

Some Anticipated Consequences of Global Warming:

Implications for the Nature of Massachusetts

A Preliminary Assessment

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Introduction.....	2
How will the climate and sea level in Massachusetts change over the next century.....	3
Projections of Climate Change .....	3
Projected Changes in Sea Levels .....	4
How will global climate change affect the Massachusetts coast? .....	4
Loss of land.....	4
Barrier Beaches.....	6
Salt Marshes and Tidal Flats.....	6
Coastal Ponds.....	7
Coastal Waterbirds.....	8
Coastal Fisheries .....	8
Other Marine Organisms.....	10
How will Global Warming Effect the Terrestrial Ecosystems of Massachusetts? .....	10
Effects on Forest Types .....	10
Effects on Forest Processes.....	11
Range Shifts.....	12
Insects .....	12
Birds.....	12
Massachusetts Forests as Carbon Sinks.....	14
Freshwater Ecosystems.....	14
Changes in Phenology.....	15
“Pest” Species .....	16
Consequences for our Ecosystem .....	16
References.....	17
Tables.....	23

## Introduction

Global warming resulting from the release of greenhouse gases by human activities now has widespread acceptance among scientists. The case has been made in a synthesis document (National Assessment Synthesis Team 2000). This report was mandated by Congress in 1990 and was researched and written by a panel of scientists from universities, government, and industry. The report establishes the facts supporting global warming and examines how temperature and sea level are likely to rise in different parts of the United States. On the international level, the Intergovernmental Panel on Climate Change (IPCC) under the auspices of the United Nations Environmental Program has released a series of documents that provides further support for global warming and a summary of potential impacts (IPCC 2001a, 2001b, 2001c, 2001d).

Temperature and CO<sub>2</sub> have fluctuated naturally during the history of the earth. Over the past two million years, there have been about 40 cycles of glaciation followed by interglacial periods of warming. These changes have occurred over a relatively short period. One of the most dramatic documented changes occurred around 12,000 years

ago, a period known as the Younger Dryas, when the mean temperature of the North Atlantic dropped about 5°C over a decade and remained cooler for about 1000 years (NRC 2002). The present steep rise in temperature is clearly related to human activities. In National Assessment Synthesis Team (2000), teams of scientists focused on how such global warming will affect different regions on the United States and different sectors, i.e., agriculture, water, human health, coastal ecosystems, and forests. We used this information and other sources to project likely changes in Massachusetts over the next century.

A specific goal of this document is to increase the awareness of our members and the general public. We focus on the potential impacts of climate change on Mass Audubon sanctuaries and, by inference, other protected lands in Massachusetts. Climate change is an abstract concept to many people, perhaps not as tangible as other threats to our ecosystems including invasive species, fragmentation of habitats, and acid precipitation. There is an impressive and growing scientific literature documenting ecological changes that are consistent with the warming of the climate that has already occurred over the past century. These include northward range shifts of birds, fish, and other groups of organisms, earlier flowering of plants and breeding of birds and amphibians, shrinkage of glaciers, thinning of the arctic ice pack, and later freezing and earlier thawing of lakes.

The ecosystems under our management will undoubtedly change in response to climate change over the next century, and we are beginning to consider the implications of these changes for our management priorities. There is still much uncertainty about how climate change will affect the earth's ecosystems. Analysis of the changes on our sanctuary system and other protected lands could serve as a barometer for climate change in New England ecosystems.

## **How will the climate and sea level in Massachusetts change over the next century**

There are now two widely accepted climatic models related to global climate change (National Assessment Synthesis Team 2000). These were produced by the Hadley Center in the United Kingdom and the Canadian Center for Climate Modeling and Analysis. Both models predict that it will get warmer, and that there will be an increase in extreme weather events. They disagree on the extent of the temperature rise (the Canadian Center model predicts a greater increase) and on the distribution of precipitation (i.e., which areas will likely be drier or wetter).

### ***Projections of Climate Change***

- 1) There has been a 1°F rise in temperature in Massachusetts between 1895 and 1999 (New England Regional Assessment Group 2001).
- 2) By 2100, CO<sub>2</sub> levels are expected to rise to levels not seen on earth for millions of years. CO<sub>2</sub> levels are strongly correlated with temperatures. This increase in CO<sub>2</sub> is the result of burning of fossil fuels (coal, oil, and natural gas) and the cutting of forests.

- 3) A 6-10°F rise in temperature is projected over next century (New England Regional Assessment Group 2001). As such, Boston's climate would resemble either Richmond (Hadley Model) or Atlanta (Canadian Model).
- 4) Annual precipitation is likely to increase by 10-30% in Massachusetts although other parts of the country may experience more frequent droughts. The Hadley and Canadian models disagree on how precipitation and freshwater runoff will change. The Hadley model predicts a 34% increase in total runoff along the Atlantic Coast whereas the Canadian model predicts a 32% decrease (Scavia et al. 2002).
- 5) Although current models do not give a clear indication that there will be an increase in the frequency of hurricanes and other severe storms, they do suggest that the intensity of storms is likely to increase. Current 25-year floods may occur as often as every four years.
- 6) There will likely be increases in smog and acid precipitation
- 7) Possible alterations in ocean currents, e.g., the Gulf Stream and North Atlantic Oscillation, could result in more dramatic and abrupt changes in climate. Such rapid climatic shifts have been noted in the past (NRC 2002). A change in the North Atlantic Oscillation and perhaps a southward movement of the Gulf Stream around 1300 A.D. may have been responsible for the "Little Ice Age", a several hundred year general cooling of much of the Northern Hemisphere in which Viking settlements on Greenland became uninhabitable.
- 8) Cooling of certain parts of the earth is also a possibility. In one scenario described by Joyce (2005), the melting of the Arctic and Greenland ice cap and the subsequent release of cold fresh water into the northern Atlantic Ocean would deflect the Gulf Stream southward, resulting in colder climate in Great Britain, other parts of Europe, and along the northeast coast of North America.

### ***Projected Changes in Sea Levels***

- 1) On average, relative sea level has risen about two mm/yr in New England over the last 100 years. With no impacts of anthropogenically induced climate change, sea level is projected to rise about 30 cm over the next 100 years. Relative sea level rise includes both increases in the level of the sea and land subsidence, both of which are occurring along the Massachusetts coast.
- 2) Under different climatic scenarios, it is estimated that sea level will rise about 50 cm in New England by 2100 with a range of 12 to 94 cm.
- 3) Global climate change related to human activities is likely responsible for the decline in the aerial extent of arctic ice by as much as 7% in the past twenty years and the thinning of the arctic ice pack by about 15% per decade (Scavia et al. 2002).

## **How will global climate change affect the Massachusetts coast?**

### ***Loss of land***

The rise in sea level combined with the anticipated increase in intense storms will likely lead to increased coastal erosion and loss of uplands along many parts of the

Massachusetts coast. One attempt to quantify the loss of upland on a broad scale for Massachusetts was carried out by Giese et al. (1987), who estimated the passive retreat of coastal upland due to relative sea level rise on a town-by-town basis. When their report was written, predictions of how high the sea level rise would rise varied more widely than they do today. Giese et al. incorporated four different projections of relative sea rise into their analysis projecting increases of 1.8, 4.7, 7.1, and 11.3 feet by 2100. The lowest of these increases is closest to the one most widely accepted now. They based their projections of upland losses on hypsometric curves (cumulative frequency diagrams). These graphs show the percent of upland at different elevation levels above sea level for each Massachusetts coastal town. Under this scenario, towns that contain MAS sanctuaries would lose land as indicated in Table 1. The global warming scenario used for the projections in Table 1 are based on an approximate 0.5 m rise in sea level due to global warming from 1980-2025, which is somewhat higher than the rates projected in the Hadley and Canadian climate models.

In a more detailed analysis of four coastal Massachusetts communities, Giese et al. (1987) projected extensive changes in wetlands areas and a sand spit with the projected sea level rise that is most similar to current predictions. Upland loss was not extensive, however they do note, “the increased potential for storm wave and flooding damage should be of concern.”

A preliminary examination of coastal areas vulnerable to future seashore changes classifies much of southeastern Massachusetts, the southern shore of Cape Cod and the Islands as either moderately or highly vulnerable to the effects of sea level rise (Thieler and Hammar-Klose 1999). This was based on the development of a coastal vulnerability index (CVI), which includes slope, type of landform and expected sea level rise. Another analysis lists outer Cape Cod, the Islands, and the Plum Island/Salisbury region as “severely eroding” with the remainder of Massachusetts as “moderately eroding (National Assessment Synthesis Team 2000).” Naturally eroding geological formations, such as coastal bluffs are likely to experience increased rates of loss. The rocky shorelines of the North Shore are less susceptible to the impacts of sea level rise.

As communities and individual landowners confront the issue of increased coastal erosion, there are likely to be increased proposals for armoring of the coast (i.e., revetments, sea walls, groins, etc.) and for pumping sand onto beaches to raise elevations. Massachusetts Audubon has been active in commenting on such proposals as they have come under permit review by the Massachusetts Environmental Policy Act (MEPA) unit and the United States Army Corps of Engineers. Environmental organizations and government resource agencies may need to allocate an increased amount of staff time to reviewing these projects and developing policy guidelines. One notion that has been discussed by the United States Environmental Protection Agency is a policy of rolling easements as a more ecologically sound response to increasing sea levels than armoring. Easements would be granted upland of current shorelines to allow the natural migration of the coast.

## ***Barrier Beaches***

Barrier beaches in Massachusetts serve as habitat for endangered species and other organisms of management concern. Narrow, undeveloped barrier islands and sand spits such as Sampson's Island, Tern Island, Smith Point, and Sunken Meadow Spit are likely to be moved shoreward as rising sea levels erode sand from the seaward side of these islands and deposit it in the relatively calm waters behind (Scavia et al. 2002). Whether they will be reduced in aerial extent or actually grow is a matter of conjecture. Sandy Neck grew more during periods of more rapid sea level rise than in more stable periods due to increased erosion of coastal bluffs that act as a sand source (D. Fitzgerald, 5/30/2002, personal communication).

New areas of "blowouts" on barrier beaches are often attractive as nesting habitats to piping plovers. With rising sea levels and increased severity of winter storms, blowouts and washovers may form with greater frequency, thus providing favorable nesting sites for the plovers, at least in the short term. We can expect greater long-term instability in these naturally unstable habitats.

According to Scavia et al. (2002) barrier beaches that are developed or covered with dune grass are less likely to migrate inland due to trapping of sand by structures. These might eventually erode and the sand deposited in sandbars offshore, much like the pattern of winter beaches.

The increase in sea level will likely raise the specter of increased armoring of barrier beaches. Revetments, groins, and similar structures interfere with the natural migration of sand along the coast and generally cause problems down current, as has occurred at Sunken Meadow Spit in Eastham and Wellfleet.

## ***Salt Marshes and Tidal Flats***

Salt marshes are habitats that flourish during periods of slowly rising sea levels. As long as the marsh can keep up with sea level rise through the steady accumulation of peat from the growth of the plants and by trapping sediment brought in by rivers and the ocean, a marsh will expand both seaward and toward the upland and remain healthy. Unfortunately, there is concern that marshes may not be able to keep up with the rapid rates of relative sea level rise that are anticipated as a result of global warming.

EPA estimated that a two-foot rise in sea level could result in a national loss of 17-43% of our wetlands. About half of that loss would occur in Louisiana, which contains about one fourth of the United States' coastal wetlands; about 1 million acres of wetlands have been converted to open water since 1940 (Burkett et al. 2001). This loss is due to sea level rise and land subsidence as channeling of rivers behind levees and the building of canals has severely reduced the natural sediment deposition from the rivers in the absence of sediment deposition. The projected loss of wetlands in coastal Louisiana with an additional 20 inch sea level rise is at least another 1.28 million acres (National Assessment Synthesis Team 2000). Changes in New England will not be as dramatic, but some losses of coastal marshes are likely.

Many salt marshes in Massachusetts may no longer be able to migrate toward the upland as sea level rises due to development around their borders. Joppa Flats, for example, is bordered by a short coastal bank and the Plum Island Turnpike. There is likely to be some transformation of the salt marsh there to tidal flats and tidal flats to subtidal flats as sea level rises. Massachusetts Audubon salt marshes at sanctuaries like Felix Neck, Wellfleet Bay, North River, Allens Pond, and Rough Meadows will become more significant because they still are surrounded by protected conservation uplands and therefore could migrate upwards.

Increasing sea levels will likely change the balance between different habitats within the salt marsh. Bertness et al. (2002) project a loss of irregularly-flooded high marsh, *Spartina patens*-dominated habitats as the more flood tolerant *S. alterniflora* migrates landward in response to sea level rise and the invasive form of *Phragmites australis* spreads seaward from the upland in response to anthropogenically-derived nutrient loading. Such high marsh habitats that may be getting “squeezed out” are nesting areas for the obligate salt marsh bird, the Salt Marsh Sharp-tailed Sparrow. Marshes are also likely to be characterized by a greater percentage of open water, such as salt pannes, a trend that is currently under investigation at the Plum Island Ecosystem Long Term Ecological Research Project.

Salt marsh restoration to make up for historical losses and degradation has been promoted strongly by the Massachusetts Office of Coastal Zone Management and the Habitat Division of the National Oceanic and Atmospheric Administration (NOAA). Two Massachusetts Audubon coastal sanctuaries, Joppa Flats and Eastern Point, have been restored, and Mass Audubon has partnered with a other organizations in restoration projects at other sites along the Massachusetts coast. Projects are based to a large extent on increasing the inundation of salt marshes by salt water to reverse the effects of past tidal restrictions, which then reduces the spread of undesirable brackish invasive species, *Phragmites australis* and *Lythrum salicaria*. The balance between salt and fresh water could be changing as a result of climate change.

Because the two climatic models (Hadley and Canadian Center) disagree on how global climate change will affect precipitation patterns in New England, it is not certain whether freshwater runoff will be increased or decreased with climate warming. Assuming no change in runoff, salinities in marshes are likely to increase due to more flushing by seawater. New culverts on salt marshes should be designed with the expected future higher high tides and more intense storms in mind.

## **Coastal Ponds**

Sesachacha Pond on Nantucket, Sengecontactet Pond on Martha’s Vineyard, and Allens Pond in Dartmouth are bordered in part by Mass Audubon sanctuaries. Natural coastal ponds typically go through periods of connection and isolation from the ocean in response to the movements of sediments and storms. Under natural conditions, the movement of sediments keeps Sesachacha Pond isolated from the ocean except during occasional breaches caused by intense storms. This breaching occurs naturally with a

period of several years. Between these episodes, the pond freshens and water levels increase. The frequency of breaching of this pond is likely to increase with sea level rise and more intense coastal storms.

Sengecontactet Pond and Allens Pond are kept artificially connected to sea permanently in the belief that regular flushing benefits shellfish and water quality. Sengecontactet Pond has two permanent openings protected by groins. In recent years, it has suffered from loss of eelgrass and scallops, possibly due to enhanced nutrient loading from increased development on Martha's Vineyard. . Allens Pond has an inlet that migrates along the beach and eventually closes if left alone. The town keeps it open. Increased sea levels may increase the frequency of flushing in these two ponds, and increased use of groundwater by development may result in a more saline environment

### ***Coastal Waterbirds***

Several scientists have examined the potential impacts of global climate change on coastal birds. Erwin et al (2001) suggested that populations of marsh specialists, such as Laughing Gulls, Foster's Terns, Clapper Rails, Seaside Sparrows, and Salt Marsh Sharp-tailed Sparrows will be vulnerable to the loss of important salt marsh nesting areas due to sea level rise. Nauset Marsh on Cape Cod lost about 180 acres, or 25.4% of its area, between 1947 and 1994 due to sea level rise. Erwin et al. (2001) speculated that wintering waterfowl and migratory shorebirds may actually benefit from increased intertidal and subtidal flats. Gailbraith et al. (2001), however, projected that mud flat habitat would decline much more than salt marshes (57% vs 12 %) in Delaware Bay under a 2°C rise in temperature over the next century. This would seriously jeopardize shorebird habitat.

A rapidly warming climate may also affect the synchrony of bird migration and food resources. Delaware Bay is the largest staging area for a number of species of shorebirds in the Atlantic Flyway during their spring migration (Clarke et al. 1993, Burger et al. 1996). These long distant migrants arrive at Delaware Bay at the same time that horseshoe crabs are spawning. Horseshoe crab eggs are a vital food source for these migratory birds (Myers 1986, Castro and Myers 1993). Will the synchrony of these two events remain as increases in global temperatures result in earlier arrivals of migrating birds? Will increased beach erosion in Delaware Bay and Monomoy Island result in less habitat for horseshoe crabs and shorebirds?

### ***Coastal Fisheries***

Several authors have documented shifts of ranges of marine fish poleward in response to global warming (Frank, et al. 1990; Murawski 1993). Coastal fishes respond to cycles of temperature, salinities, and primary production. Elevated CO<sub>2</sub> may act as a stimulant to phytoplankton growth (Hein and Sand-Jensen 1997) and thus increase primary production. Warmer temperatures may also stimulate higher activities of the consumers of phytoplankton so the net impact on fish is not clear.

Keller, et al. (1999) noted a correlation between warmer seawater temperatures and the decline in the intensity of the spring phytoplankton bloom in the northeastern United States. They attribute this decline to increased grazing by zooplankton, which in turn stimulates the pelagic food web. Changes in water temperature were related to changes in the phase of the North Atlantic Oscillation (NAO). Keller, et al. (1999) noted declines in benthic macrofauna and increases in pelagic fauna during warmer periods with a positive NAO phase.

Using this information, Walker (2001) examined the potential impact of warmer temperatures on winter flounder in Narragansett Bay. This species, which uses shallow estuaries such as Plum Island Sound and Wellfleet Bay for nursery areas, has been declining for about 25 years due primarily to overfishing. Walker speculates that warmer seawater temperatures have also contributed to the decline in winter flounder by other mechanisms including 1) reduced availability of benthic food due to greater consumption of phytoplankton by pelagic species, 2) reduction in the size of the spring phytoplankton bloom in warmer waters, and 3) decreased survival of flounder larvae due to increased predation. A mesocosm study by Keller and Klein-McPhee (2000) showed that survival and growth of larval winter flounder declined at elevated temperatures.

Warming of sea temperatures may affect predator-prey relationships with population consequences. For example, Atlantic mackerel has expanded its range north and is now feeding on juvenile cod, upon which they previously did not prey because their ranges did not overlap.

The migration patterns, spawning success, and juvenile survival of many fish and marine invertebrates are sensitive to changes in water temperatures. One might expect northern population shifts of marine species, such as Atlantic cod, in response to warmer sea temperatures (Scavia et al., 2002). Cycles in populations of yellowtail flounder, an important commercial species, have been linked to water temperatures, with warmer temperatures associated with reduced recruitment (Royce et al. 1959). Wahle and Steneck (1991) have stressed the importance to lobsters in Maine of a critical time period in a juvenile lobster's life when it transforms from a planktonic to a benthic existence. Steneck (in press) has linked warmer temperatures in August, when the juveniles make this transformation, to stronger recruitment into the lobster fishery seven years later, when newly settled juveniles reach harvestable size. Thus warmer water temperatures could affect the distribution of lobsters.

Anadromous fish are affected by temperature and freshwater discharges in their migrations upstream to spawn. With reduced winter snow accumulation and warmer winters, the springtime freshet that may stimulate upstream migration is likely to be diminished in strength. It has been hypothesized that the difficulty in restoring Atlantic salmon to the Connecticut River, the southernmost part of this species' historic range, is because this river may have harbored a genotype adapted to warmer temperatures. This genotype no longer exists. If that is so, then increasing ocean and river temperatures may make it all but impossible to restore Atlantic salmon to the more southerly rivers in its historic range (e.g., the Connecticut and Merrimack).

## **Other Marine Organisms**

Like fish, marine invertebrates and seaweeds respond to changes in water temperature. Sagarin et al. (2000) resampled study plots that had been first sampled in 1931-1933 in a rocky intertidal community at Hopkins Marine Station, Pacific Grove, California. They found changes in the abundance of macroinvertebrates consistent with predicted effects of recent warming. Most southern species increased in abundance during the 60 year time period whereas northern species decreased. Shoreline temperatures had increased by 0.79° C on an annual basis with a 1.94° C increase in summer temperatures. The changes they observed were far greater than any resulting from short-term climatic shifts, such as an El Nino Southern Oscillation Event. Changes in marine invertebrate populations attributed to warming temperatures along the Pacific coast were also reported in Barry et al., (1995). No similar analysis has been done on the east coast.

The incidence and persistence of harmful algal blooms in marine waters may increase in response to warmer water temperatures (New England Regional Assessment Group 2001). This is both a human health and an ecosystem issue.

There has been increased concern regarding the invasions by exotic marine species (Pederson, 2000). Global warming is often cited as a potential factor in these invasions, although there are no clear patterns that global warming has been responsible for increased invasions of more northerly marine habitats. Whitlatch (unpublished results) studied the settling of tunicates in Long Island Sound over several seasons and reported that years of warmer seawater temperatures were associated with a relative increase in the settlement of non-native tunicates compared to native tunicates. A 25-year trend of warming winter temperatures along the eastern coast of the United States has been implicated in the northward expansion of oyster diseases (MSX and dermo disease (Harvell et al., 1999).

## **How will Global Warming Effect the Terrestrial Ecosystems of Massachusetts?**

### ***Effects on Forest Types***

Nationally, it has been estimated that about 60% of our forested land will not sustain its current forest type under the influence of global warming (Spath 2001). The United States Environmental Protection Agency (EPA) estimates that, 30-60% of Massachusetts's forests are vulnerable to climate change (USEPA 1997). As our climate warms, there will likely be an increase in the extent of oak hickory forests at the expense of northern hardwoods (yellow birch, American beech, and sugar maple, Iverson et al. 1999). Oak-hickory forest associations dominate the regions of Virginia or Georgia that our climate is projected to resemble in 2001. Thus, the future forest in Massachusetts under global climatic change will have different trees and more than likely a different suite of understory species. There is already evidence that paper birch (*Betula papyrifera*) has receded northward in the past 50 years (LaRoe 1995). The New England

woodland wildflower and fall colors for which New England forests are famed may become a thing of the past.

Despite the differences in temperature projections in the two models, they project a similar change in vegetation (National Assessment Synthesis Team 2001). Parts of Massachusetts that are currently forested with northern hardwoods are likely to experience the greatest change in vegetation. Massachusetts Audubon sanctuaries that will be affected include Wachusett Meadow, Pleasant Valley, and several of the unstaffed sanctuaries in the central and western part of the state. Isolated communities with northern affinities, such as the spruce-fir forest that occurs on Mt. Greylock, may be particularly vulnerable to climate change since there is no place for this community type to migrate. They may only survive in isolate pockets with suitable microclimates, such as northward facing slopes at relatively high elevations.

The Nature Conservancy is trying to identify undeveloped corridors that would allow natural migration of ecosystem components northward. Due to the rather narrow north-south orientation of Massachusetts, the opportunities for this migration are limited strictly within Massachusetts borders. A more New England-wide perspective to land protection would make more sense ecologically.

One of the consequences of a change from northern hardwoods to oak hickory forests is a decline in maple sugar production in New England (New England Regional Assessment Group 2001). Production of maple syrup in Vermont, the nation's largest producer, is now only one third of what it was in 1900. Syrup production in New England is inversely correlated with winter temperatures, and this relationship is evident even on a year-to-year basis. In Vermont, the sap used to flow between mid March and mid April, but now it starts as early as the beginning of February because winter temperatures are warmer. In contrast, production of maple syrup has tripled in Canada since the 1970s. Canada now dominates the world market in maple syrup, much of it from the Gaspé Peninsula. A major factor in Canada's recent success may be the increase in the number of days in which the Gaspé winter temperatures climb above freezing, thereby promoting the flow of sap.

### ***Effects on Forest Processes***

Rising global temperatures will likely produce a cascade of effects that influence many processes of terrestrial ecosystems. As an example, Melillo et al (in press) found that the release of CO<sub>2</sub> from the soil to the atmosphere occurs at a more rapid rate in warmer forest plots. Similarly, microbial mineralization of nitrogen occurs more rapidly at warmer temperatures and the warmer temperatures allow greater degradation of more recalcitrant forms of nitrogen. In sum, there are likely to be changes in our forests at the microbial level that have as yet undetermined consequences on forest dynamics.

Elevated carbon dioxide levels influence plant growth and chemistry. This has subsequent effects on the consumption of plant material by herbivores. Coviello and Trimble (1999) suggest that plants will become less palatable and nutritious to insects, which could result in shifts in insect populations with implications for agricultural and

forest pests as well as insects of conservation concern. Mattson et al. (2004) found that elevated CO<sub>2</sub> stimulates the production of tannins and other phenolic secondary metabolites that act as defensive compounds in silver birch (*Betula pendula*) and paper birch (*B. papyrifera*). High CO<sub>2</sub> led to reduced feeding by rabbits and hares on the birches, a response that could be reversed by adding high amounts of nitrogen. These papers illustrate how wide reaching and complex some of the responses are likely to be.

## **Range Shifts**

Changes in the ranges of many different types of organisms from birds to salamanders to insects have been occurring in the past 100 years and have been attributed to warming climate (see USEPA web site for a bibliography). Parmesan and Yohe (2003) examined 1700 species of organisms and found that 279 showed long-term trends. There was an average range shift of 6.1 km per decade toward the poles consistent with what might be predicted from temperature increases. According to the Union of Concerned Scientists,

Range shifts in areas with regional warming trends have been reported in alpine plants (Grabherr et al., 1994), butterflies (Parmesan, 1996; Parmesan et al., 1999), birds (Thomas and Lennon, 1999), and mosquitoes (Epstein et al., 1998). In a study of 35 European non-migratory butterfly species, 63% had ranges that shifted to the north by 35-240 km during the past century, and only 3% shifted to the south (Parmesan et al., 1999). The range shift parallels a 0.8°C warming over Europe during the last century, which has shifted climatic isotherms northwards by an average of 120 km (Beniston et al., 1998).

## **Insects**

Milder winters and warmer night temperatures may allow destructive insects and pathogens to move into forests at higher latitudes and elevations (Kirschbaum and Fischlin, 1996). One example is the spruce bark beetle (*Ips typographus*) whose increased infestation of the boreal forests in Alaska has been attributed to warmer winters. The hemlock woolly adelgid (*Adelges tsugae*), which is devastating hemlocks in the southern New England, may be benefiting from milder winters. Forests in Massachusetts will be subjected to pathogens that formerly were limited by colder New England winters.

## **Birds**

One of the more obvious trends in the natural history of New England over the past century has been the number of “southern” birds that have expanded their ranges northward. These include such species as Carolina Wren, Red-bellied Woodpecker, Northern Cardinal, Mockingbird, Glossy Ibis, and Tufted Titmouse. Some of these expansions could be related to the proliferation in the use of bird feeders in winter, habitat changes, and wildlife management efforts. There has not been, however, a major increase in northern species moving south so climate change is likely having some role.

A large amount of literature has attributed changes in bird distributions to global climate change. Root (1988) showed that the winter ranges of 50 species of songbirds were related to the average minimum January temperatures and that their ranges could vary annually based on this temperature. Her studies on northern cardinals has led to the speculation that survival in a cold winter is related to the amount of fat a bird can store. As the average minimum temperature rises, the birds should expand their range northward. In a study of British birds, Thomas and Lennon (1997) estimated that the northern margins of the ranges of many species have moved about 18.9 km north in a 20 year period.

Valiela and Bowen (2003) examined annual Audubon Christmas Count data from Cape Cod to determine if there were changes in the winter distribution of birds since the 1930s. They related shifts in populations to both temperature and habitat changes as a way of distinguishing global from local factors. They found that the ratio of southern to northern birds wintering in Cape Cod has increased over the past 70 years as the temperature warmed. Southern species increased across all habitat types, suggesting that they were responding to warmer winters, but not to changes in habitat types. Northern birds associated with forest habitats declined since the 1970s. They attribute the increase in southern species to global warming, and the more recent decline in northern forest birds to the rapid loss of forested habitat on Cape Cod to development.

Research funded by EPA and currently being carried out by the American Bird Conservancy, the University of Michigan, Goddard Institute for Space Studies, Boston University, and Stratus Consulting is examining a number of potential changes in bird distribution, including whether Baltimore will remain a future home of Baltimore Orioles and whether warblers will no longer be able to breed in northern Minnesota and southwestern Ontario (Price and Root 2002). Price (2000) modeled the impact of the anticipated climate change on the summer distribution of Massachusetts passerines (Table 2). His model predicts that 33 species that currently nest here would be extirpated as summer residents. These include species of northern affinities, including many wood warblers, finches, flycatchers and swallows. Nine species would undergo summer range contraction. 15 species would expand their summer range, and seven species that do not breed here, may breed here in the future.

The response of birds to global warming is more complicated than a simple response to temperature, since vegetation and patterns of rainfall are also predicted to change. This is illustrated by a simulation model of nesting success of Black-throated Blue Warblers by Rodenhouse (1992) in which the author reached the conclusion that the effects of warming depends on the amount of precipitation. Greater precipitation leads to increased nesting mortality. It also leads to a longer breeding season and enhanced food resources for the birds.

A number of climate scenarios indicate future problems for certain groups of birds. The prairie pothole region of North America is an important breeding area for many of the waterfowl species that winter in the northeast; the predicted drying in this region could have continent-wide impacts. Sorenson et al. (1998) has predicted that

drying in the pothole region could lead to a 50 % decline in the waterfowl nesting success. According to the World Wildlife Fund, the Great Basin, which has geographically isolated wetlands, will also become drier and breeding areas located there may no longer be productive for birds.

Another change that may have implications on a continental scale is the decline in the tundra due to both the melting of permafrost and the expansion of the boreal forest northward. Many of our wintering waterfowl and migratory shorebirds nest in tundra habitat, thus a loss or alteration of this habitat could have profound consequences. Birds may also face changes in their migration routes, particular those that migrate through the central United States and the Great Basin, areas that are likely to become more prone to drought and those using coastal wetlands, as described earlier.

### ***Massachusetts Forests as Carbon Sinks***

Forests on Massachusetts Audubon sanctuaries and other conservation land in the Commonwealth provide obvious ecological benefits. From the perspective of global warming, our forests serve as carbon sinks, since growing trees take up carbon dioxide and sequester it as organic carbon in wood. Thus the preservation of our forests contributes to the removal of carbon dioxide from the atmosphere and provides some mitigation to greenhouse warming. At a conference held at the Yale School of Forestry in June 2000, there was much discussion about the role that conservation organizations who own land can play in carbon sequestering.

### **Freshwater Ecosystems**

Freshwater ecosystems in Massachusetts will likely be subjected to a number of changes as a result of global climate change. The exact nature of these changes is unclear. Although we are certain that the climate will continue to become warmer in the future, we do not know whether precipitation will increase or decrease.

Brooks (2002) stated that global warming could reduce the amount of time vernal pools are flooded thus affecting vernal pool inhabitants, such as spotted salamanders, with relatively long developmental periods. The actual extent of impact depends on whether there will be more or less precipitation in the future, something upon which the current climatic models do not agree. A further complication is that vernal pools will likely be ice free earlier in the season, thus leading to earlier migrations to breeding pools.

Streamflow patterns are likely to change as warmer temperatures reduce the extent and duration of the winter snowpack in New England. The 1980s and 1990s contained an unusually number of low snow years at the Hubbard Brook Experimental Forest in New Hampshire (New England Regional Assessment Group 2001), and this trend is likely to continue under increased global warming. With less winter snow, particularly in the “fringe months” of December and March, scientists predict that the typical New England hydrographic pattern in rivers of intense spring flooding followed by lower summer flow will be altered. With warmer winters there will likely be more

frequent freezing and thawing in winter and a less well-defined spring peak. This could change the patterns of migration of anadromous and other fish that are cued to spring peak flows.

The prediction of more intense storms could lead to more frequent episodic flooding throughout the year. It is not clear how riverine forests such as those that occur at Arcadia and Ipswich River wildlife sanctuaries, will respond to such a change in hydrography.

Cold water fish, inhabiting Massachusetts rivers and lakes, such as trout, are expected to suffer as a result of global warming. An EPA modeling study cited in New England Regional Assessment Group (2001) predicted a 50-100% loss of habitat for brook, brown, and rainbow trout in New England. The latter two are non-native species introduced specifically for angling, however brook trout are native. As with forest trees and animals, species at the southern limits of their distribution may experience a range shift northward that might remove them from Massachusetts.

Warmer temperatures will likely increase demand for water for human consumption during the summer. If precipitation declines overall, then this would accentuate problems of draw down. Another problem for future water supplies under the global warming scenario is the likelihood of salt water intrusion resulting from rising sea levels. These intrusions would likely increased demand on more limited freshwater sources.

## **Changes in Phenology**

Root et al. (2003), Parmesan and Yohe (2003) have recently published meta analyses showing changes in phenology consistent with global warming. Root et al. examined 143 taxa from widely different phyla (e.g., mollusks, amphibians, birds, trees, and non woody plants). Over 80% showed phenological shifts with the average being about 5 days. Parmesan and Yohe (2003) estimated that the timing of spring events has shifted 2.3 days earlier per decade.

### *Amphibians*

It is hard to predict how increasing global temperatures will affect vernal pools. On average, amphibians in the northeast are breeding several weeks earlier than in the past. Increasing temperatures without any change in precipitation will likely lead to more rapid drying out of the pools, and, therefore, less time for tadpoles to reach adulthood. This does not take into account changes in precipitation, which, as described above, is predicted to either increase or decrease depending on the model.

### *Flowering phenology*

David Wolf of Cornell has documented earlier flowering times of lilacs in Ithaca, New York. Oglesby and Smith (1996) examined time of first flowering for 15 species of spring wildflowers of the Hudson Highlands and found that six exhibited a statistically significant trend of earlier flowering times over the past 50 years. The remaining species

showed no change. The species that flowered earlier tend to occur in open areas that may warm up quicker. One fall bloomer, witch hazel (*Hammemelis virginianus*), also has been flowering earlier.

### *Bird Migration and Nesting*

Birds are showing the effects of climate change in their migrations and nesting phenology. Oglesby and Smith used the records of the Cayuga Bird Club dating back to 1903 in examining first arrival of spring migrants. Fifty-one percent of 76 species arrive earlier than they did around 1900 with an average of 5.5 days earlier. Forty six percent showed no change and two species (Louisiana Waterthrush and Mourning Warbler) actually are arriving later. Eighty five percent of those species showing an earlier spring arrival time are Neotropical migrants. A study in Germany documented later fall departure dates for migrants as well. The American Bird Conservancy website states that many bird species are arriving an average of 21 days earlier in the Upper Peninsula of Michigan.

The timing of bird nesting has also responded to warming climate. Crick et al. (1997) report earlier laying of eggs by British birds, and this corresponds with an increase in the growing season of about eight days in northern latitudes. Geese in the arctic nest about 30 days earlier than they did around 1960 (Laroe and Rusch 1996).

## **“Pest” Species**

Global warming will likely expand the range of some undesirable southern species. We have already described some of the changes that have been attributed to warming including increases in pathogens of oysters, bark beetles, and hemlock wooly adelgid. Warmer, wetter winters could increase the survival of the tick that spreads Lyme disease and the mosquitoes that are responsible for Eastern Equine Encephalitis (New England Regional Assessment Group 2000). The spread of West Nile Virus into southern New England could also be related to a warming climate. The United States Environmental Protection Agency (1995) noted that mosquitoes that can carry malaria do occur in Massachusetts. Such changes in insect-borne diseases are speculative now, since the survival of these pests will be affected by patterns of precipitation as well as temperature. Although these are human health issues, demands for spraying and for water management measures to control mosquitoes have ecosystem level effects.

## **Consequences for our Ecosystem**

Periods of global warming and cooling have occurred throughout geological time. Those organisms that have survived have done so by shifting their ranges or adapting to the new climatic conditions. The current anthropogenically-induced climate change is much more rapid than any that has taken place in the past, and this change will be occurring in a highly modified and fragmented landscape. It is uncertain which organisms and ecological communities will be able to adjust to such a rapid rate of change and what our future biological landscape will look like.

## References

- Barry, J., C. Baxter, R. Sagarin, and S. Gilman, 1995. Climate related, long-term faunal changes in a Californian rocky intertidal community. *Science* 267, 672-675.
- Beniston, M. and R.S.J. Tol, 1998. Europe. In *The Regional Impacts of Climate Change: An Assessment of Vulnerability*, 149-185, (Watson, R.T., M.C. Zinyowera, and RH Moss, eds.), Cambridge University Press, Cambridge, UK.
- Bertness, M.D., P. Ewanchuck, and B.R. Silliman. 2002. Anthropogenic modification of New England salt marsh landscapes. *Proceedings of the National Academy of Science*. 99: 1395-1398
- Brooks, R. 2002. Effects of climatic change on vernal pools. From a lecture presented at the 2002 Annual Meeting of the Association of Massachusetts Wetland Scientists, March 23, 2002, Boxborough, MA.
- Burger, J., L. Niles, and K.E. Clarke. 1996. Importance of beach, mudflat, and marsh habitats to migrant shorebirds on Delaware Bay. *Biological Conservation* 79:283-292
- Burkett, V., R. Ritschard, S. McNulty, J. J. O'Brien, R. Abt, J. Jones, U. Hatch, B. Murray, S. Jagtap, and J. Cruise. 2001. Potential Consequences of Climate Variability and Change for the Southeastern United States, pp 137-166 in: *The Potential Consequences of Climate Variability and Change: Foundation Report*, Report by the National Assessment Synthesis Team for the US Global Change Research Program, Cambridge University Press, Cambridge, UK, 620pp
- Castro, G. and J.P. Myers. 1993. Shorebird predation on eggs of horseshoe crabs during spring stopover on Delaware Bay. *The Auk* 110:927-930
- Clark, K.E., L.J. Niles, and J. Burger. 1993. Abundance and distribution of migrant shorebirds in Delaware Bay. *Condor* 95:694-705
- Coviello, C.E., and J.T. Trimble. 1999. Effects of elevated atmospheric carbon dioxide on insect-plant interactions. *Conservation Biology* 13:700-712
- Crick, H. Q. P., C. Dudley, D.E. Glue and D.L. Thompson. 1997. U.K. birds are laying their eggs earlier. *Nature* 388:526.
- Epstein, P., H. Diaz, S. Elias, G. Grabherr, N. Graham, W. Martens, E.M. Thompson, and J. Susskind, 1998. Biological and physical signs of climate change: focus on mosquito borne diseases. *Bulletin of the American Meteorological Society* 79:409-417.
- Erwin, R.M., D. Prosser, G. Sanders, D. Cahoon, and C. Roman. 2001. Sea-level rise and marsh changes along the Atlantic Coast: Implications for water birds. Poster presented at the 16th Biennial Meeting of the Estuarine Research Federation, St. Petersburg Beach, FL.

- Frank, K.T., R.I. Perry, and K.F. Drinkwater. 1990. Predicted response of Northwest Atlantic invertebrate and fish stocks to CO<sub>2</sub>-induced climate change. *Trans Amer. Fisheries Soc.* 119:353-365
- Gailbraith, H., S.H. Julius, D. Park, R. Jones, J. Clough, B Harrington, and G. Page. 2001. Potential effects of sea level rise on intertidal habitat for migrating shorebirds. Abstracts, 16th Biennial Meeting of the Estuarine Research Federation, St. Petersburg Beach, FL.
- Giese, G., D.G. Aubrey, and P. Zeeb. 1987. Passive retreat of Massachusetts coastal upland due to relative sea level rise. Massachusetts Office of Coastal Zone Management, Publ. No. 300-5-87-815491. Boston, MA
- Grabherr, G., M. Gottfried, and H. Pauli, 1994. Climate effects on mountain plants. *Nature* 369:448.
- Harvell, C.D., K. Kim, J.M. Burkholder, R.R. Colwell, P.R. Epstein, D.J. Grimes, E.E. Hofmann, E.K. Lipp, A.D.M.E. Osterhaus, R.M. Overstreet, J.W. Porter, G.W. Smith, G.R. Vasta. 1999. Emerging Marine Diseases-Climate Links and Anthropogenic Factors. *Science* 285, 1505-1510.
- Hein, M and K. Sand-Jensen. 1997. CO<sub>2</sub> increases oceanic primary production. *Nature* 388:526 - 527
- IPCC. 2001 (a). Climate Change 2001: The Scientific Basis. Report for the 3<sup>rd</sup> Assessment. Intergovernmental Panel on Climate Change. UNEP, WMO.
- IPCC. 2001 (b). Climate Change 2001: Impacts, Adaptation, and Vulnerability. Report for the 3<sup>rd</sup> Assessment Intergovernmental Panel on Climate Change. UNEP, WMO.
- IPCC. 2001 (a). Climate Change 2001: Mitigation. Report for the 3<sup>rd</sup> Assessment Intergovernmental Panel on Climate Change. UNEP, WMO.
- IPCC. 2001 (a). Climate Change 2001: Synthesis Report. Report for the 3<sup>rd</sup> Assessment Intergovernmental Panel on Climate Change. UNEP, WMO.
- Iverson, L. R., A. M. Prasad, B. J. Hale, and E. K. Sutherland. 1999. An atlas of current and potential future distributions of common trees of the eastern United States. General Technical Report NE-265. Northeastern Research Station, USDA Forest Service. 245 pp
- Keller, A.A. and C. Klein-McPhee. 2000. Impacts of elevated temperature on the growth, survival and trophic dynamics of winter flounder larvae: A mesocosm study. *Can. J. Fish Aquatic Science* 57: 2383-2395

Keller, A.A., C. Oviatt, and H. Walker. 1999. Predicted impacts of elevated temperature on the magnitude of the winter-spring phytoplankton bloom in temperate and coastal waters: A mesocosm study. *Limnol. Oceanogr.* 44:344-356

Kirschbaum M.U.F. and A. Fischlin, 1996. Climate change impacts on forests. In *Climate Change 1995 - Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses*, 95-129 (In R.T. Watson, M.C. Zinyowera, and R.H. Moss, Eds.), Cambridge University Press, Cambridge, UK.

Joyce, T. 2005. Abrupt climate change: Are we on the brink of a new Little Ice Age? Woods Hole Oceanographic Institution. Ocean and Climate Change Institute. [http://www.whoi.edu/institutes/occi/currenttopics/abruptclimate\\_joyce\\_keigwin.html](http://www.whoi.edu/institutes/occi/currenttopics/abruptclimate_joyce_keigwin.html).

LaRoe, E.T. 1996. Overview in E. T. LaRoe, G. S Farris, C. E. Puckett, P. D. Doran and M. J. Mac (eds.). *Our living resources: a report to the nation on the distribution, abundance, and health of U.S. plants, animals, and ecosystems*. U.S. Department of the Interior, National Biological Service, Washington, DC.

LaRoe, E.T., and D.H. Rusch. 1996. Changes in nesting behavior of Arctic geese. in E. T. LaRoe, G. S Farris, C. E. Puckett, P. D. Doran and M. J. Mac (eds.). *Our living resources: a report to the nation on the distribution, abundance, and health of U.S. plants, animals, and ecosystems*. U.S. Department of the Interior, National Biological Service, Washington, DC.

Mattson W., K Kuonkanen, P Niemela, R. Julkunen-Tiitto, S. Kellomaki, and J. Tahvanainen. 2004. Elevated CO<sub>2</sub> alters birch resistance to *Lagomorpha* herbivores. *Global Change Biology* 10:1402-1413

Melillo, J. M., P. A. Steudler, J. D. Aber, K. Newkirk, H. Lux, F. P. Bowles, C. Catricala, A. Magill, T. Ahrens and S. Morrisseau. (in press) Soil warming – a major consequence of global climate change. Chapter 14. In: D. Foster and J. Aber (eds.), *Forests in Time, The Environmental Consequences of 1000 Years of Change in New England*. Synthesis Volume of the Harvard Forest LTER Program. Yale University Press.

Murawski, S. 1993. Climate change and marine fish distributions: Forecasting from historical analogy. *Trans Amer. Fisheries Soc.* 122: 657-658

Myers, J.P. 1986. Sex and gluttony in Delaware Bay. *Natural History* 95:68-77

National Assessment Synthesis Team. 2000. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*. New York: Cambridge University Press.

NRC (National Research Council). 2002. *Abrupt Climate Change. Inevitable Surprises*. Committee on Abrupt Climate Change. Ocean Studies Board, Polar Research Board,

Board on Atmospheric Sciences and Climate. National Academy Press. Washington, DC.

New England Regional Assessment Group (2001). *Preparing for a changing climate: The potential consequences of climate variability and change. New England regional overview*. U.S. Global Change Research Program. University of New Hampshire. 96 pp.

O'Brien, A. (2002) Historical review of past climate change. From a lecture presented at the 2002 Annual Meeting of the Association of Massachusetts Wetland Scientists, March 23, 2002, Boxborough, MA.

Oglesby, R. and C.T. Smith 1996. Climate change in the Northeast. in E. T. LaRoe, G. S Farris, C. E. Puckett, P. D. Doran and M. J. Mac (eds.). *Our living resources: a report to the nation on the distribution, abundance, and health of U.S. plants, animals, and ecosystems*. U.S. Department of the Interior, National Biological Service, Washington, DC.

Parmesan, C., 1996. Climate and species' range. *Nature* 382, 765-766

Parmesan, C., et al. 1999. Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature* 399, 579-583.

Parmesan, C. and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421:37-42.

Pederson, J. (ed.) 2000. *Proceedings of the 1<sup>st</sup> National Conference on Marine Bioinvasions, Jan 24-27, 1999*, MIT Sea Grant Cambridge, MA.

Price, J.T. 2000. Modeling the potential impact of climate change on the summer distributions of Massachusetts passerines. *Bird Observer* 28: 224-230

Price, J.T. and T.L. Root. 2002. No orioles in Baltimore? Climate change and neotropical migrants. *Bird Conservation* 17: 12

Rodenhouse, N.L. 1992. Potential effects of climatic change on a neotropical migrant landbird. *Conservation Biology* 6: 263-272.

Royce, W.F., R.J. Buller and E.D. Premetz. 1959. Decline of the yellowtail flounder (*Limanda ferruginea*) off New England. *Fishery Bulletin* 59:169-267.

Root, T. 1988. Environmental factors associated with avian distributional boundaries. *Journal of Biogeography*. 15:489-505.

Root, T. and J.D. Weckstein. 1996. Changes in winter ranges of selected birds, 1901-1989. pp. 386-389 in E. T. LaRoe, G. S Farris, C. E. Puckett, P. D. Doran and M. J. Mac (eds.). *Our living resources: a report to the nation on the distribution, abundance, and*

*health of U.S. plants, animals, and ecosystems*. U.S. Department of the Interior, National Biological Service, Washington, DC.

Root, T.L., J. Price, K. Hall, S. Schneider, C. Rosenzweig and J.A. Pounds. 2003. Fingerprints of global warming on wild plants and animals. *Nature* 421: 57-60

Sagarin, R.D., J.P. Barry, S.E. Gilman, and C.H. Baxter. 2000. Climate-related change in an intertidal community over short and long time scales. *Ecological Monographs* 69:465-490

Scavia, D., J.C. Field, D.F. Boesch, R.W. Buddemeier, V. Burkett, D.R. Cayan, M. Fogarty, M.A. Harwell, R.W. Howarth, C. Mason, D.J. Reed, T.C. Boyer, A.S. Sallenger, and J.G. Titus. 2002. Climate impacts on U.S. coastal and marine ecosystems. *Estuaries* 25: 149-164

Sorenson, L.G., R. Goldberg, T.L. Root, and M.G. Anderson. 1998. Potential effects of global warming on waterfowl populations breeding in the Northern Great Plains. *Climatic Change* 40:343-369.

Spaeth, G. 2001. Opening Remarks. From talk given at Climate Change: Implications for New England Conservation. Yale School of Forestry. April 25, 2001.

Steneck, R. (in press). Are we overfishing American lobsters? In. Buchsbaum, R., W. Robinson and J. Pederson (Editors). *Declines in Massachusetts Bays fish and shellfish resources: A scientific review of causes*. MIT Sea Grant.

Thieler E. R., and E. S. Hammar-Klose. 1999. Vulnerability to Sea-Level Rise: Preliminary Results for the U.S. Atlantic Coast U.S. Geological Survey Open-File Report 99-593

Thomas, C.D. and Lennon, J.J., 1999. Birds extend their ranges northwards. *Nature* 399: 213.

United States Environmental Protection Agency (EPA). 1997. Climate change and Massachusetts. EPA 230-F-97-008u. 4 pp.

Valiela, I. And J.L. Bowen. 2003. Shifts in winter distribution of birds: Effects of global warming and local habitat change. *Ambio* 32:476-480

Wahle, R.A. and R.S. Steneck. 1991. Recruitment habitat and nursery grounds of the American lobster (*Homarus americanus* Milne-Edwards): A demographic bottleneck? *Marine Ecology Progress Series* 69: 231-243

Walker, H. 2001. Case Study 4: Climate variability and winter flounder abundance in southern New England. Pp. 66-67 in: New England Regional Assessment Group. 2001. *Preparing for climate change. The potential consequences of climate variability and*

*change. New England regional overview.* U.S. Global Change Research Program. Univ. New Hampshire, 96 pp.

## Tables

Table 1. Losses in acreage of upland in towns containing Massachusetts Audubon sanctuaries by 2025 based on Giese et al. (1987). These losses and percentages are for the entire town, but do not include salt marshes. Further analysis is required to determine projections for individual sanctuaries. (Place all tables and figures at the end of the document.)

Town	MAS Sanctuary	Projected acreage lost by 2025 at historical rate of sea level rise (3mm/yr)	Percent of upland lost by 2025 at historical rate of sea level rise (3mm/yr)	Projected acreage lost by 2025 under a global warming scenario	Percent of upland lost by 2025 under a global warming scenario
Dartmouth	Allen's Pond	92.4	0.27	234	0.67
Wellfleet	Wellfleet Bay	45.6	0.50	115	1.27
Barnstable	Long Pasture	167.2	0.54	423.6	1.38
Edgartown	Felix Neck	109.9	1.10	278.3	2.79
Marshfield	South Shore	27.1	0.19	68.6	0.48
Gloucester	Eastern Point	21.6	0.14	54.8	0.36
Newburyport	Joppa Flats	9.7	0.21	24.7	0.52

Table 2. Modeled changes in summer ranges of Massachusetts passerines (from Price 2000)

**1. Species that may be extirpated as summer residents:**

- a. Flycatchers: Olive-sided, Yellow-bellied, Alder, Willow, Least
- b. Swallows: Tree, Bank, Cliff
- c. Red-breasted Nuthatch
- d. Winter Wren
- e. Blue-headed Vireo
- f. Warblers: Nashville, Chestnut-sided, Magnolia, Black-throated Blue, Yellow-rumped, Black-throated Green, Blackburnian, Northern Waterthrush, Mourning, Hooded, Canada
- g. Sparrows: Vesper, Savannah, Swamp, White-throated
- h. Dark-eyed Junco
- i. Icterids: Bobolink, Rusty Blackbird
- j. Finches: Purple, Pine Siskin, Evening Grosbeak

**2. Species whose summer range may contract**

- a. Black-capped Chickadee
- b. House Wren
- c. Warbling Vireo
- d. Warblers: Blue-winged, Yellow, American Redstart
- e. Finches: Rose-breasted Grosbeak, House
- f. Sparrows: Song

**3. Species whose summer range may expand**

- a. Acadian Flycatcher
- b. Horned Lark
- c. Purple Martin
- d. Carolina Wren
- e. Northern Mockingbird
- f. Vireos: White-eyed, Yellow-throated
- g. Warblers: Pine, Prairie, Cerulean, Prothonotary, Louisiana Waterthrush, Yellow-breasted Chat
- h. Grasshopper Sparrow
- i. Orchard Oriole

**4. Species whose future range may include Massachusetts**

- a. Carolina Chickadee
- b. Loggerhead Shrike
- c. Warblers: Yellow-throated, Kentucky
- d. Summer Tanager
- e. Blue Grosbeak
- f. Dickcissel