

Climate Change and Biodiversity in Maine: A Climate Change Exposure Summary for Species and Key Habitats (Revised)



Manomet Center for Conservation Sciences

Andrew Whitman¹

Barbara Vickery²

Phillip deMaynadier³

Sally Stockwell⁴

Steve Walker³

Andrew Cutko⁵

Robert Houston⁶

¹ Manomet Center for Conservation Sciences, Brunswick, ME

² The Nature Conservancy, Brunswick, ME

³ Maine Department of Inland Fisheries and Wildlife, Bangor, ME

⁴ Maine Audubon Society, Falmouth, ME

⁵ Maine Natural Areas Program, Augusta, ME

⁶ U.S. Fish and Wildlife Service, Falmouth, ME

March 28 2013



Contents

1	Executive Summary	
1	1. Key climate change projections to 2100	
1	2. Other stressors related to climate change	
1	3. Exposure of wildlife habitats and plant communities	
2	4. Exposure of species	
2	Preface	
3	Introduction	
4	Climate Change Projections	
5	Temperature	
5	Rainfall and Snow	
6	Extreme Storm Events	
6	Length of Growing Season	
6	Drought, Soil Moisture and Streamflow	
6	Atmospheric Changes	
7	Marine Conditions	
7	Sea-level Rise (SLR)	
7	Surface Sea Temperature	
8	Ocean Salinity	
8	Ocean Acidification	
8	Summary of Climate Change Projections	
9	Other Stressors Related to Climate Change	
9	Exotic Species, Pests, and Pathogens	
10	Human Impacts Prone to Increase with Climate Change	
12	Summary of Threat Level Posed by Other Stressors Related to Climate Change	
12	Exposure of Wildlife Habitats and Plant Communities to Climate Change	
13	Coastal Habitats	
15	Summary for Coastal and Estuarine Habitats	
15	Freshwater Wetland Habitats	
18	Summary for Freshwater Wetland Habitats	
18	Upland Habitats	
21	Summary for Upland Habitats	
22	Exposure of Animal Species Groups	
22	Invertebrates	
23	Fish	
24	Amphibians and Reptiles	
24	Birds	
26	Mammals	
26	Acknowledgements	
27	Literature Cited	

Recommended Citation: Whitman, A., B. Vickery, P. deMaynadier, S. Stockwell, S. Walker, A. Cutko, and R. Houston. 2013. Climate Change and Biodiversity in Maine: A Climate Change Exposure Summary for Species and Key Habitats (Revised). Manomet Center for Conservation Sciences (in collaboration with Maine Beginning with Habitat Climate Change Adaptation Working Group) Report NCI-2013-01. 29 pp. Brunswick, Maine. Available online at: www.manometmaine.org.



Tables

- 14** Table 1. Maine key coastal and estuarine habitats, their descriptions, dominant climate change stressors, and climate change exposure.
- 17** Table 2. Maine's key freshwater wetland habitats, their descriptions, dominant climate change stressors, and climate change exposure.
- 21** Table 3. Maine key upland habitats, their descriptions, dominant climate change stressors, and climate change exposure.

Figures

- 4** Fig. 1. The three climate zones in Maine: Northern, Southern Interior, and Coastal (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.
- 5** Fig 2. Seasonal temperature change projections for Northern (green), Southern Interior (pink), and Coastal Maine (purple; from Jacobson et al. 2009)(see Fig. 1 for a map describing the location of each region).
- 7** Fig. 3. Past and projected future sea level rise (SLR) for Maine. Past trends are from the National Oceanic and Atmospheric Administration (2009). Projected trends without SLR for Portland are from the National Oceanic and Atmospheric Administration (2009). Future projections with climate change are from IPCC (2002) and Rahmstorf et al. (2007).



Executive Summary

This summary briefly reviews climate change projections and the exposure of key 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 an information resource for assessing the climate change vulnerability of key wildlife habitats, plant communities, and species of greatest conservation need.

1. 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 temperature increases occurring in northern Maine and the smallest increases occurring 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 a 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 decline slightly under low-emission scenarios and up to 50% with high-emission scenarios.
- › The length of the growing season is projected to increase by one to two days per decade.
- › Sea level is predicted to increase 20 to 80 inches by 2100. Coastal sea water temperature is predicted to increase 6° to 10°F.
- › CO₂ concentrations in the air 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.

2. OTHER STRESSORS RELATED TO CLIMATE CHANGE

As climate changes, people in Maine and elsewhere will adapt in an unpredictable fashion that will impact biodiversity. There is some evidence that pressures from development, timber harvesting, agriculture, and recreation could increase significantly and impact biodiversity and our ability to conserve biodiversity in a changing climate.

3. EXPOSURE OF WILDLIFE HABITATS AND PLANT COMMUNITIES

Maine's Comprehensive Wildlife Conservation Strategy (ME CWCS) identifies 21 key habitats 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 unpredictable 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 areas. These habitats may be greatly affected by increases in air temperature, drought, and 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, species at the southern edge of their range, and marine invertebrates 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 (and chemical measures to control them), exotic plant species, and exotic marine species on plant communities and terrestrial, aquatic, coastal, and estuarine wildlife habitats may increase.

Preface

This report updates a previous version (Whitman et al. 2010) with information from 45 peer-reviewed science references from after 2010. Both reports were developed as reference documents to help biologists and conservationists understand the magnitude and range of threats posed by climate change to Maine's wildlife, plants, and habitats, as well as the uncertainty of these projections. It is challenging to summarize climate change projections for Maine's biodiversity. Though the future path of climate change mitigation remains as uncertain as it was three years ago, all likely paths lead to significant increases in temperature (Jacobson et al. 2009). Furthermore, ecosystem complexity will continue to limit our ability to confidently predict specific responses despite increases in scientific knowledge (Beckage et al. 2010). Quite a few of the projected impacts reported here may not happen, while many unanticipated impacts will occur. For the first version of this report, there was less scientific research to consult, climate change was removed from daily life, and so adaptation was harder to consider than it is now. With climbing temperatures and widely experienced extreme weather, the threat of climate change has become tangible. Adaptation is increasingly occurring across the U.S., whether it be crisis management (e.g., aftermath of Hurricane Irene in Vermont) or proactive (e.g., City of Keene, NH; Beirbaum et al. 2012). Nonetheless, our challenge will be to use information like that reported here to create and apply adaptation strategies and practices that are cost effective yet robust to a wide range of possible impacts. Andrew Whitman



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). Global temperatures are rapidly increasing and are on track to reach within $\approx 1^\circ\text{C}$ of the maximum temperature of the past million years (Hansen et al. 2006). 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, flooding events) are occurring now (Staudinger et al. 2012, Parry et al. 2007, Root et al. 2003).

We know from modeling and 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 (Staudinger et al. 2012, Hughes et al. 1997). Species and ecosystems are projected to soon experience climatic conditions unlike any in the last one million years (Hansen et al. 2006). A recent study estimated that 15-37% of endemic species worldwide 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). Unless GHG emissions decline, climate change is inevitable (Arnell et al. 2013). Hence, many ecological impacts of climate change are now inescapable.

Climate plays a major role in determining plant and animal communities (Jacobson et al. 2009). Hence, 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, and amplifying pest and disease outbreaks (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, Hobbs et al. 2009). Increasing climate change knowledge among Maine's conservation biologists is an essential first step if they are to select and deploy new conservation strategies.

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, McCarty 2001). This report summarizes climate change exposure impacts to key species and major habitats using information derived from regional climate projections.

The original report was developed to assist experts conducting a vulnerability assessment of wildlife species of greatest conservation need (SGCN), state-listed Threatened or Endangered plant species, wildlife habitats, and plant communities in Maine. It has been revised to include new information that became available after 2010. It does not assess the potential expansion of 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 wildlife habitats and plant communities, and (3) a review of predicted climate change exposure for Maine's SGCN animal species.



Climate Change Projections

This section summarizes climate change projections for Maine from Jacobson et al. (2009) and Frumhoff et al. (2007) and highlights recent (<150 years) climate trends. 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.

Projections from Jacobson et al. (2009) are based on the Special Report on Emission Scenario A1B (Meehl et al. 2007). This scenario results in a CO₂ concentration of about 700 parts per million (ppm) by the end of the 21st century (current concentration is 387 ppm). It is widely believed to be a moderate emissions scenario and assumes a high level of economic growth, with moderate population growth, and a significant increase in renewable energy use.

Projections from Frumhoff et al. (2007) used IPCC's A1fi and B1 scenarios to represent possible higher- and lower-emissions scenarios, respectively, over the next century. The A1fi scenario represents a world with fossil fuel-intensive economic growth and human populations that peak mid-century, then decline, with atmospheric CO₂ concentrations reaching 940 ppm by 2100 (more than triple pre-industrial levels). The B1 scenario also represents high economic growth and a population that peaks mid-century. However, this scenario assumes a faster reduction in fossil fuel use, with CO₂ emissions peaking mid-century then declining below present-day emissions levels by 2100 and atmospheric CO₂ concentrations reaching 550 ppm by 2100 (about double pre-industrial levels). *Over the last two decades, increases in GHG emissions have tracked high emissions scenarios. The recent trends for biophysical variables associated with climate change are highlighted in italics in the following sections. Most but not all of these trends are consistent with climate change projections.*

Maine's climate has had a major role in determining the distribution of animal and plant species in Maine (Jacobson et al. 2009). There are three major climate zones in Maine (Fig. 1): the Northern zone has a continental climate with cold winters and is influenced by air masses from the west and north; the Southern Interior zone has the warmest summer weather and is influenced by air masses from the south and west; and the Coastal zone has a maritime climate which moderates summer and winter extreme temperatures and is influenced by air masses from the west and south. These three distinct zones will likely persist with climate change (Jacobson et al. 2009).



Fig. 1. The three climate zones in Maine: Northern, Southern Interior, and Coastal (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.

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). By 2100, average temperatures are projected to increase 3° to 14°F in winter and 3° to 11°F in summer. Like other northern regions, Maine will experience greater temperature increases than regions at more southern latitudes (Burrows et al.2010). *Increases in temperature in the last two decades are tracking high emissions scenarios (Jacobson et al.2009).*

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). From 1960, summer stormflows have increased 5% to 50%, which has increased overall summer precipitation levels by 5% to 20% in Maine, but summer base flows have declined by 5% to 20% over much of Maine (Hodgkins and Dudley 2011). *The ratio of snow to precipitation for sites in New England has declined, which parallels increasing winter temperature (Huntington et al. 2004).* If low-emissions scenarios prevail, Maine could retain much of its snow season—between two and four weeks of snow cover per winter month—but the length of Maine’s snow season could still decline by 25%. If a high-emissions scenario prevails, by 2050 the length of Maine’s snow season could decline by 50%. 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 lower winter peaks of rapid runoff. A transition between regimes could include greater ice movement and scouring throughout the winter (Dudley et al.2012). *In the last 50 years, 18 of 23 snow sampling sites in and near Maine had reductions in snowpack depth or increases in snowpack density, changes that are also consistent with increasing temperatures (Hodgkins and Dudley 2006).* Hodgkins et al. (2002) also noted reductions in ice cover in New England. *Spring ice-out (when lake ice cover ends) records between 1850 and 2000 indicate that ice out occurs nine days earlier for lakes in northern and mountainous regions, and 16 days for lakes in more southerly regions. These changes were related to warmer air temperatures.*

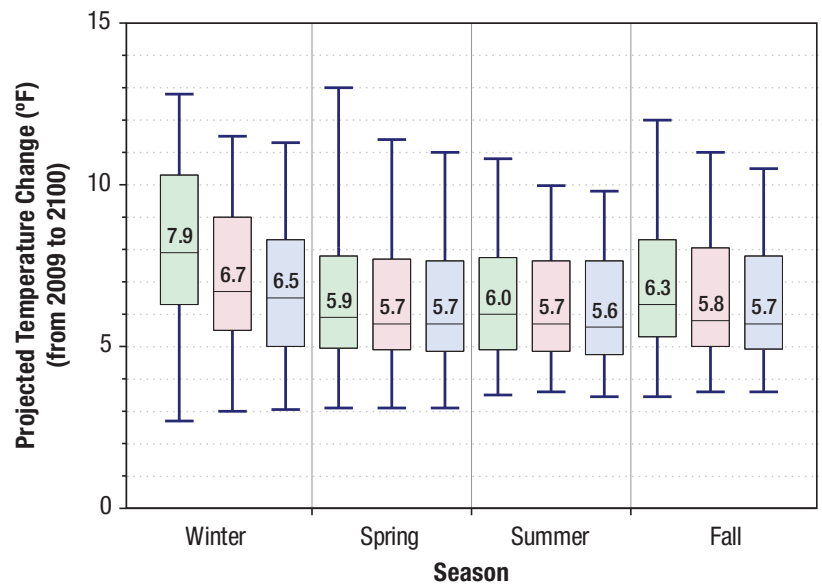


Fig 2. Seasonal temperature change projections for Northern (green), Southern Interior (pink), and Coastal Maine (purple; from Jacobson et al. 2009) (see Fig. 1 for a map describing the location of each region).

Extreme Storm Events

The frequency and severity of heavy precipitation 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 a >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 by 2100 (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). *The evidence for an increase in the frequency, intensity, or duration of extreme weather events like hurricanes is mixed and remains uncertain (Huntington 2010). The frequency of intense rain or snowstorms has nearly doubled since 1948 (Madsen and Willcox 2012).*

Length of Growing Season

The interval between first and last frost dates and length of growing season are projected to increase by one to two days per decade in response to increased air temperature (Hayhoe et al. 2007). *Since the 1960s, first-bloom dates have advanced four days for lilacs and six to eight days for apples, and grapes have advanced four days (Wake and Markham 2005). Bloom dates at Harvard University's Arnold Arboretum have advanced an average of eight days earlier from 1980 to 2002 compared with 1900 to 1920 (Primack et al. 2004).*

Drought, Soil Moisture and Streamflow

Projections about soil moisture and drought are less certain than temperature projections because summer precipitation projections could remain unchanged, decline, or increase and because other hard-to-predict factors like cloud cover would affect soil moisture. Warming will likely result in less snow, earlier melting of snow, more winter rainfall, and more rain-on-snow events (Taylor et al. 2013), which may reduce the seasonal duration and volume of groundwater recharge. Groundwater levels may peak earlier in the spring, have longer and lower base flow periods, and lower stream base flows in summer (Taylor et al. 2013). Moreover, projected temperature increases combined with most projections of less summer precipitation could result in greater evapotranspiration levels; hence, average late-summer levels of soil moisture are projected to decline, increasing 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). *On rural, unregulated rivers in New England, where snowmelt dominates the annual hydrological cycle, there has been a trend of earlier snowmelt runoff with most runoff occurring one to two weeks earlier, with most of the change happening in the last 30 years (Hodgkins et al. 2003). The timing and number of low-flow events that typically occur toward the end of summer are good indicators of stream flow, water supply, and drought and these have not significantly changed in the past 100 years in the Northeast (Hodgkins et al. 2005).*

Atmospheric Changes

CO₂ – GHG emissions are predicted to have two ecologically significant effects on atmospheric gases. The greatest impact is that CO₂ concentrations may double or triple. Greater CO₂ concentrations make it easier for plants to absorb CO₂; 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). Therefore, 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 CO₂ levels and other species do not. *Trends in atmospheric CO₂ concentrations measured at Mauna Loa show a consistent increase over the last 40 years (Tans and Keeling 2012).*



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, coastal areas will be affected the most (Kunkell et al. 2008). *A recent study of ground ozone levels and temperatures from the last 20 years in the eastern U.S. found a corresponding increase of 1.2 parts per billion (ppb) in ozone pollution for every one degree (°F) of warming (Bloomer et al. 2009).*

Marine Conditions

SEA-LEVEL RISE (SLR)

Global warming is projected to raise sea levels by causing ocean water to expand as it warms and by melting ice on land (Schaeffer et al. 2012). If high-emissions scenarios prevail, the minimum global sea level rise is projected to be 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) could easily exceed five times this estimate, i.e., 20 to 80 inches by 2100 (Schaeffer et al. 2012, National Research Council 2010a, Vermeer and Rahmstorf 2009, Rahmstorf et al. 2007). Intermediate projections range about 20 inches to 3½ feet, though high projections go to almost 7 feet (Burkett and Davidson 2012).

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" and accompanying storm surge and flooding of coastal habitats are projected to occur every two to five years (Frumhoff et al. 2007, Tebaldi et al. 2012). SLR will be greater than we anticipated in the previous document (Whitman et al. 2010). *Relative sea level has risen over the last 50 years at a rate of about 2 mm/yr at tidal gauge stations in Portland, Bar Harbor, and Eastport (National Oceanic and Atmospheric Administration 2009).*

SURFACE SEA TEMPERATURE

By 2100, regional sea surface temperatures are projected to rise 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). *Sea surface temperatures off Boothbay Harbor increased by 1° F over the last century (Frumhoff et al. 2006). Over the last 100 years, the rate of increase of coastal sea surface temperatures (SST) in the Gulf of Maine has followed the global mean SST of about 0.7°C (Shearman and Lentz 2010). The rate of increase has accelerated in recent years with sea surface temperatures increasing by about 0.23°C from 1982 to 2006, close to twice the global rate of warming over this period (0.13°C) (Belkin 2009). The velocity of climate change from 1960-2009 was 20-100 km/decade for the region, with spring temperatures advancing by 2-10 days/decade (Burrows et al. 2011).*

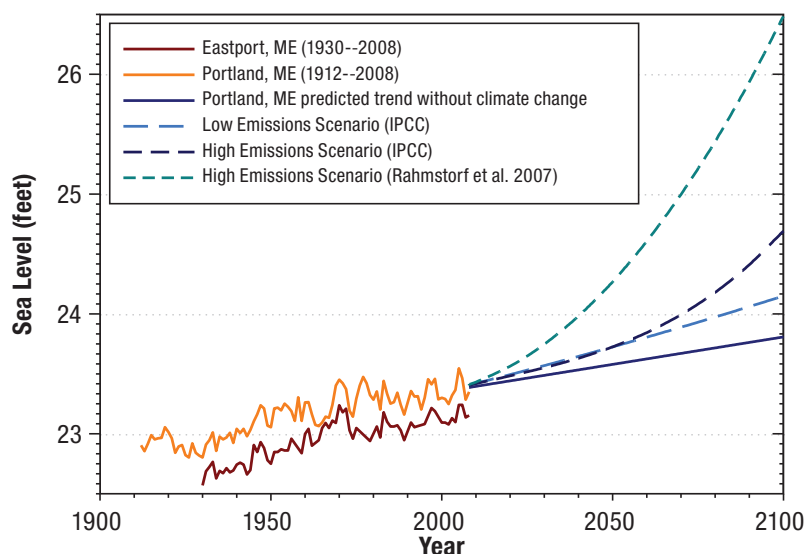


Fig. 3. Past and projected future sea level rise (SLR) for Maine. Past trends are from the National Oceanic and Atmospheric Administration (2009). Projected trends without SLR for Portland are from the National Oceanic and Atmospheric Administration (2009). Future projections with climate change are from IPCC (2002) and Rahmstorf et al. (2007).



OCEAN SALINITY

The salinity of the Gulf of Maine (GOM) 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 (OA) is the acidification of sea water by the absorption of CO₂. The ocean absorbs about one-third of current global CO₂ emissions (Sabine et al. 2004). When CO₂ combines with sea water, it lowers its pH, making the ocean more acidic (Feely et al. 2004). If this trend continues unabated, OA 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 OA may reduce the concentration of CaCO₃ (calcium 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 OA before tropical ecosystems because CaCO₃ levels are much lower at high latitudes than in tropical areas (Farby et al. 2008). Although many coastal marine systems experience large diurnal fluctuations and typically have CO₂ levels higher than equilibrium levels with the atmosphere (Andersson and Mackenzie 2012), even robust intertidal species may not be able to withstand impacts of warming and acidification (Byrne 2011). *The acidity of sea water across the globe has increased significantly by 30% since the beginning of the Industrial Revolution 250 years ago (Doney et al. 2009).*

Summary of Climate Change Projections

By 2100, average temperatures are projected to increase 3° to 14°F in winter and 3° to 11°F in summer. Maine is projected to experience an overall 2% to 14% increase in precipitation. The frequency and severity of heavy rainfall precipitation events is projected to increase. The interval between first and last frost dates and length of growing season are projected to increase by one to two days per decade. Projections about soil moisture and drought are less certain than temperature projections because summer precipitation projections are uncertain, though most projections could reduce soil moisture and increase the frequency of drought. CO₂ levels are projected to increase with rising emissions and lead to greater ozone levels at ground level. Sea level is projected to increase, as are sea water surface temperature and acidity levels. *Recent trends for most of these variables have been consistent with climate change projections, with the exception of projected trends for drought frequency.*



Photo by MNAP

Other Stressors Related to Climate Change

While climate change may pose a major threat to Maine's biodiversity, its interactions and synergisms with other related stressors and human activities could magnify the impacts of climate change and the threats to biodiversity (Driscoll et al. 2012).

Exotic Species, Pests, and Pathogens

Together with escalating global trade, tourism, and habitat loss, climate change is likely to greatly accelerate the rate and extent of biological invasions around the world (Walther et al. 2009). Moreover, climate change will challenge our perception of exotic species, pests, and pathogens. Some exotic species, pests, and pathogens may diminish in impact, while impacts of others intensify, and previously non-invasive taxa will become invasive as native species alter their distribution as a result of climate change (Walther et al. 2009). The growing trend in the large volume of plants being grown overseas for planting or retail sale in the U.S. is very likely to increase invasions by non-native forest insects and pathogens (Liebhold et al. 2012).

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 coastal areas beyond Penobscot Bay where mean summer temperatures <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 squirt 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 marine species in New England (Stachowicz et al. 2002).

Aquatic Invasive Species – Climate change may increase the spread of aquatic invasive species by (1) lessening cold temperatures that limit establishment, (2) eliminating winter hypoxia that limits survival, (3) enhancing their competitive and predatory effects on native species, and (4) increasing the disease virulence (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 (Staudinger et al. 2012). 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, becoming 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). Spruce budworm (*Choristoneura fumiferana*) outbreaks may increase in duration but not change in intensity (Gray 2008).

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 CO₂ levels (Belote et al. 2003). Computer modeling studies suggest that oriental bittersweet (*Celastrus orbiculatus*) might invade parts of northern New England (Dukes et al. 2009). The distribution of many invasive plant species currently limited by cold temperatures will likely expand due to increasing temperatures (Garamszegi 2011 and Dukes et al. 2009).

Emerging Diseases and Shifting Disease Vectors – Climate change may increase the threat posed by plant and animal pathogens. For example, the susceptibility of tree species to widespread *Armillaria* spp. might increase, as higher winter temperatures and increased drought and other stressors will allow *Armillaria* to remain active for much of the year (Dukes et al. 2009). Beech bark cankering by *Nectria* spp. and mortality in American beech (*Fagus grandifolia*) in northern Maine was worse following mild winters, dry autumns, and widespread drought (Kasson and Livingston 2011). For wildlife, climate change will increase or reduce the range of diseases or increase animal stress and their susceptibility to disease (Stenning 2010, Harvell et al. 2009). The global prevalence of the avian malaria (*Plasmodium* spp.) has been increasing at an accelerated rate and strongly associated with climate change trends (Garamszegi 2011). As a result of climate warming, infectious diseases might be an emerging threat to biodiversity as the increasing occurrence and impacts of diseases may be linked to temperature (Harvell et al. 2009, Rohr and Raffel 2010). Vector-borne diseases will generally become more common as the earth warms (Lindsay et al. 2010).

Human Impacts Prone to Increase with Climate Change

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 for development and the productivity of its forest and farm lands due to longer growing seasons and high CO₂ levels could increase. As climate changes, people in Maine and elsewhere will adapt in an unpredictable fashion that will impact biodiversity. Although highly uncertain, there is some evidence that pressures from development, timber harvesting, agriculture, and recreation could increase significantly and impact biodiversity and our ability to conserve biodiversity in a changing climate.

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 by armoring with seawalls and other hard structures (Thorne et al. 2012). Unfortunately, this may exacerbate erosion, inundation, and loss of beach and salt marsh habitats. Further, in areas where there is development immediately inland and above current high tides, natural inland “migration” of coastal wetlands will be impeded. More frequent flooding of riparian areas may create pressures for inland armoring that could be detrimental to freshwater species (e.g., Hastie et al. 2003).

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 (Staudinger et al. 2012). 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 interior forest 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 reduce mature forest habitats and threaten some northern forest species while benefiting many early-succession species currently at risk (Klopfer 2010). However, an increase in forest carbon offset projects might benefit some forest species by reducing harvest intensity slightly and increasing longer-rotation forestry and the extent of the mature forest age class. Timber harvesting in the U.S. to 2030 is projected to significantly increase as climate change increases U.S. timber productivity, global demands increase, and global forests decline (FAO 2012). The climate change-related projected increase of pest outbreaks, storms and associated wind throw, drought, and fire may increase large-scale tree mortality and the extent and impact of salvage logging operations (Driscoll et al. 2012).

Development and Habitat Fragmentation – The greatest threats are along the Maine coast where most of the population lives and where growth rates have recently exceeded 1% per year in southern Maine communities. Without considering climate change, the current projections suggest that 149,300 acres will be developed for housing in Maine by 2030 (White et al. 2009). As temperatures increase in the eastern U.S., Maine's climate will remain comparatively cooler and ameliorated by a maritime effect. Settled coastal areas south of Maine will experience both SLR and storm surges that likely will lead to large outflows of people to other regions of the U.S. (Curtis and Schneider 2011). However, Maine is likely to become increasingly attractive for U.S. residents facing heat or storm-battered coastlines elsewhere ("climate migrants"; Backus et al. 2012). The human population of Maine's Mid-coast region is projected to grow 5 to 10% (Crossett et al. 2004). Globally, 200 million to 1 billion people may become displaced due to environmental impacts of climate change (Myers 2005). Maine has already experienced an influx of climate migrants from Somalia, southern Sudan, and the Democratic Republic of Congo where changes in weather have contributed to local conflicts and displaced people, and where climate change impacts are projected to be very high compared to other regions (Busby et al. 2011). Hence, residential development, especially along coastal and inland water bodies, may expand, thereby fragmenting previously intact terrestrial and riparian habitats, increasing the area of impervious surfaces and increasing eutrophication (Bierwagen et al. 2010).

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) and a 5% to 15% regional rise in agricultural productivity (Cline 2007), an increased demand for food due to climate change-related crop failures elsewhere could lead to an expansion of agriculture in Maine, as well as other areas worldwide (e.g., Bradley et al. 2012). With climate change and a subsequent expansion of agriculture in north temperate areas, the intensity of agriculture, including the use of pesticides, may increase risk to aquatic and other species (Kattwinkel et al. 2011).

Water Resources Management – Although water is generally abundant in Maine, increasing human demand from southern Maine to Boston for water may lead to expanded water withdrawals in southern Maine. Water districts in southern Maine are considering the possibility of drawing water from Sebago Lake. Coupled with some climate change projections of reduced precipitation and runoff, increased municipal withdrawals may alter water levels and hydrology of watersheds and threaten freshwater ecosystems and their species (Driscoll et al. 2012). The projected increase in extreme precipitation events may increase municipal sewer overflow into freshwater bodies where communities have combined storm water and sewer and reduce water quality of downstream estuaries (Colgan and Merrill 2008). As increased periods of drought become more frequent, the impacts may be less intense in urbanized watersheds where reductions in stream flows might be less than reductions in non-urban watersheds (Viger et al. 2011).

Wildfire – Climate change may increase ignition, dryness, and the probability and extent of fire in some regions of Maine. Climate change may bring an increase in lightning strikes and blocking high pressure ridges which rapidly dry forest fuels. Modeled predictions suggest that fire severity due to changing weather conditions may increase overall 10% to 20% for the Northeast (Flannigan et al. 2000, 2009). These increases might accelerate late in the century (Mortiz et al. 2012). Although summer season fire risk is projected to greatly increase due to changing weather conditions (Lui et al. 2010), spring and fall fire risk, especially for northeastern deciduous



forests, may also increase (Drever et al. 2009). Under a range of models and emissions scenarios, probability and extent of northern hardwood forest burned in nearby Quebec was projected to range from a slight increase to five-fold increase (Drever et al. 2009). Fire in broad-leaved forests could increase if weather conditions lead to long, warm periods before leaf out or after leaf fall.

Summary of Threat Level Posed by Other Stressors Related to Climate Change

The chief threats posed by other stressors in synergy with climate change are coastal and estuarine invasive species as ocean waters increase, terrestrial pest species that expand with temperature increases, armoring in response to SLR, and development and habitat fragmentation as human populations expand in Maine due to pressures exerted by climate change elsewhere. IN this analysis, the threat level posed by other stressors is low because climate change may not amplify the size of threat, the certainty of the amplification by climate change is low, or both.

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). However, the equatorial, or trailing, range boundaries of many terrestrial species may not shift consistently towards the poles with climate warming because other factors may limit southern range limits for many species (Sunday et al. 2012).

Species will react differently to climate change depending on their life-history characteristics, individual thresholds and sensitivity to climate (Walther et al. 2002). The shifting distributions of species due to climate change will vary as their sensitivity to key climate variables and to other factors often vary among species (Clark et al. 2011). Disjunct species may share ranges and habitats in the future and co-occurring species may become geographically separated. This will partially breakdown existing natural communities and result in the development of new species assemblages (Williams and Jackson 2007). Response will likely also vary across trophic levels (Voigt et al. 2003, Winder and Schindler 2004) and may fundamentally change species interactions and lead to changes that cascade through ecosystems. The impacts of this reshuffling are unclear, either for species that now co-occur together or for ecosystem services provided by these natural communities (National Research Council 2010b). The complexity of these processes may defy our ability to predict their outcomes (Beckage et al. 2011).

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 changes in their 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), other tree species may take >100 years to begin to colonize significant portions of new habitat (Iverson et al. 2005). Plant species are at risk of not keeping up with climate change.

At more northern latitudes such as Maine, most mammal species (and perhaps other vertebrate species) may have sufficiently fast dispersal velocities to keep in step with these large changes (Schloss et al. 2012). However, Maine's future species may be migrating from southern regions (e.g., the Virginias), many of which may have slower dispersal velocities and must migrate through fragmented landscapes. These factors may impede their ability to keep up with climate change and delay their arrival in Maine.

There are 20 different key habitats identified in Maine's Comprehensive Wildlife Conservation Strategy covering all of Maine's coastal, freshwater wetland, and upland ecosystems (Maine Department of Inland Fisheries and Wildlife 2005). They vary in the types and levels of exposure to climate change, described in detail below.

Coastal Habitats

Maine's coast includes 3,478 miles of coastline. Although Maine's shores are largely rocky, it has extensive bays and estuaries. Maine has 75 miles of beaches, mostly in southern Maine, and about half of which are sand beaches and half of which are rock and pebble beaches. Maine has about 20,000 ac (79 km²) of salt marsh, more than any other New England state (Jacobson et al. 1987). Its marine systems are greatly influenced by the Labrador Current, a body of cold water emanating from the North Atlantic. This nutrient-rich water is highly productive when it mixes with warm water from Maine's rivers. Coastal and estuarine habitats will be exposed to all climate change stressors, including SLR, changes in water temperature, salinity, pH, and seasonal patterns of precipitation and runoff. These changes may alter hydrologic and chemical characteristics of coastal ecosystems and affect species composition and ecosystem productivity. Shoreline processes may cause land well above one meter to erode (Gutierrez et al. 2009), sediment accretion may enable wetlands to remain at sea level (Kirwan et al. 2010), and shore armoring might to maintain land that would otherwise be claimed by the sea (Titus et al. 2009).

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 that 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, turbidity, and eutrophication 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). Episodic estuarine eutrophication already occurs at the mouths of the Androscoggin River (Bricker et al. 2007) and Saco River (Sanger et al. 2002) and in the Wells Inlet (Sanger et al. 2002). Hypoxia, coupled with ocean acidification, may result in very high CO₂ levels when eutrophication occurs (Melzner et al. 2012). However, summer runoff declines could reduce estuarine eutrophication (Horton and McKenzie 2009a). With ocean acidification, seagrass beds may be the only marine habitat to potentially benefit from rising seawater ocean CO₂ (Palacios et al. 2007). In experiments with the eelgrass (*Zostera marina*), eelgrass biomass and reproductive output increased under high CO₂ conditions.

Rocky Coastline and Islands – Rocky coast and island habitats may have little exposure to climate change except where SLR reduces their extent (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 will increase severe erosion and shoreline retreat through the next century (Ashton et al. 2008). Increased intensities of tropical storms in the summer and fall and increased frequency of tropical storms in the fall and winter, further exacerbated by SLR, would result in more frequent, destructive storm surges along the coast (Chai et al. 2009).

Estuarine Emergent Salt Marsh – 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 by the end of the century, 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. The peat-based marshes of Maine are unlikely to keep up with sea level rise due to low accretion and sediment inputs (Gedan et al. 2011). 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), as is the case in Casco Bay where 20% of the shoreline is armored (Kelley and Dickson 2000).

Table 1. Maine key coastal and estuarine habitats, their descriptions, dominant climate change stressors, and climate change exposure.

KEY HABITAT AND DESCRIPTIONS	DOMINANT CLIMATE CHANGE STRESSORS	ESTIMATE OF CLIMATE CHANGE EXPOSURE
Marine Open Water – watered marine areas.	Sea temp. increase/decrease, ocean acidification	High
Estuaries and Bays – sub-tidal estuarine channels and tidal aquatic beds.	SLR, sea temp. increase, ocean acidification	Medium
Rocky Coastline and Islands – areas adjacent to water where ledge, gravel, rock, boulders, bedrock, or stones predominate.	SLR, sea temp. increase, ocean acidification	Medium
Unconsolidated Shore (beaches & mudflats) – dunes, flats, beaches with vegetation, sand, mud, or gravel.	SLR, sea temp. increase, ocean acidification	High
Estuarine Emergent Salt Marsh – estuarine/intertidal waters with emergent, herbaceous (non-woody) vegetation.	SLR, sea temp. increase, ocean acidification	High



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 (SLAMM¹; Clough and Larson 2008a). They projected SLR to result in large declines of brackish marsh, tidal swamp, and 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 two-foot SLR. Slovinsky and Dickson (2010) projected a >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 resistance 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. Rising temperature will increase evapotranspiration, soil drying, and productivity, which will favor the dominance of marsh graminoids at the expense of forb species, which are projected to become much more rare (Gedan and Bertness 2009). 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 have high exposure to SLR (Frumhoff et al. 2007).

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.

Freshwater Wetland Habitats

Freshwater wetlands account for about 30% of the surface area of Maine. These 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-periods 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



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



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 riparian-associated wetlands to extended dry periods and disrupted hydrology (Frumhoff et al. 2007). As a result, ephemeral and low-order streams and their fauna may 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, Wet Meadows, and Vernal Pools – 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. 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 and rare outwash plain pond shores by shortening effective hydroperiods (Brooks 2009). 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 hydroperiods with potential negative impacts to higher value vernal pools that are generally inundated for moderate to long periods (Babbitt et al. 2003, Baldwin et al. 2006). In addition, precipitation events could occur less frequently but more intensely and droughts could become more frequent and longer, causing pools (chiefly smaller pools) to repeatedly dry and re-flood. This could also have negative impacts on some specialized amphibians and invertebrates whose life cycles are closely tied to inundation patterns.

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 groundwater 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 groundwater levels will fall as evapotranspiration increases with temperature, unless offset by an increase in summer precipitation (Moore et al. 1997; Myer et al. 1999). If the hydraulic head in the recharge areas providing the groundwater 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). 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.

Table 2. Maine's key freshwater wetland habitats, their descriptions, dominant climate change stressors, and climate change exposure.

KEY HABITATS AND DESCRIPTIONS	DOMINANT CLIMATE CHANGE STRESSORS	ESTIMATE OF CLIMATE CHANGE EXPOSURE
Rivers & Streams – Fresh, flowing water.	Water temp. increase, drought, peak of high-flow levels shifting from spring to winter	High
Freshwater Lakes & Ponds – Permanently flooded freshwater bodies without emergent vegetation.	Water temp. increase, drought, peak of high-water levels shifting from spring to winter	High
Emergent Marsh, Wet Meadows & Vernal Pools – Fresh, shallow wetlands & water bodies with emergent, herbaceous vegetation & wet meadows dominated by grasses & sedges.	Drought, peak of high-water levels shifting from spring to winter	Medium
Shrub-scrub Wetlands – Fresh, shallow wetlands & water bodies with short woody vegetation.	Drought, peak of high-water levels shifting from spring to winter	Medium
Peatlands – Vegetation dominated by mosses, ericaceous shrubs, or sedges.	Water temp. increase, drought, peak of high-water levels shifting from spring to winter	High
Forested Wetlands – Fresh, shallow wetlands & water bodies with tall woody vegetation or dead, standing trees.	Drought, peak of high-flow levels shifting from spring to winter	Medium

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).



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.

Upland Habitats

Maine's forests cover more than 17 million acres, making it the most heavily forested state in the U.S. They span a transition from temperate oak forests in southern Maine to the boreal spruce-fir forests in the north (Barbour and Billings 1988). Climate-induced forest die-off from drought and heat stress has occurred across the globe and is expected to increase with climate change (Anderegg et al. 2012). Forest ecosystems and other upland habitats will be exposed to increasing temperatures, drought, pest impacts, exotic species, and CO₂ fertilization due to climate change. Increases in growing season length (earlier spring and later autumn) will increase evapotranspiration and likely increase drought frequency. In turn, an increase in the frequency of drought will likely increase the risk of fire and negatively impact forest productivity. A longer growing season will also increase calcium uptake and leaching, and depletion (Huntington et al. 2009).

Climate change, especially extreme events such as drought or related fire, could trigger steady or abrupt vegetation shifts when these events induce widespread tree mortality, or no vegetation shifts when climate-related mortality is low and competition is the dominant, organizing force in an upland community (Lloret et al. 2012). Paleo-climate studies of lake sediments indicate that moisture regime could determine the composition of Maine's forests through fire. More frequent droughts could range from low to high in intensity and duration and lead to increased tree mortality in sensitive species (e.g., *Fagus grandifolia*). In northern hardwood and spruce-fir forests, the impact of droughts could increase greatly when preceded by winters where snow cover is inadequate (<25 cm) and intense cold spells occur and make root systems more vulnerable to root kill (Auclair et al. 2010). Large trees may be more vulnerable to stress imposed by climate change than other size classes (Auclair et al. 2010, Mérian and Lebourgeois 2011), which might increase the vulnerability of late-successional forests. Paradoxically, an increase in forest disturbance would increase the number of disturbed sites and might facilitate the migration and the replacement of native trees by southern tree species (Flannigan et al. 2001).



It is unclear how forest communities will respond to climate change. Although there is the potential for large climate-driven range shifts in forest species and types by 2100 (Iverson et al. 2008a), species shifts are not expected to keep up with the rate of climate change, and will likely be delayed (Mohan et al. 2009). Although one Vermont study indicated upslope movement of forest communities (Beckage et al. 2008), local (Solomon and Leak 1994) and regional studies (Zhu et al. 2012) suggest a lack of forest tree species migration response to climate change in the last 40 years. Competition may be the dominant structuring force for tree communities

in forests (Zhu et al. 2012), so climate change impacts may have to be large to result in changes in regional distributions of tree species. Some tree species may take >100 years before they begin to colonize significant portions of new habitat (Iverson et al. 2005). Therefore, many present and future forest communities may be composed of plant species with migration rates far below those required to track contemporary climate change (Zhu et al. 2012).

Deciduous and Mixed Forest – Forests in the Northeast are predicted to significantly change in the next 100 years under every emissions scenario (Rustad et al. 2012, 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 and a longer growing season, potential CO₂-driven increases in photosynthesis and water-use efficiency, and changes in the nitrogen (N) cycle which increase N availability and plant productivity (Butler et al. 2012). If CO₂ 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 woolly 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). Because drought has already been linked to mortality of American beech (*Fagus grandifolia*; Kasson and Livingston 2011), this species and the forest types that it dominates might be at greater risk if climate change results in more frequent drought. Several northern tree species, including sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*), and ash spp. (*Fraxinus spp.*), have had periods of decline or reduced productivity in the past 100 years (Mohan et al. 2009).

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, and oak species (*Quercus spp.*) (Shuman et al. 2004). During past warm/dry periods, they were dominated by oak species and hickory species (*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 CO₂ levels may moderate regional declines of boreal forest due to climate change (Tang and Beckage 2010). Increased CO₂ levels can increase water use efficiency and rates of net canopy CO₂ 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*) would decline after 2050. Under the lowest emissions scenario, Maine and the Northern Forest region are predicted to lose much of their spruce-fir forest, 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. Because spruce species (*Picea spp.*) persisted in coastal refugia sites where the cold water Labrador current moderated climate change during a warming interval in about 4,000 B.P. (Schauffler and Jacobson 2002), these species might persist along the coast in Hancock and Washington Counties

Coastal and interior forests dominated by Eastern hemlock will likely decline under a low-emissions scenario due to the spread of hemlock woolly adelgid, recently established in south-coastal Maine, and could be largely eliminated from the state under a high emissions scenario (Paradis et al. 2008).



Dry Woodlands and Barrens – These habitats may be vulnerable to increased drought and invasion by exotic plant species due to 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 did 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 appears 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 CO₂ 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 years before present (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 by 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 Katahdin may be lost (Kimball 1997). The persistence of alpine communities in the Northeast during a warming period ~5,000 year BP (Miller and Spear 1999) 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 CO₂ 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 cause these habitats to expand.

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.

SUMMARY FOR UPLAND HABITATS

Terrestrial habitats are exposed primarily to air temperature changes, drought, pests, exotic species, and CO₂ 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 key upland habitats, their descriptions, dominant climate change stressors, and climate change exposure.

KEY HABITATS AND DESCRIPTIONS	DOMINANT CLIMATE CHANGE STRESSORS	ESTIMATE OF CLIMATE CHANGE EXPOSURE
Deciduous and Mixed Forest – Forests with >75% canopy closure, deciduous or coniferous & deciduous trees. » Northern hardwood types » Oak-dominated types	Air temp. increase, drought, pest impacts, exotic species, CO ₂ fertilization	Moderate (overall) » Moderate » Low
Coniferous Forest – Forest with >75% canopy closure composed of > 75% coniferous trees. » Spruce-fir types » Hemlock-dominated types » Pine types	Air temp. increase, drought, pest impacts, exotic species, CO ₂ fertilization	Moderate (overall) » Moderate » Moderate » Low
Dry Woodlands and Barrens – Pitch pine / scrub oak woodlands and barrens	Air temp. increase, drought, pest impacts	Low
Mountaintop forest (including krummholz) – Forested areas above 3,000 ft.	Air temp. increase, drought, pest impacts	High
Alpine – Mountain zones between the tree line.	Air temp. increase, CO ₂ fertilization	High
Shrub / Early Successional & Regenerating Forest – Areas dominated by woody shrubs and/or harvested before 1991 with seedling to sapling-sized trees; forestland where >50% of the overstory has been removed.	Air temp. increase, drought, exotic species	Low
Grassland, Agricultural, Old Field – Abandoned agricultural fields, blueberry barrens, crop fields, bare ground, grasslands (fields, pastures, lawns, golf courses).	Drought, exotic species	Low
Urban / Suburban – Areas where percent cover by buildings, roads, and other impervious surfaces is greater than vegetative cover.	Drought, exotic species, pest impacts	Low?
Cliff Face & Rocky Outcrops (including talus) – Exposed bedrock, talus, bare mountain tops, gravel pits.	Air temp. increase, drought	Moderate
Caves and Mines – Documented bat hibernacula.	Peak of high-flow conditions in winter?	Low



Exposure of 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). OA 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 and populations (Fabry et al. 2008). It can greatly increase the toxicity of contaminants in marine sediment to marine species (Roberts et al. 2013). It also can be made worse in estuarine and coastal waters by eutrophication (Howarth et al. 2011). Declines in pH in some estuaries are already capable of causing “death by dissolution” in juvenile bivalves (Green et al. 2009). A recent meta-analysis of OA experiments suggests that calcification for only one functional group, the bivalves, might be significantly suppressed across the range of partial pressures of CO₂ in the ocean (pCO₂) anticipated for the 21st century (Hendriks et al. 2010). High-emissions scenarios could reduce the reproduction of copepods (class: Copepoda) and sea urchins (Kurihara et al. 2004), keystone species in Maine's marine systems that can profoundly affect the structure and composition of marine ecosystems. 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 temperatures will reduce their reproductive output and/or survival rates (Mieszkowska et al. 2006).

At least one specialized non-marine, coastal invertebrate, the rare salt marsh tiger beetle (*Cicindela marginata*), is restricted to back dunes and mudflats where it is likely vulnerable to sea level rise and marsh migration.

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 and 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 (U.S. 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°F (1°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 some specialized alpine invertebrates in New England (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).

Additionally, several rare boreal butterflies and dragonflies (order: Odonata) reach the southern edge of their range in Maine's northern peatlands and fens, habitats that are at high exposure to predicted climate change impacts (Hunter et al. 2009; Table 2).

Fish

Marine and Anadromous 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, range shifts have been observed for many pelagic fish species (Rijnsdorp et al. 2009). Projections for pollock (*Pollachius spp.*), haddock (*Melanogrammus aeglefinus*), and Atlantic cod (*Gadus morhua*) indicate substantial declines in this region by 2090 based on changes in temperature and salinity (Lenoir et al. 2010). The risk of a mismatch between the distributions of diadromous predator species and their prey is likely to increase with climate change (Schweiger and Settele 2008). Climate change may also increase the severity of floods and droughts and reduce the frequency of successful annual reproduction for anadromous fishes (Limburg and Waldman 2009). If the peak spring migration of juvenile salmon (*Salmo salar*) from rivers, which is determined by photoperiod, temperature, and flow levels, becomes out of synchrony with optimal conditions in rivers, estuaries, or the ocean, salmon mortality could increase greatly (McCormick et al. 1998).

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 increase the frequency of damaging floods and ice flows that scour streambeds, causing 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 low 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 O₂ 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).



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 hydroperiods 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.

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. Finally, red-eared sliders (*Trachemys scripta elegans*), a popular pet trade turtle that has been widely introduced into northeastern water bodies, is likely to become more successful in southern Maine's ponds and lakes as climate change moderates the potential for over-winter mortality.

Birds

Seabirds – Seabirds may be vulnerable to reductions in prey due to climate change (Irons et al. 2007). Recent survival and reproduction of seabirds has been negatively correlated with warming temperatures across the globe (Sydeman et al. 2012). Seabirds with large clutch sizes respond the most to climate variability because the ratio of maximum clutch size to smallest clutch is large and reflects the size of potential reproductive differences in good and bad years (Sandvik et al. 2012). 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).



Photo by Dr. G. Hill

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) and other salt marsh species (Gardali et al. 2012). The southern range boundary of the Rusty Blackbird (*Euphagus carolinus*), a northern wetland species, has shifted northward by an average of about 143 km since 1966, perhaps in part due to climate change impacts on the abundance of wetland invertebrates, its food supply (McClure et al. 2012).

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 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 (Ahola 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 mismatching (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 (Miller-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 (e.g., passerines, Both et al. 2006; boreal breeding ducks, Drever et al. 2012). There is evidence that such trophic mismatches may be a major cause for population declines in long-distance European migrants in highly seasonal habitats (Both et al. 2010).



Mammals

At northern latitudes such as Maine's, many mammal species may be able to keep in step with climate changes (Schloss et al. 2012). However, Maine's future mammal species will likely come from southern regions (e.g., the Virginias) where mammal species have slower dispersal velocities and will have to migrate through fragmented landscapes. Some of these species will likely not keep pace and so their arrival could be delayed, including: rodents (Order: Rodentia) and shrews (Order: Eulipotyphla) (Schloss et al. 2012. Ungulates (Order: Artiodactyla), Carnivores (Order: Carnivora), possums (Order: Didelphimorphia), and rabbits and hares, (Order: Lagomorpha) are likely to keep pace (Schloss et al. 2012).

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 – Large scale variation in climate has already been shown to be responsible for significant annual fluctuations in north temperate mammal populations (Post and Stenseth 1998). 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 (Rodenhause et al. 2009), with potentially negative consequences for bat populations in Maine.



Photo by C. Raimond

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. With climate change, suitable habitat for Canada lynx is projected to decline and possibly result in their extirpation from Maine while suitable habitat for pine marten may be sufficient to retain this species to 2100 (Carroll 2007).

Acknowledgements

Funding for producing this document was provided by the Maine Outdoor Heritage Fund through the Maine Department of Inland Fish and Wildlife, the Dorr Foundation, and Manomet Center for Conservation Sciences. The following Manomet staff made many improvements to this report: Hector Galbraith, Julie Beane, John Gunn, Jennie Robbins, and Ethel Wilkerson.



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. Lehtikoinen 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.
- Anderegg, W.R., J.Kane, L. Anderegg. 2012. Consequences of widespread tree mortality triggered by drought and temperature stress. *Nature Climate Change* 2: 1758-6798.
- Andersson, A. and F. Mackenzie. 2012. Revisiting four scientific debates in ocean acidification research. *Biogeosciences* 9: 893–905.
- Arnell, N., J. Lowe, S. Brown, N. Gosling, P. Gottschalk, J. Hinkel, B. Lloyd-Hughes, R. Nicholls, T. Osborn, T. Osborne, G. Rose, P. Smith, and R. Warren. 2013. A global assessment of the effects of climate policy on the impacts of climate change. *Nature Climate Change* 1758-6798 <http://dx.doi.org/10.1038/nclimate1793>.
- 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.
- Auclair, A., W. Heilman, and B. Brinkman. 2010. Predicting forest dieback in Maine, USA: a simple model based on soil frost and drought. *Can. J. For. Res.* 40: 687–702.
- Babbitt, K.J., M.J. Baber, and T.L. Tarr. 2003. Patterns of larval amphibian distribution along a wetland hydroperiod gradient. *Canadian Journal of Zoology* 81: 1539-1552.
- Backus, G., T. Lowry, and D. Warren. 2012. The near-term risk of climate uncertainty among the US states. *Climatic Change* 116: 1-28.
- Baldwin, R.F., A.J.K. Calhoun, and P.G. deMaynadier. 2006. The Significance of Hydroperiod and Stand Maturity for Pool-breeding Amphibians in Forested Landscapes. *Canadian Journal of Zoology* 84: 1604-1615.
- Barbour, M. and W. Billings. 1988. North American Terrestrial Vegetation. Cambridge Univ. Press, Cambridge, UK.
- 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., L. J. Gross, and S. Kauffman. 2011. The limits to prediction in ecological systems. *Ecosphere* 2:125.
- 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.
- Belkin, I.M. 2009. Rapid warming of Large Marine Ecosystems. *Progress in Oceanography* 81: 207-213.
- 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.
- Bierwagen, B., D. Theobald, C. Pyke, A. Choate, P. Groth, J. Thomas, and P. Morefield. 2010. National housing and impervious surface scenarios for integrated climate impact assessments *PNAS* 2010 ; doi:10.1073/pnas.1002096107
- Bierbaum, R., J. Smith, A. Lee, M. Blair, L. Carter, F. Chapin, and L. Verduzco. 2012. A comprehensive review of climate adaptation in the United States: more than before, but less than needed. *Mitigation and Adaptation Strategies for Global Change*, 1-46.
- Bloomer, B.J., J.W. Stehr, C.A. Piety, R.J. Salawitch, and R.R. Dickerson. 2009. Observed relationships of ozone air pollution with temperature and emissions. *Geophysical Research Letters* 36(9):L09803.
- 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.
- Both, C., C. Van Turnhout, R. Bijlsma, H. Siepel, A. Van Strien, and R. Foppen. 2010. Avian population consequences of climate change are most severe for long-distance migrants in seasonal habitats. *Proceedings of the Royal Society* 277: 1259-1266.
- Bradley, B.A., D.M. Blumenthal, D.S. Wilcove, and L.H. Ziska. 2010. Predicting plant invasions in an era of global change. *Trends Ecol. Evol.* 25: 310–318.
- Bradley, B., L. Estes, D. Hole, S. Holness, M. Oppenheimer, W. Turner, H. Beukes, R. Schulze, M. Tadross, and D. Wilcove. 2012. Predicting how adaptation to climate change could affect ecological conservation: secondary impacts of shifting agricultural suitability. *Diversity and Distributions*. doi: 10.1111/j.1472-4642.2011.00875.x.



- 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.
- Bricker, S., B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks, and J. Woerner. 2007. Effects of Nutrient Enrichment In the Nation's Estuaries: A Decade of Change. NOAA Coastal Ocean Program Decision Analysis Series No. 26. National Centers for Coastal Ocean Science, Silver Spring, MD. 328 pp.
- 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.
- Burkett, V. and M. Davidson [Eds.]. 2012. Coastal Impacts, Adaptation and Vulnerability: A Technical Input to the 2012 National Climate Assessment. Cooperative Report to the 2013 National Climate Assessment., pp. 150. NOAA, Washington, DC.
- Burrows, M., D. Schoeman, L. Buckley, P. Moore, E. Poloczanska, K. Brander, C. Brown, J. Bruno, C. Duarte, B. Halpern, J. Holding, C. Kappel, W. Kiessling, M. O'Connor, J. Pandolfi, C. Parmesan, F. Schwing, W. Sydeman, and A. Richardson. 2011. The pace of shifting climate in marine and terrestrial ecosystems. *Science* 334: 652–655.
- Busby, J.W., J. Gullledge, T. Smith, K. White. 2011. Of Climate Change and Crystal Balls: The Future Consequences of Climate Change in Africa. University of Texas, Austin, TX. LBJ School of Public Affairs. Paper prepared for presentation at the American Political Science Association Annual Conference, Seattle, WA September 1–4th, 2011.
- Butler, R. and R. Vennesland. 2000. Integrating climate change and predation risk with wading bird conservation research in North America. *Waterbirds* 23: 523–540.
- Butler, S., J. Melillo, J. Johnson, J. Mohan, P. Steudler, H. Lux, E. Burrows, R. Smith, C. Vario, L. Scott, T. Hill, N. Aponte, and F. Bowles. 2012. Soil warming alters nitrogen cycling in a New England forest: implications for ecosystem function and structure. *Oecologia* 168: 819–828.
- Byrne, M. 2011. Impact of ocean warming and ocean acidification on marine invertebrate life history stages: vulnerabilities and potential persistence in a changing ocean. *Oceanogr Mar Biol* 49: 1–42.
- 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.
- Carroll, C. 2007. Interacting Effects of Climate Change, Landscape Conversion, and Harvest on Carnivore Populations at the Range Margin: Marten and Lynx in the Northern Appalachians. *Conservation Biology* 21: 1092–1104.
- Chai, F., P. Anderson, J. Kelly, L. Incze, A. Pershing, and R. Steneck. 2009. Initial Assessment of Climate Change in Maine. In: 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.
- Clark J. S. 1998. Why trees migrate so fast: confronting theory with dispersal biology and the paleorecord. *American Naturalist* 152: 204–224.
- Clark, J.S., D.M. Bell, M.H. Hersh, and L. Nichols. 2011. Climate change vulnerability of forest biodiversity: climate and competition tracking of demographic rates. *Global Change Biology* 17: 1834–1849.
- Cline, W.R. 2007. Global Warming and Agriculture: Impact Estimates by Country. Peterson Institute Press, Peterson Institute for International Economics, Number 4037, November 2007.
- 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>.
- Colgan, C.S. and S.B. Merrill. 2008. The Effects of Climate Change on Economic Activity in Maine: Coastal York County Case Study. *Maine Policy Review* 17(2).
- 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.
- Crossett, K., T. Culliton, P. Wiley, and T. Goodspeed. 2004. Population Trends Along the Coastal United States: 1980–2008. National Oceanic and Atmospheric Administration. National Ocean Service, Management and Budget Office. Dept. of Commerce, Washington, DC.
- 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.
- Curtis, K. and A. Schneider. 2011. Understanding the demographic implications of climate change: estimates of localized population predictions under future scenarios of sea-level rise. *Population and Environment* 33: 28–54.
- 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.
- Doney, S., W. Balch, V. Fabry, and R. Feely. 2009. Ocean acidification: a critical emerging problem for ocean sciences. *Oceanography* 22:16-25.
- Drever, M.C., R.G. Clark, C. Derksen, S.M. Slattery, P. Toose, and T.D. Nudds. 2012. Population vulnerability to climate change linked to timing of breeding in boreal ducks. *Global Change Biology*, 18: 480–492.
- Drever, C.R., Y. Bergeron, M.C. Drever, M. Flannigan, T. Logan, and C. Messier. 2009. Effects of climate on occurrence and size of large fires in a northern hardwood landscape: historical trends, future predictions, and implications for climate change in Témiscamingue, Québec. *Applied Vegetation Science* 12:261-272.
- Driscoll, D.A., A. Felton, P. Gibbons, A.M. Felton, N.T. Munro, and D.B. Lindenmayer. 2012. Priorities in policy and management when existing biodiversity stressors interact with climate-change. *Climatic Change* 111:533–557.
- Dudley, R.W., L.E. Hay, S.L. Markstrom, and G.A. Hodgkins. 2012. Watershed scale response to climate change—Cathance Stream Basin, Maine: U.S. Geological Survey Fact Sheet 2011–3128, 6 p.
- 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.
- Dukes, J., J. Pontius, D. Orwig, J. Garnas, V. Rodgers, N. Brazee, B. Cooke, K. Theoharides, E. Stange, R. Harrington, J. Ehrenfeld, J. Gurevitch, M. Lerdau, K. Stinson, R. Wick, and M Ayres. 2009. Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? *Canadian Journal of Forest Research*. 39: 231-248.
- 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.
- FAO. 2012. The North American Forest Sector Outlook Study – 2006-2030. Geneva Timber And Forest Study Paper 29. Food and Agriculture Organization, Rome, Italy.
- 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.
- Flannigan, M.D., M.A. Krawchuk, W.J. de Groot, B.M. Wotton and L.M. Gowman. 2009. Implications of changing climate for global wildland fire. *International Journal of Wildland Fire*. 18: 483-507.
- Flannigan, M.D., B.J. Stocks, and B.M. Wotton. 2000. Forest fires and climate change. *Science of the Total Environment* 262: 221-230.
- Flannigan, M., I. Campbell, M. Wotton, C. Carcaillet, P. Richard, and Y. Bergeron. 2001. Future fire in Canada's boreal forest: paleoecology results and general circulation model-regional climate model simulations. *Can. J. For. Res.* 31: 854-864.
- Foden, W., G. Mace, J.-C. Vié, A. Angulo, S. Butchart, L. DeVantier, H. Dublin, A. Gutsche, S. Stuart and E. Turak. 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.
- Fogarty, M., L. Incze, K. Hayhoe, D. Mountain, and J. Manning. 2007. Potential climate change impacts on Atlantic cod (*Gadus morhua*) off the northeastern USA. *Mitigation and Adaptation Strategies for Global Change* 13: 453-466.
- 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.
- Garamszegi, L. 2011. Climate change increases the risk of malaria in birds. *Global Change Biology* 17: 1751–1759.
- Gardali T., Seavy NE, DiGaudio RT, Comrack LA (2012) A Climate Change Vulnerability Assessment of California's At-Risk Birds. *PLoS ONE* 7(3): e29507. doi:10.1371/journal.pone.0029507.



- Gedan, K.B., and M.D. Bertness. 2009. Experimental warming causes rapid loss of plant diversity in New England salt marshes. *Ecological Letters* 12:842–848.
- Gedan, K.B., A.H. Altieri, and M.D. Bertness. 2011. Uncertain future of New England salt marshes. *Marine Ecology Progress Series* 434: 229–237.
- 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. Cairns, 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.
- Gray, D.R. 2008. The relationship between climate and outbreak characteristics of the spruce budworm in eastern Canada. *Clim. Change*, 87: 361–383.
- Green, M., G. Waldbusser, S. Reilly SL, et al. 2009. Death by dissolution: sediment saturation state as a mortality factor for juvenile bivalves. *Limnol Oceanogr* 54: 1037–47.
- 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.
- Groffman, P., L. Rustad, P. Templer, J. Campbell, L. Christenson, N. Lany, and N. Rodenhouse. 2012. Long-Term integrated studies show complex and surprising effects of climate change in the northern hardwood forest. *BioScience* 62: 1056–1066.
- Gutierrez, B., N. Plant, and E. Thieler. 2011. A Bayesian network to predict coastal vulnerability to sea level rise. *Journal of Geophysical Research* 116: F02009.
- Hansen, J., M. Sato, R. Ruedy, K. Lo, D.W. Lea, and M. Medina-Elizade, 2006: Global temperature change. *Proc. Natl. Acad. Sci.* 103: 14288–14293.
- 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.
- Harvell, D., S. Altizer, I.M. Cattadori, L. Harrington, and E. Weil. 2009. Climate change and wildlife diseases: when does the host matter the most? *Ecology* 90: 912–920.
- Hastie, L., P. Cosgrove, N. Elli, and M. Gaywood 2003. The threat of climate change to freshwater pearl mussel populations. *Ambio* 32: 40–46.
- 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.
- Hendriks, I., Duarte, C., and Álvarez, M. 2010. Vulnerability of marine biodiversity to ocean acidification: A meta-analysis. *Estuarine, Coastal and Shelf Science*, 86(2), 157–164.
- 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. Hobbs, R., E. Higgs, and J. Harris. 2009. Novel ecosystems: implications for conservation and restoration. *Trends in Ecology and Evolution* 24: 599–605.
- Hodgkins, G., and R. Dudley. 2011. Historical summer base flow and stormflow trends for New England rivers. *Water Resour. Res.*, 47 W07528, doi:10.1029/2010WR009109.
- Hodgkins, G., R. Dudley, and T. Huntington. 2003. Changes in the timing of high river flows in New England over the 20th century. *Journal of Hydrology* 278:244–252.
- Hodgkins, G., R. Dudley, and T. Huntington. 2005. Summer low flows in New England over the 20th century. *American Water Resources Association Journal* 41:403–412.
- 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.
- Howarth, R., F. Chan, D. Conley, J. Garnier, S. Doney, R. Marino, and G. Billen. 2011. Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. *Front Ecol Environ* 9:18–26.
- Hughes, J., G. Daily, and P. Ehrlich. 1997. Population diversity: Its extent and extinction. *Science* 278: 689–692.
- Hunter, M.L., C. Burns, P. deMaynadier, L. Incze, W. Krohn, P. Vaux, and B. Vickery. 2009. Biodiversity. Pages 30–33 in Jacobson, G.L., I.J. Fernandez, P.A. Mayewski, and C.V. Schmitt (editors). *Maine's climate future: An initial assessment*. University of Maine, Orono, Maine. 70 pp.
- Huntington, T. 2003. Climate warming could reduce runoff significantly in New England, USA. *Agricultural and Forest Meteorology* 117: 193–201.

- Huntington, T.G. 2010. Climate warming-induced intensification of the hydrologic cycle: A review of the published record and assessment of the potential impacts on agriculture. *Advances in Agronomy* 109: 1-53.
- Huntington, T.G., G.A. Hodgkins, B.D. Keim, and R.W. Dudley. 2004. Changes in the proportion of precipitation occurring as snow in New England (1949 to 2000). *Journal of Climate* 17:2626–2636.
- Huntington, T. G., A.D. Richardson, K.J. McGuire, and K. Hayhoe. 2009. Climate and hydrological changes in the northeastern United States: recent trends and implications for forested and aquatic ecosystems. *Canadian Journal of Forest Research* 39: 199-212.
- 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.
- 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.
- Irons, D.B. et al. 2007. Fluctuations in circumpolar seabird populations linked to climate oscillations. *Global Change Biology* 14: 1455–1463.
- 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/mainescimatefuture/>
- 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.
- Kasson, M.T. and W.H. Livingston. 2011. Relationships among beech bark disease, climate, radial growth response and mortality of American beech in northern Maine, USA. *For. Path.* doi: 10.1111/j.1439-0329.2011.00742.x
- Kelley, J.T., and S.M. Dickson. 2000. Low-cost bluff-stability mapping in coastal Maine: providing geological hazard information without alarming the public. *Env Geosci* 7:46–56.
- Kelly, M. and N. Adger. 2000. Theory and Practice in Assessing Vulnerability to Climate Change and Facilitating Adaptation. *Climatic Change*, 47: 325-352.
- Kasson, M. and W. Livingston. 2011. Relationships among beech bark disease, climate, radial growth response and mortality of American beech in northern Maine, USA. *Forest Pathology* 42: 52–56.
- Kattwinkel, Mira, Jan-Valentin Kühne, Kaarina Foit, and Matthias Liess. 2011. Climate change, agricultural insecticide exposure, and risk for freshwater communities. *Ecological Applications* 21:2068–2081.
- 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.
- Kirwan, M., G. Guntenspergen, A. D'Alpaos, J. Morris, S. Mudd, and S. Temmerman. 2010. Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters* 37: L23401.
- Klopfer, S.D. 2010. Final Report: Establishing a Regional Initiative for Biomass Energy Development for Early-Succession SGCN in the Northeast. A final report for USFWS Regional Conservation Need Grants Program. Conservation Management Institute at Virginia Tech, College of Natural Resources and Environment, Charlottesville, VA.
- 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., C. Maclead, M. Santos, G. Pierce, H. Crick, and R. Robinson. 2006. Potential effects of climate change on marine mammals. *Oceanography and Marine Biology: An Annual Review* 44: 431-464.
- 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.



- Lenoir, S., G. Beaugrand, and A. Lecuyer. 2010. Modeled spatial distribution of marine fish and projected modifications in the North Atlantic Ocean. *Global Change Biology* 17: 115-129.
- 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.
- Liebold, A.M., E.G. Brockerhoff, L.J. Garrett, J.L. Parke, and K.O. Britton. 2012. Live plant imports: the major pathway for forest insect and pathogen invasions of the U.S. *Frontiers Ecol. Environ.* 10: 135-143.
- Limburg, K. and J. Waldman. 2009. Dramatic Declines in North Atlantic Diadromous Fishes. *BioScience* 59:955-965. 2009.
- 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>.
- Lloret, F., A. Escudero J. Iriondo, J. Nezvalta, and F. Valladares. 2012. Extreme climatic events and vegetation: the role of stabilizing processes. *Global Change Biology* 18: 797-805.
- 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.
- Lui, Y., J.A. Stanturf, and S.L. Goodrick. 2010. Trends in global wildfire potential in a changing climate. *Forest Ecology and Management* 259: 685-697.
- 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.
- Madsen, T. and N. Willcox. 2012. When It Rains, It Pours: Global Warming and the Increase in Extreme Precipitation from 1948 to 2011. Environment America Research & Policy Center. Boston, MA.
- Maine Department of Inland Fisheries and Wildlife. 2005. Maine's comprehensive wildlife conservation strategy. Maine Department of Inland Fisheries and Wildlife. Augusta, Maine.
- 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.
- McClure, C., B. Rolek, K. McDonald, and G. Hill. 2012. Climate change and the decline of a once common bird. *Ecol. Evol.* 2: 370-378.
- McCormick, S., L. Hansen, T. Quinn, and R. Smith. 1998. Movement, migration, and smolting of Atlantic salmon (*Salmo salar*). *Canadian Journal of Fisheries and Aquatic Science* 55 (Suppl. 1): 77-92.
- 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.
- Meehi, G., T. Stocker, W. Collins, P. Friedlingstein, A. Gaye, J. Gregory, A. Kitoh, R. Knutti, J. Murphy, A. Noda, S. Raper, I. Watterson, A. Weaver, and Z.-C. Zhao. 2007. Global Climate Projections. In 'Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change'. (Eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller). pp. 747-845. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.
- Melzner, F., J. Thomsen, W. Koeve, A. Oschlies, M. Gutowska, H. Bange, H. Hansen, and A. Körtzinger. 2012. Future ocean acidification will be amplified by hypoxia in coastal habitats. *Marine Biology* 159: 1-14.
- Mérian, P. and F. Lebourgeois. 2011. Size-mediated climate-growth relationships in temperate forests: A multi-species analysis. *Forest Ecology and Management* 261: 1382-1391.
- Mieszkowska, N., R. Leaper, P. Moore, M. Kendall, M. Burrows, D. Lear, E. Poloczanska, K. Hiscock, P. Moschella, R. Thompson, R. Herbert, D. Laffoley, K. Baxter, A. Southward, 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 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.
- Miller-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.

- Mohan, J., R. Cox, and L. Iverson. 2009. Composition and carbon dynamics of forests in northeastern North America in a future, warmer world. *Canadian Journal of Forest Research*. 39: 213-230.
- 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.
- Moritz, M. A., M.-A. Parisien, E. Batllori, M. A. Krawchuk, J. Van Dorn, D. J. Ganz, and K. Hayhoe. 2012. Climate change and disruptions to global fire activity. *Ecosphere* 3(6):49.
- 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. Impacts of climate change on aquatic ecosystem functioning and health. *Journal of the American Water Resources Association* 35: 1373-1386.
- Myers, N. 2005. Environmental refugees: An emerging security issue. Paper presented at the 13th Economic Forum, Prague, May 23–27, 2005.
- National Oceanic and Atmospheric Administration. 2009. (Update to data originally published in: NOAA. 2001.) Sea level variations of the United States 1854–1999. NOAA Tech. Report NOS CO-OPS 36. <http://tidesandcurrents.noaa.gov/publications/techrpt36.pdf>.
- National Research Council. 2010a. 7 Sea Level Rise and the Coastal Environment. *Advancing the Science of Climate Change*. Washington, D.C.: The National Academies Press. pp. 243–250.
- National Research Council. 2010b. 9 Ecosystems, Ecosystem Services, and Biodiversity. *Advancing the Science of Climate Change*. Washington, DC: The National Academies Press, 2010.
- 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, and J. Jenkins. 2008. Potential effects of climate change and rising CO₂ 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.
- Palacios, S. and R. Zimmerman. 2007. Response of eelgrass *Zostera marina* to CO₂ enrichment: possible impacts of climate change and potential for remediation of coastal habitats. *Marine Ecological Progress Series* 344:1–13.
- 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. and H. Galbraith. 2004. Observed Impacts of Global Climate Change in the U.S. *Pew Center on Global Climate Change Report*. Washington, D.C.
- 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. Abstract, Ecological Society of America, Annual meeting, August 7, 2009, Albuquerque, AZ.
- Post, E. and N.C. Stenseth. 1998. Large-scale climatic fluctuation and population dynamics of moose and white-tailed deer. *Journal of Animal Ecology* 67: 537–543.
- 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.
- Primack, D., C. Imbres, R.B. Primack, A. Miller-Rushing, and P. del Tredici. 2004. Herbarium specimens demonstrate earlier flowering times in response to warming in Boston. *American Journal of Botany* 91:1260–1264.
- 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.
- Rehfish, 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.
- Roberts, D., S. Birchenough, C. Lewis, M. Sanders, T. Bolam, and D. Sheahan. 2013. Ocean acidification increases the toxicity of contaminated sediments. *Global Change Biology* 19: 340-351.
- 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.
- Rohr, J.R. and T.R. Raffel. 2010. Linking global climate and temperature variability to widespread amphibian declines putatively caused by disease. *Proceedings of the National Academy of Sciences of the United States of America* 107: 8269-8274.
- 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.
- Rustad, L., J. Campbell, J. Dukes, T. Huntington, K. Lambert, J. Mohan, and N. Rodenhouse. 2012. Changing climate, changing forests: The impacts of climate change on forests of the northeastern United States and eastern Canada. Gen. Tech. Rep. NRS-99. Newtown Square, PA: U.S.D.A., Forest Service, Northern Research Station. 48 p.
- 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 CO₂. *Science* 305: 367-371.
- Sandvik, H., K.E. Erikstad, and B.E. Sæther. 2012. Climate affects seabird population dynamics both via reproduction and adult survival. *Marine Ecology Progress Series* 454: 273-284.
- Sanger, D.M., M.D. Arendt, Y. Chen, E.L. Wenner, A.F. Holland, D. Edwards, and J. Caffrey. 2002. A synthesis of water quality data: National Estuarine Research Reserve System-wide monitoring program (1995-2000). National Estuarine Research Reserve Technical Report Series 2002:3. South Carolina Dept. Nat. Res., Marine Resources Division Contribution No. 500. 135 p.
- Schauffler, M. and G.L. Jacobson. 2002. Persistence of coastal spruce refugia during the Holocene in northern New England, USA, detected by stand-scale pollen stratigraphies. *Journal of Ecology* 90: 235-250.
- Schaeffer, M., W. Hare, S. Rahmstorf and M. Vermeer. 2012. Long-term sea-level rise implied by 1.5°C and 2°C warming levels. *Nature Climate Change*. Published online 24 June 2012.
- 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.
- Schloss, C., T. Nuñez, and J. Lawler. 2012. Dispersal will limit ability of mammals to track climate change in the Western Hemisphere. *Proceedings of the National Academy of Sciences* 109: 8606-8611.
- Schob, C., P. Kammer, P. Choler, and H. Veit. 2009. Small scale plant species distribution in snowbeds and its sensitivity to climate change. *Plant Ecology* 200: 91-104.
- Schweiger, O., and J. Settele, et al. (2008). Climate change can cause spatial mismatch of trophically interacting species. *Ecology* 89(12): 3472-3479.
- Shearman, R., and S. Lentz. 2010. Long-Term Sea Surface Temperature Variability along the U.S. East Coast. *J. Phys. Oceanogr.* 40: 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.
- Staudinger, M., N. Grimm, A. Staudt, S. Carter, F. Stuart Chapin, III, P. Kareiva, M. Ruckelshaus, and B. Stein. 2012. Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 Natl. Climate Assess.. Coop. Rep. to the 2013 National Climate Assessment. 296 p. Available at: <http://assessment.globalchange.gov>.
- Slennig, B. 2010. Global climate change and implications for disease emergence. *Veterinary Pathology Online* 47: 28-33.
- 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., R. Steneck, and R. 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.
- Sunday, J., A. Bates, and N. Dulvy. 2012. Thermal tolerance and the global redistribution of animals. *Nature Climate Change* 2: 686-690.
- Sydeman, W.J., S.-A. Thompson, and A. Kitaysky. 2012. Seabirds and climate change: roadmap for the future. *Marine Ecology Progress Series* 454:107-117.
- 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.
- Tans, P. and R. Keeling. 2012. Recent Mauna Loa CO₂. NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and Scripps Institution of Oceanography (scrippsco2.ucsd.edu/). Accessed 9/15/12.
- Taylor, R., B. Scanlon, P. Döll, M. Rodell, R. van Beek, Y. Wada, L. Longuevergne, M. Leblanc, J. Famiglietti, M. Edmunds, L. Konikow, T. R. Green, J. Chen, M. Taniguchi, M. Bierkens, A. MacDonald, Y. Fan, R. Maxwell, Y. Yechieli, J. Gurdak, D. Allen, M. Shamsudduha, K. Hiscock, P. Yeh, I. Holman, and H. Treidel. 2013. Ground water and climate change. *Nature Climate Change* 3: 322-329.
- Tebaldi, C., B. Strauss, and C. Zervas. 2012. Modelling sea level rise impacts on storm surges along US coasts. *Environ. Res. Lett.* 7: 014032.
- 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.
- Thorne, K., J. Takekawa, and D. Fisk. 2012. Ecological Effects of Climate Change on Salt Marsh Wildlife: A Case Study from a Highly Urbanized Estuary. *Journal of Coastal Research* 28: 1477 – 1487.
- Titus, J., D. Hudgens, D. Trescott, M. Craghan, W. Nuckols, C. Hershner, and J. Wang. 2009. State and local governments plan for development of most land vulnerable to rising sea level along the US Atlantic coast. *Environmental Research Letters* 4: 044008.
- U.S. Fish and Wildlife Service. 2009. Climate Change Adds Challenges to Freshwater Mussel Conservation. Fort Snelling, MN (accessed 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.
- Vermeer, M and S. Rahmstorf. 2009. Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences*. 106: 21527-2153.
- Viger, R.J., L.E. Hay, S.L. Markstrom, J.W. Jones, and G.R. Buell. 2011. Hydrologic Effects of Urbanization and Climate Change on the Flint River Basin, Georgia. *Earth Interact.*, 15, 1-25.
- Voigt, W., J. Perner, A. Davis, T. Eggers, J. Schumacher, R. Bahrmann, B. Fabian, W. Heinrich, G. Kohler, D. Lichter, R. Marstaller, and F. Sander. 2003. Trophic levels are differentially sensitive to climate. *Ecology* 84: 2444-2453.
- Wake, C.P., and A. Markham. 2005. Indicators of climate change in the Northeast 2005. *Clean Air—Cool Planet*: Portsmouth, NH.
- 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.
- Walther, G.-R., A. Roques, P.E. Hulme, M.T. Sykes, P. Pyšek, I. Kühn, M. Zobel, S. Bacher, Z. Botta-Dukát, H. Bugmann, B. Czúcz, J. Dauber, T. Hickler, B. Jarošík, M. Kenis, S. Klotz, D. Minchin, M. Moora, W. Nentwig, J. Ott, V.E. Panov, B. Reineking, C. Robinet, V. Semchenko, W. Solarz, W. Thuiller, M. Vilà, K. Vohland, and J. Settele. 2009. Alien species in a warmer world: risks and opportunities. *Trends Ecol. Evol.* 24: 686-693.
- Weltzin, J., J. Pastor, C. Harth, S. Bridgman, K. Updegraff, and C. Chapin. 2000. Response of bog and fen plant communities to warming and water table manipulations. *Ecology* 81:3464-3478.
- White, E., A. Morzillo, and R. Alig. 2009. Past and projected rural land conversion in the US at state, regional, and national levels. *Landscape and Urban Planning*. 89: 37-48.

- Whitman, A., B. Vickery, P. deMaynadier, S. Stockwell, S. Walker, A. Cutko, and R. Houston. 2010. Climate Change and Biodiversity in Maine: A climate change exposure summary for participants of the Maine Climate Change Species Vulnerability Assessment. Manomet Center for Conservation Sciences (in collaboration with Maine Beginning with Habitat Climate Change Adaptation Working Group) Report NCI-2010-2. 22 pp. Brunswick, Maine.
- Williams, J. and S. Jackson. 2007. Novel Climates, No-Analog Plant Communities, and Ecological Surprises: Past and Future. *Frontiers in Ecology and Evolution* 5: 475-482.
- 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.
- Winder, M. and D. Schindler. 2004. Climate change uncouples trophic interactions in an aquatic ecosystem. *Ecology* 85:2100-2106.
- 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.
- Zhu, K., C.W. Woodall, and J.C. Clark. 2012. Failure to migrate: lack of tree range expansion in response to climate change. *Global Change Biology* 18: 1042–1052.
- 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 I. Lysenko. 2000. Water birds on the edge: First circumpolar assessment of climate change on Arctic-breeding water birds. UN Environment Programme and World Conservation Monitoring Centre. Available at: <http://www.unep-wcmc.org/climate/waterbirds/report.pdf>.









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.

The Natural Capital Initiative at Manomet is helping people create an economy based on sustainability.