy makers. The National Center for Environmental Assessment, Office of Research and Development of the U.S. Environmental Protection Agency published a comprehensive research paper titled Effects of Climate Change on Aquatic Invasive Species and Implications for Management and Research in 2008. This document is a collaborative effort by organizations researching and managing invasive species and climate change. The aim was to produce management strategies intended for use throughout the United States. Some examples used are species found within the Gulf of Maine.

Of the research that has been carried out in this field, most is based on terrestrial or freshwater environments. Not as much research has been done on marine ecosystems.

2. Multitude of Organizations and Protection Orders

Again, the problem faced when attempting to get clear information is the number of agencies dealing with the same issues. In government the levels range from federal, provincial, territorial, state, district, county, municipal, and at times groups supporting a single watercourse or park. There are various departments within the federal governments alone that hold responsibility for managing invasive species. There are lists published on government websites that link to many organizations all carrying out similar work and giving information in similar ways. It is difficult to know which is the authoritative resource. A sample of organizations in the United States that have information of their websites is: USGS Invasive Species Program; USDA National Invasive Species Information Center; US Environmental Protection Agency; Aquatic Nuisance Species Task Force; National Invasive Species Council; and Northeast Aquatic Nuisance Species Panel. The GoM falls under the NEANS group for regionality. Of course any data are specific to the US side despite the waters and species within having no borders. In Canada there are fewer organizations and it appears the GoM falls under Fisheries and Oceans Canada. The groups and committees responsible for climate change rarely appear to overlap, if at all. This lack of cohesion accounts for duplication of and limitations of work.

3. Lack of Legislation

The protection of species also falls under various agencies and acts. While a lot of work is being carried out in some focus areas such as the Great Lakes, other important ecological areas such as the GoM are being overlooked. At the moment there is currently no invasive-species legislation or invasive-species management plan guidance that requires the consideration of climate-change effects on AIS or their management (Bierwagen et al., 2008). This is true for both Canada and the US. However, there are some states considering climate change in their action plans on invasive species. In an article for *Conservation Biology*, Bierwagen et al. (2008) note:

> Only the Virginia plan included a general discussion of climate change, although at least 3 other states (Connecticut, Maine, and Massachusetts) briefly mentioned climate change as a potential factor in management and decision making. For example, Maine mentioned climate change specifically as a cause for the possible further spread of AIS and proposed monitoring climatic conditions to provide early warning of new populations. Overall, 84% of the plans assessed did not explicitly mention climate change.

Canada has no research priority that mentions risks of climate change and invasive species.[26]

4. Modelling and Software choices

In a study titled 'Will climate change be beneficial or detrimental to the invasive swede midge in North America? Contrasting predictions using climate projections from different general circulation models' (Mika et al., 2008) climate projections are based on two general circulation models of global climate: Canadian Centre for Climate Modelling and Analysis GCM (CGCM2) and the Hadley Centre model (HadCM3) (Mika et al., 2008). In order for risk assessment to be carried out or projections of possible effects to be made, there are multiple models on which to base these. If studies do theorize on possible outcomes it is not always clear which model the author has used.

Also, software used for predictions is not always specific enough or is written by different organizations basing their models on different data and assumptions.

Further Work

1. Scientific Study: Research Polarization

- More research is needed on invasive species and climate change specifically aimed at the Gulf of Maine.
- Better use of available research and extrapolations by experts in the fields of climate change and species biology.
- More research generally to be focused on the marine environment.

2. Multitude of Organizations and Protection orders

- Create umbrella groups in Canada and the US to oversee the crosscutting groups such as those responsible for invasive species and climate change. These can then have definitive information on available research and policy making. Have collaborative agreements for cross border issues (note: this is being done to some extent within the Great Lakes).
- On the GoMC website have links to the sites and literature most useful in this field, perhaps through the Climate Change Network.

3. Lack of Legislation

- Acknowledge that climate change will have an effect on invasive species and

[26] http://www.dfo-mpo.gc.ca/science/publications/fiveyear-quinquennal/index-eng.htm

create policies that will address this. This should be done at a federal level with a coordinated effort between the two countries (see above).

- Within the GoM have scientists and subcommittee members suggest guidelines for policy makers.

4. Modelling and Software choices

- Scenarios based on alternative models should be made available and made clear to users.
- Software should be standardized and made available to users with specific criteria for real situations rather than models based on grand generalizations.

Conclusion

This report represents a starting point for those interested in understanding the possible impacts of climate change on invasive species in the Gulf of Maine. Although it is not meant to be a definitive guide to existing and future invasive species in the gulf, it can help those concerned to better understand how climate change may exacerbate the invasive situation.

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Appendix A: United States Environmental Protection Agency, Oceans, Coasts, & Estuaries, Pathways for Invasive Species Introduction[27]

- **Ballast Water**: Since 95% of all foreign goods by weight enter the U.S. through its ports, the potential for invasive species impacts on coastal communities is immense.
- **Boat Hulls, Fishing Gear and Other Recreational Pathways**: Boat hulls, fishing boots (felt-soled wading boots transport whirling disease organisms from stream to stream) and equipment, diving gear, and other recreational items that are transported among several water bodies have been known to spread invasive species problems to new waters. Some zebra mussels and milfoil have been introduced via these pathways.
- **Aquaculture Escapes:** Non-native shrimp, oysters and Atlantic salmon in the Pacific Northwest, are just a few examples of non-native mariculture species that have generated concern over disease and other impacts that might arise from their escape.
- **Intentional Introductions**: The introduction of non-indigenous species into ecosystems with few controls on reproduction or distribution.
- **Aquaria Releases:** Escapes or intentional release of unwanted pets can be a source of new non-native species in all parts of the country. The invasive algae Caulerpa is thought to have been introduced to U.S. waterways after being discarded from aquaria.
- **Live Food Industry**: The import of live, exotic foods and the release of those organisms can result in significant control costs, e.g. the snakehead fish in Maryland. Asian swamp eels are spreading through the Southeast after introduction as a food source.
- **Vehicular Transportation**: Both private and commercial transportation are major factors in the movement and range expansion of non-native species throughout the U.S.
- **Escaped Ornamental Plants, Nurseries Sales, or Disposals**: Many invasive plant problems began as ornamental plantings for sale in nurseries and garden shops. Purple loosestrife, for example, is sold as an ornamental plant but takes over native vegetation in wetlands, and can clog western streams preventing water withdrawal and recreational uses. Only some problem species are currently banned from sale.
- **Cross-basin Connections**: From small channels to major intercoastal waterways, new connections between isolated water bodies have allowed the spread of many invasive species. Great Lakes invasions increased markedly

[27] http://www.epa.gov/owow/invasive_species/pathways.html

after the opening of the St. Lawrence Seaway in 1959.

- **Fishing Bait Releases:** Discarding unused bait can introduce species that disrupt their new ecosystems and eliminate competing native species; examples include non-native crayfish, baitfish that overpopulate certain waters, and earthworms that are depleting the organic duff layer in northern forests where no indigenous earthworms existed.
- **Illegal Stockings**: Although prohibited by law, people release fish into new waters and sometimes cause severe impacts. Yellowstone Lake's world-class cutthroat trout fishery is now jeopardized by an illegal release of lake trout.
- **Domestic Animals Gone Feral:** The impact of feral house cats on birds and small mammals in natural areas is well documented; escaped feral pigs from farms have recently begun to do significant damage to soils and plants in the Smokey Mountains.
- **Pathogens Spread by Non-natives to Vulnerable Native Species**: Non-native species problems include pathogens carried by resistant non-natives to vulnerable native species. Whirling disease, which has decimated rainbow trout in many western rivers, was originally introduced when European brown trout, tolerant of whirling disease, were imported to U.S. waters and hatcheries.
- **Disposal of Solid Waste or Wastewater**: Seeds, viable roots or other propagules of invasive plants may be easily spread to receiving waters through wastewater discharge, then spread by water flow to distant areas downstream.
- **Science/laboratory Escapes, Disposals or Introductions**: Accidental or intentional release of laboratory animals has introduced some non-native species into U .S. waters.
- **Seafood Packing and Disposal**: Much seafood is packed in seaweed prior to distribution. Because seafood is transported long distances, organisms in packing seaweed may reach new waters as an unintended by-product.
- **Biological Control Introductions**: Ideally, introducing a second non-native species to control an invader should result in diminished numbers of both species after control is accomplished, but some introduced controls have backfired because they attack non-target species. Mongoose introduced in Hawaii to control rats have wiped out many native bird species.
- **Past Government Programs:** The establishment of a new invader is sometimes an unanticipated outcome of a government program; kudzu, for example, was originally introduced through a government-sponsored erosion control program.
- **Moving and Depositing Fill in Wetlands**: Seeds and viable parts of invasive plants contained in fill material may rapidly colonize the new substrate, which then compete with native species within the wetlands.
- **Land/water Alterations That Help Spread Invaders:** Many invaders are adept at rapid pioneering where soil has been disturbed or water levels or routes have been changed, leaving a temporary gap in occupation by native flora and fauna.

Appendix B: Fisheries and Oceans Canada, Key Pathways for Introduction or Spread[28]

1. **Shipping:** This pathway includes large ocean-going vessels with ballast capability (commercial shipping, naval, and cruise vessels) that operate in Canada's offshore, nearshore and inland waters. These vessels unintentionally transport invasive species that attach themselves to ship hulls or that survive in the ballast water that is taken on in foreign ports. Historically, alien species in ballast water are considered to be the largest single source of aquatic invasive species in Canada's waterways.
2. **Recreational and commercial boating:** This pathway consists of the in-water use and overland transportation of all watercraft other than large ocean-going vessels with ballast capabilities, such as commercial shipping, naval and cruise vessels, which are covered in the shipping pathway. Powerboats, yachts, personal watercraft, sailboats, canoes, float planes, paddleboats, and associated equipment (such as trailers or fishing equipment), as well as commercial fishing, education and research, and charter boat vessels are included in this pathway.
3. **Use of live bait:** This pathway consists of the public and commercial use of live organisms (including minnows, frogs, aquatic and terrestrial worms, leeches, and aquatic or terrestrial insects and larvae) to catch fish. Recreational anglers collect their own or buy commercially-sold live bait.
4. **Aquarium and water garden trade:** This pathway consists of the intentional or unintentional release of aquatic organisms including fish, invertebrates, plants, amphibians and reptiles sold for use indoors in aquariums and outdoors in ornamental ponds and water gardens. Owners may intentionally release species into open waters because they have outgrown aquariums or are no longer wanted. Species may also be intentionally introduced for control of weeds or unwanted organisms like the mosquito or as part of certain cultural practices. Unintentional release can occur when fish, aquatic invertebrates, or plants escape outdoor ponds naturally (seeds spreading) or during unexpected overflow events (flooding). Although many aquarium species are tropical and cannot survive Canadian winters, there are numerous examples of fish, invertebrates, and plants that have been introduced or have spread in Canada as a result of aquarium releases.
5. **Live food fish:** This pathway refers to any fish or other aquatic organisms imported or transferred live within Canada for distribution and sale for human consumption.

[28] http://www.dfo-mpo.gc.ca/science/enviro/ais-eae/plan/plan-eng.htm#key_pathways_introduction_spread

6. **Unauthorized introductions:** Unauthorized introductions are defined as any introduction or transfer of fish (including shellfish) or marine plant not performed or authorized by a federal, provincial or territorial fisheries management agency.
7. **Canals and water diversions:** This pathway consists of canals and channels used for shipping and bulk water diversion. These create artificial connections allowing the free movement of species across physical barriers, between watersheds (inter-basin), and within watersheds (intra-basin).