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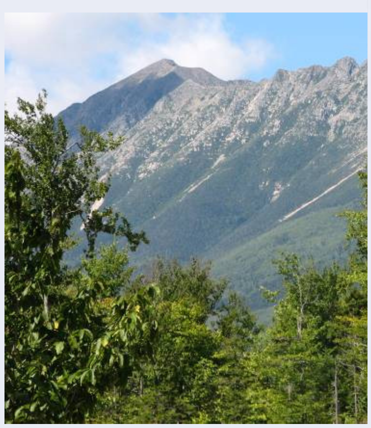

CLIMATE CHANGE AND BIODIVERSITY IN MAINE:

A CLIMATE CHANGE EXPOSURE SUMMARY FOR PARTICIPANTS OF THE MAINE CLIMATE CHANGE SPECIES VULNERABILITY ASSESSMENT

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Executive Summary

1. This summary briefly reviews climate change projections and the exposure of wildlife habitats, plant communities, and species in Maine to climate change. Its goal is to provide wildlife and conservation biologists with a technical summary that they can use as information resource for assessing the vulnerability of wildlife habitats, plant communities, and species to climate change.

2. **Key climate change projections to 2100**
   - Average temperatures are projected to increase 3° to 14° Fahrenheit (F) in winter and 3° to 11°F in summer with the greatest warming in northern Maine and the least along the coast.
   - Precipitation is projected to increase 2 to 14 %. Precipitation will increase in the winter, spring, and fall but change little in the summer. A 10 to 15% increase in precipitation is projected for the winter.
   - An increase in evapotranspiration rates due to temperature increases, coupled with no change in summer precipitation and lengthened growing season, will reduce late summer soil moisture and stream flow levels.
   - Maine's streams and rivers are projected to undergo a significant hydrological shift from a snowmelt-dominated regime with high-flow and ice scouring conditions in the spring to a rain-dominated regime with reduced high-flow conditions in winter.
   - Length of the snow season is projected to slightly decline under low emission scenarios and up to 50% with high emission scenarios.
   - The length of growing season is projected to increase by 1 to 2 days per decade.
   - Sea level is predicted to increase 5 to 15 inches, or possibly much more than that, and coastal sea water temperature is predicted to increase 6° to 10°F.
   - CO_2 concentrations are predicted to double by 2100.
   - Ocean acidification is projected to reach levels unprecedented in the past several million years and be irreversible for millennia.

3. **Exposure of wildlife habitats and plant communities** – The Maine State Wildlife Action Plan (SWAP) identifies 21 key habitat types in the state for which the following predictions should be considered:
   - Coastal habitats most likely to be affected by climate change include: Unconsolidated Shore (beaches and mudflats) and Estuarine Emergent Salt marsh. These habitats will be greatly affected by the rate and amount of sea level rise.
   - Aquatic habitats most likely to be affected by climate change include: Cold-water Freshwater Lakes and Ponds, Cold-water Rivers and Streams, ephemeral wetlands, and Peatlands. These habitats will be greatly affected by temperature increases and changes in hydrology.
   - Terrestrial habitats most likely to be affected by climate change include: Coniferous Forest (many types including boreal forest types [especially spruce flats] and types dominated by eastern hemlock), Mountaintop Forest (including krummholz), and Alpine habitats. These habitats may be greatly affected by increase in air temperature and the forested habitats may be affected by climate-induced outbreaks of pest species.

4. **Exposure of species** – All groups of native species are predicted to be greatly affected by climate change:
   - Boreal and alpine species, cold-water species, species using low-lying coastal habitats, and species at the southern edge of their range are expected to be most negatively affected.
   - Populations of other native species that are highly specialized in their habitat use or have very low populations may also be affected.
   - Effects from insect pest species, exotic plant species, and exotic marine species on plant communities and terrestrial, aquatic, and coastal and estuarine wildlife habitats may increase.

5. **Other Considerations** - Climate change is also likely to have significant impacts on the condition and distribution of key ecosystem services beyond biodiversity and that are also dependent on wildlife habitats, including nature-based recreation, locally-grown food, wood products, and fisheries.

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User Instructions

Please carefully review portions of this document relevant to the species you are scoring. We created this document to give survey participants a quick reference on climate change exposure and a common starting point. Although you may wish to use additional reference material, this is not required.

1. All participants should read the sections titled "1. Introduction" and "2. Climate Change Projections" (4 pages) in order to appreciate the range of projected climate change impacts to Maine's ecosystems.
2. All participants should read the habitat sections related to the species that they have chosen to score. There are three habitat sections: "3A. Marine", "3B. Aquatic" and "3C. Terrestrial" (2-3 pages each).
3. Plant ecologists may need to re-read habitat sub-sections in "3B. Aquatic" and "3C. Terrestrial" about the specific habitats for the plant species that they have chosen to score.
4. Wildlife ecologists should read taxonomic sub-sections in "4. Animal Species Groups" about the taxonomic groups for the animal species that they have chosen to score.

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1. Introduction

Earth's atmosphere is undergoing unusual changes that may be altering the global climate (Jacobson et al. 2009). Over the last decade and a half, scientific consensus has emerged that climate change is occurring, and at a faster rate than was originally predicted (Parmesan and Galbraith 2004). Not only is the climate demonstrably changing, but the ecological consequences that were recently predicted to occur decades from now (e.g., species range shifts, animal community disruptions, flooding events linked to changes in rainfall patterns) are now occurring (Parry et al. 2007, Root et al. 2003). We know from modeling and field research that if these impacts continue to grow, ecosystems will undergo major changes (Galbraith et al. 2006) that threaten both biodiversity and the delivery of critical ecosystem services (Hughes et al 1997). A recent global study estimated that 15–37% of endemic species could become extinct by 2050 (Thomas et al. 2004). Although many efforts are working to reduce emissions of greenhouse gases (GHGs), climate change will likely continue as the already elevated atmospheric levels of GHGs will persist for centuries (Frumhoff et al. 2007). Hence, ecological impacts due to climate change now are inescapable.

Climate change will greatly affect Maine's ecosystems and biodiversity in many ways, possibly including (but not limited to): shifting species distributions, increasing drought stress for plant communities and aquatic systems, raising temperatures, amplifying pest and disease outbreaks, and increasing plant growth fertilized by higher ambient CO_2 levels (Jacobson et al. 2009, Frumhoff et al. 2007). Managing the variety of changes will be challenging for even the most experienced wildlife and conservation biologists because they will be working under novel and ever-changing climate regimes, and plant and wildlife communities (Lawler et al. 2010). Increasing climate change knowledge among Maine's wildlife and conservation biologists is an essential first step if they are to select and deploy new, practical strategies to conserve Maine's biodiversity.

One means for building the knowledge of wildlife and conservation biologists about climate change is to involve them in a climate change vulnerability assessment (Kelly and Adger 2000), an approach now recommended by national groups such as the Association of Fish and Wildlife Agencies (Association of Fish and Wildlife Agencies 2009). One type of climate change vulnerability assessment uses the expert opinions of climate scientists, wildlife and conservation agency staff, academia, and other expert biologists to assess the relative vulnerability of species and habitats to climate change. The results of this assessment can be further used to prioritize and direct adaptive conservation measures. Vulnerability can be assessed by breaking it into three components: (1) exposure to significant climate change impacts, (2) sensitivity to climate change impacts, and (3) capacity to adapt to new climate regimes (Kelly and Adger 2000, McCart. 2001). This report summarizes climate change exposure impacts to the species and major habitats using information derived from regional climate projections.

This report has been developed to assist experts conducting vulnerability assessments of species of greatest conservation need (SGCN), wildlife habitats, and plant communities in the State of Maine (adaptation capacity will also be assessed later). It does not assess the potential expansion of and colonization by native species and habitats more common in areas south of Maine. It has three parts: (1) a summary of climate change projections for Maine, (2) a review of predicted climate change exposure for Maine's major wildlife habitats and plant communities, and (3) a review of predicted climate change exposure for Maine's SGCN animal species.

2. Climate Change Projections

This section summarizes climate change projections for Maine from Jacobson et al. (2009) and Frumhoff et al (2007). Readers should review these reports for more information. Finer-scale projections for Maine were not included because they were not better at distinguishing projected regional climate change trends.

Temperature

Maine is projected to become warmer in all four seasons within 100 years (Jacobson et al. 2009). Projected temperature increases will be greatest in the Northern climate division, and lowest in the Coastal climate division (Fig. 1). Average temperatures are projected to increase 3° to 14°F in winter and 3° to 11°F in summer, by 2100.

Rainfall and Snow

Maine is projected to experience an overall 2 to 14% increase in precipitation with precipitation increases in the winter, spring, and fall but little change in precipitation in the summer (Jacobson et al. 2009). An 8.4 to 15.9% increase in precipitation is projected for the winter (Jacobson et al. 2009). Greater precipitation increases are projected under high GHG emissions scenarios, which also project a greater proportion of winter precipitation falling as rain (Hayhoe et al. 2007). If low emissions scenarios prevail, Maine could retain much of its snow season—between two and four weeks of snow cover per winter month. If a high emissions scenario prevails, by 2050 Maine's snow season could decline by about half. These projected trends could lead to a significant hydrological shift in Maine's streams and rivers, from a more gradual snowmelt-dominated regime with greatest peak runoff and ice scouring conditions in the spring (in the Northern and Southern Interior climate divisions) to a rain dominated regime with the greatest lower peaks of rapid runoff in winter. A transition between regimes could include greater ice movement and scouring throughout the winter.

The frequency and severity of heavy rainfall events is projected to increase under low and high emissions scenarios but with some uncertainty (Jacobson et al. 2009, Hayhoe et al. 2007). The Northeast may experience >10% increase in the number of annual extreme rainfall events and a 20% increase in the maximum amount of rain that falls in a five-day period in a year (Frumhoff et al. 2007). The possible combination of increasing summer temperatures and unchanging summer precipitation levels could yield higher levels of evapotranspiration and reduced stream flows (Huntington 2003). Hence, annual flows may decline 11 to 13% and July-September flows may decline 48% in Maine (Huntington 2003).

Fig. 1. The three climate divisions in Maine (from NOAA's National Climatic Data Center and after Jacobson et al. 2009). These climate divisions span 54%, 31%, and 15% of the state's total area, respectively.

Length of Growing Season

The interval between first and last frost dates and length of growing season are projected to increase by 1 to 2 days per decade in response to increased air temperature (Hayhoe et al. 2007).

Soil Moisture and Drought

Projections about soil moisture and drought are less certain because summer precipitation projections could remain unchanged, decline, or increase and because other hard-to-predict factors like cloud cover would affect soil moisture. Projected increases in temperature combined with most projections of summer precipitation suggest would yield greater evapotranspiration levels; hence, average late-summer levels of soil moisture are projected to decline and that would increase the frequency of drought (Hayhoe et al. 2007). The frequency of short-term (one to three months) drought is projected to greatly increase in Maine under all scenarios and become more widespread under high emissions scenarios (Hayhoe et al. 2007). Medium-term (three to six months) drought and long-term drought (> six months) are projected to become slightly more frequent (Hayhoe et al. 2007).

Atmospheric Changes

CO_2 - GHG emissions are predicted to have two ecologically significant effects on atmospheric gases. The greatest impact is that CO_2 concentrations may double or triple. Greater CO_2 concentrations make it easier for plants to absorb CO_2, hence plant productivity, including forest productivity, is projected to increase (Ollinger et al. 2008). As a result, plants may reduce the production of secondary compounds in leaves that ward off pests and pathogens (Ollinger et al. 2008). Hence, while plant and forest productivity increases, so might outbreaks of pest species (Ollinger et al. 2008). Experimental studies have found that some plant species increase productivity in response to elevated CO_2 levels and other species do not.

Ozone - Another notable atmospheric impact is that temperature increases might increase the breakdown of atmospheric hydrocarbons into ozone, increase ozone concentrations, and potentially damage terrestrial ecosystems (Kunkell et al. 2008). While there is ample uncertainty about the size of ozone increase, it is likely to affect coastal areas the most (Kunkell et al. 2008).

Coastal and Estuarine Conditions

Sea-level Rise (SLR)

Global warming could raise sea levels by causing ocean water to expand as it warms and by melting ice on land. If high emissions scenarios prevail, global sea level is projected to rise at least 5 to 15 inches by 2100 (Jacobson et al. 2009). However, these projections do not account for the recent melting of major ice sheets or the potential for accelerated melting and, hence, are likely conservative. Future sea level rise (SLR) may exceed three times this estimate, i.e., 15 to 45 inches by 2100 (Rahmstorf et al. 2007). With an increase in sea level, Maine's coast may also face substantial increases in the extent and frequency of coastal flooding and erosion. By 2050, the "100-year coastal storm" is projected to occur every two to three years (Frumhoff et al. 2007).

Surface Sea Temperature

By 2100, regional sea surface temperatures are projected to rise an additional 4 to 5°F under the lower emissions scenario and 6 to 8°F under the higher emissions scenario (Frumhoff et al 2006). In the near term, this may be ameliorated by periodic influxes of cold water from the Labrador Current. The frequency of these influxes is driven by Arctic climate change impacts on the North Atlantic and depends on current trends in sea ice, freshwater export, and surface ocean salinity in the Arctic (Greene et al. 2008).

Ocean Salinity

The salinity of the Gulf of Maine (GOM) system could be affected by climate change impacts on the salinity of the Labrador Current and by varying precipitation levels and seasonal river flows on coastal waters. In the GOM, the Labrador Current strongly affects salinity by bringing cold, relatively low-salinity water from the Labrador Sea around Newfoundland and Nova Scotia through the Northeast Channel to the Gulf of Maine (Townsend 1998). It is expected to become fresher as precipitation and melting in the Arctic increase (Curry et al. 2003, Greene and Pershing 2004). Such a pattern occurred in the 1990s and is predicted to re-occur (Greene et al. 2008).

Ocean Acidification

Ocean acidification is the acidification of sea water by the absorption of CO_2. The ocean absorbs about 1/3 of current global CO_2 emissions (Sabine et al. 2004). When CO_2 combines with sea water, it lowers its pH, which makes the ocean more acidic (Feely et al. 2004). If this trend continues unabated, ocean acidification will reach a level that is unprecedented in the past several million years and will be irreversible for millennia (Feely et al. 2004). Increases in sea water acidity or ocean acidification will reduce the concentration of $CaCO_3$ (carbonate), which can impede or prevent calcification by marine organisms (Orr et al. 2005) including plankton, clams, crabs, shrimp, and lobster. The effects cannot be precisely projected, but there is a risk of profound changes to coastal and pelagic food webs (Orr et al. 2005). Marine ecosystems in high latitudes may show the effects of ocean acidification before tropical ecosystems because $CaCO_3$ levels are much lower at high latitudes than in tropical areas (Farby et al. 2008).

Stressors Related to Climate Change

Exotic Species, Pests, and Pathogens

Coastal and Estuarine Invasive Species – Climate change will likely increase the threat posed by invasive marine species (Occhipinti-Ambrogi 2007). For example, warming sea temperatures may allow invasive species such as the Asian shore crab (*Hemigrapsus sanguineus)* to colonize areas of Maine's coast beyond Penobscot Bay where mean summer temperatures cooler than 54°F (13°C) prevail (Stephenson et al. 2009). Under a low emissions scenario with a 3.6°F (2°C) rise in global temperature, the invasive Asian shore crab (*Hemigrapsus sanguineus*) is projected to extend its range northward into Atlantic Canada at high densities (Van Guelpen et al. 2005). With warming, some species such as invasive sea quirt species may establish earlier in the season and out compete native species because community composition is often determined by which species settles first (Stachowicz et al. 2002). Rising mean winter water temperature has been correlated to invasions by exotic coastal and estuarine species in New England (Stachowicz et al. 2002).

Aquatic Invasive Species – Climate change may enhance the introduction of aquatic invasive species by (1) eliminating cold temperatures that limit establishment, (2) eliminating winter hypoxia that limits survival, (3) enhancing their competitive and predatory effects on native species, and (4) by increasing the virulence of some diseases (Rahel and Olden 2008). Asian clam (*Corbicula fluminea*) is a recent invasive aquatic species in the Northeast that displaces native mussel species (Graney et al. 1980). This species is limited to water temperatures > 35-37°F but may be adapting to colder temperatures.

Terrestrial Pest Species – Increased temperatures will likely make terrestrial ecosystems more vulnerable to native and exotic pests. The populations of balsam wooly adelgid (*Adelges piceae*) and hemlock wooly adelgid (*Adelges tsugae*, HWA) are held in check in Maine by low winter temperatures, although recent, mild winters may be responsible for the expansion of both species (Paradis et al. 2008). Under low emissions scenarios, a HWA infestation covering the southern half of Maine is projected. In New Hampshire, the recent population trend of forest caterpillars has been increasing, become more variable, and is correlated with summer thermal sums (Reynolds et al. 2007). An increase in forest pest outbreaks could significantly increase nutrient cycling and nitrogen leaching to surface waters (Murdoch et al. 2000).

Terrestrial Exotic and Invasive Plant Species – Climate change is predicted to make plant communities more vulnerable to exotic and invasive plant species by increasing the frequency of disturbance events that lead to rapid change in plant communities (Dale et al. 2001). Because most exotic plant species have high growth rates and long-distance dispersal traits, they have a competitive advantage over native species for colonizing and establishment, especially following ecosystem disturbance (Dukes and Mooney 1999). In forests, invasive species, both exotic and native, may reduce the resilience of plant communities to climate change by overwhelming forest regeneration of native species (Burke and Grime 1996). One exotic plant species, Japanese honeysuckle (*Lonicera japonica*), increased growth and percent cover in an experimental study of a forest plant community when exposed to elevated CO_2 levels (Belote et al. 2003).

Other Stressors

As humans adapt to climate change, their actions may have far-ranging impacts on Maine's biodiversity: There will be efforts to protect property from SLR and expand renewable energy. Maine may become more attractive than other regions and the productivity of its forest and farm lands could increase. Hence, the impact of these activities on Maine's biodiversity could expand:

Armoring – With rising seas and more frequent storm surges, it is likely that both municipalities and private landowners will seek ways to protect coastal property and infrastructure. Unfortunately, this may exacerbate erosion and inundation of beaches and salt marshes. Further, in areas where there is development immediately inland and above current high tides, natural inland "migration" of coastal wetlands will be impeded.

Wind Energy Development – The shift toward renewable energy has led to an increase in wind power on high-elevation sites and a greater number of access roads and new corridors for power lines. Wind power could pose an increasing threat to sensitive mountaintop species and migratory birds and bats. Poorly routed power line corridors could fragment forest habitats for forest interior species. Conversely, energy right-of-ways will provide more habitat for early successional scrub-shrub species. Finally, energy development in general may provide new routes for exotic and invasive species to penetrate previously intact forest ecosystems.

Forest Management – Widespread biomass harvesting for energy production could threaten some northern forest species and reduce mature forest habitats. However, an increase in forest carbon offset projects might benefit some forest species by reducing harvest intensity slightly and increasing longer-rotation forestry.

Habitat Fragmentation – As temperatures increase in the eastern U.S, Maine's climate will remain comparatively cooler and ameliorated by a maritime effect. This may make Maine even more attractive for people escaping warming climates and development elsewhere. Hence the new residential development, especially along coastal and inland water bodies may expand, thereby fragmenting intact terrestrial and riparian habitats.

Agriculture – Although agriculture occupies a small proportion of land in Maine and is generally declining , the extent of agricultural land has expanded slightly in coastal counties. When coupled with an increasing growing season in northern New England (Wolfe et al 2008), increased demand for food due to climate change related crop failures elsewhere could lead to an expansion of agriculture.

3. Exposure of Wildlife Habitats and Plant Communities to Climate Change

The composition of nearly every plant community and wildlife habitat in Maine is likely to be affected by climate change (Jacobson et al. 2009). Over 44% of the Maine landscape is predicted to change to other habitats in the next 100 years making Maine the state with the greatest percent of area vulnerable to climate change (Malcolm and Markham 2000).

Climate change is predicted to alter species distributions, their life histories, community composition, and ecosystem function at global and local scales (McLaughlin et al. 2002). The most commonly studied impact is range shift of species. Most species will likely shift ranges north and/or upwards in elevation (Davies et al. 2009, Davis and Shaw 2001). Yet, range shifts may not be symmetrical because the factors that determine a species' range limits vary at different boundaries (Varrin et al. 2007). Although southern limits may be governed by biotic factors (e.g., competition), the northern limits may be governed by abiotic factors (e.g., climate; McCarty 2001). This has large implications for predicting climate change impacts to species. As climate envelopes shift north, species whose northern range limits are determined by temperature will be released by these limits and will shift north (e.g., winter temperature for the northern cardinal in Maine [*Cardinalis cardinalis*]). At southern range limits, species may experience increasing biotic stress that leads to range contraction (e.g., pine marten [*Martes americana*] competition by fisher [*Martes pennanti*], which is mediated by snow depth limits; Krohn et al. 1995).

Based on current projections, rates of change for climate, species ranges, and habitats will be high. Across the globe, climate change velocity is projected to exceed the capacity of many species and communities to keep up with their climate niche space (Malcolm et al. 2005). For species moving in an unbroken wave front, the migration rates required to keep up with projected change in climate niche are extremely high by historical standards (Clark 1998, McLachlan et al. 2005). In a simulation study from Ontario, required movement rates averaged 3280 ft/yr (1,000 m/yr) for tree species (Malcolm et al. 2005). This exceeds typical rates following the recent glacial retreat, which were <1640 ft/yr (500 m/yr; Clark 1998) or perhaps even <328 ft/yr (100 m/yr; McLachlan et al. 2005), although some tree species may have achieved rates of >3280 ft/yr (1,000 m/yr; Clark 1998). Hence, some tree species may take >100 years to begin to colonize significant portions of new habitat (Iverson et al. 2005).

3A. Coastal and Estuarine Habitats

Marine Open Water - Projected changes in coastal water temperatures may increase the occurrence of warm-water species from the south and result in a retreat of cold-water species to northern marine systems (Frumhoff et al. 2007). Most projections for the northwest Atlantic and Gulf of Maine predict warming sea temperatures. The surface sea temperatures (SST) in the Gulf of Maine are projected to increase, with the greatest increases in winter SSTs, which could affect species intolerant of the higher SSTs (Van Guelpen et al. 2005). However, it is also possible that climate change might temporarily increase the circulation of cool, low-salinity water from the Labrador Current into the Gulf of Maine and reduce sea water temperatures (Jacobson et al. 2009, Greene et al. 2008). This can increase water column stratification, which in turn may be linked to observed changes in phytoplankton, zooplankton, higher trophic level consumer populations, and the entire marine food web. As a result, some northern species might temporarily move south (Greene et al. 2008). Sea temperatures increase following an increasing trend in air temperatures, may initially cool due to the strengthening of the Labrador Current, or may follow a warming trend that is periodically interrupted by cold water pulses from the Labrador Current.

Estuaries and Bay – Projected changes in water temperature may increase the occurrence of warm-water species from the south and result in a retreat of cold-water species to northern marine systems. Increases in variation of seasonal river flow will increase sedimentation and turbidity of coastal waters (Ashton et al. 2007). This, if coupled with sea temperature increases, could reduce productivity and habitats of seaweed beds, kelp beds and eel grass beds (Horton and McKenzie 2009a). However, summer runoff declines could reduce estuarine eutrophication (Horton and McKenzie 2009a).

Rocky Coastline and Islands – Rocky coast and island habitats may have little exposure to climate change (Frumhoff et al. 2007).

Unconsolidated Shore – Beach/dune ecosystems will be highly susceptible to impacts from SLR and storm events (Gulf of Maine Council Habitat Restoration Subcommittee 2004). By 2050, the "100-year storm" is projected to occur every two to three years in the Northeast (Frumhoff et al. 2007). SLR is projected to result in severe erosion and shoreline retreat through the next century (Ashton et al. 2008).

Table 1. Maine State Wildlife Action Plan (SWAP) coastal and estuarine habitats, dominant climate change stressors, and climate change exposure.

SWAP Habitat	Dominant Climate Change Stressors	Estimate of Climate Change Exposure
Marine Open Water	Sea temp. increase/decrease, ocean acidification	High
Estuaries and Bays	SLR, Sea temp. increase, ocean acidification	Medium
Rocky Coastline and Islands	SLR, sea temp. increase, ocean acidification	Medium
Unconsolidated Shore (beaches & mudflats)	SLR, sea temp. increase, ocean acidification	High
Estuarine Emergent Salt Marsh	SLR, sea temp. increase, ocean acidification	High

Estuarine Emergent Salt marsh – Maine has about 20,000 ac (79 km^2) of salt marsh, more than any other New England state (Jacobson et al. 1987). Future tidal marsh acreage will be determined by: (1) accretion (the natural accumulation of marine sediments within a salt marsh) in relation to the rate of SLR, (2) the erosion rates on the seaward marsh edge, and (3) the availability of space that allows marsh to migrate inland. Marshes will be affected by both SLR and storm events. In the Northeast, SLR is likely to outpace accretion and inundate existing coastal marshes, resulting in rapid loss and conversion (from high to low marsh to mudflat) and result in landward salt marsh migration and the replacement of other tidal marshes (Ashton et al. 2007, Hartig et al. 2002). Accretion potentially might reduce flooding, but this depends on sediment availability and accumulation rates of organic matter. In Maine, many high salt marsh environments may revert to low salt marsh habitats (Slovinsky and Dickson 2008), or may disappear altogether if their landward migration is blocked (Jacobson et al. 2009).

Four studies have projected sea-level changes in Maine. For a small portion of Rachel Carson National Wildlife Refuge (NWR) in southern Maine, Slovinsky and Dickson (2008) used static inundation models and projected a large loss of high salt marsh area and large increase in low salt marsh area for scenarios with a 1-ft, 2-ft, and 3-ft increase in sea level. A second projection study covered the Rachel Carson NWR using the Sea Level Affecting Marshes Model (SLAMM[1]; Clough and Larson 2008a). They projected SLR to result in large declines of brackish marsh, tidal swamp, estuarine beach, but an increase in tidal flat, salt marsh, and transition salt marsh by 2100.

A third study used static inundation models and LIDAR elevation data to model a 2-foot SLR, Slovinsky and Dickson (2010) projected >50% loss of high salt marsh area and small (~15%) to large (>>100%) increases in low salt marsh area at three sites in mid-coast Maine: Back Bay (Portland), Cousins River (Yarmouth), and Thomas Bay (Brunswick).

A fourth study was conducted by Clough and Larson (2008b) at Moosehorn NWR in eastern Maine using SLAMM. SLR was projected to result in a decline in brackish marsh, but an increase in salt marsh, estuarine beach, and transition salt marsh by 2100. The Moosehorn NWR's high tide range (approximately 20 ft [6 m]), combined with the significant vertical relief, help to explain the predictions of resilience to SLR at this site. This projection suggests that the salt marshes of eastern Maine may be less vulnerable to SLR than the salt marshes of mid-coast and southern Maine.

Overall, salt marsh habitat of southern and mid-coast Maine may be more vulnerable to SLR than eastern Maine because brackish marsh and potentially high salt marsh are the most vulnerable to SLR. Salt marshes in eastern Maine may be less vulnerable to SLR because they are dominated by low salt marsh and high-relief coastal topography. Plant species occupying coastal wetlands, including salt marshes, tidal marshes and swamps, and low-lying, non-tidal freshwater wetlands in the coastal zone are projected to be exposed to rising sea level (Frumhoff et al. 2007).

Climate Change Exposure Summary for Coastal and Estuarine Habitats

Coastal and estuarine habitats are exposed to the full suite of climate change stressors (Table 1). Open water and estuarine ecosystems may principally be affected by SLR and possibly by changes in water temperature, salinity, and pH. Changes in seasonal patterns of precipitation and runoff may alter hydrologic and chemical characteristics of coastal marine ecosystems, affecting species composition and ecosystem productivity of coastal and estuarine ecosystems.

[1] Like any model, SLAMM entails various assumptions, simplifications, and uncertainties. The reliability of forecasts is also a function of data input accuracy. More information on the SLAMM model is available here: http://www.warrenpinnacle.com/prof/SLAMM/index.html. It models and makes assumptions about accretion, soil saturation, overwash, erosion, and inundation.

3B. Freshwater Wetland Habitats

Freshwater wetland systems will likely be increasingly exposed to changes in hydrology and temperatures due to climate change. This could change annual flow patterns and lower summer water levels for aquatic habitats. For water bodies, water temperatures will increase. For wetlands, lower water levels may affect hydro-period and vegetation.

River and Stream Habitats – River and stream habitats will be affected by rising temperatures, and changes in flow patterns and ice break up. A shift from a snowmelt-dominated regime to a regime of winter runoff, coupled with projected precipitation increases, may increase winter flooding of riparian and wetland habitats and soil erosion and sedimentation, which could destabilize stream and river channels (Ashmore and Church 2001). Periods of high stream flow in the spring are projected to occur earlier and decrease in length, while summer low-flow periods will last longer (Hayhoe et al. 2007), possibly subjecting wetlands, including *vernal pools*, to extended dry periods and disrupting their hydrology (Brooks 2009, Frumhoff et al. 2007). As a result, vernal pools, ephemeral streams, low-order streams, outwash plain pond shores, and their fauna have high vulnerability to climate change (Brooks 2009). Mid-winter thaws are predicted to become more frequent, leading to more river bed scouring events (Beltaos and Burrell 2003).

Climate change could alter the chemistry of streams and rivers. Increases in extreme rainfall events, coupled with interludes of longer dry periods, could increase the frequency of highly-concentrated pulses of non-point pollutants (e.g., phosphorus, nitrates, acid rain, pesticides, herbicides). A reduction in snowmelt could reduce acidic pulses that now occur in spring runoff. Re-flooding of drought-exposed wetlands after a period of low-water levels can briefly increase methyl-mercury production in surface waters (Murdoch et al. 2000). Mid-winter thaws could become more frequent leading to more frequent ice jam conditions and river bed scouring events (Beltaos and Burrell 2003). Eventually, rivers in the region may become ice free, a trend that would be enhanced by an increase in winter rainfall; seasonal ice scouring that is essential for maintaining some river shore plant species could then disappear (Beltaos and Burrell 2003).

Freshwater Lakes and Ponds – Changes to lake ice duration and surface water temperatures will strongly affect primary productivity, dissolved oxygen (DO), thermal habitat, and invertebrate and fish communities. Climate change may increase or reduce productivity. Lakes may experience longer ice-free periods due to warmer temperatures and this may increase biological activity (Schindler et al. 1996). However, the likelihood of oxygen depletion in lakes could increase with climate change (e.g., Mackenzie-Grieve and Post 2006), especially in oligotrophic water bodies (Murdoch et al. 2000). Increased lake temperatures could reduce levels of dissolved oxygen saturation, which, when coupled with likely increases in primary production, could deplete summer oxygen. Lengthened periods of water stratification during summer could also increase the frequency of anoxia in bottom waters and reduce DO habitat availability in summer.

Emergent Marsh and Wet Meadows – Emergent marsh and wet meadow habitats are strongly susceptible to alterations in hydrology, including both surface water runoff and groundwater discharge (Environment Canada 2004). Changes in the timing and amount of annual precipitation predicted with climate change will likely affect the distribution of wetland systems, particularly vernal pools and wet meadows, and for many wetland plant species. These changes may require that wetland-dependent species relocate via available corridors to other wetland systems if they are to survive. Extended droughts that occur earlier in the growing season, along with elevated temperatures and lower groundwater table, may reduce the distribution and condition of wetlands throughout the state. Reduced summer discharge of rivers into the coastal zone could cause saltwater intrusions into upper tidal reaches of rivers and affect tidal wetlands (Murdoch et al. 2000).

Climate change could affect vernal pools by shortening effective hydroperiods. Temperature increases will increase evapotranspiration and could result in a negative annual water balance earlier in the year and in earlier pool drying. This would result in shortened spring hydroperiods with potential negative impacts to vernal pool fauna. In addition, precipitation events could occur less frequently but more intensely and droughts could become more frequent and longer and cause pools (chiefly smaller pools) to repeatedly dry and re-flood. This could also kill developing amphibian and invertebrate eggs or larvae.

Peatlands – Many North American peatlands have lasted for millennia through long wet and dry periods, but their future stability under climate change is uncertain (Environment Canada 2004). Maine's peatlands may be vulnerable to climate change because their distribution is governed primarily by climate (Davis and Anderson 2001). Increases in summer drought, despite overall increasing precipitation, could also impair southern peatlands (Gorham 1991, Burkett and Kusler 2000). Fens may be vulnerable to changes in ground water level, which plays a crucial role in the accumulation and decay of organic matter and governs plant community structure (Seigel and Glaser 2006). Under most emissions scenarios, they could decline because ground water levels will fall as evapotranspiration increases with temperature, unless offset by an increase in summer precipitation (Moore et al. 1997; Myer et al. 1999). Some fens may be resilient if their water input flows from deep groundwater systems (Winter 2000). Overall, bogs are vulnerable to declines in precipitation levels because precipitation is their only water input (Winter 2000). Jacobson et al. (2009) suggests that increased drought could dry out thousands of acres of peatlands. In ombrotrophic bogs, shrubs may increase their dominance at the expense of graminoids if climate change decreases water levels and increases temperatures (Weltzin et al. 2000). Overall, climate change might cause some peatlands to decline and community compositional changes in other peatlands, such as bog plant communities slowly converting into fen plant communities. If the hydraulic head in the recharge areas providing the ground water that sustains calcareous fens decreases with climate change, non-calcareous tolerant species may out-compete calcareous plant species (Siegel and Glaser 2006, Almendinger and Leete 1998).

Forested Wetlands – Forested wetlands may become more influenced by declining high flows from summer rainfall and less dependent on spring flow events and ice jams (Prowse and Beltaos 2002). The corresponding decline in high flow periods, together with longer growing season evaporation periods, may reduce soil moisture of some floodplain forests. The unique floodplain forests of the Saco, Penobscot, upper Kennebec, and Sebasticook Rivers could convert to meadow or upland forests (Jacobson et al. 2009). Reduced summer discharge in rivers into the coastal zone could result in saltwater intrusions into upper tidal reaches of rivers, which could affect riparian swamps (Murdoch et al. 2000). High-flow conditions in the spring are projected to occur earlier and be shorter in duration, while summer low-flow conditions could last longer (Hayhoe et al. 2007), possibly subjecting seasonal headwater streams and wetlands, including vernal pools, to extended dry periods that disrupt their hydrology (Frumhoff et al. 2007).

Other Aquatic Habitats – High-flow conditions in spring are projected to occur earlier while low-flow conditions in summer will last longer (Hayhoe et al. 2007), possibly subjecting other aquatic habitats to extended periods of low water (Frumhoff et al. 2007). Aquatic vegetation communities may be fairly resilient to direct impacts of increased temperatures but climate change might increase phosphorus levels, reduce oxygen saturation, and accelerate eutrophication (McKee et al. 2003).

Climate Change Exposure Summary for Freshwater Wetland Habitats

Aquatic habitats are likely to be exposed to many climate change stressors (Table 2), although the uncertainty of precipitation projections makes it difficult to predict impacts (Jacobson et al. 2009). Changes in seasonal patterns of precipitation and runoff due to climate change will likely alter hydrologic characteristics of aquatic systems, affecting their composition and ecosystem productivity. Populations of aquatic organisms may decline in response to changes in the frequency, duration, and timing of extreme precipitation events, such as floods or droughts. Changes in the seasonal timing of snowmelt will alter stream flows, potentially interfering with the reproduction of many aquatic species. Open water bodies will also be strongly affected by increasing water temperature, as air temperatures are likely to increase, and by an extended period of low-water conditions in the summer. Wetlands may be affected by longer periods of low-water conditions in the late-summer.

Table 2. Maine State Wildlife Action Plan (SWAP) freshwater wetland habitats, dominant climate change stressors, and climate change exposure.

SWAP Habitats	Dominant Climate Change Stressors	Estimate of Climate Change Exposure
Rivers & Streams	Water temp. increase, drought, peak of high-flow levels shifting from spring to winter	High
Freshwater Lakes & Ponds	Water temp. increase, drought, peak of high-water levels shifting from spring to winter	High
Emergent Marsh & Wet Meadows	Drought, peak of high-water levels shifting from spring to winter	Medium
Shrub-scrub Wetland	Drought, peak of high-water levels shifting from spring to winter	Medium
Peatlands	Water temp. increase, drought, peak of high-water levels shifting from spring to winter	High
Forested Wetland	Drought, peak of high-flow levels shifting from spring to winter	Medium

3C. Upland Habitats

Deciduous and Mixed Forest – Forests in the Northeast are predicted to significantly change in the next 100 years under every emissions scenario (Prasad et al. 2007). The extent of oak and pine forest types is projected to increase and expand into central and possibly northern Maine (Iverson et al. 2008a). Under the lowest emissions scenario, Maine is predicted to retain its northern hardwood forest. Northern hardwood tree species may achieve increased growth rates under any emissions scenario due to higher temperatures, a longer growing season, and potential CO_2-driven increases in photosynthesis and water-use efficiency. If CO_2 fertilization does not occur, growth rates are projected to slightly increase. Under the higher emissions scenario, growth rates of northern hardwoods may decline by 2100 due to temperature stress (Ollinger et al. 2008). Under high emissions scenarios, oak-hickory forest types are projected to dominate most of southern and central Maine and Maine will lose northern hardwood forest. In contrast, Tang and Beckage (2010) projected a modest loss of regional northern hardwood forest. Hemlock wooly adelgid is projected to expand into southern Maine with warming and eliminate Eastern hemlock (*Tsuga canadensis*) (Paradis et al. 2008). Birch-aspen forests would also be highly vulnerable to climate change (Neilson 1995).

Paleo-climate studies of lake sediments indicate that moisture regime could determine the composition of Maine's future forest. During past warm/moist climate periods (warmer than present), forests were dominated by Eastern hemlock, American beech (*Fagus grandifolia*), and oak spp. (*Quercus* spp.) (Shuman et al 2004). During past warm/dry periods, they were dominated by oak spp. and hickory spp. (*Carya* spp.) and Eastern hemlock greatly declined perhaps because of drought (Shuman et al 2004).

Coniferous Forest Habitats – Boreal coniferous forest habitats are predicted to decline across the region. The fertilization effect of increasing atmospheric CO_2 levels may moderate regional declines of boreal forest due to climate change (Tang and Beckage 2010). Increased CO_2 levels can increase water use efficiency and rates of net canopy CO_2-fixation by inducing the stomatal closure of plants and reducing leaf transpiration (Tang and Beckage 2010). In contrast, Ollinger et al. (2008) projected growth rates for balsam fir (*Abies balsamea*) and red spruce (*Picea rubens*) that would decline after 2050.

Coastal and interior forests dominated by Eastern hemlock will likely decline under a low emissions scenario due to the spread of hemlock wooly adelgid and could be largely eliminated from Maine under a high emissions scenario (Paradis et al. 2008). Under the lowest emissions scenario, Maine and the Northern Forest region are predicted to lose much of their spruce-fir forest, which would including upland spruce-fir forest and lowland spruce flats (Prasad et al. 2007). Birch/aspen forests and boreal mixed wood forests (birch, black/red spruce, and balsam fir) would also be greatly reduced by 2100 (Prasad et al. 2007). Tang and Beckage (2010) also projected a significant decline of boreal conifer forest with some boreal forest areas persisting in the mountains.

Dry Woodlands and Barrens – These habitats may be vulnerable to increased drought and invasion by exotic plant species due climate change. Many barren community types, including sandplain grasslands and pitch pine barrens, only occur as fragmented patches on today's landscape and are closely associated with outwash sands. Potential for these communities and their species to shift range may be limited.

Mountaintop Forest (including krummholz) – Coniferous forest habitats that are sub-alpine are predicted to decline greatly across the region. In northern New England, a 7°F (3°C) summer temperature increase is projected to potentially eliminate nearly all sub-alpine forest except for small patches in New Hampshire's Presidential Range (136 ac [55 ha]) and on Mount Katahdin in Maine (49 ac [20 ha]; Rodenhouse et al. 2008). This projection may not be accurate, as this climate niche modeling study did not factor in (1) the competitive advantage of sub-alpine spruce and fir over other tree species on low-quality, high-elevation sites (Lee et al. 2005) and (2) the effects of extreme events like icing on stature and structure of sub-alpine forests (Kimball and Weihrauch 2000).

Many tree species are limited by soil type and may individually make future elevation shifts (Lee et al. 2005). Hence, a simple ecotone shift of current plant community types in response to climate change is not expected. An upward shift of sugar maple (Acer *saccharum*) might be limited because suitable substrate is lacking at high elevations (Lee et al. 2005). On the other hand, American beech might increase in abundance above its current elevation limits (Solomon and Leak 1994), even displacing spruce and fir on some soils (Lee et al. 2005). Eastern hemlock, common to shallow, coarse, or poorly drained soils at low elevations, may expand its distribution upward as it id during past warmer periods (Spear et al. 1994) and displace spruce and fir on poorer soils (Lee et al. 2005). White pine (*Pinus strobus*) shifted its elevation limits in the past in response to warming (Shuman et al. 2004). The forest montane ecotone between northern hardwood forest and spruce-fir forest in Vermont already appear to be rapidly shifting upward (Beckage et al. 2008).

Hence, the current pattern of montane forest community zonation could disappear (Lee et al. 2005).

Alpine Habitats – Alpine habitats can be strongly affected by climate change (Kimball and Weihrauch 2000, Lesica and McCune 2004), including changes in temperature and CO_2 concentration. With warming, tree lines can be expected to rise in elevation, which will reduce the extent of alpine habitats (Spear 1989, Miller and Spear 1999). Using pollen and macrofossils, similar tree line shifts occurred during warming about 3,500 year BP. Because tree line represents the long-term average climatic history of a site, it is predicted to occur at elevations lower (i.e., warmer) than expected because of the relatively slow upslope movement of trees. Moreover, the elevation of tree line is also affected wind and ice (Kimball and Weihrauch 2000). This, coupled with the fact that alpine communities persisted through the Holocene warming period (Miller and Spear 1999), suggest that alpine habitats may persist under low emissions scenarios. In the nearby Chic Choc Mountains, tree line has not shifted but alpine meadow habitats have declined 0.11%/year and shrub habitats have expanded by 0.28%/year from 1973 to 2004 (Fortin and Pilote 2008). Walther (2002) has documented climate-related elevation shift of alpine plants and rising tree line across the globe. Across the Northeast, alpine habitat islands smaller than Mount Washington and Mount Katadhin may be lost (Kimball 1997). The persistence of alpine communities in the Northeast during a warming period ~5,000 year BP (Miler and Spear 1989) suggests that alpine plant species may persist through 2100, though perhaps to a reduced extent. Graminoid species may outperform other species due to greater drought resistance and enhanced competitive ability at higher CO_2 levels. Snow bed species well adapted to sites that stay cool may be especially vulnerable to climate change (Schöb et al. 2009).

Grassland, Agricultural, Old Field – These habitats may be vulnerable to increased drought and increases in exotic plant species. Projected increases in drought may increase the likelihood of fire and other forest disturbances (Ollinger et al. 2008), which might increase these habitats.

Other Terrestrial Habitats – Little is specifically known about how climate change might affect other Maine SWAP habitats including: Shrub / Early Successional & Regenerating Forest, Urban / Suburban, Cliff Face & Rocky Outcrops (including talus), and Caves and Mines.

Climate Change Exposure Summary for Upland Habitats

Terrestrial habitats are primarily exposed to air temperature changes, drought, pests, exotic species, and CO_2 fertilization (Table 3). Dominant plant species will shift ranges in response to climate changes. Modest drought increases may limit many plant species and plant communities. Increasing pest and exotic species are expected to affect composition of wildlife habitats and plant communities. Coniferous forest, mountaintop forest, and alpine areas are projected to decline greatly in Maine and the Northeast (H. Galbraith, pers. comm.). Modest declines may occur for many deciduous and mixed forest types while oak-hickory forest types are projected to increase. Other terrestrial habitats may also experience climate change impacts.

Table 3. Maine State Wildlife Action Plan (SWAP) upland habitats, dominant climate change stressors, and climate change exposure.

SWAP Habitat	Dominant Climate Change Stressors	Estimate of Climate Change Exposure
Deciduous and Mixed Forest	Air temp. increase, drought, pest impacts, exotic species, CO_2 fertilization	High
Coniferous Forest	Air temp. increase, drought, pest impacts, exotic species, CO_2 fertilization	High
Dry Woodlands and Barrens	Air temp. increase, drought, pest impacts	Low
Mountaintop Forest (including krummholz)	Air temp. increase, drought, pest impacts	High
Alpine	Air temp. increase, CO_2 fertilization	High
Shrub / Early Successional & Regenerating Forest	Air temp. increase, drought, exotic spp.	Low
Grassland, Agricultural, Old Field	Drought, exotic spp.	Low
Urban / Suburban	Drought, exotic spp., pest impacts	Low?
Cliff Face & Rocky Outcrops (including talus)	Air temp. increase, drought	Moderate
Caves and Mines	Peak of high-flow conditions in winter?	Low

4. Animal Species Groups

Invertebrates

Coastal and Estuarine Invertebrates – Climate change poses many threats to coastal and estuarine invertebrates, including: ocean acidification, sea temperature change, air temperature increases (for intertidal species), and the facilitation of invasive species. Ocean acidification will reduce the concentration of carbonate, which is needed by clams (class: Bivalvia), mussels (Bivalvia), lobsters (subphylum: Crustacea), barnacles (subphylum: Crustacea), sea urchins (class: Echinoidea), corals (class: Anthozoa), and some plankton, to build their shells and other hard parts (Fabry et al. 2008). Ocean acidification might not affect all marine species but it will dissolve the shells of some species and prevent other species from building their shells properly (Orr et al. 2005), which affects their ecology, mortality, and populations (Fabry et al. 2008). High emissions scenarios could reduce the reproduction of copepods and sea urchins (Kurihara et al. 2004), important species in Maine's marine systems. Many subarctic marine species may be replaced by temperate species from south of Cape Cod as the Gulf of Maine warms because many subarctic species reach the southern edge of their range in the Gulf of Maine (Adey and Steneck 2001) and rising summer temperature will reduce their reproductive output and/or survival rates (Mieszkowska et al. 2006).

Aquatic Invertebrates – Aquatic invertebrates could be subjected to significant changes in hydrology and increased water temperatures driven by climate change (Williams et al. 2007). One such change, projected increases in winter rain, could increase the frequency of floods and ice flows that scour streambeds and kill aquatic insect larvae (Frumhoff et al. 2007). In warmer, dry years, mayflies (order: Ephemeroptera) may emerge earlier and be smaller than in high-water years when emergence was delayed and feeding by larvae was extended (Harper and Peckarsky 2006). Climate-induced changes in temperature and flow pattern could accelerate emergence, thereby reduce mayfly size, fecundity, and population viability. Freshwater mussels (class: Bivalvia) are susceptible to climate change impacts including: warmer water temperatures, longer periods of low flows, other changes in seasonal flows, floods, and impacts on host fish species (US Fish and Wildlife Service 2009). If summers become drier, mussel beds would be more vulnerable to drying out. A consequence of increased temperatures could be that female mussels release glochidia into the water column earlier, thus uncoupling the timing of mussel and host fish reproduction cycles, especially in anadromous fish. A decline in host Atlantic salmon (*Salmo salar*) and brook trout (*Salvelinus fontinalis*) populations could reduce recruitment of some mussel species. For freshwater mussel species with critical host relationships with cold-water fish; their reproductive success may decline as suitable thermal habitat for their host species diminishes (New Hampshire Fish and Game Department 2005) which could include eastern pearlshell (*Margaritifera margaritifera*) and brook floater (*Alasmidonta varicosa*) in Maine.

Terrestrial Invertebrates – In Massachusetts, the emergence of butterfly (order: Lepidoptera) species is correlated with spring temperatures and is predicted to emerge two days earlier for every 1.8^{o}F (1^{o}C) increase in temperature (Polgar et al. 2009). Butterfly and moth species (order: Lepidoptera) have been widely shown to shift northward in response to climate change (Parmesan et al. 1999). Walther (2002) has documented across the globe climate-related northward range shifts for 39 butterfly species. Climate change may reduce the extent of habitat for alpine invertebrates (McFarland 2003). The phenology of invertebrate pollinators and host plants could become asynchronous, with deleterious impacts to both pollinators and hosts (Hegland et al. 2009).

Fish

Marine and Anadramous Fish - Climate change may affect marine species by: disrupting food webs, enhancing habitat conditions for invasive species, causing range shifts, creating asynchrony between key life history events and appropriate habitat conditions, and increasing the negative impacts of other environmental stressors in estuaries and coastal bays (Connelly et al. 2007). A key concern is the projected transformation of estuaries from being dominated by salt marsh habitats to being dominated by open water habitats where primary productivity is driven by macro-algae, submerged aquatic plants, or phytoplankton (Erwin et al 2006). Major changes in secondary production might also occur. The loss of the detritus food web within emergent marshes might severely jeopardize nursery areas for commercially important fisheries (Bertness 1999). In the North Atlantic, some range shifts have been observed for pelagic fish species (Rijnsdorp et al. 2009).

Inland Fish – Cold-water habitats are predicted to decline in the region as air temperatures warm and, subsequently, water temperatures increase. Many warm-water species will replace cold-water fish species (Eaton and Scheller 1996). In summer, warmer water temperatures and anoxia in deep waters could increase the release of methyl-mercury in aquatic habitats and, consequently, increase mercury levels in fish (Scheuhammer and Graham 1999).

Streams and Rivers – Fish species in lowland streams and species that require cool water (e.g., trout, salmon), are likely to be the most severely affected by climate change in Maine (Williams et al. 2007). The percent of streams with temperatures suitable for cold-water salmonids is predicted to decline, with southern coastal and interior areas becoming marginal habitat (Williams et al. 2007). Projected increases in winter rain could result in more frequent damaging floods and ice flows that scour streambeds, causing erosion and in-stream sedimentation, killing eggs, larvae, and adult fish that cannot find suitable refuge (Frumoff et al. 2007). In summer, water quality might be diminished by lowered water levels or decreased river flows, increases in temperature, prolonged summer dry seasons, and heavier rainfall (Vasseur et al., 2008).

Lakes and Ponds – Stefan et al. (2001) predicted that the percentage of lakes suitable for cold-water fisheries would decline 45% in the northern U.S. Much of this decline is expected because cold hypolimnetic refuges could shrink and have reduced O_2 levels (Stefan et al. 2001). Moreover, native warm-water fish species are expected to colonize new lakes, which can lead to local extirpation of native minnows and negative impacts on native top predators (MacCrae and Jackson 2001).

Reptiles and Amphibians

Terrestrial Amphibians and Reptiles – Climate change may affect amphibians (class: Amphibia) and reptiles (class: Reptilia) in four ways (Lind 2008): (1) increasing variability of environmental and habitat conditions; (2) altering the phenology (timing) of events essential to their life history; (3) increasing impacts of pathogens and invasive species; and (4) amplifying the effects of other environmental stressors (e.g., chemicals) (Lind 2008). Over the long term, the frequency and duration of extreme temperature and precipitation events may reduce the persistence of local populations, their dispersal capabilities and the functionality of metapopulations. Synergisms among a variety of environmental stressors have been documented to adversely affect native amphibians and reptiles, and climatic changes may exacerbate these stressors. Longer lasting summer low-flow periods with occasional rainfall may affect vernal pools and other seasonal wetlands (Hayhoe et al. 2007) that are essential for many species. A large proportion of northeastern amphibians use vernal pools for breeding or foraging activity (Calhoun and deMaynadier 2008) and thus potential shortening of vernal pool hydroperiod could negatively impact habitat quality and extent for several amphibian species in Maine (Brooks 2009). This change in hydro-regime would negatively impact developing larval amphibians, which require a minimum period for development to metamorphosis (Brooks 2009).

For turtles (order: Testudines), climate change may increase or decrease population growth rates (Inkley 2004). For example, painted turtles (*Chrysemys picta*) grow larger in warmer years and may reach sexual maturity faster (Frazer et al. 1993). On the other hand, warming may lead to the loss of snow cover, which insulates hatchlings that overwinter in the nest against the killing effects associated with rapid temperature changes during winter hibernation (Breitenback et al. 1984). In nearby Nova Scotia, Hermand and Scott (1994) speculated that the Blanding's turtle (*Emydoidea blandingii*) may be highly vulnerable to climate change impacts, such as declines in water levels and further isolation of wetlands due to water level declines. In Maine, Blanding's turtles more frequently use pocket swamps and vernal pools with longer hydro-periods than those with shorter hydro-periods (Beaudry et al. 2009), which suggests that climate change could be another stress to this state's already endangered population.

Birds

Seabirds – Seabirds may be vulnerable to reductions in prey due to climate change (Irons et al. 2007). Common Murre (*Uria aalge*) showed population declines with large temperature shifts in either direction. This pattern was replicated during both climate oscillations. Negative population trends in seabirds may also indicate changes in the underlying marine food webs. Hence, similar widespread fluctuations in response to climate shifts are likely for other ecosystem components (marine mammals, fish, and invertebrates). Loss of nesting island habitats by rising sea levels will also have consequences for these species. SLR may reduce nesting and loafing habitat for seabirds, including Roseate terns (*Sterna dougallii*) and common terns (*Sterna hirundo*) (New Hampshire Fish and Game Department 2005).

Shorebirds – During their energetically demanding migrations, many shorebird (Charadriiformes) species depend on tidal sand and mud flats for foraging. Up to 50% of shorebird foraging habitats during migration may be at risk at some sites in the U.S. (Galbraith et al. 2005). Climate change may also increase mortality on the wintering grounds by reducing the quality of their prey and roost site availability (Durell et al. 2006). Moreover, extensive loss of breeding habitat (40-57%) due to climate change (IPCC 2002) also threatens shorebird populations (Galbraith et al. 2005, Zöckler 2000).

Wetland Species – Wetland species may face an increasingly variable hydrological cycle where some wetlands dry out in some years and result in smaller clutch sizes, nesting failures, and reduced fecundity (Wormworth and Mallon 2006). Coastal wetlands will also be affected, due to rising sea level and changes in seasonal flows. SLR and variable rainfall could limit wading bird access to feeding areas and result in a wider variation in wader reproduction (Butler and Vennesland 2000).

Forest Species – Populations of boreal forest species are expected to greatly decline as the extent of their boreal forest habitat declines (Rodenhouse et al. 2008). Under low emissions scenarios, the extent of northern hardwood forest may increase, but many new northern hardwood areas are likely to have low forest productivity and be low-quality habitat, resulting in low nesting productivity and greater population vulnerability due to other factors (Rodenhouse et al. 2008). Under high emissions scenarios, the extent of northern hardwood forest may decline, as presumably will populations of bird species associated with northern hardwoods (Rodenhouse et al. 2008).

Migrant Bird Species – Migrant species may be at higher risk than non-migrant species because climatic change may affect migrant species in their wintering areas, during migration, and on their breeding grounds (Aloha et al. 2004). They are exposed to the additive climatic risk for each habitat used each year, with the sum total being cumulative catastrophic effects (Huntley et al. 2006). The winter survivorship of many neo-tropical migrants may decline if predicted reductions in precipitation and increased drought occur on their winter areas in Central and northern South America (Rodenhouse et al. 2009). Moreover, climate change is affecting the phenology of bird migration, with many migratory bird species having shifted their arrival dates up to three weeks earlier over 70 years (Price and Root 2002).

Both phenological miscuing (responding inappropriately to climate change) and phenological disjunction (where a species becomes asynchronous with its environment) have been shown for some migrant bird species (Crick 2004). With disjunction, egg hatching can occur when food supplies are less abundant, as peaks in food availability can shift to track local weather patterns. Such shifts in migration phenology have the potential to decouple bird migration peaks and egg hatching/fledging times from peaks in food supply (e.g., McCarty 2001). Short-distance migrants may use temperature of wintering areas as a migration cue such that their migration patterns are still in synchrony with food availability (Milller-Rushing et al. 2008). The migration times of most long-distance migrants may not be changing (Miller et al. 2008), but in some species this pattern has already led to disruption of time-sensitive relationships, such as those between breeding time and food abundance (Both et al. 2006).

Mammals

Marine Mammals – Climate change effects for most whales (Cetacea) are unknown (Learmonth et al. 2006). Seals (Phocidae) may experience a reduction in coastal loafing and nursing habitat due to SLR (New Hampshire Fish and Game Department 2005).

Terrestrial Mammals – Increases in temperature may affect boreal mammal species (Jacobson et al. 2009). For example, the moose (*Alces alces*) population growth rate in northern Minnesota was strongly negatively associated with mean summer temperatures of the preceding summer and the species is expected to be extirpated from Minnesota under high emissions scenarios (Murray et al. 2005). Increased summer drought frequency seems likely to reduce the abundance of small flying insects with aquatic larval stages upon which many bat species forage (Rodenhouse et al. 2009), with potentially negative consequences for bat populations in Maine.

Carnivores – Some mammals may have species ranges that are defined by both their climate niche space and by competing species that are often closely related (Dormann et al. 2009). For example, Canada lynx (*Lynx canadensis*) and pine marten are both dependent on deep snow to avoid competing with their respective congeners, bobcat (*Lynx rufus*) and fisher. Once annual snowfall declines below a key threshold—106 in/yr (270 cm/yr) for lynx (Hoving et al. 2005) and 76 in/yr (192 cm/yr) for marten (Krohn et al. 1995)—both species may decline and eventually disappear, to be replaced by their competitors, bobcat and fisher, respectively.

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Literature Cited

Adey, W., and R. Steneck. 2001. Thermogeography over time creates biogeographic regions: a temperature/space/time-integrated model and an abundance-weighted test for benthic marine algae. Journal of Phycology 37:677-698.

Ahola, M., T. Laaksonen, K. Sippola, T. Eeva, K. Rainio and E. Lehikoinen E. 2004. Variation in climate warming along the migration route uncouples arrival and breeding dates. Global Change Biology 10: 1610–1617.

Almendinger, J., and J. Leete. 1998. Peat characteristics and groundwater geochemistry of calcareous fens in the Minnesota River Basin, U.S.A. Biogeochemistry 43: 17-41.

Ashmore, P., and M. Church. 2001. The Impact of Climate Change on Rivers and River Processes in Canada. Geological Survey of Canada Bulletin 555". Ottawa, Ontario. Natural Resources Canada. http://atlas.nrcan.gc.ca/site/english/maps/climatechange/potentialimpacts/sensitivityriverregions/1

Ashton, A., J. Donnelly, and R. Evans. 2007. A Discussion of the Potential Impacts of Climate Change on the Shorelines of the Northeastern USA. Prepared for the Northeast Climate Impacts Assessment, Union of Concerned Scientists, Woods Hole Oceanographic Institution, Woods Hole, MA.

Association of Fish and Wildlife Agencies. 2009. Voluntary Guidance for States to Incorporate Climate Change into State Wildlife Action Plans & Other Management Plans. A Collaboration of the Association of Fish and Wildlife Agencies' Climate Change and Teaming With Wildlife Committees, Washington, D.C.

Beaudry, F., P.G. deMaynadier, and M.L. Hunter, Jr. 2009. Seasonally dynamic habitat use by Spotted (Clemmys guttata) and Blanding's Turtles (*Emydoidea blandingii*) in Maine. Journal of Herpetology 43: 636-645.

Beckage, B. B. Osborne, D. Gavin, C. Pucko, T. Siccama, and T. Perkins. 2008. A rapid upward shift of a forest ecotone during 40 years of warming in the Green Mountains of Vermont. PNAS 105: 4197–4202.

Belote, R., J. Weltzin, and R. Norby. 2003. Response of an understory plant community to elevated [CO2] depends on differential responses of dominant invasive species and is mediated by soil water availability. New Phytologist 161:827–835.

Beltaos, S, and B.C. Burrell. 2003. Climate Change and river ice breakup. Canadian Journal of Civil Engineering. 30:145-155.

Bertness, M. 1999. The Ecology of Atlantic Shorelines. Sinauer Associates, Inc. Sunderland, MA.

Both, C., S. Bouwhuis, C. Lessells, and M. Visser. 2006. Climate change and population declines in a long-distance migratory bird. Nature 441:81-83.

Breitenback, G. L., J. D. Congdon, and R. C. Sels. 1984. Winter temperatures of Chrysemys picta nests in Michigan: effects on hatchling survival. Herpetologica 40:76–81.

Brooks, R.T. 2009. Potential impacts of global climate change on the hydrology and ecology of ephemeral freshwater systems of the forests of the northeastern United States. Climatic Change 95:469–483.

Burke, M.J., and J.P. Grime. 1996. An experimental study of plant community invasibility. Ecology 77:776-790.

Burkett, V. and J. Kusler. 2000. Climate change: potential impacts and interactions in wetlands of the United States. Journal of the American Water Resources Association 36: 313-320.

Butler, R. and R. Vennesland. 2000. Integrating climate change and predation risk with wading bird conservation research in North America. Waterbirds 23: 523-540.

Calhoun, A.J.K. and P.G. deMaynadier (Editors). 2008. Science and Conservation of Vernal Pools in Northeastern North America. CRC Press, Boca Raton, FL. 363 pp.

Clark J. S. 1998. Why trees migrate so fast: confronting theory with dispersal biology and the paleorecord. American Naturalist 152: 204-224.

Clough, J. and E. Larson. 2008a. Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Moosehorn NWR. Prepared For: Dr. Brian Czech, US FWS, National Wildlife Refuge System, Arlington,VA. Warren Pinnacle Consulting, Inc. PO Box 253, Warren VT.

Clough, J. and E. Larson. 2008b. Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Rachel Carson NWR. Prepared For: Dr. Brian Czech, US FWS, National Wildlife Refuge System, Arlington,VA. Warren Pinnacle Consulting, Inc. PO Box 253, Warren VT.

Clough, J.S. and R.A. Park, 2007, Technical Documentation for SLAMM 5.0.1 February 2008, Jonathan S. Clough, Warren Pinnacle Consulting, Inc, Richard A. Park, Eco Modeling. http://warrenpinnacle.com/prof/SLAMM

Connelly, W., L. Kerr, E. Martino, A. Peer, R. Woodland, and D. Secor. 2007. Climate and Saltwater Sport Fisheries: Prognosis for Change. Report to the FishAmerica Foundation (FAF-6093R) University of Maryland Center for Environmental Science, Solomons, MD. Technical Report Series No. TS-537-07

Crick, H. 2004. The impact of climate change on birds. Ibis 146 (Suppl.1): 48–56.

Curry, R., B. Dickson, and I. Yashayaev. 2003. A change in the freshwater balance of the Atlantic Ocean over the past four decades. Nature 426:826-829.

Dale, V., L. Joyce, S. Mcnulty, R. Neilson, M. Ayres, M. Flannigan, P. Hanson, L. Irland, A. Lugo, C. Peterson, D. Simberloff, F. Swanson, B. Stocks, and B. Wotton. 2001. Climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. Bioscience 51:723-734.

Davies, T.J., A. Purvis, and J. Gittleman. 2009. Quaternary Climate Change and the Geographic Ranges of Mammals. Am. Nat. 174: 297–307.

Davis, R. and D. Anderson. 2001. Classification and distribution of Freshwater peatlands in Maine. Northeastern Naturalist 8:1-50.Davis, M. B., and R. G. Shaw. 2001. Range shifts and adaptive responses to quaternary climate change, Science 292: 673-679.

Dukes, J.S., and H.A. Mooney. 1999. Does global change increase the success of biological invaders? Trends in Ecology and Evolution 14: 135-139.

Durell, S., R. Stillman, R. Caldow, S. McGrorty, A. West, and J. Humphreys. 2006. Modeling the effect of environmental change on shorebirds: A case study on Poole Harbor, UK. Biological Conservation 131: 459-473.

Eaton, J.G., and R.M. Scheller. 1996. Effects of climate on fish thermal habitat in streams of the United States. Limnology and Oceanography 41:1109-1115.

Environment Canada. 2004. Threats to Water Availability in Canada. National Water Research Institute, Burlington, Ontario. NWRI Scientific Assessment Report Series No. 3 and ACSD Science Assessment Series No. 1. 128 p.

Erwin, R., G. Sanders, D. Prosser, and D. Cahoon. 2006. High tides and rising seas: potential effects on estuarine waterbirds. Studies in Avian Biology 32: Pages 214-228.

Fabry, V.J., B.A. Seibel, R.A. Feely, and J.C. Orr. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES Journal of Marine Science 65:414-432.

Feely, R., C. Sabine, K. Lee, W. Berelson, J. Kleypas, V. Fabry, and F. Millero. 2004. Impact of anthropogenic CO2 on the CaCO3 system in the oceans. Science 305: 362–6.

Foden, W., Mace, G., Vié, J.-C., Angulo, A., Butchart, S., DeVantier, L., Dublin, H., Gutsche, A., Stuart, S. and Turak, E. 2008. Species susceptibility to climate change impacts. In: J.-C. Vié, C. Hilton-Taylor and S.N. Stuart (eds). The 2008 Review of The IUCN Red List of Threatened Species. IUCN Gland, Switzerland.

Fortin, F. and J.-L. Pilote. 2008. Multidate mapping approach to determine alpine and subalpine vegetation variation on Mount Jacques Cartier, Quebec, eastern Canada (1973-2004). University of Moncton, Moncton, New Brunswick, Canada.

Frazer, N. B., J. L. Greene, and J. W. Gibbons. 1993. Temporal variation in growth rate and age at maturity of male painted turtles, Chrysemys picta. American Midland Nat. 130:314–324.

Frumhoff, P.C., J.J. McCarthy, J.M. Melillo, S.C. Moser, and D.J. Wuebbles. 2007. Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions. Synthesis report of the Northeast Climate Impacts Assessment (NECIA). Cambridge, MA: Union of Concerned Scientists (UCS).

Galbraith, H. R. Jones, R. Park, J. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2005. Global Climate Change and Sea Level Rise: Potential Losses of Intertidal Habitat for Shorebirds. USDA Forest Service Gen. Tech. Rep. PSW-GTR-191.

Gehrels, W., D. Belknap, S. Black, and R. Newnham. 2002. Rapid sea-level rise in the Gulf of Maine, USA, since AD 1800. The Holocene 12: 383 - 389.

Gorham, E., 1991. Northern Peatlands: Role in the Carbon Cycle and Probable Response to Climatic Warming. Ecological Applications 1: 182-195.

Graney, R., D. Cherry, J. Rodgers, Jr., and J. Caims, Jr. 1980. The influence of thermal discharges and substrate composition on the population structure and distribution of the Asian clam, *Corbicula fluminea*, in the New River, Virginia. The Nautilus 94: 130-35.

Greene, C., A. Pershing, T. Cronin, and N. Ceci. 2008. Arctic climate change and its impacts on the ecology of the North Atlantic. *Ecology* 89:S24-S38.

Harper, M. and B. Peckarsky. 2006. Emergence cues of a mayfly in a high-altitude stream Ecosystem: potential response to climate change. Ecological Applications 16: 612–621.

Hartig, E., V. Gornitz, A. Kolker, F. Mushacke, and D. Fallon. 2002. Anthropogenic and climate-change impacts on salt marshes of Jamaica Bay, New York City. Wetlands 22: 71–89.

Hayhoe, K., C.P. Wake, T.G. Huntington, L. Luo, M. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T. Troy, and D. Wolfe. 2007. Past and future changes in climate and hydrological indicators in the U.S. northeast. Climate Dynamics 28:381-407.

Hegland, S., A. Nielsen, A. La´ zaro, A.-L. Bjerknes, and O. Totland. 2009. How does climate warming affect plant-pollinator interactions? Ecology Letters 12: 184–195.

Herman, T. and F. Scott. 1994. Protected areas and global climate change: assessing the regional and or local vulnerability of vertebrate species. In: Pernetta, J.C., R. Leemans, D. Elder, and S. Humphrey (eds.). Impacts of Climate Change on Ecosystems and Species: Implications for Protected Areas. IUCN, Gland, Switzerland.

Horton, S. and K. McKenzie. 2009. Identifying Coastal Habitats at Risk from Climate Change Impacts in the Gulf of Maine. Climate Change Network, Gulf of Maine Council on the Marine Environment, 35 pp.

Hoving, C., D. Harrison, W. Krohn, R. Joseph, and M. O'Brien. 2005. Broad-scale predictors of Canada lynx occurrence in eastern North America. Journal of Wildlife Manage. 69: 739-751.
Hughes, J., G. Daily, and P. Ehrlich. 1997. Population diversity: Its extent and extinction. Science 278: 689-692.

Huntington, T. 2003. Climate warming could reduce runoff significantly in New England, USA. Agricultural and Forest Meteorology 117: 193–201.

Huntley, B., Y. Collingham, R. Green, G. Hilton, C Rahbek, and S. Willis. 2006. Potential impacts of climatic change upon geographical distributions of birds. Ibis 148:8-28.

Inkley, D. B., M. G. Anderson, A. R. Blaustein, V. R. Burkett, B. Felzer, B. Griffith, J. Price, and T. L. Root. 2004. Global climate change and wildlife in North America. Wildlife Society Technical Review 04-2. The Wildlife Society, Bethesda, Maryland, USA. 26 pp.

Irons, D.B. et al. 2007. Fluctuations in circumpolar seabird populations linked to climate oscillations. Global Change Biology 14: 1455 – 1463.

IPCC. 2002. Climate change and biodiversity. Gitay, H., R.T. Suarez, and O. Watson (Eds) Technical Paper V, IPCC Working Group II Technical Support Unit.

Iverson, L.R., A.M. Prasad, and S. Matthews. 2008a. Modelling potential climate impacts on trees of the northeastern United States. Mitigation and Adaptation Strategies for Global Change 13:487–516.

Iverson, L. R., A. M. Prasad, S. N. Matthews, and M. Peters. 2008b. Estimating potential habitat for 134 eastern US tree species under six climate scenarios. Forest Ecology and Management 254:390-406.

Iverson, L. R., A. M. Prasad, and M. W. Schwartz . 2005. Predicting potential changes in suitable habitat and distribution by 2100 for tree species of the eastern United States. Journal of Agricultural Meteorology 61:29-37.

Jacobson, G.L., I.J. Fernandez, P.A. Mayewski, and C.V. Schmitt (editors). 2009. Maine's Climate Future: An Initial Assessment. Orono, ME: University of Maine. Accessed online at: http://www.climatechange.umaine.edu/mainesclimatefuture/

Jacobson, H. and J. Kelly. 1987. Distribution and abundance of tidal marshes along the coast of Maine. Estuaries 10: 126-131.

Jurasinski, G. and J. Kreyling. 2007. Upward shift of alpine plants increases floristic similarity of mountain summits. Journal of Vegetation Science 18: 711-718

Kelly, M. and N. Adger. 2000. Theory and Practice in Assessing Vulnerability to Climate Change and Facilitating Adaptation. Climatic Change, 47: 325-352.

Kimball, K. 1997. New England Regional Climate Change Impacts on Recreation and Tourism. New England Regional Climate Change Impacts Workshop Summary Report, Sept. 3-5. pp. 129-131.

Kimball, K. and D. Weihrauch. 2000. Alpine vegetation communities and the alpine-treeline ecotone boundary in New England as biomonitors for climate change. In: S.F. McCool, D.N. Cole, W.T. Borrie, J. O'Loughlin (comps.). Wilderness science in a time of change conference—Volume 3: Wilderness as a place for scientific inquiry; 1999 May 23–27; Missoula, MT. Proceedings RMRS-P-15-VOL-3. Ogden, UT. USDA Forest Service, Rocky Mountain Research Station. p. 93-101

Krohn, W., K. Elowe, and R. Boone. 1995. Relations among fishers, snow, and martens: development and evaluation of two hypotheses. For. Chron. 71: 97-106.

Kunkel, K., H. Huang, X. Liang, J. Lin, D. Wuebbles, , Z. Tao, A. Williams, M. Caughey, J. Zhu, and K. Hayhoe. 2008. Sensitivity of future ozone concentrations in the Northeast U.S. to regional climate change. Mitigation and Adaptation Strategies for Global Change. 13: 597-606.

Kurihara, H., S. Shimode, and Y. Shirayama. 2004. Sub-lethal effects of elevated concentration of CO2 on planktonic copepods and sea urchins. Journal of Oceanography 60:743-750.

Lawler, J., T. Tear, C. Pyke, M. Shaw, P. Gonzalez, P. Kareiva, L. Hansen, L. Hannah, K. Klausmeyer, A. Aldous, C. Bienz, and S. Pearsall. 2010. Resource management in a changing and uncertain climate. Front Ecol Environ 8: 35-43.

Learmonth, J.A., Maclead, C.D., Santos, M.B., Pierce, G.J., Crick, H.Q.P., Robinson, R.A. 2006. Potential effects of climate change on marine mammals. Oceanography and Marine Biology: An Annual Review 44: 431-464.

Lesica, P. and B. McCune. 2004. Decline of arctic-alpine plants at the southern margin of their range following a decade of climatic warming. Journal of Vegetation Science 15:679-690.

Lee, T.D., J.P. Barrett, and B. Hartman. 2005. Elevation, substrate, and the potential for climate-induced tree migration in the White Mountains, New Hampshire, USA. Forest Ecology and Management 212: 75–91.

Lind, A. 2008. Amphibians and Reptiles and Climate Change. U.S. Department of Agriculture, Forest Service, Climate Change Resource Center. Accessed online on 1/2/09 at: http://www.fs.fed.us/ccrc/topics/amphibians-reptiles.shtml.

Logan, J.A., and K.W. Gottschalk. 2007. Climate change induced invasions by native and exotic pests, GTR NRS-P-10. St. Paul, MN: USDA Forest Service, Northern Research Station.

MacCrae, P.S. and D.A. Jackson. 2001. The influence of smallmouth bass (*Micropterus dolomieu*) predation and habitat complexity on the structure of littoral-zone fish assemblages. Canadian Journal of Fisheries and Aquatic Sciences 58: 157-170.

Mackenzie-Grieve, J. and J. Post.2006. Projected impacts of climate warming on production of lake trout (*Salvelinus namaycush*) in southern Yukon lakes. Canadian Journal of Fisheries and Aquatic Sciences 63: 788-790.

Malcolm, J. and A. Markham. 2000. Global warming and Terrestrial Biodiversity Decline. World Wildlife Fund, Gland, Switzerland.

Malcolm, J. D.Puric-Mladenovic and H.Shi. 2005. Projected tree distributions, tree migration rates, and forest types in Ontario under a 2°C global temperature rise. Pp. 52-99 in: T. Tin (ed.). Implications of a 2°C global temperature rise for Canada's natural resources. World Wide Fund For Nature, Gland, Switzerland.

McCarty, J.P. 2001. Ecological consequences of recent climate change. Conservation Biology 15:320-331.

McFarland, K. 2003. Conservation assessment of two endemic butterflies (White Mountain arctic, *Oeneis melissa semidea*, and White Mountain fritillary, *Boloria titania montinus*) in the Presidential Range alpine zone, White Mountains, New Hampshire. VT Institute of Natural Science, Woodstock, VT.

McKee, D., D. Atkinson, S. Collings, J. Eaton, A. Gill, I. Harvey, K. Hatton, T. Heyes, D. Wilson, and B. Moss. 2003. Response of freshwater microcosm communities to nutrients, fish, and elevated temperature during winter and summer. Limnol. Oceanogr. 48: 707–722.

McLachlan, J. S., J. S. Clark, and P. S. Manos. 2005. Molecular indicators of tree migration capacity under rapid climate change. Ecology 86:2088–2098.

McLaughlin, J. , J. Hellmann, C. Boggs, and P. Ehrlich. 2002. Climate change hastens population extinctions. Proceedings of the National Academy of Sciences (USA) 99:6070–6074.

Mieszkowska, N., Leaper, R., Moore, P., Kendall, M.A., Burrows, M.T., Lear, D., Poloczanska, E., Hiscock, K., Moschella, P.S., Thompson, R.C., Herbert, R.J., Laffoley, D., Baxter, J., Southward, A.J. and S. Hawkins. 2006. Marine biodiversity and climate change: assessing and predicting the influence of climatic change using intertidal rocky shore biota. Scottish Natural Heritage Commissioned Report No. 202.

Miller, N., and R. Spear. 1999. Late quaternary history of the alpine flora of the New Hampshire White Mountains. Géographie physique et Quaternaire 53(1):33.

Miller-Rushing, A. and R. B. Primack. 2008. Global warming and flowering times in Thoreau's Concord: a community perspective. Ecology 89: 332–341

Milller-Rushing, A, T. Lloyd-Evans, R. Primack, and P. Satzinger. 2008. Bird migration times, climate change, and changing population sizes. Global Change Biology 14:1959–1972.

Moore, M., M. Pace, J. Mather, P. Murdoch, R. Howarth, C. Folt, C. Chen, H. Hemond, P. Flebbe and C. Driscoll. 1997. Potential effects of climate change on freshwater ecosystems of the New England/Mid-Atlantic Region. Hydrological Processes : 925-947.

Murdoch, P., J. Baron, and T. Miller. 2000. Potential effects of climate change on surface-water quality in North America. Journal of The American Water Resources Association 36: 347-366.

Murray, D., E. Cox, W. Ballard, H. Whitlaw, M. Lenarz, T. Custer, T. Barnett, and T. Fuller. 2005. Pathogens, nutritional deficiency, and climate Influences on a declining moose population. Wildlife Monogr. 166: 1–30.

Musante, A., P. Pekins, and D. Scarpitti. 2007. Metabolic impacts of winter tick infestations on calf moose. Alces 43: 101-110.

Myer, J., M. Sale, M. MulHolland, and L. Poff. 1999. Imp acts of climate change on aquatic ecosystem functioning and health. Journal of the American Water Resources Association 35: 1373-1386.

Neilson, R. 1995. A model for predicting continental scale vegetation distribution and water balance. Ecological Applications. 5:362-385.

New Hampshire Fish and Game Department. 2005. New Hampshire State Wildlife Action Plan. Concord, NH.

Occhipinti-Ambrogi, A. 2007. Global change and marine communities: Alien species and climate change. Marine Pollution Bulletin 55: 342-352.

Ollinger, S., C. Goodale, K. Hayhoe, J. Jenkins. 2008. Potential effects of climate change and rising CO_2 on ecosystem processes in northeastern U.S. forests. Mitigation and Adaptation Strategies for Global Change 13: 467–485.

Orr, J., V. Fabry, O. Aumont, L. Bopp, S. Doney, R. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R. Najjar, G. Plattner, K. Rodgers, C.L. Sabine, J. Sarmiento, R. Schlitzer, R. Slater, I. Totterdell, M. Weirig, Y. Yamanaka, and A. Yool. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437: 681-686.

Paradis, A., J. Elkinton, K. Hayhoe, and J. Buonaccorsi. 2008. Effect of winter temperatures on the survival of hemlock woolly adelgid, *Adelges tsugae*, and the potential impact of global warming on its future range in eastern North America. Mitigation and Adaptation Strategies for Global Change. In press.

Parmesan, C., N. Ryrholm, C. Stefanescu, J. K. Hill, C. D. Thomas, H. Descimon, B. Huntley, L. Kaila, J. Kullberg, T. Tammaru, J. Tennent, J. A. Thomas, and M. Warren. 1999. Poleward shifts in geographical ranges of butterfly species associated with regional warming, Nature, 299, 579-583.

Parry, M.L., O.F. Canziani, J.P. Palutikof and Co-authors. 2007. 2007: Technical Summary. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, Pp.: 23-78.

Polgar, C., E. Ellwood, and R. Primack. 2009. Effect of temperature on spring emergence of butterflies: Implications of climate change altering insect phenology. Abstrcat, Ecological Society of America, Annual meeting, August 7 2009, Albuquerque, AZ.

Prasad, A., L. Iverson., S. Matthews, and M. Peters. 2007-ongoing. A Climate Change Atlas for 134 Forest Tree Species of the Eastern United States [database]. http://www.nrs.fs.fed.us/atlas/tree, Northern Research Station, USDA Forest Service, Delaware, Ohio.

Price, J. and T. Root. 2001. Climate change and Neotropical migrants. Transactions of the North American Wildlife and Natural Resources Conference 66: 371-379.

Prowse, T. and S. Beltaos. 2002. Climatic control of river-ice hydrology: a review. Hydrolog. Process. 16: 805-822.

Rahel, F. and J. Olden. 2008. Assessing the effects of climate change on aquatic invasive species. Conservation Biology 22: 521–533.

Rahmstorf, S., A. Cazenave, J. Church, J. Hansen, R. Keeling, D. Parker, and R. Somerville. 2007. Recent climate observations compared to projections. Science 316:709.

Rehfisch, M. and H. Crick. 2003. Predicting the impact of climatic change on Arctic-breeding waders. Wader Study Group Bulletin 100: 86-95.

Reynolds, L., M. Ayres, T. Siccama, and R. Holmes. 2007. Climatic effects on caterpillar fluctuations in northern hardwood forests. Canadian Journal of Forest Research 37: 481-491.

Richardson, A., A. Bailey, E. Denny, C. Martin, and J. O'Keefe. 2006. Phenology of a northern hardwood forest canopy. Global Change Biology 12: 1174-1178.

Rijnsdorp, A. D., M. Peck, G. Engelhard, C. Mollmann, and J. Pinnegar. 2009. Resolving the effect of climate change on fish populations. ICES Journal of Marine Science 66: 1570-1583.

Rodenhouse, N., S. Matthews, K. McFarland, J. Lambert, L. Iverson, A. Prasad. T. Sillett, and R. T. Holmes. 2008. Potential effects of climate change on birds of the Northeast. Mitigation and Adaptation Strategies for Global Change 13:517–540.

Rodenhouse, N., L. Christenson, D. Perry, and L. Green. 2009. Climate change effects on native fauna of northeastern forests. Canadian Journal of Forest Research 39: 249-263

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

Sabine, C., R. Feely, N. Gruber, R. Key, K. Lee, J. Bullister, R. Wanninkhof, C. Wong, D. Wallace, B. Tilbrook, F. Millero, T.-H. Peng, A. Kozyr, T. Ono, and A. Rios. 2004. The oceanic sink for anthropogenic CO_2. Science 305: 367-371.

Scheuhammer, A.M. and J.E. Graham. 1999. The bioaccumulation of mercury in aquatic organisms from two similar lakes with differing pH. Ecotoxicology 8: 49-56.

Schindler D. S. Baley, B. Parker, K. Beaty, D. Cruikshank, E. Fee, E. Schindler, and M. Stainton. 1996. The effects of climatic warming on the properties of boreal lakes and streams at the Experimental Lakes Area, northwestern Ontario. Limnology and Oceanography 41: 1004–1017.

Shuman, B., P. Newby, Y. Huang, and T. Webb III. 2004. Evidence for the close climatic control of New England vegetation history. Ecology 85: 1297–1310

Siegel, D., and P. Glaser. 2006. Potential effects of climate change on spring fens and their endangered floral species. Geological Society of America Abstracts 38: 328.

Slovinsky, P. and S. Dickson. 2008. 309-06b: Demonstration Project: Impacts of Future Sea Level Rise on the Coastal Floodplain. MGS Open-File 06-14. A report prepared by the ME Geological Survey for the ME Coastal Program/ME State Planning Office for National Oceanic and Atmospheric Administration. Augusta, ME.

Slovinsky, P. and S. Dickson. 2010. Assessment of LIDAR for Simulating Existing and Potential Future Marsh Conditions in Casco Bay. Casco Bay Estuary Partnership, Portland, ME; Maine Geological Survey, Department of Conservation, Augusta, ME.

Solomon, D. and W. Leak. 1994. Migration of tree species in New England based on elevational and regional analyses. U.S.D.A. Forest Service Research Paper NE-688.

Spear, R.W. 1989. Late-quaternary history of high-elevation vegetation in the White Mountains of New Hampshire. Ecological Monographs 59:125-151.

Spear, R.W., M. Davis, and L. Shane. 1994. Late quaternary history of low- and mid-elevational vegetation in the White Mountains of New Hampshire. Ecol. Monographs 64: 85-109.

Stachowicz, J., T. Terwin, and R. Whitlatch. 2002. Linking climate change and biological invasions: ocean warming facilitates nonindigenous species invasions. Proc. Natl. Acad. Sci. 99:15497-15500.

Stefan, H.G., X. Fang, and J.G. Eaton. 2001. Simulated fish habitat changes in North American lakes in response to projected climate warming. Trans. Amer. Fish. Soc. 130:459-477.

Stephenson, E.H., R.S. Steneck, and R.H. Seeley. 2009. Possible temperature limits to range expansion of non-native Asian shore crabs in Maine. Journal of Experimental Marine Biology and Ecology 375: 21-31.

Tang, G. and B.Beckage. 2010. Projecting the distribution of forests in New England in response to climate change. Diversity and Distributions 16:144-158.

Thomas, C., A. Cameron, R. Green, M. Bakkenes, L. Beaumont, Y. Collingham, B. Erasmus, M. Ferreira de Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A. van Jaarsveld, G. Midgley, L. Miles, L. Ortega-Huerta, A. Peterson, O. Phillips, and S. Williams. 2004. Extinction risk from climate change. Nature 427: 145–148.

U.S. Fish and Wildlife Service. 2009. Climate Change Adds Challenges to Freshwater Mussel Conservation. Fort Snelling, MN 9accessed on January 5 2010 at: http://www.fws.gov/midwest/climate/mussels.htm).

Van Guelpen, L. G.Pohle and G.Chmura. 2005. Impacts of Sea Surface Temperature Changes on Marine Species in the Northwest Atlantic. P. 22-51 in: T. Tin (ed.). Implications of a 2°C global temperature rise for Canada's natural resources. World Wide Fund For Nature, Gland, Switzerland

Vasseur, L.; N. Catto, D. Burton, O. Chouinard, J. Davies, L. DeBaie, G. Duclos, P. Duinker, D. Forbes, L. Hermanutz, J. Jacobs, L. Leger, K. McKenzie, K. Parlee, and J. Straatman. 2008. Atlantic Canada. In: D.S. Lemmen, F.J. Warren, J. Lacroix, and E. Bush (eds.). From Impacts to Adaptation: Canada in a Changing Climate 2007. Government of Canada, Ottawa, ON, p. 119-170.

Walther, G., E. Post, P. Convey, A. Menzel, C. Parmesan, T. Beebee, J. Fromentin et al. 2002. Ecological responses to recent climate change. Nature 416: 389–395.

Weltzin, J., J. Pastor, C. Harth, S. Bridgham, K. Updegraff, and C. Chapin. 2000. Response of bog and fen plant communities to warming and water table manipulations. Ecology 81:3464–3478.
Williams, J., A. Haak, N. Gillespie, H. Neville, and W. Colyer. 2007. Healing Troubled Waters Preparing Trout and Salmon Habitat for a Changing Climate. Trout Unlimited, Arlington, VA.

Winter, T. 2000. The vulnerability of wetlands to climate change: A hydrologic landscape perspective. Journal of the American Water Resources Association 36:305–311.

Wolfe, D., L. Ziska, C. Petzoldt, L. Chase, and K. Hayhoe. 2008. Projected change in climate thresholds in the Northeastern U.S.: Implications for crops, pests, livestock, and farmers. Mitigation and Adaptation Strategies for Global Change 13: 5-6.

Wormworth, J. and K. Mallon. 2006. Bird Species and Climate Change: The Global Status Report version 1.0 A report to: World Wide Fund for Nature, United Kingdom.

Ziska, L.H. and K. George. 2004. Rising carbon dioxide and invasive, noxious plants: Potential threats and consequences. World Resource Review. 16:427-447.

Zockler C. and Lysenko I. 2000. Water birds on the edge: First circumpolar assessment of climate change on Arctic-breeding water birds. United Nations Environment Programme & World Conservation Monitoring Centre. Available at: http://www.unep-wcmc.org/climate/waterbirds/report.pdf.

MANOMET Center for Conservation Sciences

Science at Work for a Sustainable World

Manomet's mission is to conserve natural resources for the benefit of wildlife and human populations. Through research and collaboration, Manomet builds science-based, cooperative solutions to improve sustainability.

Natural Capital, or ecosystem services, includes all goods and services that we get from nature, such as clean water and air, food, carbon, biodiversity, and wood products. The Natural Capital Initiative at Manomet is helping people conserve functional ecosystems to sustain the well-being, environment, and prosperity of current and future generations.