4 — NATURAL RESOURCES AND HABITAT

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4 Natural Resources and Habitat

Introduction

Since climate is a major determinant of ecosystem function and the distribution, abundance, and behavior of organisms, climate change is likely to trigger fundamental responses in and alterations to Massachusetts ecosystems. Climate change will have a significant impact on the biological diversity of Massachusetts and the Northeast as northern, cold-adapted, niche species are lost or replaced by more southern generalist species. Ecological relationships and processes will be undermined by climate change, and there remain many uncertainties in our understanding of ecological response.

Ecological changes in response to climatic change have been observed in the northeastern United States, as plants leaf out and bloom earlier (Wolfe et al., 2005), amphibian breeding seasons start earlier (Gibbs and Breisch, 2001), and Atlantic salmon spring migrations begin sooner (Juanes et al., 2004). In addition to these direct impacts, species and ecosystems face a broad range of indirect climate-related threats. Two examples are the way temperature changes cause decoupling of bird migration and food source timing and provide a competitive advantage to non-native insects and plants.

It is also important to recognize that the observed ecological changes in North America and elsewhere have occurred under a relatively modest average global temperature increase of only 0.74°C (1.3°F); the additional increase of 3° to 5°C (5° to 10°F) predicted for the Northeast is likely to have increased impacts on ecosystems.

This chapter addresses vulnerabilities and adaptation strategies for four ecosystem types: forest, coastal, aquatic, and wetland. The chapter examines these broad ecosystem types to provide a better understanding of how climate change will affect fish, wildlife, plants, and natural resource functions and ecosystem services over time, across the state, and within regions. Strategies that enhance the functions of these ecosystems can also significantly benefit the economy, infrastructure, public health and safety, coastal resources, and other sectors.

Current Stressors

Evaluation and assessment of the impacts of climate change to natural systems, and strategies to abate these threats, should be conducted in the context of current stressors on ecosystems and populations such as: the loss of habitat and ecosystem function caused by development, fragmentation, invasive species, or other threats. These stressors will continue to be a persistent factor affecting the viability of natural systems. In fact, even without the additional threat of climate change, many elements of the state's biodiversity face an uncertain future. Climate change is occurring at such a rapid rate that changes to species and ecosystem function may occur in a disruptive way resulting in loss of species and ecological values.

Economic Benefits of Natural Resources

Healthy and functional ecosystems support several important sectors of the economy and provide valuable social benefits (TEEB, 2009). Having resilient ecosystems can buffer these ecosystem services against the significant impacts that are occurring or are projected to occur due to climate change.

Intact forested watersheds, wetlands, and rivers support clean drinking water and help water suppliers avoid the need for billions of dollars of water purification infrastructure and operations. Protecting functional floodplains and other wetlands prevents the need for additional flood control infrastructure and flood damage repairs. Coastal wetlands act as important natural buffers that prevent storm and flood damage to expensive inland infrastructure. Estuaries are the breeding ground and nurseries for many species of marine organisms that play important ecological and economic roles.

An added benefit of healthy and properly functioning ecosystems is improved resistance to invasive plants, animals, insects, and diseases. As a result, fewer resources are needed for control of these ecologically and economically costly threats. Forests and other naturally vegetated landscapes sequester atmospheric carbon, equivalent to approximately 10 percent of Massachusetts' carbon emissions. Conservation of wetland soils with significant carbon stores (i.e., peat) also prevents the release of additional carbon to the atmosphere.

It is estimated that each acre of forest in Massachusetts provides $1,500 annually in economic value from forest products, water filtration, flood control, and tourism. For the state's 3.1 million acres of forest, this equals $4.6 billion annually (Campbell, 2000).

About 40 percent of Massachusetts residents who are 16 years or older engage in wildlife-related recreation, contributing slightly more than $1.6 billion to the Massachusetts economy. The multiplier effect on the Massachusetts economy of the direct expenditure of $1.6 billion dollars is approximately $2.6 billion. This supports about 27,000 jobs, providing $975 million in wages, $213 million in state income and state tax revenue, and $243 million in federal revenue.

Forest harvesting directly supports 3,700 jobs for foresters, loggers, sawmill workers, and wood processing plant workers in Massachusetts; the wood products industry produces over $385 million of goods annually (American Forest and Paper Association, 2011).

Overall Vulnerabilities

There are similar vulnerabilities across ecosystems based on projected changes in temperature, precipitation (timing and amount), increased storm intensity, drought and the number of extreme heat days, sea level rise, and increased coastal storm surge. Many of these parameters affect ecosystem processes (e.g., stream flow), individual species and populations.

What forms will these changes take? Until recently, our dominant model of change was for habitats to slowly replace each other as their optimum climatic conditions shifted. Thus, we might expect to see the highly vulnerable spruce-fir forests at upper elevations replaced by northern hardwood forest as it moves upslope to track its optimum climatic conditions. This model of entire communities shifting is important in evaluations of what may occur to habitats under climate change. However, this model may not fully represent what actually could occur.

Different organisms have different intrinsic rates of response to climate change. For example, a northeastern warbler such as the American redstart can potentially shift its breeding range northward by several hundred kilometers in only a few days. Yet, the majority of the plants that make up the breeding habitat of this species are far less able to respond as rapidly. Rather than entire ecosystems or communities shifting their distributions across the landscape, we may see them dissociating and separating, then reconfiguring into potentially novel combinations upslope or further north or not reconfiguring at all. This dissociation and reconfiguring has become the dominant model of how ecological communities may be affected by climate change.

The overall approach to assessing the potential vulnerabilities of natural resources to climate change and development of adaptation strategies is presented in the Figure 7.

This chapter assesses the relative vulnerabilities of the state's various habitat types. Each ecosystem category is reviewed for specific associated functions (e.g. biodiversity, flood attenuation) and assessed for the impact to and vulnerabilities of individual functions. These results are used to develop potential adaptation strategies which, if implemented, could help ecosystems resist climate effects, make vulnerable ecosystems more resilient, and assist ecosystems likely to be lost to move into new structures and functions. This analysis represents a generalized assessment that can be informed and refined by other assessments being conducted by the Manomet Center for Conservation Sciences, The Nature Conservancy, the Division of Fisheries and Wildlife, and others.

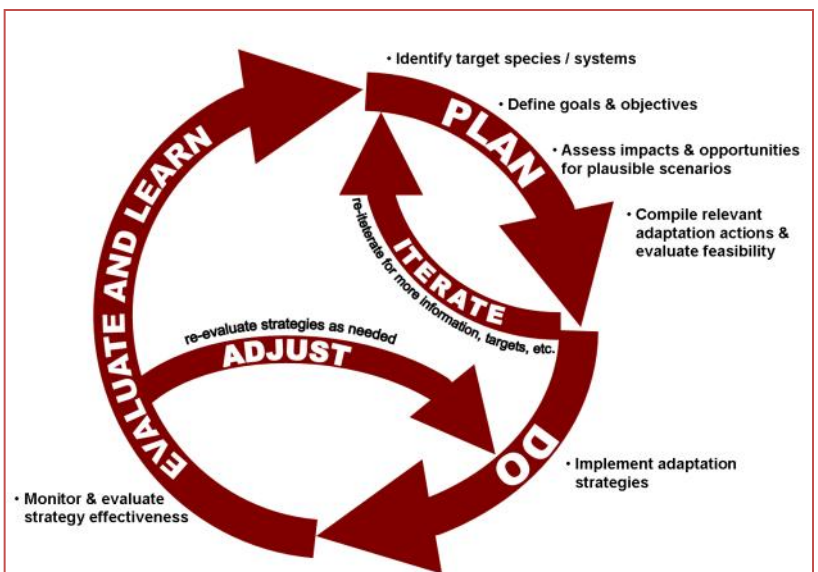


Figure 7: *Climate change adaptive management framework*
Source: Adapted from Glick et al. (2009); Heller and Zavaleta (2009)

This analysis does not look at direct potential impact to specific fisheries, wildlife and plant species and populations. The assumption is that health and diversity of ecosystems serve as a surrogate for maintaining biological diversity. Nevertheless, significant changes in natural communities and populations will occur as a consequence of climate change and these changes may have significant impacts on diversity and status of populations, societal perception of wildlife, and public health.

Adaptation Strategies

In general, adaptation strategies for natural resources and habitats include land and water protection (such as acquisition and easements), land and water management, regulation changes, targeted public funding, increased agency cooperation and coordination, and enhanced and focused monitoring.

All of these adaptation strategies should be used in an adaptive management framework (Figure 7). These adaptation strategies may be used to resist climate change impacts on important habitats to increase habitat resilience or, when habitat vulnerability to climate change impacts is great, to facilitate change from one habitat type to another. Many of these strategies will also serve to mitigate the effects of climate change by sequestering carbon.

It is anticipated these adaptation strategies will be implemented by a broad array of partners including federal, state, and local governments, non-governmental organizations, and others. Significant progress is already being made toward coordinated action through entities such as the Massachusetts Climate Change and Wildlife Alliance (www.climateandwildlife.org).

Climate Change Habitat Vulnerability Rankings: Climate Change & Wildlife Management

Massachusetts agencies are taking steps to develop stronger science-based information so that their climate change related decisions will be better informed. Funded by a grant from the Wildlife Conservation Society, the Manomet Center for Conservation Sciences began working in early 2008 with the Massachusetts Department of Fish and Game's (DFG) Division of Fisheries and Wildlife (MassWildlife) and other partners, including The Nature Conservancy, to improve "climate-smart" criteria in the existing State Wildlife Action Plan (SWAP). The SWAP is MassWildlife's "blueprint" for future conservation in Massachusetts.

A panel of experts drawn from MassWildlife, the Manomet Center, and The Nature Conservancy conducted assessments of 20 key Massachusetts habitats with the following questions in mind:

- How do the fish and wildlife habitats rank in terms of their likely comparative vulnerabilities to climate change?
- How will the representation of these habitats in Massachusetts be altered by a changing climate?
- What degree of confidence can be assigned to the above predictions?
- Which vertebrate species in greatest need of conservation are likely to be most vulnerable to climate change?

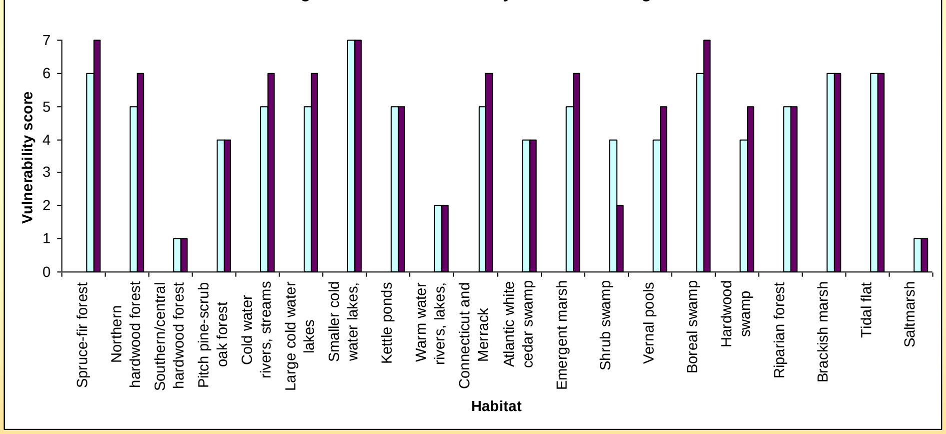


Figure 1.Habitat Vulnerability to Climate Change

Note*: The left bar in each pair represents a doubling of CO2, while the right bar is a tripling of* CO_2*.*

The comparative vulnerabilities of the habitats were evaluated under two emissions scenarios and scored on a vulnerability scale. The study also identified likely future ecological trajectories, assigned confidence scores, and identified other non-climate stressors that could interact with and exacerbate the effects of climate change. The analyses show that different ecological systems are more or less vulnerable to climate change and, consequently, that we can expect to see major changes in their distributions across the Massachusetts landscape.

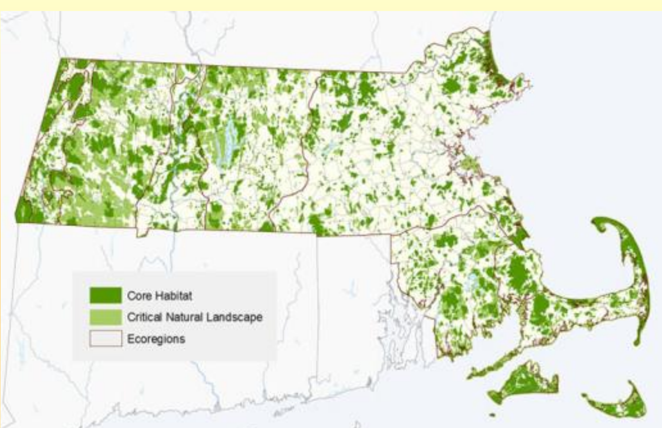
The results of this project are presented in a series of reports. This first report, "Climate Change and Massachusetts Fish and Wildlife: Introduction and Background," provides background to the project by describing how biodiversity conservation is currently carried out by MassWildlife; the history, objectives, and methods of the SWAP; and how the climate in Massachusetts has been changing and is expected to change over the remainder of this century. The subsequent reports, "Climate Change and Massachusetts Fish and Wildlife: Habitat and Species Vulnerability" and "Climate Change and Massachusetts Fish and Wildlife: Habitat Management," address habitat and species vulnerabilities, likely ecological shifts under climate change, and potential management/conservation options. A detailed review of the findings is found on the DFG website at: http://www.mass.gov/dfwele/climatechange.htm

Guiding Principles

While many strategies are unique to specific ecosystems (e.g. allowing inland migration of coastal wetlands in the face of rising sea levels) and are detailed in the following sections, many no-regrets climate adaptation approaches apply to all ecosystem types that help protect and restore ecological resilience. Several principles rooted in ecology, conservation biology, and ecosystem management, and well-supported in current climate adaptation literature (Heller and Zavaleta, 2009; Mawdsley et al., 2009; Beier and Brost, 2010) serve as core climate adaptation strategies:

- Protect ecosystems of sufficient size—Anchor conservation in sites of sufficient size and quality to remain resilient over centuries, recover from disturbances, maintain space for the breeding requirements of component species, allow space for dynamics, and protect internal gradients and topographic variation.
- Protect ecosystems across a range of environmental settings—Represent key geophysical settings across gradients reflecting combinations of topography, geology, and elevation. Focus conservation efforts on places that are critical to biodiversity in the present and are likely to be critical in the future.
- Protect multiple example ecosystems to capture redundancy—It is unlikely that conservation will succeed at every site, as future climate is complex and local—and regional-scale impacts are unpredictable. Protecting replicate sites in many independent places ensures that at least some examples will persist through centuries.
- Maintain large-scale ecosystem processes and prevent isolation—Ecosystems and species are dependent on regional scale processes such as hydrologic cycles and disturbance regimes. It is important to maintain high quality source breeding habitats and connectivity across habitats to facilitate species dispersal, migration, and maintenance; protect local connectivity for individuals, as well as regional movements of populations to facilitate climate change adaptation; protect land and water; and identify compatible land uses in areas critical to connectivity. Intact landscapes that capture the most robust examples of ecosystems represent the best opportunities to protect and enhance ecosystem function and biodiversity.
- Limit ecosystem stressors—Strategies that focus on reducing threats, such as habitat conversion and fragmentation (i.e., development), invasive species, and airborne and waterborne pollutants, can maintain ecosystem resilience and allow ecosystems to provide a full range of functions and services.
- Maintain ecosystem diversity—Preserve as many options as possible for natural adaptation in response to climate change. Expect and plan for species losses and possible gains from other regions.
- Use nature-based adaptation solutions—Allowing intact forest, wetland, river, and coastal ecosystems to function as "green infrastructure" that protects ecological, economic, and social values is an economical climate adaptation approach. These "soft engineering" should be considered wherever possible as alternatives to "hard engineering" solutions. As an example, where appropriate, protection of coastal wetlands can be an alternative to coastal armoring for reducing the impacts of sea level rise and storm surge.

BioMap2



The Massachusetts Department of Fish & Game's Division of Fisheries and Wildlife and Natural Heritage and Endangered Species Program (NHESP), in partnership with The Nature Conservancy's Massachusetts Program, developed BioMap2 to protect the state's biodiversity in the context of projected effects of climate change.

BioMap2 combines NHESP's 30 years of rigorously documented rare species and natural community data with spatial data identifying wildlife species and habitats that were the focus of the Division of Fisheries and Wildlife's 2005 State Wildlife Action Plan (SWAP). BioMap2 also integrates The Nature Conservancy's assessment of large, well-connected, and intact ecosystems and landscapes across the Commonwealth, incorporating concepts of ecosystem resilience to address anticipated climate change impacts.

Protection and stewardship of BioMap2 Core Habitat and Critical Natural Landscape are essential to safeguard the diversity of species and their habitats, and intact and resilient ecosystems, across Massachusetts. A summary report and interactive web viewer can be found at: http://www.mass.gov/dfwele/dfw/nhesp/land_protection/biomap/biomap_home.htm.

- Embrace adaptive management—Ecosystem managers should develop flexible concepts for understanding natural systems. The effectiveness of protection and management should be verified through monitoring, and long-term ecological monitoring projects that inform climate adaptation decisions should be supported.
- Develop a unified vision for collaborative conservation of natural resources—Analyses such as the State Wildlife Action Plan and BioMap2 (2010) serve as blueprints for ecosystem protection and restoration and galvanize the conservation community to engender long-term ecological resilience. Public funding and progressive, flexible, and climate-responsive regulations will be crucial to abate the threats of climate change on natural resources and provide long-term protection of green infrastructure.

Forested Ecosystems

Existing Resources

Forests covered the great majority of Massachusetts prior to European settlement. Then, in the 18th and 19th centuries, there was dramatic alteration of the forest landscape due to logging practices and the conversion of forest to agriculture (Foster et al., 1997). Today, about 62 percent (three million acres) of the approximately five million acres of Massachusetts is forested (Alerich 2000) and over 90 percent of that is upland forest (MassGIS).

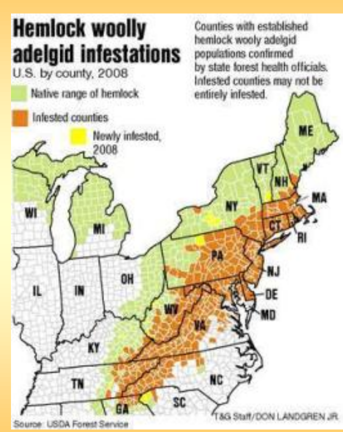
There are many forest types in Massachusetts, including spruce/fir and pitch pine/scrub oak. Two general types of upland forest occur in Massachusetts—namely northern hardwood (beech, birch, maple) forest in western and north-central Massachusetts, and central hardwood (oak, hickory) forest in eastern and south-central Massachusetts. Within the northern hardwood region, the northern hardwood-hemlock-white pine type is most common, with the spruce-northern hardwood type occurring only in the higher elevations. Within the central hardwood region of Massachusetts, oak-hickory-white pine-hemlock is most common, with pitch pine-oak occurring on the relatively infertile, sandy soils associated with coastal areas of eastern Massachusetts and portions of the Connecticut River valley in central Massachusetts.

Upland forests provide important functions including support for a variety of habitats and wide-ranging biological diversity, purification of air and water, moderation of subsurface and overland water flow, and the sequestration of carbon in both the above-ground growing vegetation and in the organic components of forest soils. In addition, forests provide scenic, recreational, and tourism benefits and a rural quality of life for many citizens.

Upland forests also provide energy to streams in the form of organic material. Small streams rely on this energy almost exclusively to initiate their trophic interactions and food webs. These forests provide important filters along wetlands, rivers, and streams. Upland forests stabilize soils and sediments in often high-gradient streams, thus minimizing erosion; help to moderate temperature by providing shade to small streams; provide important habitat for wildlife species that occupy vernal pools; and provide either direct or indirect habitat benefits to wildlife species including forest-dependent species, such as warblers and thrushes, and forest dwelling salamanders, such as marbled and Jefferson salamanders.

Terrestrial Invasive Species—The Hemlock Woolly Adelgid

One pest that appears to be expanding its habitat as a result of climate change is the Hemlock Woolly Adelgid. This small, almost microscopic creature from Japan feeds on and destroys hemlock trees. Here in the U.S., it has no natural predator, and has been severely thinning hemlock populations. Some believe it will eliminate the entire hemlock population in the Southern Appalachians within the next decade. Colder temperatures have limited the agelgid's northern spread, but as winters become milder in New England, experts expect the agelgid to continue its march north.



The insect has already found its way into Massachusetts. In 2001, the state authorized $60,000 to introduce 10,000 Japanese lady bugs to eat the adelgid. While the numbers of adelgid decreased after a particularly cold winter, the lady bug population seems to have largely vanished, and it is making a comeback. The town of Weston, MA spent $5,000 in the fall of 2008 to treat 100 trees, and has authorized further expenditures of $25,000. While treatments on individual and wide scale levels can help keep the numbers of adelgid in check, there is no permanent solution or preventive defense. Continued vigilance will be required to maintain the existing Hemlock populations.

Impacts and Vulnerabilities

Climate change will cause changes in species composition and forest structure. While common species such as maples may decline in abundance and oaks may increase under climate change, more vulnerable species such as spruce may be extirpated from portions of the state or their distribution may be significantly reduced. Climate change, in conjunction with other stressors, will alter forest function and its ability to provide wildlife habitat, and could reduce the ability of forests to provide ecological services such as air and water cleansing.

Massachusetts can experience a greater intensity and frequency of forest-disturbing weather events, including ice storms, localized or regional wind events such as microbursts or hurricanes, and more frequent and longer droughts and associated wildfire. All of these conditions can suddenly kill or alter the vigor of native trees, thereby opening the forest to new species. The same climate change phenomena that affect trees could also impact forest-dependent species such as song birds, forest floor plants, and invertebrates, as well as disrupt predator-prey relationships, and alter phenological patterns and other, often complex, ecological processes. Some changes may be slow while others may proceed quickly once critical thresholds are met (e.g., forest pests).

Predicted change in species composition from increased ambient temperatures is generally a function of the extension of northern limits of species that have limited cold tolerance and a change in the habitat suitability. Range shifts in tree distribution (historically, forest types have shifted at the range of 12 to 15 miles every 100 years) will change the relative proportions of forest tree species. The migration of tree species in response to habitat changes, however, is likely to be much slower than the predicted changes in habitat due to climate change. It is also important to note that movement is likely to occur at the individual species level and not by groups of species. The speed at which these impacts take place may come either quickly or over decades. Northern forest types such as spruce-fir will likely disappear from Massachusetts. Red spruce and balsam fir will likely have decreasing reproductive success, northern hardwoods will recede to higher elevations within the state and northward out of the state, and southern forest types such as central, transitional, southern hardwoods will likely increase in abundance. Changing climate factors and forest types will also likely alter the composition and role of myriad other species defining forests including vertebrates, invertebrates, shrubs, herbs, non-vascular plants, fungi, and bacteria.

Invasive insects and diseases will also respond to climate change; hemlock woolly adelgid is likely to expand northward while the response of others, such as the emerald ash borer, the Asian longhorned beetle (currently attacking hardwoods in Worcester), or the widespread beech bark disease, is uncertain. Overall, the negative impacts of invasive species may increase as native forests are increasingly stressed and become more vulnerable to changes in mean and maximum air temperatures and subsequent changes in the water cycle.

The following strategies could be considered for implementation to mitigate potential climate change impacts on forest resources.

Potential Strategies

For a forest ecosystem to maintain its biodiversity, it should be able to absorb small perturbations, prevent them from amplifying into large disturbances (resistance), and return to the original level of productivity, function, structure and, in some cases, species composition following a disturbance (resilience). The resistance and resilience of ecosystems are dependent on their sizes, conditions and landscape contexts.

1. Land Protection—Secure Large Unfragmented Forest Blocks

Forest ecosystem functions can be greatly impaired by forest fragmentation caused by roads, development, and infrastructure. To maintain these functions, an important climate adaptation strategy is to identify and protect resilient forest ecosystems—both forest reserves and actively managed forests—based on the principles outlined in the guiding principles section of this chapter.

2. Policy, Flexible Regulation, Planning, and Funding

Consider establishing landowner incentives for forest ecosystems. Because nearly 80 percent of forests in Massachusetts are privately owned, incentives for private land owners to keep their forest lands as forest and manage them for compatible natural resource values will be crucial for both climate adaptation and mitigation (i.e. carbon sequestration) strategies, as such incentives are less costly than purchasing these parcels as conservation land. These potential strategies are,

a. Establish mechanisms to pursue a goal of "no net loss of forests," such as funding for technical assistance to implement smart growth and reduce development footprint on forests, mitigation requirements for forest conversions, and to increase tree planting in

Government Takes the Initiative

Over the last four years, the Massachusetts Executive Office of Energy and Environmental Affairs and its agencies have invested an unprecedented $218 million to permanently protect more than 85,000 acres of land and create or restore 114 urban parks.

urban/suburban open land. This could add to permanent forest conservation of key wildlife corridors for climate adaptation and of exceptionally productive forests for sequestration.

b. Add state tax incentives to "keep forests as forests," including a state tax credit for the cost of professionally prepared forest management plans (the main impediment to adding acreage to the state Forest Tax Law).

c. Establish an initiative to promote the buying of local forest produce.

3. Management and Restoration

For greatest resilience and adaptability, Massachusetts forests should exhibit a balance of forest structure, composition, and age classes across the state and across ownership, as well as a mix of approaches to forest management, with forest reserves controlled by natural processes, as well as actively managed forests that provide forest products in addition to carbon sequestration and other functions and services. This goal may be achieved through the following strategies.

a. Reserve Management. Encourage forest reserve management to allow natural processes to determine the long-term structure, composition, function, and dynamics of the forest to the maximum extent possible. Use the general approach and the Forest Reserve Management Guidelines developed as a result of the Department of Conservation and Recreation's (DCR) Forest Futures Visioning process and informed by EEA's Forest Reserve policy developed in the early 2000's.

b. Reserve Selection and Designation. For forest reserves to maintain their ecological function over long periods, forests managed as reserves should be large (The Nature Conservancy recommends >15,000 acres each), minimally fragmented, and representative of varied ecological settings that define Massachusetts' forest biodiversity. The Forest Futures Visioning process recommended that DCR designate the approximately 310,000 acres of land within the forest and parks system as Reserves, Parklands, and Woodlands to prioritize the ecosystem services these lands provide.

c. Manage invasive species. Launch an initiative to remove invasives from large unfragmented forest blocks on state land in collaboration with non-profit partners. Invasive exotic plants homogenize a forest, reduce the diversity of species composition, and weaken resistance to change. Established procedures can reduce the impact of forestry practices on the spread of invasive species (e.g., cleaning of machines to remove seed or root cuttings before moving to a new site), monitoring for their presence and controlling them early.

d. Protect regeneration. Delays in regeneration reduce the ability of the forest ecosystem to function consistently over time. Manage activities that limit the ability of native trees, wildflowers and herbs to regenerate, such as over-browsing by white-tailed deer and damage from all terrain vehicle (ATV) activity.

e. Practice prudent fire management. In fire adapted and fire dependent forest types (e.g. pitch pine-scrub oak), utilize current fire management practices to maintain the ecosystem processes and breadth of biodiversity of these systems. Consider establishing a fire management council to facilitate prescribed fire management in fire-adapted pitch pine/scrub ecosystems on a landscape scale. More frequent and pronounced droughts are expected to couple with an overall increase in forest growth, and this combination would mean that fire-adapted systems could see increased frequency and/or intensity of fire and associated risk to human life and property.

f. In some cases, enhance sequestration through planting. Planting native seed stock of local genetic origin in these stands can

Forest Reserve Management in Massachusetts

The Massachusetts Department of Conservation and Recreation (DCR) is implementing the Forest Reserve Management Guideline recommendations and will designate over 100,000 acres of DCR lands as Reserves within eleven "Ecological Land Units" that capture the forested settings of the Commonwealth. In addition, "Parklands" which will make up approximately 75,000 acres of DCR lands, will be managed primarily for recreation, human experiences and cultural values. Reserves and Parklands will be set aside from active forest management. DCR will designate approximately 120,000 acres of "Woodlands" to be managed as demonstration forests, focusing on restoring late successional conditions and sustainable production of timber.

return the forest to full stocking. This increases capacity to sequester carbon while also increasing resilience. In the absence of browsing pressure or dense invasive species, forests will naturally regenerate to fill gaps produced by disturbances.

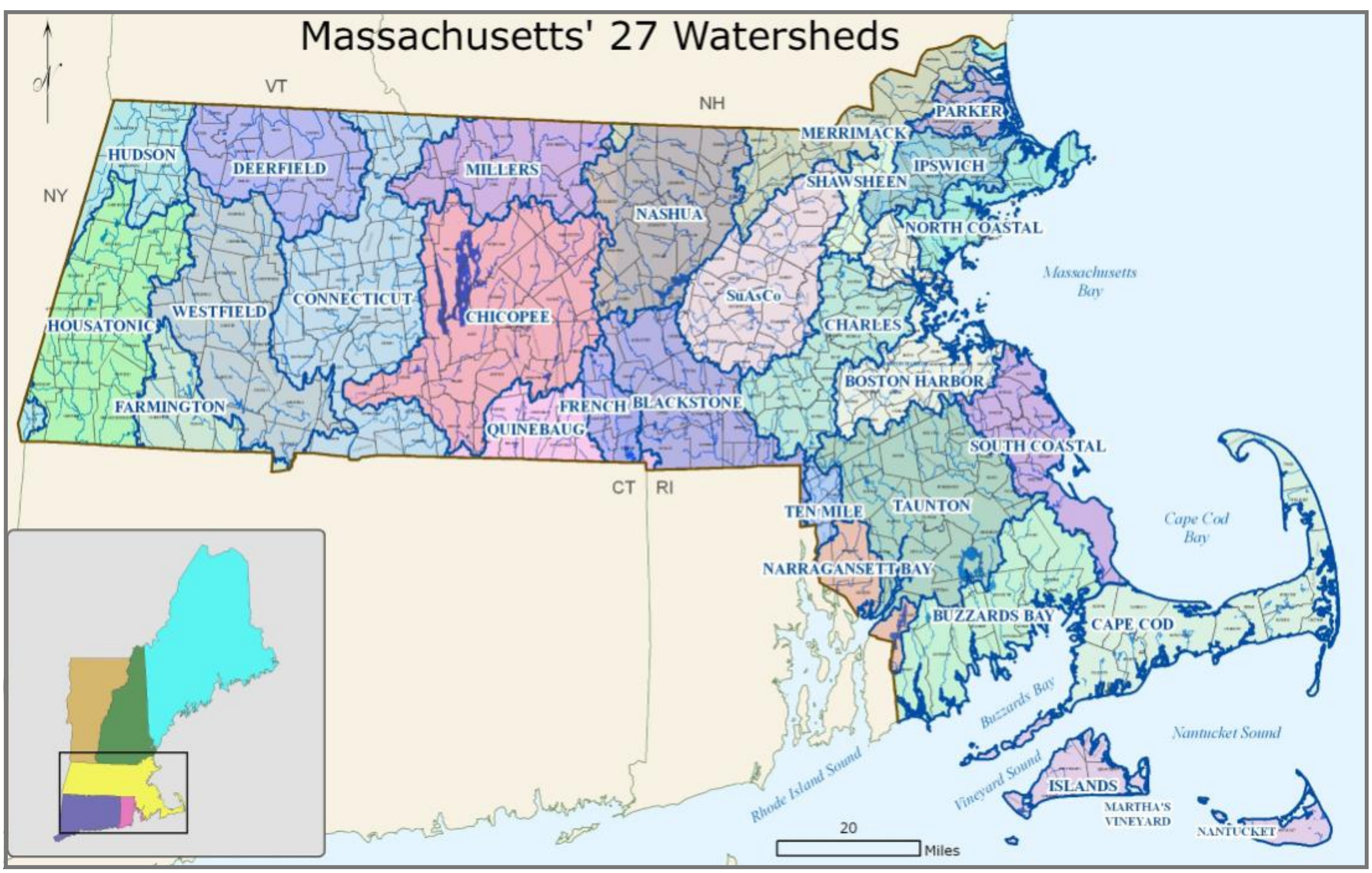
4. Monitoring, Research, and Adaptive Management. Support long-term ecological monitoring programs such as the DCR's Continuous Forest Inventory, a data set collected over 50 years which provides invaluable information on the status and trends of the state's forest resources), and the joint DCR/MassWildlife/University of Massachusetts program for long-term monitoring of plant community dynamics on paired forest reserves and actively managed state lands.

Aquatic Ecosystems

Aquatic ecosystems refer to rivers, streams, lakes, and ponds. Although many ecologists consider wetlands and salt marshes under this category, these systems are addressed in separate sections in this report.

There are 27 major river basins in Massachusetts. Mainstem rivers such as the Connecticut and Merrimack are characterized by wide, low gradient streambeds meandering through broad river valleys with extensive flood plains. Large and mid-sized mainstem rivers and their larger tributaries vary considerably, but have some common features. Moving from their headwaters to their mouths, gradient in these rivers typically declines and sediment sizes decrease. Organically enriched soils become more widespread as floodplains widen, due to deposition of organic material in slower moving waters. These rich floodplains are the foundation for productive floodplain forests, shrub swamps, and other habitats. However, floodplain forest is already one of the most uncommon and degraded ecosystems in Massachusetts (Swain and Kearsley, 2001), and faces further threat from a combination of earlier spring runoff, more frequent low flow conditions (during spring runoff and summer droughts), and more frequent high flow conditions (during winter flood events). This combination would fundamentally alter the hydrologic periodicity of these dwindling riparian ecosystems, likely favoring invasive, exotic plant species, which are already a major threat to these unique areas.

Small streams in the upper reaches of a watershed originate where rainfall, runoff, and groundwater first come together to form defined stream channels, typically with year-round flow. These streams account for the majority of the linear stream miles in



Massachusetts. They accumulate and assimilate all upstream inputs, perturbations, and degradations and transmit them to reaches downstream. In most cases, small streams rely on groundwater for a high percentage of their annual flow and have food webs that are highly dependent on additions of nutrients from the surrounding vegetation. These streams often have naturally low fish diversity, low productivity and relatively high gradients. The substrates may be dominated by boulder and cobble in high-gradient watersheds like the Westfield River, or gravel and sand in lower gradient watersheds like the Taunton River. It has long been realized that healthy small streams contribute to the integrity of a watershed by maintaining the soil, increasing infiltration, reducing the impacts of flooding, and maintaining summer base flow. These functions not only support biodiversity, wildlife, and river processes, but also provide crucial flood control services and drinking water protection.

Massachusetts has nearly 3,000 named lakes and ponds, totaling over 150,000 surface acres. Some lakes, such as the kettlehole ponds on Cape Cod, were naturally formed over 10,000 years ago during the retreat of the last Ice Age. While many of the state's lakes and ponds were created or enhanced by dams and are thus positioned at the headwaters to streams and rivers, they are a crucial link in the overall aquatic community. Many of these lakes and ponds support drinking water and recreational needs in addition to providing habitat for a wide variety of fish and wildlife.

Impacts and Vulnerabilities

Aquatic ecosystems are vulnerable to climate change. Predicted changes in timing, frequency, and duration of precipitation events, more intense storms, a shift from winter snow to rain, more frequent and longer summer droughts, and increases in temperature trends and extreme high temperatures will affect both lotic (flowing water) and lentic (still water) habitats.

Water quality and quantity are expected to be adversely affected by predicted increased temperature, drought, an increase in the number of extreme heat days, and a decrease in summer precipitation. Higher temperatures, along with changes in stream flow, will degrade water quality. Warmer, drier conditions will lead to deeper and stronger thermal stratification in lakes which will decrease the volume of the deeper, cooler, well oxygenated water that is critical summer habitat to a number of species. As a result, this habitat may be eliminated from many shallower lakes and ponds. In addition, non-native species will likely become a bigger problem for lake and stream ecosystems under warmer conditions (Ramsar, 2002). In general, climate change can influence the establishment and spread of invasive species and can reduce resilience of native habitats to these species (U.S. EPA, 2008). Increased mobilization of non-point source nutrients, and suspended solids from more intense winter rain storms, followed by higher summer temperatures, will result in more algal blooms (e.g., blue-green algae) and vigorous growth of aquatic vegetation leading to eutrophication in lakes and impounded rivers.

A projected increase in average winter temperatures will decrease the amount of snowpack and ice and negatively impact aquatic ecosystems. Reduced ice cover on lakes and ponds will result in more winter sunlight and more abundant aquatic vegetation, while less melting snowpack will reduce spring groundwater recharge. A shift to winter rains will potentially lead to more runoff, flooding, greater storm damage, scour, and erosion during a time when there is reduced vegetative cover and low evapotranspiration (the combination of evaporation from the ground and transpiration from plants) during the winter months. Peak river flows are predicted to occur earlier as higher average temperatures and a shift from winter snow to rain accelerate the spring melt. Flooding, and an accompanying loss of vegetative cover, could reduce many ecological functions, causing effects such as reduced primary productivity and loss of carbon storage; degradation of wildlife habitat, in-stream aquatic habitat, and water quality; and increased incidence of water-borne disease, sedimentation, pollutant loading of waterways, and surface runoff (Ramsar, 2002). In waterways and waterbodies, increased temperatures are likely to cause loss of thermal refuges for coldwater species, decreases in dissolved oxygen, changes to hydrologic mixing regimes, and changes in biogeochemical cycling (Ramsar, 2002).

Higher summer temperatures, less summer precipitation, and an increase in drought frequency and duration will affect both water quantity and quality. Some intermittent streams may cease flowing earlier in the season and more frequently and some perennial streams may become intermittent. In some rivers and streams, coldwater habitat will be replaced by warm water habitat. This will likely be accompanied by marked changes in the species that live in these habitats.

Climate change can affect fisheries through changes in abundance, distribution, and species composition. Fisheries in small rivers and lakes are believed to be

more susceptible to changes in temperature and precipitation than those in larger rivers and lakes (Ramsar, 2002). As coldwater habitats warm, coldwater fisheries, which are already stressed by reduced habitats and population losses, will be especially affected. Though some adult fish may tolerate higher stream temperatures, in certain circumstances they will not reproduce. Climate change may affect stream flow by increased flooding incidences from extreme precipitation events, and low flow occurrences in late fall. Flooding, in turn, can scour stream bottoms where fish eggs are lodged. The earlier seasonal growth of plants could result in lower stream base flows earlier in the spring and negatively affect primary productivity.

The predicted changes in precipitation patterns can also increase stormwater discharge, which can affect both water quantity and quality. Hydrologic changes from increased flooding can amplify erosion and scour in streams and initiate channel incision. Problems associated with channel incision include undermining of structures, downstream sedimentation, severe bank erosion and widening, and degradation of aquatic and riparian habitats. Overbank floods that once spilled across the floodplain can become confined within the channel, and the river can get disconnected from the floodplain, leading to a loss in the ability of the floodplain to provide flood storage, storm damage prevention, groundwater recharge, pollution attenuation, sediment transport/storage, and protection of water quality. Under these conditions, flora and fauna that are adapted to a floodplain environment may experience a loss of habitat and range. Without periodic inundation, there would be a loss of wetlands and fisheries-related hatching and nursery areas.

As rivers incise, their banks fail and the channels become over-wide in proportion to depth. Sediment transport decreases, and there is greater deposition of sediments, especially mid-channel. Flows can become discontinuous, creating barriers to fish movement. Shallower flows can lead to increased temperatures and lower dissolved oxygen levels. Increased erosion in rivers can result in scour at restrictions such as culverts, often perching or undermining these structures so that they present barriers to aquatic organism movement and pose a threat to public safety.

Potential Strategies

Adaptation strategies should strive to integrate the protection of rivers, streams, lakes, riparian areas, floodplains, and wetlands with comprehensive land-use, watershed, and floodplain/buffer management, and targeted land acquisition. Strategies to be considered include:

1. Land Protection. Use land acquisition and conservation restrictions to target protection of vulnerable intermittent headwater streams and their buffer areas. Acquisition could be supplemented by stream easements. Well-protected headwater streams and lakes that provide high quality, cold-water flows will be integral to maintaining suitable downstream conditions during periods of warming.
2. Policy, Flexible Regulation, Planning, and Funding
    a. Facilitate streamlined permitting of aquatic habitat management projects.
    b. Develop streamflow criteria and regulations to encourage re-establishment of natural flow regimes in rivers and streams.
    c. Provide greater protections to vulnerable intermittent streams through legislation, or by encouraging local bylaws.
3. Management and Restoration
    a. Identify vulnerable river reaches, establish and protect belt-width-based river corridors, restore floodplains, and increase use of bioengineering techniques for bank stabilization.
    b. Identify and protect remaining critical coldwater fish habitat areas and seek to reconnect high quality habitats by removing in-stream barriers and re-establishing in-stream flows.
    c. Identify and implement strategies for early detection, rapid response, and prevention of invasive exotic plants and animals that out-compete native species and gradually reduce the diversity of species composition.
4. Monitoring, Research, and Adaptive Management. For aquatic system resilience, standardize monitoring protocols, improve communication with existing long-term ecological research monitoring sites, monitor pilot adaptation

strategies, and support existing monitoring networks that have a nexus with adaptation strategies.

a. Through geomorphic assessment, identify vulnerable river reaches and monitor rivers for disconnection from floodplains.

b. Update Federal Emergency Management Agency (FEMA) floodplain maps to reflect current conditions and predictions of future conditions.

Coastal Ecosystems

Seaward of the sandy beaches and rocky coastlines, beyond the salt bays and estuaries, Massachusetts' territorial waters extend three nautical miles out into the Gulf of Maine. The land under this area of open ocean is the relatively shallow continental shelf, which supports coastal ecosystems. Depths of seawater can range from 100 feet to a little more than 1,000 feet, but there are no deep trenches in Massachusetts waters.

Almost all of Massachusetts' salt waters are in estuaries and bays; very little is open ocean. Massachusetts has three great bays: Massachusetts Bay, which includes the area between Gloucester and Brant Rock, north of Plymouth; Cape Cod Bay, which includes the area from Plymouth to the tip of Cape Cod; and Buzzards Bay, extending from the Westport River near the Rhode Island border, east to the Cape Cod Canal and south to the last of the Elizabeth Islands (see "Massachusetts' Coastal Zone" map). Within the great bays are smaller bays such as Nahant Bay north of Boston, and Hull, Hingham, and Quincy bays south of Boston—all within the Massachusetts Bay.

Estuaries are affected by tidal flows and are considered brackish water, although the degree of salinity varies. Estuaries often have associated salt marsh habitat and are rich in nutrients, providing a valuable nursery for finfish, shellfish, and other macro- and micro-invertebrates, and supporting a wide range of vertebrate wildlife. These habitats are vital links in the life histories of diadromous fishes (those that spend part of their lifecycle in salt water and part in fresh water), which rely on these complex ecosystems to provide food and protection. There are estuaries all along coastal Massachusetts, but the most extensive system lies just west of Plum Island, feeding into Plum Island sound and the marshes of Essex County. A second extensive estuary system is in the Nauset Marsh/Pleasant Bay area on outer Cape Cod. Numerous shorter estuaries are along the south side of Cape Cod. The East Branch of the Westport River is one of the longest estuaries in Massachusetts.

Located between the high spring tide and mean tide levels of protected coastal shores, salt marshes and the adjacent tidal flats comprise one of the most productive ecosystems on earth. In spite of the stresses of wide variations in temperature, salinity, and degrees of inundation, the salt-tolerant vegetation of the salt marsh community provides the basis of complex food chains in both estuarine and marine environments. It also provides habitat for various species of wildlife, including migrating and overwintering waterfowl and shorebirds, and the young of many species of marine organisms. In the northeastern United States, salt marsh communities are dominated by two species of perennial, emergent grasses adapted to growth in salty soils—Saltmarsh Cordgrass and Saltmeadow Cordgrass. While these dominant species give the community a deceptively simple, grassland-like appearance, salt marsh systems are heterogeneous and provide a variety of habitats. For example, pans—the open areas in a marsh—are important to migrating waterfowl.

Impacts and Vulnerabilities

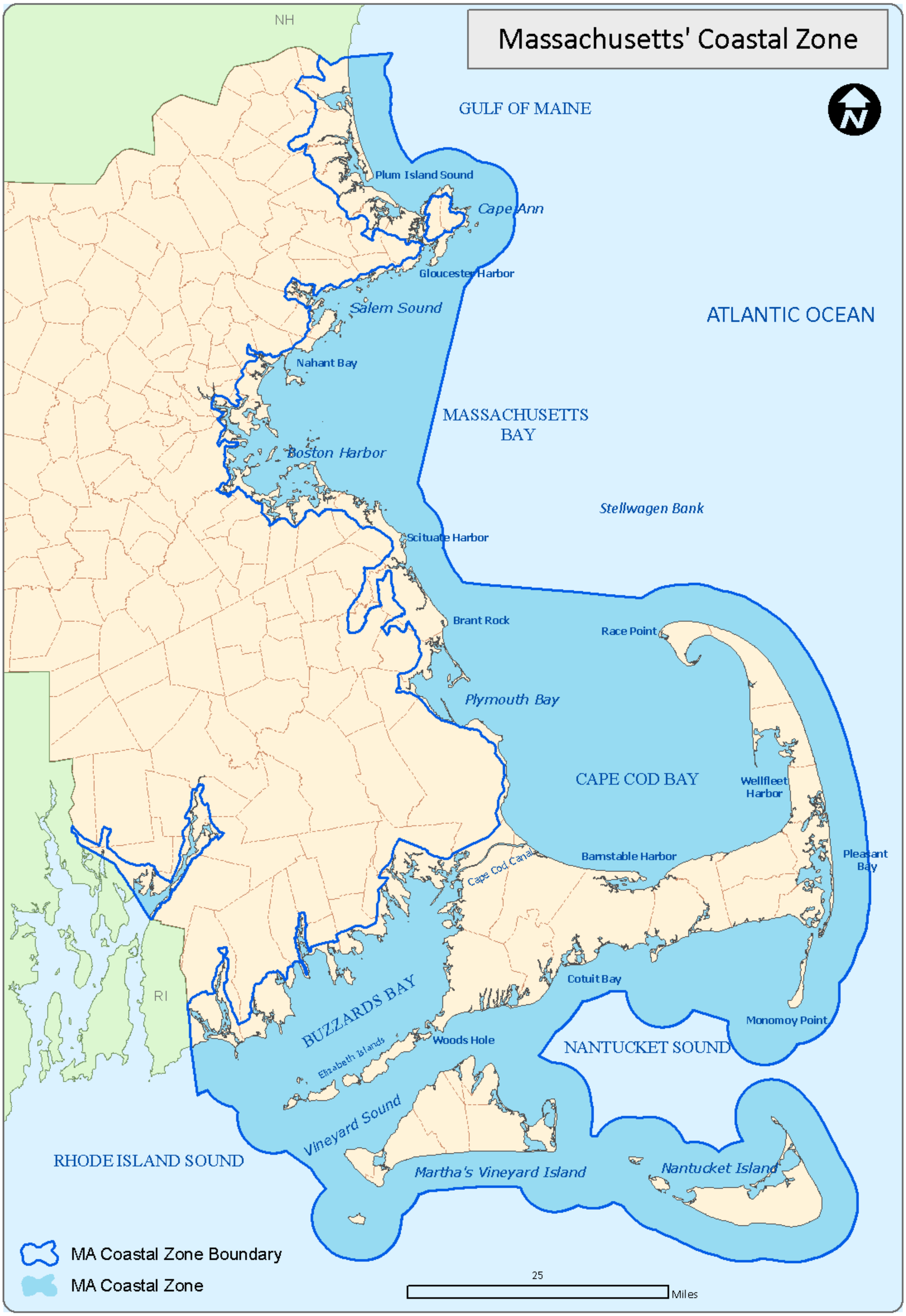
Coastal ecosystems will be particularly vulnerable to the impact of climate change due to the nature of their locations. In addition to responding to increased temperature, variable precipitation, and extreme weather events, sea level rise—a major climate change-related threat to Massachusetts—will expose these critical habitats to increased loss and decimation. It is anticipated that important coastal habitats will be lost and reduction of sediment load to beaches and other coastal habitats will limit the ability of these areas to maintain accretion at a rate that could match sea level rise.

Potential Strategies

A number of adaptation strategies should be explored to identify ways to mitigate potential climate change impacts to coastal ecosystems.

1. Land Protection

   a. Identify and protect undeveloped areas that are upgradient from coastal wetlands to allow wetland migration and buffer intact ecosystems; and


Massachusetts' Coastal Zone
NH
GULF OF MAINE
Plum Island Sound
Cape Ann
Gloucester Harbor
Salem Sound
ATLANTIC OCEAN
Nahant Bay
MASSACHUSETTS BAY
Boston Harbor
Stellwagen Bank
Scituate Harbor
Brant Rock
Race Point
Plymouth Bay
CAPE COD BAY
Wellfleet Harbor
Barnstable Harbor
Cape Cod Canal
Pleasant Bay
Cotuit Bay
BUZZARDS BAY
RI
Monomoy Point
Woods Hole
Elizabeth Islands
NANTUCKET SOUND
Vineyard Sound
RHODE ISLAND SOUND
Martha's Vineyard Island
Nantucket Island
MA Coastal Zone Boundary
MA Coastal Zone
25
Miles

Projected change in intertidal habitats at Parker River

The vulnerability of selected intertidal habitats in Massachusetts to climate change has been evaluated by the U.S. Fish and Wildlife Service through simulation of sea level rise at coastal Massachusetts National Wildlife Refuge sites, including the Parker River. The investigators modeled the fates of intertidal habitats using four global sea level rise scenarios. Predicted sea level rises of 0.39m (1.3 ft), 0.69m (2.3 ft), 1.0m (3.28 ft), and 1.5m (4.9 ft) by the year 2100 were superimposed on current rates of sea level rise.

At the Parker River, the extents of the intertidal habitats appear to be highly sensitive to even relatively modest sea level rise changes, with marked losses and gains occurring under the 0.39m (1.3 ft) sea level rise scenario. The habitat types that suffer greatest reductions in extent under most sea level rise scenarios are brackish marsh and tidal flats, with reductions of 50 to 99 percent. As sea level rises, intertidal land will become subtidal (hence, the increase in open water and loss of tidal flats), while saltmarsh will extend further upgradient as the inundation and salinity changes—at the expense of the brackish marshes it will replace. It is important to note, however, that the ability to move upgradient may be highly restricted by the lack of open undeveloped upland.

Projected change in intertidal habitats at Parker River

Intertidal Habitat	Current area (acres)	0.39 meter		0.69 meter		1.0 meter		1.5 meter	
		Area Change	% Change	Area Change	% Change	Area Change	% Change	Area Change	% Change
Brackish marsh	2,306	1,955	-15	1,114	-52	458	-80	3.9	-99
Salt marsh	150	423	182	1,206	704	1,715	1043	818	445
Tidal flat	803	327	-59	303	-62	382	-52	1,605	99
Estuarine open water	1,500	2,104	40	2,218	48	2,379	59	2,579	72
Ocean beach	226	264	17	266	18	261	15	22.3	-90

b. Develop high-resolution elevation models (based on LiDAR data) to identify and prioritize protection of areas that may become wetlands in the future as sea level rises.

2. Policy, Flexible Regulation, Planning, and Funding
   a. Expand use of ecological solutions to sea level rise. Hurricane Katrina dramatically illustrated the adverse consequences of removing natural ecological wetland buffers to coastal storms and relying entirely on engineered solutions. Investigate the benefits of shifting from engineering-based and infrastructure-focused solutions toward a union of engineering and ecological planning;
   b. Consider developing more flexible conservation regulations that take into account potential sea level rise and changing floodplains; and
   c. Encourage integrated community planning. Coastal habitats in Massachusetts are often areas with competing interests, stakeholders, and multiple jurisdictions. Extend planning of coastal areas beyond the state and federal agencies and involve other stakeholders to ensure representation of varied interests. (See Chapter 8 on details about assistance provided by Massachusetts Coastal Zone Management through their StormSmart Coasts program.)
3. Management and Restoration
   a. Identify, assess and mitigate existing impediments to inland migration of coastal wetlands. As sea levels continue to rise, the whole system of coastal wetlands and subtidal habitats will move inland. This cannot occur in areas where the topography does not permit it, or where barriers, such as roads, seawalls, or settlements, prevent it;
   b. Identify and assess potential restoration of coastal wetlands. Sea level rise destroys habitats since the rate of rise exceeds the rate at which wetland soils are replenished by sediments. It may be possible at some sites to mitigate this and preserve the wetlands;

c. Manage the spread of invasive species. Support efforts to reduce nutrient loading of waterways and waterbodies.

4. Monitoring, Research, and Adaptive Management. Track the movement of tidal resources as they respond to sea level rise using on-the-ground sensing (e.g., more tide gauges), and remote sensing (e.g., increased regular photo coverage of vulnerable areas). Integrate this information into management plans so that decision-makers are alerted when management thresholds that trigger new policies are reached.

Wetland Ecosystems

Wetlands have always been an important feature of the Massachusetts landscape. Common wetland types include wooded deciduous swamps, emergent wetlands, wet meadows, bogs, and vernal pools. As Massachusetts is a coastal state and one of the most densely populated states in the country, development pressures, and accompanying wetland losses, are a reality. It has been estimated that, by the mid-1980s, Massachusetts had lost approximately 28 percent of its estimated original wetland base. More recent data suggest that about 1700 acres (approximately 0.2 percent) changed during the period from the mid 1990s to present (MassDEP, 2011). Activities causing the most loss are residential development, commercial development, sand and gravel operations, and agriculture. Of these losses, wooded deciduous swamps are the most highly impacted.

Existing Resources

For purposes of this document, wetlands in this chapter refer to freshwater wetlands such as shrub and forested swamps, emergent marshes, bogs and fens, vernal pools, and related ecosystems. Shrub swamps are shrub-dominated wetlands occurring on mineral or mucky mineral soils that are seasonally or temporarily flooded or saturated. They often occur as successional areas between freshwater marsh and forested swamp (Mitsch & Gosselink, 2007) and occur in association with other wetland types in wetland complexes.

Forested swamps, the most abundant type of all wetlands in the northeastern United States (Golet et al., 1993), are wetlands where trees dominate the vegetation and there is generally little buildup of peat. They usually occur as patches within the surrounding upland matrix forest. In the warmer southern and eastern sections of the state and in the central hardwood area, forested swamps are dominated by red maple or Atlantic white cedar.

Bogs are among the best-known peatlands and generally have the thickest peat deposits. Bog communities receive little or no streamflow and they are isolated from the water table, making them the most acidic and nutrient-poor of peatland communities. Several of the state's listed rare animal species are found in bogs. Marshes and wet meadows are some of the most important inland habitats for many species of animals, both rare and common.

Vernal pools are relatively common, with some 30,000 statewide. These are ephemeral wetlands that fill annually, mainly in the spring, from precipitation, runoff, and rising groundwater. In most years, they become completely dry later in the season, losing their water to evaporation and transpiration over the summer. This wet-dry cycle prevents fish from becoming established permanently and presents an important fish-free, if temporary, breeding habitat for many species.

Impacts and Vulnerabilities

Changes in the timing, frequency, and duration of precipitation and increases in flooding will cause changes in water depths, hydroperiods, and flow dynamics. Loss of snow and ice will result in a loss of ice-related structural changes to banks and floodplains. If reduced precipitation and increased drought occur during the season when animals breed and develop in vernal pools, then the length of time that vernal pools hold water could be reduced, potentially leading to a reduction in vernal pool populations.

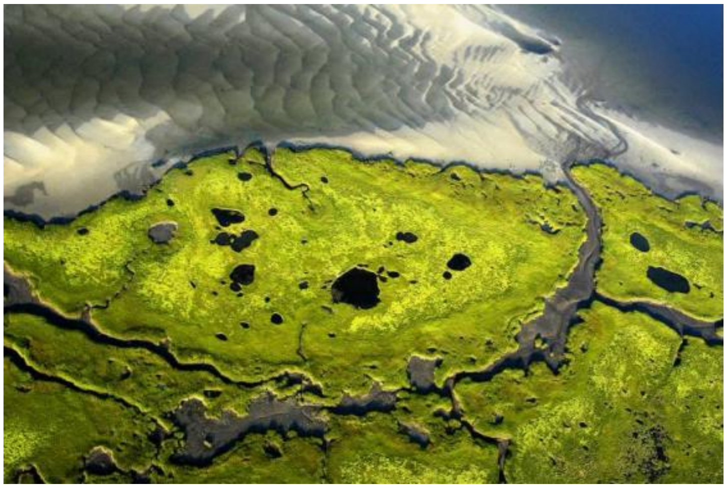
With increased temperatures, species and wetland types that are more typical of cooler and/or higher northern areas (such as northern bogs, spruce-fir boreal swamps, hemlocks) may be reduced or disappear. Wetlands dominated by conifers usually found in cool conditions may become more deciduous, changing their biogeochemistry and potentially the entire wetland habitat. Southern species, including invasives and pests, could move northward or expand their presence in locations that are currently at the northern edge of their range and could stress some native species. Native New England species and populations may become less competitive relative to southern species/populations when the growing season lengthens and temperatures warm.

Increased temperatures can also dry the peat wetland soils, resulting in oxidation and release of stored organic carbon to the atmosphere and changes in pH. Wetland soils may lose saturation. The surface can become less absorptive and more prone to scour, erosion, and runoff, thus reducing groundwater recharge and storage function. Higher temperatures may also cause reduction or loss of isolated vegetated wetlands and drier or transitional fringes of bordering vegetated wetlands. Reductions in regulated wetland size might be temporary or permanent, depending on overall climatic changes. In some cases, former wetlands would no longer be regulated and would be treated as uplands, but would have the potential to return to wetland status and function during wetter times and, therefore, continue to provide crucial buffering capability to upland developed areas.

Potential Strategies

Various adaptation strategies should be investigated as ways to mitigate potential climate change impacts to wetland ecosystems.

1. Land Protection
   a. Identify and protect resilient wetland ecosystems. Focus land protection on areas with high ecological integrity and resiliency over time. Priority areas include large undeveloped blocks of habitat that contain diverse wetland complexes, large wetland systems, and intact riverine systems with abundant associated wetlands.
   b. Identify and prioritize protection of migration corridors between wetland areas and between wetlands and the associated upland habitat including large resilient parcels connected by migration corridors. Planning should include both aquatic and terrestrial connectivity.
   c. Preserve and acquire buffer zones. Buffer zone protection should incorporate predictions for wetland resource and ecological migration resulting from climate changes.
   d. Use LiDAR and other data to identify important wetlands and ensure that a variety of wetland types is represented in land protection planning.
   e. Protect the natural hydrologic function of wetlands with large peat deposits. When peat deposits are exposed to oxygen, they release stored carbon. Preventing the release of carbon stored in peat provides climate change mitigation.
2. Policy, Flexible Regulation, Planning, and Funding
   a. Develop flexible and climate-responsive regulations to support ecological adaptation and resilience.
   b. Survey wetlands across the state to identify vulnerable reaches.
   c. Encourage the passage of bylaws and use of other tools to strengthen protection of isolated vegetated wetlands that are most vulnerable to climate change. Consider revising the Massachusetts Department of Environmental Protection (DEP) "Handbook for Delineating Bordering Vegetated Wetlands Under the Massachusetts Wetlands Protection Act" to include flexible wetland delineation criteria for use when drought and below-normal precipitation conditions are observed in the field. Review U.S. Army Corps of Engineers Draft Interim Wetland Delineation Manual for applicability in Massachusetts.
   d. Explore strategies to improve protection of buffer zones around vulnerable wetlands and vernal pools.
   e. Promote restoration of floodplains.
   f. Consider climate change when evaluating development in vulnerable wetland and floodplain areas.
   g. Consider changes to the 401 Water Quality Certification Regulations to address vulnerable isolated vegetated wetlands.



3. Management and Restoration
    a. Develop flexible and climate-responsive management strategies to support ecological adaptation and resilience.
    b. Coordinate and share information with other states in the Northeast, and maximize coordination between state agencies and between state and local government and federal agencies.
    c. Promote riparian zone and floodplain management, restoration and preservation by removing restrictions between rivers and floodplains, daylighting streams, removing dams, and integrating brownfields remediation projects with floodplain restoration.
    d. Encourage application of geotextiles and bioengineering techniques for erosion control and stream stability. Discourage traditional engineering solutions to flood control such as berms, channelization, channel widening, and armoring of banks.
4. Monitoring, Research, and Adaptive Management
    a. Monitor different types of wetlands. Establish long-term research and monitoring sites.
    b. Support research on adaptive strategies and pilot projects.
    c. Prepare and distribute a wetlands, waterways/waterbodies and climate change adaptation best management practices handbook.
    d. Consolidate existing MassGIS and Natural Resources Conservation Services soils mapping that identify peat deposits in Massachusetts, and utilize as a planning tool for management of soil carbon stores.

Conclusion

Analysis across habitat categories yielded several similar broad principles for potential adaptation strategies. These were grouped in four categories: Land and Water Protection; Land and Water Management and Restoration; Policy, Flexible Regulation, Planning and Funding; and Monitoring, Research, and the Effective Use of Adaptive Management Techniques. Although strategies are specific to habitat categories, the commonalities across habitats were striking. Many recommended strategies reflect ongoing initiatives that require refocusing and enhancements to incorporate climate change as a factor in decision-making. For example, the land acquisition process at DFG, which already considers habitat connectivity and occurrence of unfragmented interior forest blocks, was recently re-adjusted to also consider climate change as a factor. Land acquisition at EEA and its other agencies is also undergoing a similar effort. Results from the Climate Change and Massachusetts Fish and Wildlife reports will be used to inform implementation strategies of the State Wildlife Action Plan—the major guidance document for decision-making relative to wildlife and habitat management.

This chapter identifies forests, wetlands, rivers, and streams as critical habitats with an array of functions that may be affected by climate change. Protecting these ecosystems, and their functions, will be a crucial step in helping natural systems and human communities cope with climate change. It will be important to develop a flexible regulatory approach that will allow time-sensitive responses to threats, and development of flexible wetland definitions that reflect on-the-ground realities. One of the greatest challenges identified in this chapter is the need to develop an efficient monitoring program that informs an adaptive management decision framework.

The symbol signifies adaptation strategies that are also climate change mitigation actions.

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- http://www.sciencedaily.com/releases/2009/02/090226122730.htm
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