MARYLAND
State Wildlife Action Plan

SWAP

Keeping common species common

Chapter 6
Climate Change

MARYLAND
FOUNDED 1634

MARYLAND
DEPARTMENT OF
NATURAL RESOURCES

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Introduction

Many challenges confront fish and wildlife populations. Threats to these populations can be local, statewide, regional, national, or global in scale. This chapter provides information regarding the threats from climate change. Although global in scale, climate change impacts can be seen on all levels of scale. Climate change has affected and continues to affect not only wildlife species and their habitats, but also all aspects of human life (health, economy, culture, etc.). The phrase "climate change" is often used as an umbrella term that refers to long-term alterations of climate patterns. Climate change threatens species and their habitats due not only to warming temperatures and changes in precipitation patterns, but also to the exacerbation of already present stressors. Given the importance and relevance of climate change to a wide range of today's conservation actions, this chapter of the State Wildlife Action Plan (SWAP) is dedicated to this threat and related information.

Chapter 6 is organized into three main sections. The first section discusses widespread changes from climate change on both regional and state scales. Numerous related impacts to Maryland's Species of Greatest Conservation Need (SGCN) and their habitats are occurring, such as sea-level rise, changes in rainfall and temperature patterns, increased storms and flooding, and shifts in timing of plant and animal activities as a result of changing climate patterns. Exploring multiple assessment tools, the second section looks at the amount of risk and vulnerability placed onto Maryland's SGCN and their associated key wildlife habitats. The last section focuses on actual impacts to SGCN from climate change; this section looks at all species taxa groups included in Maryland's SWAP (Plan). Scientific names for SGCN are included in Appendices 1a and 1b. Scientific names for other species are included in the text of the chapter.

A synthesis of climate change in the Northeast and Midwest (Staudinger et al. 2015a) was provided by the Northeast Climate Science Center (NE CSC) and partners to help guide the 22 states within its geographical footprint in their efforts to incorporate climate change information into their 2015 SWAP revision (Figure 6.1). Nested within the U.S. Department of Interior, the NE CSC conducts research to meet the needs of the regional natural resource community to anticipate, monitor, and adapt to climate change. The NE CSC is supported by a consortium of partners that includes the University of Massachusetts Amherst, College of Menominee Nation, Columbia University, Marine Biological Laboratory, University of Minnesota, University of Missouri Columbia, and the University of Wisconsin. Unless stated otherwise, all citations in this section for the Northwest, Midwest, U.S. Atlantic Coast, and Appalachians are excerpted from Staudinger et al. (2015a). In addition, several sections of Chapter 6 are composed of mostly verbatim text from selected chapters in Staudinger et al. (2015a), with permission. A chapter author citation at the beginning of a section indicates that reprinted text appears in that section.

Climate trends in Maryland are incorporated in this chapter from Boesch (2008). Sea-level rise projections in Maryland were updated in 2013 and results excerpted from Boesch et al. (2013). The Maryland Climate Change Assessment (Boesch 2008) was undertaken by the Scientific and Technical Working Group of the Maryland Commission on Climate Change as part of the Commission's charge to address the drivers and causes of climate change and prepare for its likely consequences in Maryland. The Assessment was based on an extensive literature review, model projections, and reviews of international, national, and regional assessments of the impacts of climate change. This technical working group was comprised of Maryland-based scientists, engineers, and other experts, who worked

over 10 months to investigate climate change dynamics, including current and future climate models and forecasts, and evaluate the likely consequences of climate change to Maryland's agricultural industry, forestry resources, fisheries resources, freshwater supply, aquatic and terrestrial ecosystems, and human health.
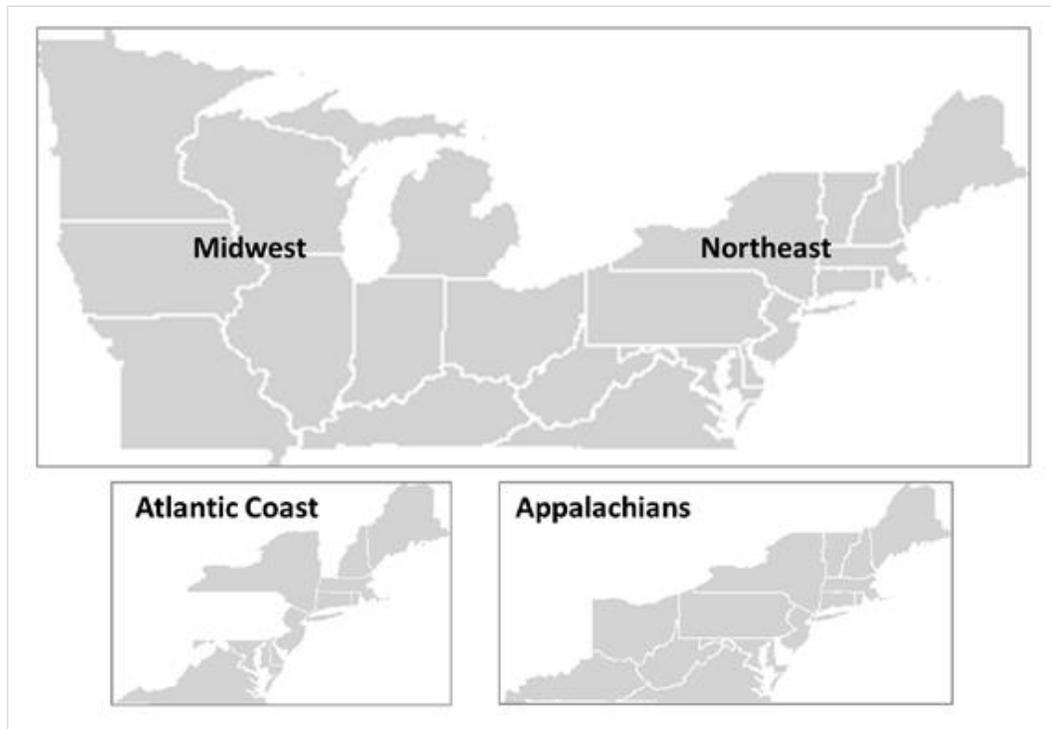
Figure 6.1 Geographical footprint and sub-regions of the DOI Northeast Climate Science Center (NE CSC). Source: Bryan et al. 2015.

Climate Change from a Regional, Sub-regional, and State Perspective
(includes text excerpted from Bryan et al. 2015)

Summary
The climate is changing rapidly in ways that have already impacted wildlife and their habitats. Certain species populations and habitats are increasing, while others are decreasing or remaining stable. For some species there is not enough information for biologists to know how they are being affected. This first section is a summary of the observed past and projected future climate changes in the Northeast, including discussions of the uncertainties associated with climate projections. Climate changes are best viewed from a regional perspective, but within that perspective there are differences within sub-regions that should be considered (Figure 6.1). Fortunately, considerable work has been done at the state level so that managers in Maryland may incorporate climate considerations with other stressors in conservation plans with greater confidence. In the short term (i.e., over the next 5-20 years), the most useful for planning purposes of the State Wildlife Action Plan (SWAP), the direction and magnitude of warming in the global climate are more or less consistent across all emissions scenarios and with strong

agreement across models. A number of large-scale regional changes affecting the overall terrestrial landscape, excerpted from Bryan et al. (2015), include the following:

- Warming is occurring in every season, particularly in winter and particularly at higher latitudes, at higher elevations, and inland (i.e., away from the ocean and lake coasts).
- Heat waves may become more frequent, more intense, and last longer.
- Precipitation amounts are increasing, particularly in winter, with high-intensity events in summer.
- Snow is shifting to rain, leading to reduced snow cover extent and depth, as well as harder, crustier snowpacks.
- Stream flows are intensifying.
- Streams are warming.
- Thunderstorms may become more severe.
- Floods are intensifying, yet droughts are also on the rise as dry periods between events lengthen.
- Growing seasons are getting longer, with more growing degree days accumulating earlier in the season.

In addition, localized climate change is occurring in sub-regions including at the state level:
- U.S. Atlantic coast
  - Sea level is rising at an accelerating rate.
  - Tropical cyclones and hurricanes may be intensifying and storm tracks have been shifting northward along the coast.
  - Oceans are warming and becoming more acidic.
- Appalachians
  - Warming may be occurring more rapidly at higher elevations.
  - Greater intensification of heavy rainfall events may be occurring.
- Maryland
  - Maryland climate trends track well with regional projections.
  - Chesapeake Bay water temperatures are increasing.
  - The frequency of Bay freezes will decrease with warmer winters.
  - Sea-level rise in coastal Maryland is occurring at a faster rate than in the region.

Interpretation of Climate Data and Uncertainty for Smart Conservation Actions

The Earth's climate is changing faster than some species and ecosystems can adapt. As a result, approaches that help wildlife adapt to climate change will facilitate transitions of many climate-sensitive species if conservation actions need to be implemented. Climate science is a complex focus for novel research, and biologists are well aware of the uncertainties and knowledge gaps which often paralyze efforts to plan and act. Amidst the uncertainty, there are many trends that are definite for the Northeast: the climate is warming, resulting in longer growing seasons, more extreme events, and many related impacts on wildlife and habitats (e.g., increased pests and disease, vegetation shifts). For these more certain aspects of climate change, plans and actions can be made with a higher degree of confidence. For areas that are less certain (e.g., local scale changes in precipitation and its impact on surface hydrology, such as terrestrial drought, river and stream flows, vernal pool formation, etc.), conservation planners should consider the actions they might take and whether they have the tools in place for the full range of projected outcomes (Bryan et al. 2015). Considering and prioritizing conservation actions for climate change in the context of other stressors (which may actually affect populations in a shorter time period) can be a "no regrets" strategy that yields the best results over time.

2003: Hurricane Isabel (left, NASA)*, and resultant flooding in Annapolis* (Dan Boesch, UMCES)

Terms that scientists use to discuss climate models can be confusing to differentiate: *projection, prediction, forecast*, and *scenario* are some important terms in this chapter. *Projections* show a range of what *could* happen based on a range of future *scenarios*. In contrast, *predictions* describe what *will* happen assuming one particular scenario plays out. A *forecast* is a prediction used exclusively in predicting short-term (days to weeks) weather and thus not applicable in this context. Model projections or what could happen are *not* predictions (what will happen) because the final outcome depends on how climate policies and human activities change over time. Climate change projections are based on a standard set of 4-5 "emissions scenarios," ranging from a worst-case scenario, in which emissions continue at present magnitudes ("business-as-usual"), to a low-emissions scenario under which global policies lead to major reductions in emissions (Nakićenović et al. 2000; Moss et al. 2010). The emissions of concern are gases that

trap heat in the atmosphere ("greenhouse gases"; carbon dioxide, methane, nitrous oxide, and fluorinated gases).

Climate models can produce varying results within the same emissions scenario depending on how they represent more complex atmospheric processes (e.g., convection, cloud physics, surface-atmosphere interactions). Models also vary in resolution. Global models do not adequately capture local-scale climate features, as is necessary for most management planning applications, and thus fine scale (1-50 km) models have been developed for a subset of the globe using a variety of "downscaling" techniques. The downscaling approach used can also yield different model results. While downscaling is a necessary step for adequately representing the local climate, the technique does not necessarily reduce the uncertainty in the global projections, and may, in fact, introduce new uncertainties due to differences in how models capture fine-scale atmospheric processes (Bryan et al. 2015).

When describing projected trends, biologists attempt to convey the approximate likelihood of possible future conditions using the terms defined in Table 6.1. Trends are considered likely (or greater) if model projections agree with each other, are supported by observed trends, or stand up to expert judgment. This applies most often to precipitation projections, which can show equal magnitudes of wetter or drier conditions in the future.

Though many aspects of future climate are uncertain, there are approaches managers can take to cope with these uncertainties, such as scenario planning, structured decision-making, and adaptive management (Chapter 8). For help in interpreting Maryland specific climate information, assistance can be provided by the University of Maryland Center for Environmental Science.

Table 6.1 Numerical definitions of terms used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) to convey the likelihood of a given outcome. Source: adapted from Mastrandrea et al. 2010 in Bryan et al. 2015.

Term	Likelihood of the Outcome
Very likely	90 – 100% probability
Likely	66 – 100% probability
About as likely as not	33 – 66% probability
Unlikely	0 – 33% probability
Very unlikely	0 – 10% probability

Widespread Changes on a Regional and State Scale

Surface Air Temperature
Warming is occurring in all states and seasons.
Over the last century, mean temperature in the Midwest and Northeast regions has increased by approximately 1.4°F and 1.6 °F, respectively (Hayhoe et al. 2007; Hayhoe et al. 2008; Kunkel 2013). In the Northeast region, annual temperature has increased 0.16°F per decade during the time period of 1895-2011. In evaluating the changes in Maryland's climate over the 21st century, biologists must keep in mind that climatic regimes will continue to vary across the state. Historically, western Maryland has cooler winters and summers and less precipitation during the

winter than the rest of the state. Changes that occur regionally will overlay these within-state differences, perhaps with some greater warming during the summer to the west than on the Eastern Shore. Temperature is projected to increase substantially, especially under higher emissions. The increase in average summer temperatures in terms of degrees of warming is greater than that in winter. Annual average temperature in Maryland is projected to increase by about 3°F by mid-century and is likely unavoidable. If current trends continue, summer temperatures are projected to increase by as much as 9°F by the end of the century (Boesch 2008).

Magnitudes of temperature increases over mountain regions in the Northeast have been found to be larger than over low-elevation regions (Bradley et al. 2004; Bradley et al. 2006; Diaz et al. 2014). This finding leads projections to indicate a more rapid increase in summer daily highs (Thibeault & Seth 2014) and a lengthening of the growing season in the Appalachian Mountain range compared to the surrounding landscape. No matter the variability in rate with elevation, warming in general will likely lead to decreased depths and earlier melting of snow in mountain regions (Barnett et al. 2005).

Heatwaves may become more frequent and more intense and last longer.
Anthropogenic warming has led to more extreme heat events globally (Fischer & Knutti 2015). However, several studies point to a distinct "warming hole" over the past half century across the eastern U.S., where the number of warm days have been either stagnant or slightly decreasing (Alexander et al. 2006; Perkins et al. 2012; Donat et al. 2013). In addition, linear trends over the past half century indicate a slight increase in the number of cool days. While daytime extremes show cooler trends, nights have been getting warmer, and the number of cold nights has decreased. Long warm spells early in the spring season are particularly threatening to vegetation as such spells can trigger premature leaf-out and flowering (Cannell & Smith 1986; Inouye 2000), leaving the plant vulnerable to frost damage later in the season.

The average annual frequency of days with a maximum temperature exceeding 90°F in Maryland is projected to grow gradually over the century, but more dramatically later in the century. Near the end of the century under the lower emissions scenario, the model averages project about 64 days per year will exceed 90°F and 10 days per year would exceed 100°F. Under the higher emissions scenario, these numbers would grow to 95 and 24 days per year, respectively. These numbers would be higher in urban areas due to the urban 'heat island' effect. Put another way, these projections indicate that toward the end of the century, under the higher emissions scenario, it would be a rare summer day when the high temperature did not top 90°F and there would be nearly a month where temperatures reached 100°F (Boesch 2008).

Precipitation
Annual precipitation is increasing, particularly in winter, though with less certainty in future projections than for temperature.
Annual total precipitation has increased over the past century on a global scale (Zhang et al. 2007). In the midwestern and northeastern United States, the last two decades (1991-2012) were wetter than the first 60 years of the twentieth century by about 10-15% (Walsh et al. 2014). Precipitation events are expected to become less frequent, with more consecutive dry days or extreme dry spells, but last longer (i.e., be more persistent; Schoof 2015; Guilbert et al. 2015).

Heavy rainfall events occurring at a reduced frequency raises the risk for both flooding and drought (Horton et al. 2014). Projections consistently predict wetter winters (Hayhoe et al. 2007; Rawlins et al. 2012; Kunkel 2013; Alder & Hostetler 2013; Schoof 2015), though with more rain than snow. Drier summers are projected, particularly for the southern Midwest, with some areas seeing little change or some increasing. Rainfall events in the summer are anticipated to become more intense and shorter with longer dry periods between events, resulting in little change in the seasonal total. More frequent severe thunderstorm activity may mean more frequent hail events in summer (Gensini & Mote 2015).

Precipitation in Maryland is projected to increase during the winter, but become more episodic, with more accumulation in extreme events. Projections of precipitation are much less certain than projections for temperature; mean projections indicate modest increases of approximately 10% in the winter and spring. Droughts lasting several weeks are more likely to occur during the summer due to increased intermittent rainfall and evaporation with warmer temperatures (Boesch 2008).

Heavy rainfall events are intensifying, particularly in the Northeast.
The Northeast region has seen a pronounced increase in the frequency and intensity of extreme precipitation events in the past several decades (Groisman et al. 2005, 2013; Kunkel 2013; Schoof 2015; Guilbert et al. 2015), a trend which is caused at least in part by anthropogenic climate change (Min et al. 2011; Fischer & Knutti 2015). The Northeast has seen the largest increases in heavy precipitation events compared to the rest of the country (a 74% increase in the heaviest 1% of all events since 1958; Groisman et al. 2013).

Intensity increases are projected for all seasons (Toreti et al. 2013) at a rate faster than the increase in annual mean precipitation (Kharin et al. 2013). The greatest increase in the number of heavy precipitation events are projected for northern latitudes, higher elevations, and coastal areas (Thibeault & Seth 2014). The Northeast region, particularly along the Atlantic coast and Appalachians, should see the largest increase in number, intensity, and inter-annual variability of extreme precipitation events (Ning et al. 2015). For small watersheds in Maryland, the likelihood of flooding depends not only on total amount of precipitation but also on its intensity at smaller spatial and temporal scales. Concentration of rainfall intensities over a small area associated with flood generation will be much higher. Observed rainfall amounts associated with recurrence intervals of 1 to 100 years are already 170% to 300% greater than the one-day rainfall amounts projected from the climate models near the end of this century (Boesch 2008).

Less snow is expected as events occur less frequently and shift to rain, though more intense snowfall events may lead to local increases in snowpack and totals.
Snowfall trends in response to climate change are complex and vary regionally. Climatic warming is resulting in a shift from snow to rain, leading to decreases in snow. However, areas that will remain cold enough for snow (e.g., northern latitudes and high elevations) may see localized increases in snowfall due to more intense precipitation events. In Maryland, no season is projected to experience a substantial decrease in mean precipitation; however, some models project small declines in summer or fall precipitation and larger increases of up to 40% in winter precipitation by the end of the century. At the same time, large decreases are projected in winter snow volume (25% less in 2025 to 50% less in 2100 regardless of emission scenario). While

Maryland does not receive large amounts of snowfall compared with states to the north, these reductions are large enough to reduce the spring river discharge associated with melting snow. Also, snow accumulation is very likely to be less common in western Maryland (Boesch 2008). Projections suggest that precipitation amounts and frequency of extreme events on the slopes of the Appalachian Mountains are likely to increase and the shift from snow to rain under warming climate will cause heavier runoff and flooding (Shi & Durran 2015).

Surface Hydrology

This section discusses changes in hydrology on the terrestrial surface (e.g., soil moisture, evapotranspiration, stream flow and temperature, surface runoff, and groundwater levels). Changes in hydrology pertaining to the Atlantic Ocean are discussed later.

Soil moisture trends and evapotranspiration rates are uncertain.

Many habitats across the U.S. are predicted to experience net drying during the next 50 years, even in areas where precipitation is predicted to increase (Brooks 2009; Wuebbles et al. 2014). Trends in soil moisture are difficult to predict given that rainfall events are becoming less frequent (suggesting drier soils), yet more intense and longer lasting (suggesting wetter soils). Many studies indicate increasing trends in evapotranspiration as the climate warms and is thus able to contain more water vapor, and, as precipitation increases, increased moisture availability (Hayhoe et al. 2007; Wuebbles et al. 2014; Pan et al. 2015). Some trends in the Northeast are statistically significant (Hayhoe et al. 2007), however, there is generally a lot of uncertainty about how the hydrologic environment will shift and impact evapotranspiration rates. In Maryland, the water available for runoff or groundwater recharge is projected to decrease by 2 to 7 mm per month during the summer and increase by 6 to 7 mm per month during the winter by the end of the century; spring and fall projections show more modest changes. Perhaps more relevant than the average rainfall is how that rainfall is delivered. There is little change projected for the precipitation in the one quarter of months that are driest. However, the range of precipitation from 25% to 75% of the time suggests a trend towards increasing precipitation in the wet winter and summer months (Boesch 2008). In spite of moderate increases in precipitation, increases in temperature in the models lead to decreases in soil moisture throughout the year. This is consistent with recent studies showing a change in the trend in North American soil moisture toward drying over the past 30 years.

Stream flow is intensifying, but varies by season and sub-region, and is not proportional to increases in extreme rainfall.

Climate change will have significant impacts on the flows of rivers and streams throughout the Northeast. The most direct sources of these changes are projected shifts in temperature, rainfall, and evapotranspiration. These changes are unlikely to be uniform across the region and will be altered by the specific characteristics of the individual basins. Basin characteristics that are very likely to have particular impacts include the basin's vegetation, degree of urbanization, underlying geology, longitude, latitude, elevation, the contribution of groundwater, and basin slope. Diminished groundwater reserves, linked to declining snow pack, will impact base flows in streams (Hayhoe et al. 2008). Earlier winter-spring peak flows in the range of 6-8 days have also been observed in the Northeast and Midwest and are thought to be linked to increased snowmelt and rain-on-snow episodes (Hodgkins & Dudley 2006). This trend is projected to continue during the 21st century (Campbell et al. 2011). Changes in the timing and the magnitude

of spring snowmelt in the eastern U.S. are crucial to maintain ecosystem functions, since some aquatic species rely on the time and volume of stream flows for vital life cycle transitions (Hayhoe et al. 2007; Comte et al. 2013).

Stream temperatures are rising.
Warming has been observed in many streams across the continent (Webb 1996; Bartholow 2005), as well as in projections (Mohseni et al. 1999). Warming stream temperatures seem to be more a function of warmer nights than warmer days or daily averages (Diabat et al. 2013). Consideration of how climate change is likely to impact Maryland's freshwater ecosystems rests not only on the assumptions underlying climate models and scenarios, but also on future decisions regarding water use and watershed management (Boesch 2008). Except for deep reservoirs, fresh waters become warmer as air temperatures increase. The spawning time of native fish may shift earlier if waters begin to warm earlier in the spring, and species that require prolonged periods of low temperatures may not survive (Palmer et al. 2008). For fish, amphibians, and water-dispersed plants, habitat fragmentation due to small dams or the isolation of wetlands and tributaries due to drought conditions may also result in elimination of their local populations as stream temperatures rise. Higher water temperatures can result in lower concentrations of dissolved oxygen in all but swift flowing waters, which may present an additional stress on organisms (Nelson & Palmer 2007).

Aquatic ecosystems in watersheds with significant urban development are expected to experience not only the greatest changes in temperature, but also greater temperature spikes during and immediately following rain storms; such drastic temperature increases could result in the local loss of species. Higher peak flows associated with urbanization result in well-documented decreases in native biodiversity (Walsh et al. 2005). Drier and hotter conditions during summer months are likely to result in the loss of small wetlands and intermittent or ephemeral streams, potentially resulting in negative impacts on the water quality downstream. Wetlands and streams experiencing reductions in water levels or baseflow often have stressed biota and stream-side vegetation, reduced dissolved oxygen levels, and loss of habitat for species that depend on currents (Allan et al. 2005). Physiological stress combined with habitat fragmentation (isolated stream pools and wetlands), may dramatically reduce survival and constrain dispersal (Boesch 2008).

Chesapeake Bay temperatures are rising.
Climate models currently do not resolve at the scale of estuaries, even for an estuary as large as the Chesapeake Bay. However, observations of Chesapeake water temperatures date back to the 1940s. These observations show a trend of water temperature increasing by 0.4°F per decade, with much of that increase over the past 30 years, correlated with increasing air temperatures. This amounts to a warming of 2.8°F over much of the Bay since 1940. A statistical model was used to quantify the relationship between air temperature and Chesapeake Bay surface water temperature based on these historical observations. This relationship was then applied to project Bay temperatures as a function of climate-model projections of air temperature. Because the Chesapeake Bay is shallow in most places, surface water temperature is not only closely related to the air temperature, but also reflects temperatures in the shallows where many benthic organisms such as seagrasses, oysters, or crabs live. The projected average temperature increases for the Chesapeake Bay closely follow the air temperature increases, suggesting increases of 4°F

by 2050 in the high emissions scenario and 2.5°F for the low emissions scenario. This additional warming is of a similar magnitude to that observed in the Bay since 1940. By 2100, the model projections suggest warming of 9°F and 5°F for the higher and lower emissions scenarios, respectively (Boesch 2008).

Oceans are warming and becoming more acidic.
Warming of the ocean waters has been observed in recent decades, with many of the highest temperature records collected within the last 10 years (Mann & Emanuel 2006; Holland & Webster 2007; Domingues et al. 2008; Rhein et al. 2013). This suggests a direct link with anthropogenic climate change. Changes in coastal water ecology have been observed along the northern Atlantic coast (Oviatt 2004; Nixon et al. 2009). With more carbon in the atmosphere from human activity (Sabine et al. 2004), and thus greater absorption of carbon by the Earth's oceans (Feely et al. 2004; Canadell et al. 2007; Cooley & Doney 2009), the oceans and coastal waters are becoming more acidic (Walsh et al. 2014). The pH level of the oceans and coastal waters will continue to drop as atmospheric carbon continues to rise (Rhein et al. 2013). Ocean acidity has not changed in the last 300 million years with the exception of a few rare events (Caldeira & Wickett 2003), highlighting the impact of recent anthropogenic climate change. More importantly, these changes in ocean acidity are irreversible over the next several thousand years and thus will have prolonged impacts on marine and aquatic ecosystems (Bryan et al. 2015).

Extreme Events
Floods are becoming more intense.
Increasing trends in floods, associated with increases in annual precipitation, have been observed in the Northeast, making the region susceptible to increases in flood events (Peterson et al. 2013; Wuebbles et al. 2014). It is expected that overall annual precipitation totals will increase over the Northeast region throughout the century, but that precipitation events will become less frequent. As a consequence, the events that do occur are projected to be more intense, raising the risks of both flooding and drought (Horton et al. 2014). Increased stream "flashiness" (how quickly flow in a river or stream increases or decreases during a storm) and higher runoff peaks are likely to mobilize chemicals associated with sediment particles.

Droughts are becoming more frequent.
The average number of consecutive dry days over the region is projected to increase by 1-5 additional days (Sillman et al. 2013; Ning et al. 2015), suggesting a potential increase in drought frequency. However, simultaneous increases in annual precipitation (Schoof 2015), particularly extreme rain events, may help minimize the severity of droughts. Thus, statistically significant increases in the frequency of short-term (lasting 1-3 months) droughts are projected with minimal threat of increased long-term droughts (Hayhoe et al. 2007).

The models for Maryland project an increase in the duration of annual dry spells, from about 15 days on average at present, to 17 days for the higher emissions scenario, and a smaller increase under the lower emissions scenario. Most of this increase is projected to occur during the latter part of the century. Based on these projections, it is likely that summer-fall droughts of modest duration will increase, especially after the middle of the century and that under the higher emissions scenario. The models suggest that, at present, a month-long drought can be expected to

occur every 40 years, but this might increase to occurring every 8 years in 2100 under the higher emissions scenario. There would be no appreciable change for the lower emissions path (Boesch 2008). The models predict that while some moderate increase in short-term droughts may occur, increases in extreme precipitation events are more likely in the long-term (Boesch 2008).

Coastal storms, such as tropical cyclones, hurricanes, and Nor'easters, may be intensifying.
Changes in the frequency and intensity of tropical cyclones (warm season coastal storms) or Nor'easters (cool/cold season coastal storms) would modify coastal flood risks. The balance of evidence suggests that the strongest tropical cyclones may become more intense due to climate change and warming of the upper oceans (Knutson et al. 2010; Christensen et al. 2013), as has already been observed over the past 40-45 years (Emanuel 2005; Webster et al. 2005). Hurricane intensity is also projected to increase (Emanuel et al. 2008; Ting et al. 2015). It is unclear how Nor'easter storms may change (Horton et al. 2015), although some research suggests growing risk for the northernmost parts of the U.S. Atlantic coast, and decreasing risk for southern parts (Colle et al. 2010).

For Maryland, in terms of human infrastructure, it is not only mean sea level that is of concern, but the height of tides and storm surges. Tidal range in a semi-enclosed bay or estuary is influenced by the depth of the water body. If sea level rises substantially, the volume of the estuary will increase, reducing frictional resistance along the bottom and changing its resonance properties. Increasing tidal range over time has, in fact, been observed at a number of East Coast tide gauges (Flick et al. 2003 as cited in Boesch et al. 2013).

The tidal range in the Chesapeake Bay is greatest at the mouth and decreases up the Bay due to friction along the bottom acting to slow tidal currents as the tide progresses from the mouth to the head of the estuary. A one-meter rise in sea level will allow more efficient propagation of the tidal wave in the bay and shift the resonant period closer to the tidal frequency. As it does, it could increase the tidal amplitude resulting in an approximate 0.05 m (0.16 ft) increase in tidal range over much of the Maryland portion of the bay, but a much greater increase of up to 0.2 m (0.66 ft) in the upper bay and the heads of some of its tidal rivers (Zhong & Foreman 2008 as cited in Boesch et al. 2013). Modern record storm surges of more than 2 m (7 ft) were experienced in portions of the Chesapeake Bay during Hurricane Isabel in 2003; storm surge levels were highest in the uppermost Bay and tidal Potomac River near Washington, District of Columbia (Li et al. 2014). While the frequency of tropical storms is not projected to increase as a result of global warming during the 21st century, highly intense storms are projected to become more common (Knutson et al. 2010). Moreover, because of warming of sea surface temperatures, tropical storms should maintain more of their intensity as they progress to the higher latitudes along the Mid-Atlantic coast.

Biological Indices
Growing seasons are getting longer, more growing days are expected, and winters are becoming more severe.
Growing season length is generally defined as the number of days between the dates of the last spring frost and the first autumn frost. Frosts occur when the minimum daily temperature drops below freezing (32 °F). While the average date of the last spring freeze is getting earlier,

fluctuations in temperature in a given season are getting wider (Rigby & Porporato 2008; Augspurger 2013), implying that climate change is likely to result in more frequent frost damage on plants (Bryan et al. 2015). Growing degree days (GDD) is an index that is used to estimate the timing of certain events in the phenology of plants and animals, such as leaf-out and pest invasions. GDD for a given day is the average of the daily minimum and maximum temperature minus some base temperature above which biological events (e.g., blooming, leaf-out) are triggered. Projections estimate an increase in GDD of 35-41% in the Northeast over the next half century, with strong agreement among the models (Kunkel 2013). More important than the increase in GDD is the shift in timing of when GDD becomes large enough to trigger certain events. As the climate warms, the date at which GDD begins accumulating is very likely to be earlier. This may provide opportunities for some warm climate vegetation while negatively impacting cold-adapted species (Bryan et al. 2015).

The climate models for Maryland project decreases in the number of frost days, where temperatures dip below freezing, and increases in the length of the frost-free growing season. Increases in growing season have been observed over the past 50 years (Christidis et al. 2007).While an increase in growing season may be a boon for gardeners, the increased active growth time coupled with reductions in soil moisture will likely cause some regions of the state to experience increased water demand for crop and landscape irrigation.

Sea level is rising at an accelerating rate.
The coastal region of the Northeast has high, and growing, vulnerability to coastal flooding (Horton et al. 2014). This high vulnerability is due to low slope coastal areas, especially in southern parts of the region, with the potential for regional sea-level rise that is faster than the global average (Yin et al. 2009). While global sea levels have risen by about 8 inches since 1900, much of the Northeast has experienced approximately 1 foot of sea level rise, whereas the Mid-Atlantic states have experienced approximately 1.5 feet of sea-level rise during that same time period (Horton et al. 2014). Sea-level rise threatens coastal environments, through more frequent coastal erosion, flooding, and salt water intrusion (Kane et al. 2015), as well as more severe flooding during storms (Horton et al. 2014). Storms are likely to become more destructive in the future as sea-level rise contributes to higher storm surges (Anthes et al. 2006).

Sea-level rise poses a particular threat to the U.S. Atlantic coast due to the more rapid than average rate of increase expected in the area, as well as the particular vulnerability of developed coastal areas, including New York City. Sea-level rise is much less responsive to emissions reductions than temperature (Solomon et al. 2009); therefore, even under an aggressive climate change mitigation policy, sea level will continue to rise for the rest of the 21st century and beyond. Due to the near certainty of continued sea-level rise, coastal adaptation is essential if society is to prevent increasing damage from flooding events. It should be noted that sea-level rise impacts can penetrate far inland in our tidal estuaries. Saltwater intrusion into coastal ecosystems and aquifers are very likely to be issues of increasing concern. Furthermore, in low lying areas, rainfall flooding may become worse due not only to heavier rain events, but because high sea levels will reduce drainage to the ocean (Horton et al. 2014). This may enhance pollution issues, especially in (formerly) industrial sites (Bryan et al. 2015). Figure 6.2 depicts the counties in Maryland that are the most vulnerable to sea-level rise (Boesch et al. 2013).
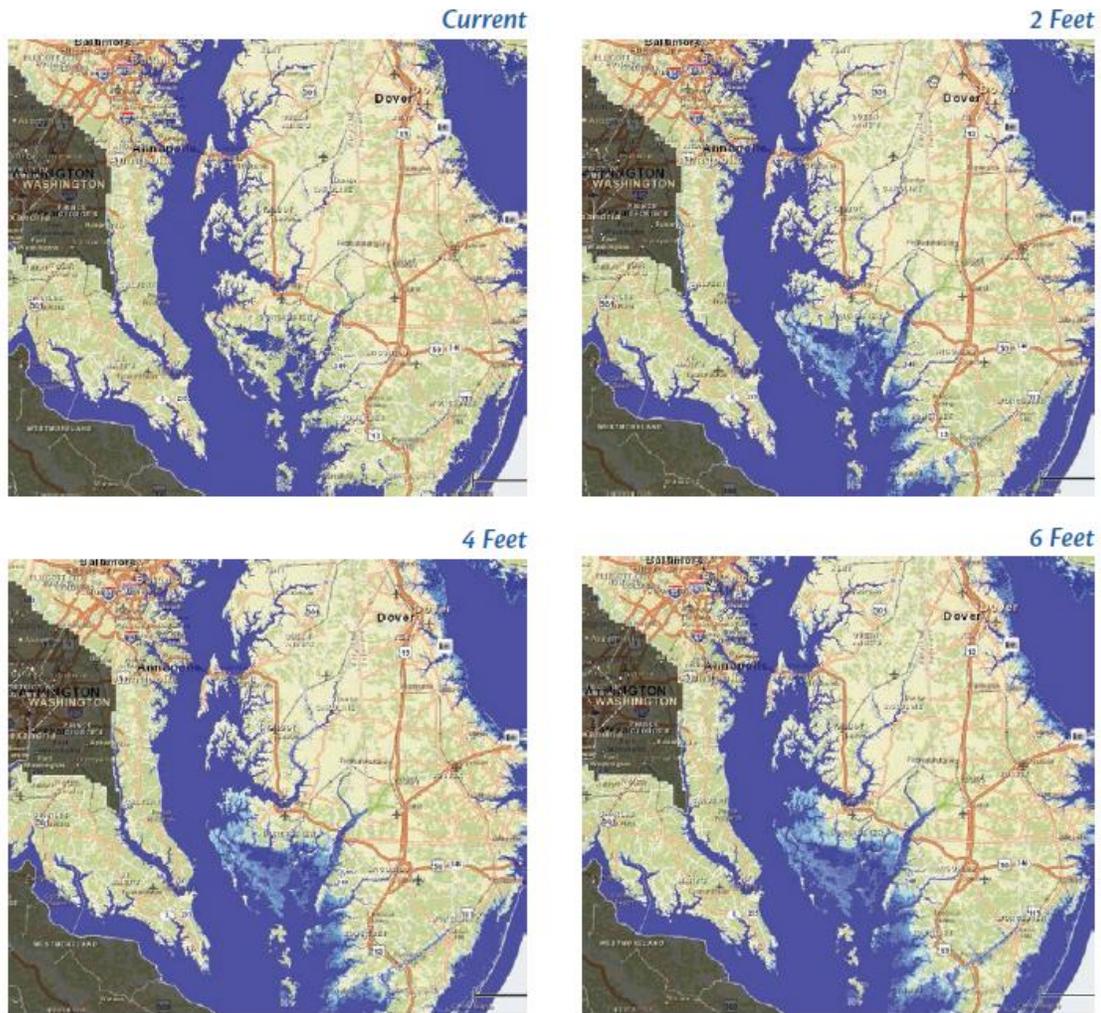
Figure 6.2 Sea-level rise map showing land inundation under current conditions (top left), under 2 feet of sea-level rise (top right), under 4 feet of sea-level rise (bottom left), and under 6 feet of sea-level rise (bottom right). Maps are derived from high resolution LIDAR imaging. Source: NOAA Sea-level rise and Coastal Flooding Impacts Viewer http://www.csc.noaa.gov/digitalcoast/tools/slrviewer as cited in Boesch et al. 2013.

Historic tide gauge records demonstrate that sea levels are rising along Maryland's coast. Due to a combination of global sea-level rise and land subsidence, sea levels have risen as much as 1.6 feet within Maryland's waters over the last 120 years (Figure 6.3). As the climate changes, sea levels are expected to continue to rise, potentially twice as fast as in the 20th century. Maryland is at risk of experiencing another one foot rise in sea level by 2050 and as much as two additional feet by 2100, contributing to higher storm wave heights, greater flooding in low-lying coastal areas, exacerbated shoreline erosion, and damage to property and infrastructure (Boesch et al. 2013).
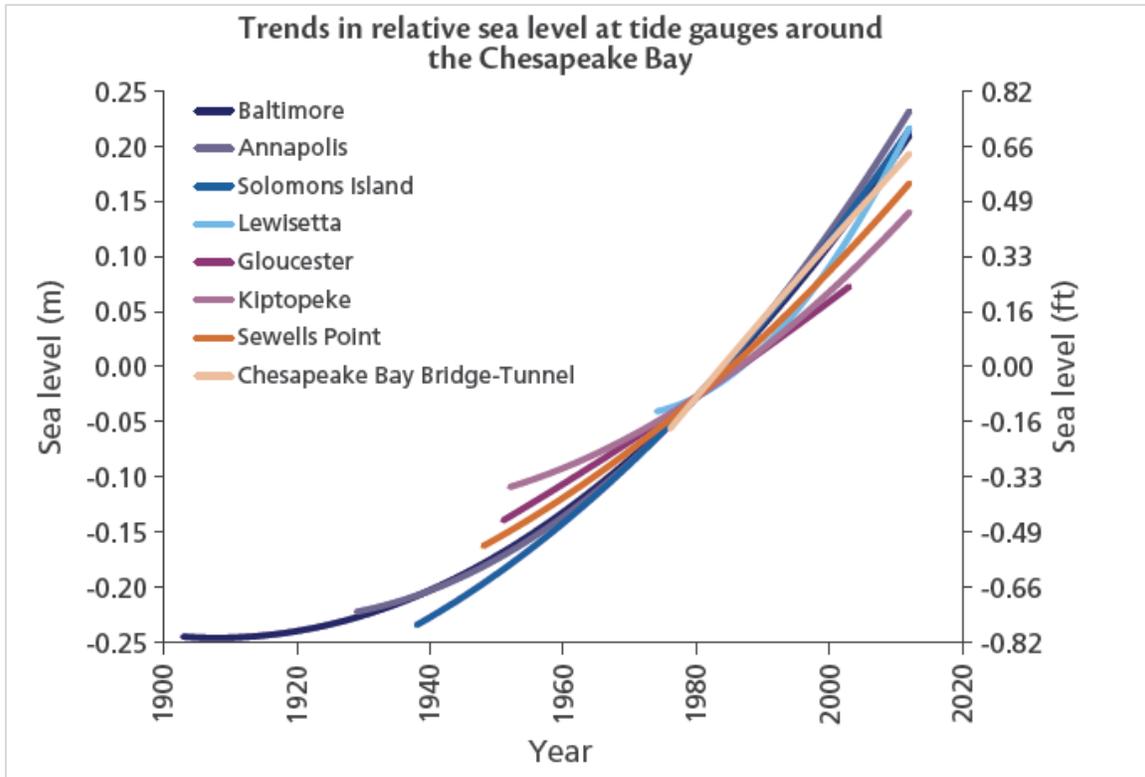
Figure 6.3 Relative sea-level rise over the past century from analysis of tide gauge records from the Chesapeake Bay; sea level is relative to 1980. Source: Ezer & Corlett 2012 as cited in Boesch et al. 2013.

Maryland Species of Greatest Conservation Need and Key Wildlife Habitats at Greatest Risk to Climate Change

(includes text excerpted from Staudinger et al. 2015b)

Summary

The objectives of this section are to describe climate change vulnerability, its components, the assessments that biologists used for Maryland's 2015 SWAP, and the vulnerability results for selected Species of Greatest Conservation Need (SGCN) and their key wildlife habitats. Vulnerability is defined as the susceptibility of a species, system or resource to the negative effects of climate change and other stressors.

- Climate change vulnerability is comprised of three separate but related components: exposure, sensitivity, and adaptive capacity.
- Climate Change Vulnerability Assessments targeting ecological systems can be focused at the species, habitat, or ecosystem level; there are different interpretations, treatments, and approaches to assessing climate change vulnerability. Therefore, it is important to examine the specific factors that were considered and the definitions used to evaluate the vulnerabilities of conservation targets within each study.
- NatureServe's Climate Change Vulnerability Index (CCVI) was the most commonly used framework across studies included in this synthesis to assess fish and wildlife species across the Northeast and Midwest; freshwater mussels, amphibians, and fish were scored

as either extremely or highly vulnerable, while the majority of birds and mammals received low vulnerability rankings.

- Almost 40% of Maryland's globally rare plants are "extremely vulnerable" to climate change using the CCVI. USDA's Climate Change Atlas data suggests that higher elevation trees such as red spruce and coastal trees such as swamp tupelo will not adapt well as the climate changes in Maryland.
- Most invasive plants and animal species in this assessment are likely to respond well to climate change.
- For northeastern region habitats scored using the Manomet model, Appalachian Northern Hardwood Forest is critically vulnerable to climate change and drier habitats such as Pine Barrens are least vulnerable.
- Freshwater aquatic and coastal habitats are highly vulnerable to sea-level rise.
- Recent studies suggest that coldwater riverine habitat may not be as vulnerable to climate change as previously thought.

Vulnerability to Climate Change

Components of Climate Change Vulnerability

Vulnerability is defined by the Intergovernmental Panel on Climate Change (IPCC 2007, 2014) as the susceptibility of a species, system, or resource to the negative effects of climate change and other stressors. Under this definition, vulnerability is composed of three separate but related components: *exposure*, *sensitivity,* and *adaptive capacity*.

Exposure is defined as the character, magnitude, and rate of change a species experiences, including both direct and indirect impacts of climate change. Examples of direct impacts would include changes in temperature, precipitation, and extreme events; indirect exposure could involve habitat shifts due to changing vegetation or ocean acidification. *Sensitivity* provides an indication of the degree to which a species or habitat is likely to be affected, and is linked to its dependence on current environmental and ecological conditions. Sensitivity factors could include temperature requirements or dependence on a specific hydrological regime. Finally, *adaptive capacity* is the ability of a species to cope and persist under changing conditions through local or regional acclimation, dispersal or migration, adaptation, and/or evolution (Dawson et al. 2011; Glick et al. 2011). A species potential for behavioral changes, dispersal ability, and genetic variation are all good examples of factors relating to adaptive capacity. Additional examples of all three components of climate change vulnerability are presented in Table 6.2 (Staudinger et al. 2015b).

Table 6.2 Examples of the three components of climate change vulnerability: exposure, sensitivity, and adaptive capacity. Note that examples are organized by column, and examples from each row are not related. Source: Staudinger et al. 2015b.

Exposure	Sensitivity	Adaptive capacity
Air and water temperatures	Species geographic range	Genetic diversity
Precipitation	Environmental or physiological niche	Genetic bottlenecks
Humidity	Thermal tolerance	Behavioral adaptation
Soil moisture	Hydrological niche and/or tolerance	Dispersal and/or migration ability
Wind	Low or intolerance to disturbance	Phenotypic plasticity
Solar radiation	Habitat specificity	Genotypic plasticity
Sea-level rise	Prey specificity	Ecological plasticity
Flooding	Dependent or competitive trophic relationships	Adaptive evolution
Drought	Low tolerance or intolerance to invasive species	Phenological shifts
Water runoff	Population or stock size	Mobility
River flow (timing, intensity and frequency)	Population size and age structure	Distribution relative to natural and anthropogenic barriers
Evapotranspiration	Mobility	Resiliency to stressors
Ocean acidification	Reproductive strategy	
Currents	Spawning cycle	
Salinity	Early life history survival and settlement requirements	
Extreme events	Population growth rate	
Snow-pack depth, ice cover, ice-edge cover	Interspecific or phenological dependence	
Fire regimes	Low tolerance or intolerance to non-climate anthropogenic stressors such as pollution	
Impacts from other anthropogenic stressors such as land-use change or harvest		

Climate Change Vulnerability Assessments (CCVA) are emerging tools in the fields of climate science, conservation, management, and adaptation. By assessing climate change vulnerability and considering risk in the context of other environmental stressors (e.g., exploitation, pollution, land use change, disease), natural resource managers can identify which species and systems are relatively more vulnerable or resilient to climate change, ascertain why they are vulnerable or resilient, and use this information to prioritize management decisions (Glick et al. 2011). Managers must also be aware that differences exist in the interpretation of climate change vulnerability in the literature as well as across different institutions and sectors (e.g., policy, scientific, natural resources). The vulnerability of a species, system, or resource to climate

change has been considered a starting point for conservation efforts and a characteristic brought about by other stressors (e.g., environmental, anthropogenic) that is exacerbated by climate change (O'Brien et al. 2004). Vulnerability may also be viewed as the consequence or result of the net impacts of climate change minus actions to reduce the effect of climate change (i.e., adaptation) (O'Brien et al. 2004). These different interpretations have important implications for how research, management decisions, and actions related to a resource are made (Staudinger et al. 2015b).

Different approaches for evaluating vulnerability may also differ in how they consider the three components of exposure, sensitivity, and adaptive capacity. For example, some assessments evaluate adaptive capacity; some have combined it as part of sensitivity, and some have ignored it completely (Joyce et al. 2011; Beever et al. 2015; Thompson et al. 2015). The ability of biologists to understand and predict species and systems responses to climate change is limited when adaptive capacity is not explicitly considered. Thus it is important to evaluate the uncertainties related to each of the three components and other relevant factors, including those that were or were not able to be assessed. Such an evaluation will highlight areas where additional research or monitoring is needed to inform future decisions and conservation actions (Staudinger et al. 2015b).

Traits and Characteristics Affecting Species Vulnerability to Climate Change

A recent study conducted by Pacifici et al. (2015) reviewed 97 studies published during the last decade reporting on the risk and vulnerability of global species to climate change. They concluded that species traits rather than taxonomy and distribution were relatively more important in determining climate change vulnerability.

Biological traits or characteristics that may lessen opportunities or make species populations more vulnerable under future climate change include:
- Specialized habitat and/or microhabitat requirements
- Specialized dietary requirements
- Narrow environmental tolerances or thresholds that are likely to be exceeded due to climate change at any stage in the life cycle
- Populations living near the edge of their physiological tolerance or geographical range
- Dependence on habitats expected to undergo major changes due to climate
- Dependence on specific environmental triggers or cues that are likely to be disrupted by climate change
- Dependence on interspecific interactions which are likely to be disrupted by climate change
- Poor ability to disperse to or colonize a new range
- Low genetic diversity; isolated populations
- Restricted distributions
- Rarity
- Low phenotypic plasticity
- Long life-spans or generation times, low fecundity or reproductive potential or output

Biological traits or characteristics that may create opportunities or benefit species under future climate change include:

- Broad habitat or dietary generalists
- High phenotypic plasticity
- Disturbance-adapted species
- Large thermal tolerances
- High dispersal capabilities
- Short life-spans or generation times, high fecundity and reproductive potential or output

(Both et al. 2009; Glick et al. 2011; Bellard et al. 2012; Lurgi et al. 2012; Staudinger et al. 2013; Pacifici et al. 2015).

Climate Change Vulnerability Assessment Tools

Types of Climate Change Vulnerability Assessment Approaches

There is no standard method or framework to assess vulnerability to climate change. A variety of approaches are reported in the literature, and implemented by different institutions and organizations globally. The three most commonly used methods are correlative or empirical models, mechanistic or process-based models, and trait based assessments. Correlative models relate current or historical geographical distribution/range occurrence observations of a species or group with climate projections to identify future habitat suitability. Mechanistic models evaluate fundamental niche and fitness of a species under changing environmental conditions, taking into account the specific mechanisms underlying physiological responses and simulates dispersal, functioning, and population dynamics. Trait-based assessments predict the risk of population decline and extinction by evaluating exposure to climate change and species-specific traits and characteristics. Trait based assessments can include abundance indices, monitoring observations, population viability analysis, demographic models and/or expert opinion (Staudinger et al. 2012; Pacifici et al. 2015).Generally, the approach chosen to evaluate vulnerability should be based on the goals of the practitioners, confidence in existing data and information, and the resources available. More information on these model and assessment approaches, as well as examples, are detailed in Staudinger et al. (2015b). Maryland biologists used a combination of approaches to assess vulnerability of SGCN and key wildlife habitats, including the incorporation of studies and assessments completed by other researchers.

Maryland's Climate Change Vulnerability Assessment Approaches
Individual Species Assessments

Rare Animals and Plants
Maryland biologists selected the Nature Serve Climate Change Vulnerability Index (CCVI) to assess rare animals and plants. The CCVI is a relatively easy to use traits-based assessment tool designed for use with any species of fish and wildlife (Young et al. 2011). This tool allows biologists to assess large numbers of species and compare results across both species and taxa, and is useful for discerning patterns in the data (Young et al.2014). The CCVI is a Microsoft Excel-based tool, and includes detailed instructions on obtaining climate data and calculating the degree of expected change in temperature, moisture, and other factors. The remaining factors assessed by the CCVI are weighted by the magnitude of exposure, and are grouped into indirect exposure factors (including sea-level rise, barriers to dispersal, and land use changes), and species-specific sensitivity factors (Staudinger et al. 2015b).

Trees

The Climate Change Atlas was developed by researchers with the USDA Forest Service Northern Research Station to model the current and projected future habitat suitability by 2100 for 134 tree species and 147 birds in the Eastern United States based on high and low climate scenarios. Maryland Natural Heritage Program (NHP) biologists thought that examining these correlative models for trees would help to determine how forest communities in Maryland might shift with climate. Model outputs can be filtered by state which made it useful for NHP biologists to evaluate the potential future distribution of selected trees within Maryland. Only models that had "high reliability" were selected from the Atlas for the assessment.

Tree Atlas models are based on three factors: 1) components that comprise suitable habitat for each species, such as temperature, precipitation, soil characteristics, and elevation; 2) species-specific characteristics or traits that influence a species ability to adapt to changing conditions such as sensitivity to pests, or shade intolerance (modeling these factors is difficult so the researchers used ranks for positive and negative traits relating to adaptability); and 3) ability to colonize new areas. A species may have suitable habitat available but may not be able to migrate because of barriers, such as urban areas or large agricultural fields. These models can be useful to managers that need to make decisions regarding assisted migration or where to strategically plant trees to facilitate migration in fragmented landscapes (Iverson et al 2008). More information on model components and functions are available from http://www.fs.fed.us/nrs/atlas/.

Invasive Plants and Animals

No treatment on the effects of climate change on species would be complete without a section on invasive plants and animals and how climate may affect habitat suitability or unsuitability for these species. The Maryland Invasive Species Council (MISC) has a list of invasive species and potential future invasive species in Maryland. To assess potential impacts of climate change relative to invasive plants and animals, Maryland biologists reviewed published studies that indicated how specific invasive species responded or were thought to respond to climate change. They found that many invasive species adapt easily to climate change because of the traits and characteristics outlined earlier in this chapter that they possess.

Habitat Assessments

Non-coastal Terrestrial Habitats

The NEAFWA Habitat Vulnerability Model was developed by the Northeastern Association of Fish and Wildlife Agencies (NEAFWA), the North Atlantic Landscape Conservation Cooperative (NALCC), the Manomet Center for Conservation Sciences (Manomet), and the National Wildlife Federation (NWF) to consistently evaluate the vulnerability of non-coastal terrestrial habitats across all 13 states in the Northeastern United States (Manomet & NWF 2013a). The NEAFWA Habitat Vulnerability Model is based on an expert-panel approach and contains four modules which can be used within Microsoft Excel (Manomet & NWF 2013a). Maryland NHP biologists participated in this effort.

After the 13 northeastern states were evaluated, results for each habitat were reviewed by an expert panel and resubmitted for evaluation if needed. The initial vulnerability assessment

completed using this model evaluated 13 habitat types in the Northeast region. To investigate potential geographical variation in habitat vulnerabilities to climate change across the Northeast Region, the entire region was divided into four latitudinal zones, corresponding approximately to the major bioclimatic zones (I-IV) of the region (Figure 6.4). Maryland is located in zone IV (Manomet & NWF 2013a).

Coastal Habitats

With its expansive coastline, low-lying topography, and growing coastal population, the Chesapeake Bay region is one of the most vulnerable places in the nation to the impacts of sea-level rise. Many places along the Chesapeake Bay have seen a one-foot increase in relative sea-level rise over the 20th century, with six inches due to global warming and six inches due to naturally subsiding coastal lands – a factor that places the Chesapeake Bay region at particular risk (Zervas 2001). Already, many of the Bay's coastal marshes and small islands have been inundated. At least 13 islands in the Bay have disappeared entirely, and many more are at risk of being lost soon (Glick et al. 2008; U.S. EPA 2008).
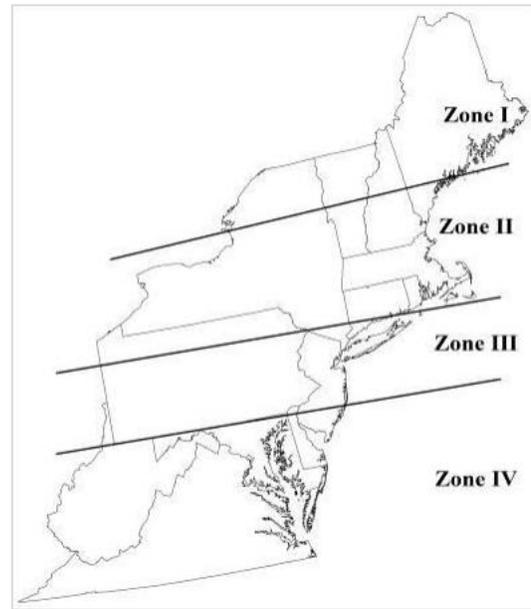

Figure 6.4 Latitudinal zones used in the Manomet and NWF model.
Source: Manomet & NWF 2013a.

Much research and attention to sea-level rise in the Chesapeake Bay has already occurred at the national and state level. Maryland biologists selected a study that had already been completed in the Chesapeake Bay to ascertain risk to coastal key wildlife habitats. In this particular study, Glick et al. (2008) applied the Sea Level Affecting Marsh Model (SLAMM) 5.0 to the entire Chesapeake Bay region and Delaware Bay, comprising slightly over seven million hectares. SLAMM models change in tidal marsh area and habitat type and simulates the dominant processes involved in wetland conversions and shoreline modifications. Within SLAMM, there are five primary processes that affect wetland fate under different scenarios of sea-level rise: inundation, erosion, overwash, saturation, and salinity.

The model results were divided into 12 sites to facilitate model interpretation by managers, and are shown in Figure 6.5. Successive versions of the model have been used to estimate the impacts of sea-level rise on the coasts of the U.S. (Titus et al. 1991; Lee et al. 1992; Park et al. 1993; Galbraith et al. 2002; Glick 2006; Glick et al. 2007; Craft et al. 2009). A thorough accounting of SLAMM model processes and the underlying assumptions and equations can be found in the SLAMM 5.0 technical documentation (Clough & Park 2007).

In addition to the SLAMM model outputs, the Maryland Department of Natural Resources (MD DNR) has an online interactive map called the Coastal Atlas where state and local planners can explore coastal and ocean resources for better site and project planning. This tool includes datasets for sea-level rise and storm surge projections. These two tools are useful for NHP biologists to discern the vulnerability of specific sites with SGCN and key wildlife habitats.

Coldwater Riverine Habitats
Of all the rivers and streams systems that occur in the region, the coldwater stream habitat is thought to be most vulnerable to climate change. Climate change vulnerability studies done on coldwater stream habitat were reviewed by the Manomet Center for Conservation Sciences and the National Wildlife Federation for NEAFWA. The scientists involved in this review concluded that coldwater fish habitat in the Northeast is vulnerable to climate change. These studies also largely agree that the risks

Figure 6.5 The twelve Chesapeake Bay output sites. Source: Glick et al. 2008.

posed to this habitat type are due to its current rate of loss to anthropogenic development, habitat destruction and fragmentation (leading to loss of connectivity), and the coldwater fish species intrinsic physiological limitations to coldwater habitat. Many of these studies (Meisner 1990; Reis & Perry 1995; U.S. EPA 1995; Flebbe et al. 2006; Trumbo 2010; Jones et al. 2013; CCVI studies performed in West Virginia, Maryland, New York and Maine) specifically identify climate change as a source of current and future potential risk to coldwater fish populations. However, more recent work suggests an evolution in thinking about the magnitude of the risk posed by climate change, the conclusions of which will be reported in the following results section (Manomet & NWF 2013b).

Maryland Climate Change Vulnerability Assessment Results
Individual Species Assessment

Rare Animals and Plants
Nature Serve's Climate Change Vulnerability Index (CCVI) was selected as the method used to assess the vulnerability of Maryland's SGCN to climate change based on global and state ranks. All SGCN were categorized based on global and state status ranks and placed into conservation

status groups (Appendix 3h). Species that were categorized in status groups A and B were run through the Nature Serve CCVI as biologists surmised that those status groups would be comprised of the species most likely to have conservation action priorities tied to their vulnerability in conjunction with other stressors. Figure 6.6 illustrates numbers by taxon of SGCN in status groups A and B.

Maryland biologists used Nature Serve's CCVI to index 265 SGCN's vulnerability to climate change (Figure 6.7, Appendix 6a). Kemp's Ridley and loggerhead sea turtles are not easily scored by the CCVI and were assessed as being vulnerable according to Hawkes et al. (2009). In general, the CCVI identified flatworms, freshwater mussels, tiger beetles, butterflies, freshwater fish, amphibians, and freshwater turtles as being the most vulnerable to climate change. Birds that occupy coastal habitats affected by sea-level rise and some mammals were found to be vulnerable as well.
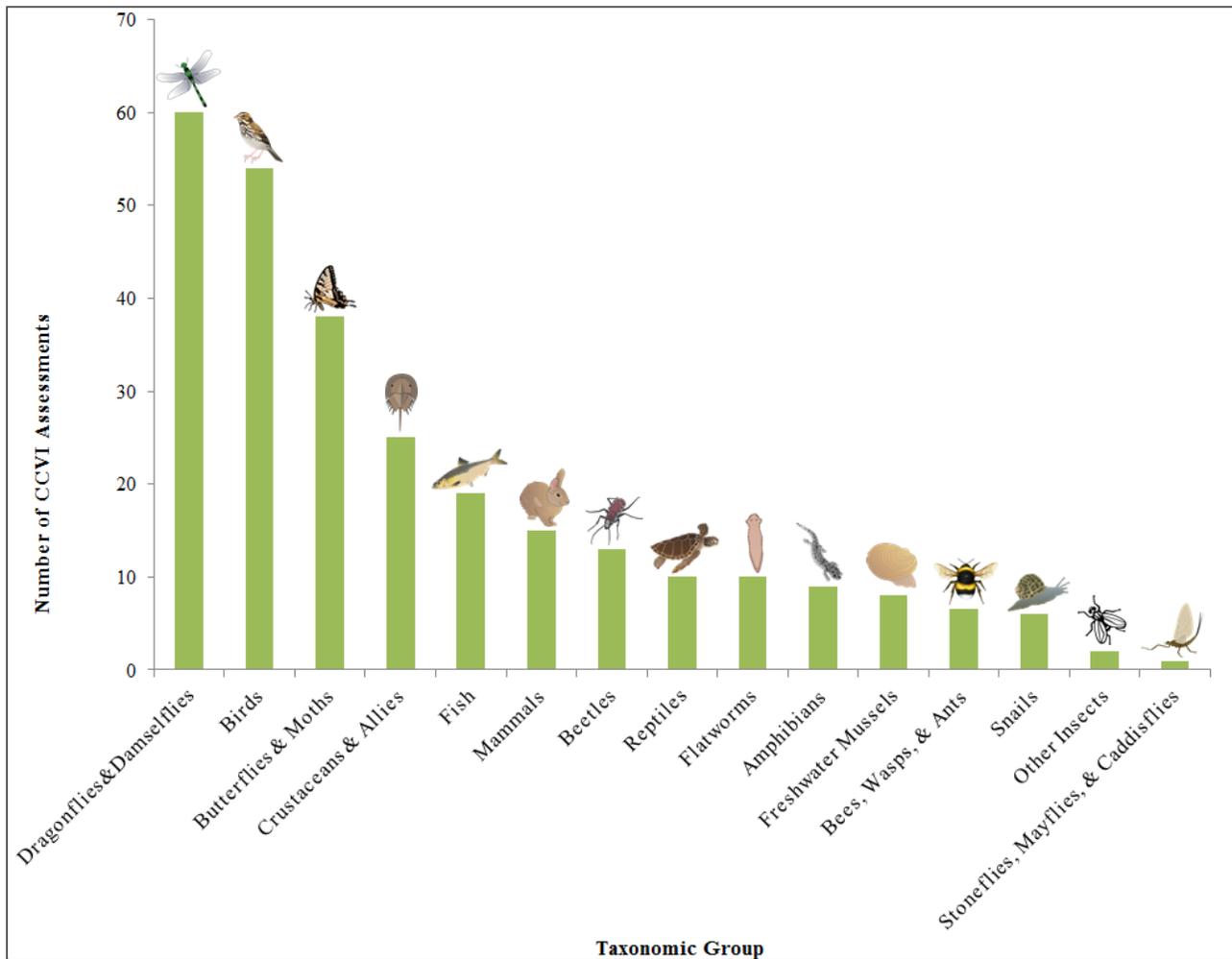
**Figure 6.6 Number of SGCN animals per taxon in status groups A and B;** conservation status group A refers to highest conservation status and group B refers to the high conservation status based on global and state conservation status ranks (for more information on conservation status groups, see Chapter 3).
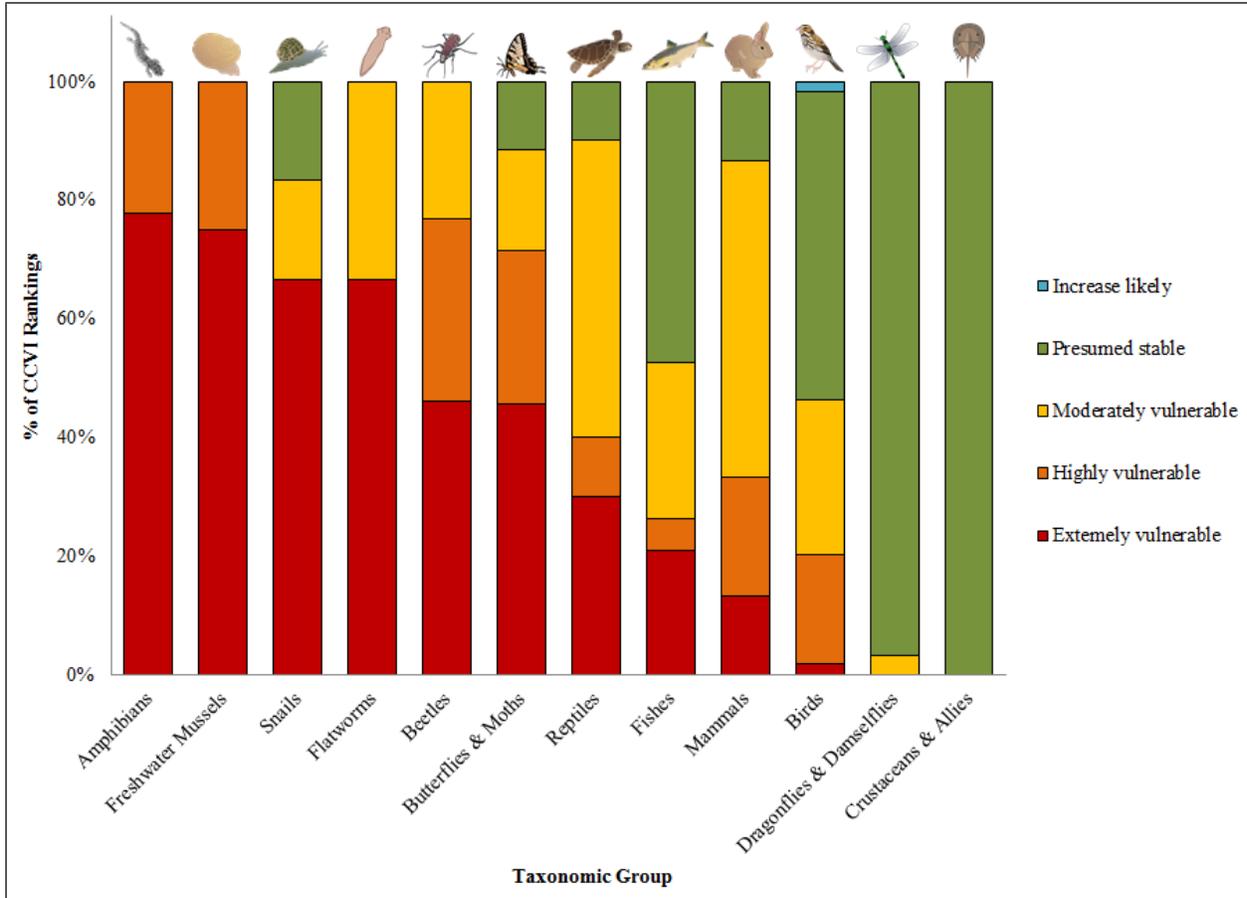
Figure 6.7 Percentage of SGCN animals by taxon for vulnerability using Nature Serve's CCVI.

Biologists have also investigated the role that a warming climate plays in the flowering response in plants. A 30-year study in the Washington, District of Columbia area showed that 89 of 100 plants representing 44 families of angiosperms bloomed 4.5 days earlier and correlated directly with an increase in local temperature (Abu-Asab et al. 2001). Another longer term study of 150 years in Concord, Massachusetts suggested that flowering time response can influence community-wide patterns of species loss when data is analyzed phylogenetically. In this study, plants that do not respond to temperature have decreased in abundance (Willis et al. 2008). McDonald et al. (2009) suggested in a reply to this paper that deer herbivory was the likely cause given the area where the study took place did not allow hunting. However, this was refuted by the original authors when they reanalyzed the data to incorporate deer herbivory (Willis et al. 2009). A study on orchids in the Catoctin Mountains in Maryland concluded similarly that the decrease in abundance of orchids was due to deer herbivory (Knapp & Wiegand 2014). Although not a requirement for the SWAP, Maryland biologists also applied the CCVI to selected rare plants that had a global rank of G1 (critically imperiled), G2 (imperiled), or G3 (vulnerable). A total of 47 species were run through the model and 19 (40%) were found to be "extremely vulnerable" to climate change (Appendix 6b).

Trees
As with individual plants, managers may find it useful to examine the future habitat suitability in their state or region of individual tree species to serve as guidance for various projects. Results

for Maryland trees in the Central Appalachians and the Mid-Atlantic can be found in Appendix 6c (Iverson et al. 2008; Landscape Change Research Group 2014; Butler et al. 2015). No trees examined in this analysis were projected to become extirpated from the state due to climate change, though Appalachian (hemlock)/northern hardwood forests, large stream floodplain and riparian forests, small stream riparian forests, and spruce/fir forests were determined to be the most vulnerable ecosystems (Butler et al. 2015).

Invasive Plants and Animals
Climate change for species does not always translate into species loss or reduction in abundance. Sometimes climate can enable non-native species to colonize new areas, extending their range, or worse, allow invasive species to gain a foothold in plant communities already under attack from a number of stressors in addition to climate change. A summary list of scientific papers that investigated how climate change affects invasive species that are of concern in Maryland is presented in Appendix 6d. This information is not exhaustive but serves as a starting point for understanding how invasive species in Maryland may respond to a changing climate. Most of the invasive species reviewed are likely to respond favorably to climate change.

Terrestrial Habitat Assessments

Non-coastal Terrestrial Habitats
To date, regional ecologists have participated in 11 studies that evaluated the climate change vulnerability of terrestrial, aquatic, and coastal habitats across the Northeast and Midwest. A total of 224 unique assessment records were compiled for habitats across the region (Staudinger et al. 2015b). A total of 69,347,600 acres of wetland and upland habitat were evaluated using the NEAFWA Habitat Vulnerability Model. This comprises approximately 60% of the total wildlife habitat (excluding developed areas and agricultural land) in the NEAFWA Region (Manomet & NWF 2013a). Habitat vulnerabilities from this study in Maryland (Zone IV) are depicted in Table 6.3 (Manomet & NWF 2013a); the rest of the region's results can be found in Staudinger et al. (2015).

In Maryland, the evaluated regional habitats encompass key wildlife habitats such as Hemlock-Northern Hardwood Forests, Cove Forests, High Elevation Ridge Forests, and Montane Bogs/Fens, which are restricted to higher elevations and contain a high number of species with northerly distributions (J. Harrison, MD DNR, pers. comm.). For many of the habitats that are vulnerable to climate change and that occur in two or more zones (Montane Spruce-Fir Forest, Northern Hardwood Forest, Appalachian Northern Hardwood Forest, Central Oak-Pine Forest), vulnerabilities increase from north to south as their bioclimatic range limit is approached. The ability of some habitats to migrate within their respective bioclimatic range may be limited if their persistence is reliant on certain substrates or particular geological formations (Harrison 2015, pers. comm.). Examples in Maryland include those key wildlife habitats that are characterized by calcareous substrates, such as Basic Mesic Forests and Basic Glades (e.g., Limestone Glades), or Oak-Hickory Forests over localized areas of mafic igneous and metamorphic rocks (e.g., metabasalt, amphibolite, gabbro), which are much less common throughout the state than acidic substrates (J. Harrison, MD DNR, pers. comm.).

Table 6.3 Vulnerabilities to climate change stressors and future vulnerabilities to non-climate stressors of northeastern non-coastal terrestrial habitats found in Maryland. Source: Manomet and NWF 2013a.

Terrestrial Habitat	Climate Stressors	Non-climate Stressors
Appalachian Northern Hardwood Forest	Highly Vulnerable	Vulnerable
Central Oak-Pine Forest	Vulnerable	Vulnerable
Pine Barrens	Least Vulnerable	Least Vulnerable
Central-Southern Appalachian Spruce-Fir Forest	Critically Vulnerable	Critically Vulnerable
North Atlantic Coastal Plain Basin Peat Swamp	Less Vulnerable	Less Vulnerable
Laurentian-Acadian Marsh	Less Vulnerable	Vulnerable
Laurentian-Acadian Shrub Swamp	Less Vulnerable	Vulnerable

Although general circulation models are relatively consistent in future temperature projections, they are less consistent with future precipitation results (Manomet & NWF 2013a). Precipitation models may vary for the same area with some models showing an increase in precipitation while others indicating a decrease in precipitation. This uncertainty is further compounded by a small degree of uncertainty about temperature predictions and how it might affect evapotranspiration rates on the ground (Manomet & NWF 2013a). This may have great implications for many of Maryland's wetland habitats which are characterized by groundwater recharge and/or seasonal flooding. What is clear is that many of Maryland's wetland habitats that support a number of SGCN plant and animals are highly vulnerable in sustained patterns of low precipitation and high evapotranspiration rates (Harrison 2015, pers. comm.) According to the NEAFWA Habitat Vulnerability Model (Manomet & NWF 2013a) those Maryland key wildlife habitats that scored highly vulnerable are Montane Bog and Fens, Montane – Piedmont Acidic Seepage Swamps, Montane – Piedmont Basic Seepage Swamps, Piedmont Seepage Wetlands, Coastal Plain Seepage Swamps, Piedmont Upland Depression Swamps, Delmarva Bays, and Coastal Plain Flatwoods and Depression Swamps.

In Maryland, key wildlife habitats that occupy dry, fire-prone landscapes are likely to benefit from a changing climate. These habitats such as Coastal Plain Oak-Pine Forests and Montane – Piedmont Oak-Pine Forests are widespread matrix forest systems in Maryland and occupy thousands of acres. Other key wildlife habitats that may benefit from droughts and an increase in fire frequency include Coastal Plain Pitch Pine Forests, Shale Barrens, and Serpentine Barrens. These habitats are considered rare in Maryland and are a conservation target for land managers who frequently use prescribed fire as a management tool (J. Harrison, MD DNR, pers. comm.). Non-climate stressors that already impact many habitats will continue to be important stressors in the future. For example, invertebrate pests such as hemlock woolly adelgid *(Adelges tsugae),* have already greatly impacted hemlock stands in the central and southern Appalachians. In some areas, these pests are a major determinant of the condition and distribution of these habitats. The same applies to an over-abundance of white-tailed deer in northeastern forests and their effects on the habitat through grazing and browsing, or the invasion of native plant communities by

exotic species. While climate change may increasingly exert adverse effects on these habitats, current stressors will continue to be important, conceivably more important in some cases.

Coastal Habitats
Entire Study Area Results
Model results (Sea Level Affecting Marsh Model (SLAMM) 5.0) vary considerably by site, but overall the most significant changes to coastal wetlands and other habitats occur in the eastern and southern regions of the Chesapeake Bay, and along the coastal barrier islands and beaches (Glick et al. 2008). Assuming 69 cm of sea-level rise by 2100, the area of irregularly flooded (brackish) marsh throughout the region will decline by 83%. Overall, the area of tidal marshes (including tidal freshwater marsh, irregularly flooded marsh, transitional saltmarsh, and saltmarsh) declines by 36% under this scenario. Ocean and estuarine beaches also fare poorly, declining by 69% and 58%, respectively, by 2100. In addition, more than half of the region's important tidal swamp is at risk, declining by 57% by 2100. While the percentage of undeveloped dry land lost by 2100 is small (4%), that figure is deceptive, as much of the area incorporated in the model sites extends far inland. This translates to 413,724 acres of coastal land lost, primarily due to inundation or erosion. As expected, the impacts are even more dramatic under the 1.5 meter scenario, which is about 4 feet – still below the 4 ½-foot projection suggested above. In this case, virtually all of the region's ocean beach and irregularly flooded marshes (more than 442,607 acres) are projected to disappear by 2100, as would 75% of tidal swamp and about 50% of the tidal flats, tidal fresh marsh, and estuarine beaches. While there is some conversion to transitional and saltmarsh, most of the habitat lost converts to open water (Glick et al. 2008).

Susquehanna River & Northern Chesapeake Bay
Given the relatively significant influx of sediments into the upper Chesapeake Bay from the Susquehanna River and its tributaries, many of the marshes in this region are projected to keep pace with lower rates of sea-level rise through accretion. However, the dominant marsh at this site (irregularly flooded) lives at a fairly precarious threshold. It could potentially withstand sea-level rise of 39 cm by 2100, but 97% of this marsh is predicted to be lost when the sea-level rise increases to 69 cm. Dry land is generally of a high enough elevation that it will not readily convert to wetlands. Only 2% of dry land is predicted to be lost even given 1 meter of sea-level rise. LiDAR elevation coverage was available for the northeastern corner of this site only (Glick et al. 2008).

Baltimore
A significant amount of coastal habitat has already been lost in this area from extensive urban development. Most of the remaining marsh lands surrounding Baltimore are predicted to be lost under higher sea-level rise scenarios. Three to four percent of dry land will be subject to inundation depending on the scenario chosen. Dry lands are generally built at higher enough elevation to avoid much risk. Even under a scenario with two meters of global sea-level rise by 2100, only 2% of land (both developed and undeveloped) are predicted to be inundated (Glick et al. 2008).

Annapolis

As is the case through the entire study area, marsh lands are subject to inundation under regimes of higher sea-level rise. However, the amount of marsh lands in Annapolis is already rather limited. Some fringes of dry land are at risk, with 3-4% conversion predicted. Under a scenario with a 2 meter rise, 6% of both dry land and developed land are predicted to be at risk of inundation. The most significant model prediction for this site may be the expansion of swamp in Shady Side. Swamp expansion is predicted due to the rise in the water tables at this site (Glick et al. 2008).

Eastern Bay Region

There are considerable low-lying marshes and dry lands in this region. Even under 39 cm of sea-level rise, roughly one quarter of marsh and 4% of dry land is predicted to be lost. Under higher scenarios, those numbers become 60% of marsh and 7% of dry land. Some swamp expansion is also predicted at this site due to soil saturation (Glick et al. 2008).

Cambridge, Maryland and Surrounding Peninsula

Blackwater National Wildlife Refuge (NWR) lies south of Cambridge and has historically provided habitat for a diverse and abundant collection of fish and wildlife. Sea-level rise is a major threat to the low lying marsh areas in this region and dramatic habitat losses are predicted for this site. In addition to sea-level rise, another reason this area is so vulnerable is that land subsidence is greater in this area than for many other parts of the Chesapeake Bay, possibly due to groundwater withdrawal for agriculture. In addition, marshes in much of the Eastern Shore appear to have relatively lower rates of natural accretion (Kearney et al. 1998). Significant changes in the composition and extent of coastal habitats occur at this site. Roughly 32 - 45% of dry land and 66 - 98% of marshes are predicted to be lost by 2100 depending on the scenario chosen. Within the past century, thousands of acres of marshlands already have been converted to open water. The model predicts that the significant losses of marshes at Blackwater will continue unless effective management practices can be implemented (Glick et al. 2008).

Chincoteague Bay Region

The bay and ocean-side habitats of the Chincoteague Bay region are extremely important for some of the largest populations of migratory waterfowl, waterbirds, and shorebirds on the East Coast. Assateague Island also has some of the most pristine beaches in the Mid-Atlantic region. A combination of overwash and inundation results in fairly significant effects of sea-level rise with predicted losses of dry land ranging from 4-8% (Glick et al. 2008). In addition, 15% of nearby developed land would be lost given 50 cm of sea-level rise and 52% of developed land would be inundated given 2 meters of sea-level rise unless these lands are adequately protected (Glick et al. 2008).

Deal Island, North Tangier Sound, and Crisfield

Farther south along the Eastern Shore of the Chesapeake Bay is Tangier Sound and some of the Bay's larger islands (including Smith Island, Deal Island, and Tangier Island). This area supports some of the most lucrative commercial and recreational fisheries in the Bay, and both its economy and ecology depend on healthy marshes and seagrass beds. This site, modeled with high resolution LiDAR data, shows similar types of results as Blackwater NWR north of it. The islands of North Tangier Sound are predicted to be mostly lost given 39 cm of sea-level rise and

completely lost under a scenario of 69 cm. The mainland doesn't fare much better with 12-23% of dry land lost to inundation. Total marsh losses are predicted to range from 12% to 49% under the scenarios. Again, however, much of this is due to conversion of dry lands to marshes (Glick et al. 2008). Although the model used for this study does not directly address changes to submerged aquatic vegetation, several other studies suggest that the critical seagrass beds in this area are also at significant risk from sea-level rise due to increasing water depth and deposition of sediments from the Blackwater area to the north due to lost wetlands and increased erosion rates (Kearney et al. 2002).

Coldwater Riverine Habitats

Earlier and larger scale studies (Meisner 1990; U.S. EPA 1995) projected large coldwater riverine habitat reductions (generally greater than 50%, and up to 100%), depending on the emissions scenario, the time scale, and the general circulation models used. However, recent studies conducted at the watershed or sub-watershed scale examining the relationship between air and water temperatures indicate that the influence may not be as drastic as previously thought (O'Driscoll & Dewalle 2006; Trumbo 2010; Kelleher et al. 2012; Kanno et al. 2013; U.S. Forest Service, ongoing). Many streams may be better buffered against air temperature increases than previously appreciated due to site-specific non-climatic factors, such as groundwater inflow rate, adjacent land use, and stream shading. For example, Bogan et al. (2003) found that the water inflows of almost 10% of streams were dominated by cold water inputs from groundwater aquifers. Other studies show that the relationship, or lack thereof, between air and water temperatures may not be so clear cut. For example, Mohseni and Stefan (2003) found a roughly constant increase of water temperature with air temperature up to $20^{\circ}C$, but, beyond that temperature, water temperature increased more slowly with air temperature thereafter (Manomet & NWF 2013b).

While climate change may not have such drastic effects as previously predicted on coldwater fish populations in the Northeast, lower elevation and southern streams will likely be affected, and "traditional stressors," which have already resulted in significant habitat losses, will continue to exert their effects. The cumulative impacts of climate change and other stressors might result in rates of habitat loss for fish populations that are greater than previously experienced. All of the projections about vulnerabilities need to be considered, however, against the backdrop of major uncertainties about adaptive capacity. These factors are particularly relevant to Maryland given the state's more southern location relative to northeastern states (Manomet & NWF 2013b).

Wildlife Responses to Climate Impacts with a Focus on Regional Species of Greatest Conservation Need (RSGCN)

(includes text excerpted from Morelli et al. 2015)

Summary

- Climate change will have cascading effects on ecological systems.
- These changes are expected in shifts of timing, distribution, abundance, and species interactions.
- Some wildlife groups, including montane birds, salamanders, cold-adapted fish, and freshwater mussels, could be particularly affected by changes in temperature, precipitation, sea and lake levels, and ocean processes.
- Interspecific interactions and land use change could exacerbate the impacts of climate change.
- A focus on habitat connectivity, water quality, and invasive species will increase resilience for wildlife populations in the face of climate change.

The objectives of this section are to summarize how regional biodiversity has already responded and is expected to respond to climate change; summarize information on specific RSGCN species responses to climate change to date and anticipated under future scenarios; characterize the greatest uncertainties about how biodiversity and RSGCN species will respond to climate change in the future; and highlight where other factors are expected to exacerbate the effects of climate change. This information was obtained by Morelli et al. (2015) through a systematic review of the peer-reviewed literature, primarily using the Web of Science to search for papers on each species related to "climate," "temperature," or "precipitation." Though some papers were undoubtedly missed, this search allows biologists to review some of the ways that climate change may affect regional species of conservation concern. The information in this section is helpful for Maryland biologists to anticipate effects of climate change on Maryland SGCN.

This section reviews the responses to climate change for the 367 Regional Species of Greatest Conservation Need (RSGCN) identified by the Northeast Fish and Wildlife Diversity Technical Committee (NEFWDTC) and technical experts from states' natural resource agencies (Appendix 3i). Of these regional species, 185 are Maryland Species of Greatest Conservation Need (SGCN). **In the following sections, those species with the common name underlined are RSGCN, and those with an asterisk (*) are Maryland SGCN. Additional species are included because of their impacts on natural systems or because of likely climate change impacts.**

Introduction

As previously stated, Maryland is experiencing climate changes that may have cascading effects on ecological systems. Some wildlife species are already responding to these changes with distribution shifts northward, upslope, upstream, and to deeper depths (Staudinger et al. 2013; Melillo et al. 2014). Interdependent species will likewise shift, adapt in place, or be unable to cope with the changes; some shifts will not be synchronized, as species respond to different cues at different rates. For some species, shifts could be hindered by a lack of habitat connectivity or other barriers that prevent movement or adaptation. Increased disturbance related to climate change could increase establishment of invasive or pest species. Changes in species abundance and distribution are more likely to occur at the edge of a species range than in its center (Trumbo

et al. 2011; Morelli et al. 2012). All of these factors combined will likely result in community turnover, with novel species assemblages, including complex interactions between species and new predators (Herstoff & Urban 2014). Given Maryland's location in the mid-Atlantic region, and resultant animal and plant communities with affinities both north and south of the state, biologists predict that communities in Maryland will change with a changing climate in both expected and unexpected ways.

Vertebrates
Mammals

Small Mammals
Small mammals play an important role in their respective ecosystems as seed and fungal spore dispersers and prey for birds and other mammals. They also have the potential to play an important role in climate adaptation, particularly in more arid ecosystems, where they can mediate vegetation change (Curtin et al. 2000). These roles may be affected by the shifting patterns of precipitation and temperature across the United States. Many small mammals in the Northeast and Midwest regions have broad temperature tolerances. Thus, climate change will likely be mediated through indirect effects on their life history and distribution. For example, the American red squirrel (*Tamiasciurus hudsonicus*), an important predator on eggs and nestlings in the spruce-fir ecosystem of northern New England and the upper Midwest, appears to be expanding its range upslope (T.L. Morelli, unpublished data), possibly in response to reduced snowpack or greater food availability. However, there are examples of geographically-limited species that could be highly vulnerable to warming temperatures, such as the Allegheny woodrat* *(*Manjerovic et al. 2009).

Precipitation patterns can also drive small mammal abundance and distribution in response to climate change. For example, smoky shrews* move more when it rains, especially in dry environments (Brannon 2002). Star-nosed moles (*Condylura cristata*) are dependent on rain events for dispersing, and thus may be adversely affected in areas where rainfall events are projected to become less common (McCay et al. 1999). Extreme events can also have a detrimental effect on small mammal populations, and thus overall diversity, by favoring particular species (Pauli et al. 2006).

Not all effects of climate change will be negative. The New England cottontail (*Sylvilagus transitionalis*) may benefit from decreased snow cover and forest disturbance in the Northeast. But indirect effects through changing relationships with other species such as predators and competitors are hard to predict. For example, if climate change affects eastern cottontail species positively, there may be increased competition between New England cottontails and other eastern cottontail species (Fuller & Tur 2012). If so, the Appalachian cottontail* in Maryland may be adversely affected and shift northward as this species prefers cooler microclimates than the eastern cottontails.

Northern flying squirrels* are an example of a species threatened by the indirect effects of climate change. Their northern forest habitat is shifting northward (Iverson et al. 2008). Moreover, climate change may decrease the fungi and lichen that are important food sources for the northern flying squirrel*. Most notably, habitat and temperature changes are already allowing

southern flying squirrels (*Glaucomys volans*) to expand northward, with a subsequent decline of northern flying squirrels* associated with disease transmission and competition (Smith 2012). Furthermore, climate-induced hybridization was detected between southern flying squirrels and northern flying squirrels* in the Great Lakes region and Pennsylvania as a result of increased sympatry after a series of warm winters (Garroway et al. 2010).

Bats

Climate change induced habitat loss may lead to decreasing wildlife diversity, including bat species. For example, hoary bats* in the Northeast have been known to roost in eastern hemlock (*Tsuga canadensis*) trees (Veilleux et al. 2009). The eastern hemlock, however, is expected to be substantially reduced by the hemlock woolly adelgid, a tree pest increasing in population size and distribution due in part to climate change (Paradis et al. 2008). While hoary bats* in Maryland are not known to roost in eastern hemlock (D. Limpert, MD DNR, pers. comm.), the loss of this important habitat could be devastating to some regional populations.

Increasing climate variability may have a large effect on some bat species, with both increases and decreases in precipitation having potentially negative impacts. Some species, such as big brown bats* (O'Shea et al. 2011), have shown higher mortality in response to the extreme droughts that may increase in the future. Lower weight gain for juvenile and adult female big brown bats* was associated with years of lower rainfall and higher temperatures in the spring and summer (Drumm et al. 1994). Decreased summer precipitation may even lead to higher mortality (e.g., little brown myotis*, Frick et al. 2010).

On the other hand, increases in precipitation at the right time may bode well for insectivorous bat species (Moosman et al. 2012). Climate change may increase riparian habitat in some areas of the Northeast and Midwest in coming decades, which has been shown to be important for bat foraging (e.g., hoary bats* and big brown bats*; Menzel et al. 2005). Even heavy rains in spring may have a positive effect on reproduction, as shown in big brown bats* in Indiana, which otherwise seemed resilient to natural fluctuations in climate (Auteri et al. 2012).

The eastern red bat* is an example of a species that may be expanding its range in response to climate change, in this case into Canada (Willis & Brigham 2003). Bats are not as active in very cold climates and thus may begin to become more active in the future. However, cold-adapted species at the southern edge of their distribution, like the eastern red bat*, might disappear out of the Northeast and Midwest (Arndt et al. 2012). Increased temperatures have also been shown to have a negative effect on northern long-eared bat* (Johnson et al. 2011).

Disease is an important consideration when discussing bats in the Northeast and Midwest. The connection between white-nosed syndrome and climate change is still unclear, but warming climates could ultimately reduce vulnerability of little brown myotis* and other bats to this cold-adapted fungal pathogen (Ehlman et al. 2013).

Carnivores

Generalist species like the coyote (*Canis latrans*) are more likely to persist during periods of rapid environmental change than specialist species (Malcolm et al. 2002; Koblmüller et al. 2012). Martínez-Meyer et al. (2004) found that climatic variables were poor predictors of coyote

distributions through past periods of climate change and suggested that distributions were determined by factors not directly related to climate. Effects of climate change on abundance are unclear, although coyote abundance is typically tied to the abundance of its prey species (Todd & Keith 1983; Knowlton & Gese 1995; O'Donoghue et al. 1997). An observed trend toward greater coyote abundances at lower latitudes has been interpreted by some as resulting from greater food availability in the southern U.S. during the critical winter months (Windberg 1995). If this interpretation is correct, milder winters may result in higher abundances in the Midwest and Northeast. However, as with many other carnivores in the region, potential climate-related impacts on coyote abundance will likely depend upon climate-related impacts on prey species abundances (Morelli et al. 2015).

Marine Mammals
Not much is known about how most marine mammals are responding to climate change, although one study predicted that warming oceans and changes in sea ice cover would affect distributions, including decreases in pinniped and cetacean richness at lower latitudes and potential increases in cetaceans at higher latitudes (Kaschner et al. 2011).

Whales will likely be affected by several indirect changes in the oceans. For example, climate and oceanographic change is expected to affect habitat and food availability of sei whales*; migration, breeding locations, and prey availability are influenced by ocean currents and water temperature (National Marine Fisheries Service 2011). For baleen whales, loss of sea ice may lead to a decrease in krill populations; a severe decrease has been modeled for blue whale* populations (Wiedenmann et al. 2011). Furthermore, climate change may be leading to hybridization in blue whales* and other species (Attard et al. 2012). On the other hand, changes in prey populations are correlated with increases in some populations. Northern right whales* have increased over the last decade, apparently in response to increased populations of their primary copepod prey in the Gulf of Maine, which in turn is likely due to changes in large-scale climate-related circulation patterns (Meyer-Gutbrod & Greene 2014), although this trend is confounded by population expansion as protection has aided recovery.

Other Mammals
American beavers (*Castor canadensis*) are habitat specialists, requiring streams with gentle gradients and at least intermittent flow and lakes or ponds with standing water (Howard & Larson 1985; Baker & Hill 2003). Climate projections for the Northeast and Midwest generally predict that increased temperatures will lengthen the growing season and increase the frequency of short-term drought and decreased soil moisture, resulting in some reduction of suitable habitat for beavers. If so, decreases in beaver populations could exacerbate climate effects as the presence of beavers has been associated with increased groundwater recharge, higher summer stream flows, and refugia for cold-adapted species such as some amphibians (Gurnell 1998; Westbrook et al. 2006; Popescu & Gibbs 2009).

Birds
The Climate Change Bird Atlas (Matthews et al. 2007, 2011) is an interactive database that generates the current status and potential future status considering effects of climate change of 147 birds in the eastern United States. This model uses Breeding Bird Survey data with 11 environmental variables and 88 tree species to create the models of current suitable habitat for

each species. Climate model scenarios were then applied to model potential future habitat. The results for birds that occur in Maryland are found in Appendix 6e (Morelli et al. 2015).

Grassland Birds

Changing precipitation regimes could have large effects on grassland bird populations. One study found that grasshopper sparrow* densities were positively correlated with May precipitation (Ahlering et al. 2009). Climate appears to drive the abundance of at least some grassland bird species, especially the grasshopper sparrow* but also the bobolink*, Henslow's sparrow*, sedge wren*, and upland sandpiper* (Thogmartin et al. 2006).

A study of the effect of a drought in North Dakota on grassland birds showed a decline in species richness and abundance, with detrimental (although primarily short-term) effects on nearly all species studied, including grasshopper sparrow*, upland sandpiper*, mourning dove (*Zenaida macroura*), eastern kingbird (*Tyrannus tyrannus*), field sparrow (*Spizella pusilla*), vesper sparrow*, and brown-headed cowbird (*Molothrus ater*) (George et al. 1992). On the other hand, forest loss due to drought may cause grasshopper sparrows* to increase across the eastern United States (Naujokaitis-Lewis et al. 2013). Similarly, northern bobwhite* will likely increase in the Midwest and parts of the Northeast as pine woodland and savanna replace a number of hardwood forests (Matthews et al. 2007; Rodenhouse et al. 2008).

Forest Birds

Perhaps best studied is the effect of climate change on forest-dwelling birds of the order Passeriformes. The effects of changing temperature and precipitation regimes will have many impacts on passerines. First, in a taxa group known for its seasonal migrations, one of the biggest concerns is phenological mismatch, with food and habitat available at different times than those to which the species was formerly cued. Studies have shown that birds today are arriving earlier to their breeding grounds across the northern U.S. (Butler 2003; Marra et al. 2008; Wilson 2013). Wood thrush* and Louisiana waterthrush* have advanced their arrival times in the Northeast over the last century (Butler 2003). The scarlet tanager* has been shown to be vulnerable to shifting seasons and mistiming of spring migration (Zumeta & Holmes 1978). Black-throated blue warblers* studied in New Hampshire initiated breeding earlier in warmer springs, with early breeders more likely to have a second brood, leading to higher reproductive rates (Townsend et al. 2013). Non-passerine migratory species are also affected. American woodcock* distribution has expanded in recent decades, possibly in response to climate change (Thogmartin et al. 2007), and this short-distance disperser has begun arriving to its breeding grounds earlier in the spring in the Northeast (Butler 2003). Climate variability could exacerbate problems with timing. For instance, late spring storms and extreme weather events have been shown to kill migrating birds (Zumeta & Holmes 1978; Dionne et al. 2008).

On the other end of the breeding season, a study in Rhode Island showed that some birds are departing later in the autumn, including the black-and-white warbler*, blackpoll warbler (*Dendroica striata*), red-eyed vireo (*Vireo olivaceus*), eastern towhee (*Pipilo erythrophthalmus*), hermit thrush (*Catharus guttatus*), song sparrow (*Melospiza melodia*), yellow-rumped warbler (*Dendroica coronata*), gray catbird (*Dumetella carolinensis*), veery*, white-throated sparrow (*Zonotrichia albicollis*), and the ruby-crowned kinglet (*Regulus calendula*) (Smith & Paton 2011).

Birds may also be affected by climate change through shifts in habitat. The Canada warbler*, for example, is projected to shift its distribution northward as the boreal and northern hardwood forest types that it inhabits shift northward, with the most severe model projections showing complete extirpation from the northeastern U.S. (Rodenhouse et al. 2008). Likewise, the Bicknell's thrush* is expected to contract its U.S. range by more than half as temperatures increase and its habitat subsequently shifts northward. Similar negative trends are expected for other birds that inhabit the montane spruce-fir forest of the Midwest and Northeast at the southern edge of their range, including ruby-crowned kinglet, blackpoll warbler, spruce grouse (*Alcipennis canadensis*), three-toed woodpecker (*Picoides tridactylus*), black-backed woodpecker (*P. arcticus*), yellow-bellied flycatcher (*Empidonax flaviventris*), gray jay (*Perisoreus canadensis*), boreal chickadee (*Poecile hudsonica*), and white-winged crossbill (*Loxia leucoptera*) (Rodenhouse et al. 2008). The blue-headed vireo (*Vireo solitarius*) is predicted to decline 6% to 8% across its range within the next 50 years due to shifts in its conifer habitat (Rodenhouse et al. 2009).

The 2010 Northeast Landscape Capability Dataset for blackburnian warbler* depicts the potential capability of the landscape throughout the northeastern U.S. to provide habitat for this species based on approximate 2010 environmental conditions. Landscape capability (LC) integrates factors influencing climate suitability, habitat capability, and other biogeographic factors affecting the species prevalence in the area. All locations are scored on a scale from 0 to 100, with a value of 0 indicating no capacity to support the species and 100 indicating optimal conditions for the species. The blackburnian warbler* is predicted to have a 71% reduction in LC in the Northeast by 2080 (Figure 6.8). In contrast, the eastern meadowlark* is expected to maintain its population throughout most of its northeastern U.S. extent through 2080 (Figure 6.9).
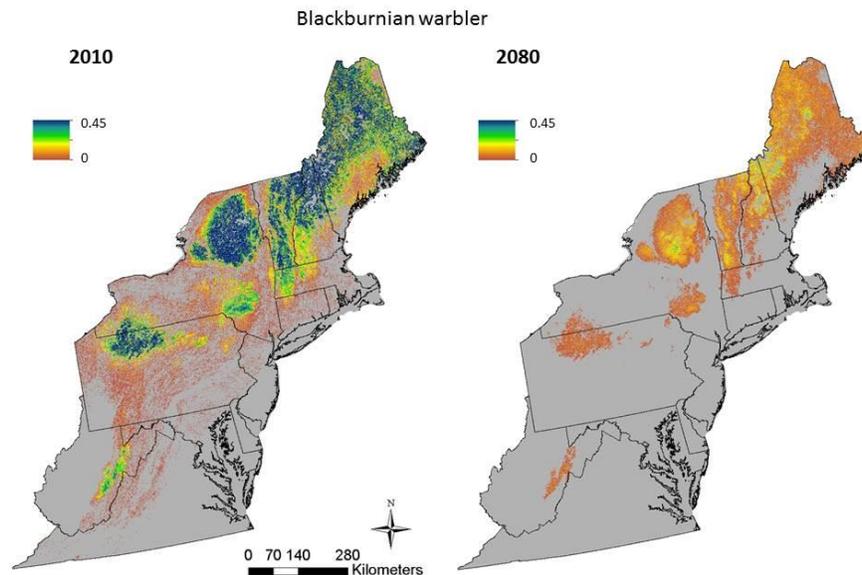

Figure 6.8 Change in landscape capability (LC) from 2010 to 2080 for the blackburnian warbler.
Source: 2010 Northeast Landscape Capability Dataset.
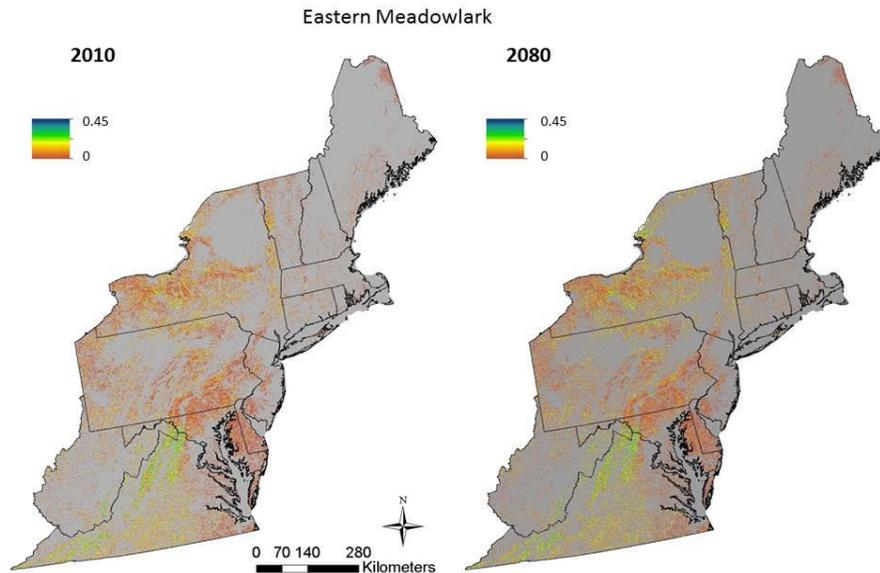
Figure 6.9 Change in landscape capability (LC) from 2010 to 2080 for the eastern meadowlark.
Source: 2010 Northeast Landscape Capability Dataset.

On the other hand, species like the black-throated green warbler* may remain stable due to more flexible habitat use and large population size, despite potential negative impacts from habitat change driven by increasing temperatures and forest pests, as well as mismatched phenology (Cullen et al. 2013). Some species may see positive impacts of climate change, such as the eastern wood-pewee (*Contopus virens*), which has been arriving earlier in the spring and is expected to increase in abundance in response to precipitation and other climate changes (Rodenhouse et al. 2008). Similarly, the hooded warbler* may increase in abundance in the Northeast and Midwest, especially along the northern edge of its range. Likewise, species that depend on early successional habitat may see increases due to climate change-induced increases in disturbance (Cullen et al. 2013).

Populations of ruffed grouse* have been declining in much of the eastern U.S. as early successional habitats have given way to mid-aged and mature forest (Blomberg et al. 2009). The distribution of this species is closely associated with the distribution of quaking aspen *(Populus tremuloides)* (Kubisiak 1985), and population densities are typically high in this forest type (Dessecker et al. 2007). Declines in quaking aspen due to climate change, reduced logging, and forest succession could lead to declines in ruffed grouse* populations compared to recent centuries (Iverson et al. 2008; Worrall et al. 2013). Moreover, snow cover can be important for overwinter survival in ruffed grouse*, as they will burrow into deep soft snow during cold winter periods (Whitaker & Stauffer 2003). Warming temperatures will likely change snow quantity and characteristics, such as crusting conditions, making snow roosting more difficult. Models predict that, over the long term, climate change will greatly reduce the proportion of the Northeast that is capable of supporting ruffed grouse* (Matthews et al. 2007; DeLuca & McGarigal 2014). Studies of ruffed grouse* also highlight a cascading effect of climate change: plants may produce more chemical compounds to defend themselves from being consumed and

become less nutritious with warming temperatures, posing an increasing threat to the birds that consume them (Buskirk 2012).

Complex interspecific interactions must also be considered. Black-billed cuckoo (*Coccyzus erythrophthalmus*), for example, feeds primarily on gypsy moth caterpillars, which are expected to increase in abundance with climate change (Cullen et al. 2013). Cuckoo nest parasitism of other species could increase as a result. Likewise, competitive interactions could exacerbate or even drive species shifts. For instance, if climate change causes Carolina chickadees (*Poecile carolinensis*) to expand northward, black-capped chickadees (*P. atricapillus*) may see a significant range reduction due to competitive exclusion (Wilson 2012). A study by Cox et al. (2012) highlighted the complex effects of climate change; they found an interaction effect of temperature and forest cover on the productivity of the Acadian flycatcher* and the indigo bunting (*Passerina cyanea*). Higher temperatures were correlated with lower productivity due to increased nest predation by snakes, but only in areas with higher forest cover, which otherwise had higher productivity. Greater forest cover resulted in greater productivity because of reduced brood parasitism and increased nest survival, whereas greater temperatures reduced productivity in highly forested landscapes because of increased nest predation but had no effect in less forested landscapes. Climate change can also reduce access to prey through phenological mismatch. For instance, aerial insectivores like flycatchers may see food shortages due to climate change (Nebel et al. 2010).

Land use change is an important consideration for projecting changes of populations into the future. Dramatic geographic shifts upslope and northward are projected for the hooded warbler* (Sohl 2014), which seems to already be shifting its breeding distribution north in response to climate change (Melles et al. 2011). Land use change models predict diverse local-scale changes in habitat suitability; for example, development around the Great Lakes is a limiting factor for range expansion for this species and others (Naujokaitis-Lewis et al. 2013).

Wetland Birds
Precipitation and percentage of wetland area, which are affected by climate change, are good predictors of abundance for many bird species, including the black tern (*Childonias niger*) and the marsh wren* in the Prairie Pothole region of the northern Great Plains (Forcey et al. 2014). The black tern, American bittern*, American coot (*Fulica americana*), pied-billed grebe*, and sora*, five waterbird species common to the region, are projected to lose significant parts of their range; in some cases, such as for sora* and black tern, this loss could be up to 100% (Steen & Powell 2012). The Prairie Pothole region of the Midwest and Great Plains is an area characterized by a high density of shallow wetlands that produces 50-80% of the continent's ducks (Sorenson et al. 1998). Climate models project increased drought conditions for this region, resulting in northward shifts in breeding distributions, with the potential for dramatic reductions in overall waterfowl populations (Sorenson et al. 1998). In addition, loss of pothole wetlands through drying can concentrate predators, which would have a greater impact on birds nesting in the remaining potholes. Duck production has been shown to vary greatly from year to year due to changes in the area of wetlands in this region linked to variable weather patterns (Klett et al. 1988).

Typical responses to drought conditions in waterfowl include decreased frequency of breeding and re-nesting, decreased clutch sizes, shortened breeding season, and other responses that depress production (Davies & Cooke 1983; Krapu et al. 1983; Cowardin et al. 1985; Sorenson et al. 1998). Dramatically reduced duck populations could potentially reduce the number of birds that migrate throughout the rest of the country. For example, although the blue-winged teal* breeds from coast to coast, its distributional center is located in the Prairie Pothole region of the Northern Great Plains. Changes in migration timing are also likely and have already been documented for this species in Massachusetts and New York (Butler 2003).

Climate variability is expected to increase in the Northeast and Midwest, with more precipitation coming in fewer events. Rainfall has been shown to have a negative effect on nest abundance in herons and egrets in San Francisco, especially in particularly wet or particularly dry years, (Kelly & Condeso 2014). The rusty blackbird* has retracted its continental range northward by over 100 km since the 1960s, and its presence is correlated with cyclical climate patterns, indicating climate change is having a strong negative effect on this once common species (McClure et al. 2012).

Coastal Birds

Many bird species, such as wading birds, are dependent upon coastal habitats that may be reduced as sea level rises and interacts with nearshore development (National Wildlife Federation and Manomet Center for Conservation Sciences 2014). In addition to direct habitat loss from sea-level rise, changes in precipitation and increased temperatures could lead to salt accumulation in soils and less productive habitat, ultimately resulting in reductions in suitable bird habitat (Woodrey et al. 2012). However, the areal extents of some tidal flats are projected to increase, which may benefit some shorebirds and other waterbirds.

Piping plovers* have been well-studied in the context of climate change impacts on coastal environments. They appear to have low adaptive capacity (Saunders & Cuthbert 2014). Projections indicate that populations of this beach-nesting shorebird will lose critical nesting habitat due to the dual pressures of sea-level rise and urban development (Seavey et al. 2011; National Wildlife Federation and Manomet Center for Conservation Sciences 2014). Sea-level rise and urban development together could result in loss of habitat for salt marsh wildlife as well (Thorne et al. 2012). These effects are exacerbated by the nutrient enrichment that often accompanies development, which can eventually cause community shifts (Woodrey et al. 2012). As fresher marshes convert to brackish or salt marshes with increasing salinity, least bitterns* may become less common, although clapper rails (*Rallus longirostris*) and seaside sparrows* could benefit (Rush et al. 2009).

The saltmarsh sparrow* is another species that has been investigated extensively for its response to climate change. DeLuca and McGarigal (2014) predict that landscape capability in the Northeast, based on climate change, will have a 59% reduction for this species by 2080. This sparrow seems particularly sensitive to sea-level rise and storm events, with nest failure strongly linked to increased flooding (Bayard & Elphick 2011). Similarly, common loon (*Gavia immer*) occurrence is predicted to decrease significantly with climate change as sea-level rise reduces the availability of the black spruce-related habitat the species prefers (Rodenhouse et al. 2008, 2009).

Extreme events, specifically severe winter storms, could cause increased mortality for the great blue heron*, <u>little blue heron*</u>, <u>snowy egret*</u>, <u>tricolored heron*</u>, and green heron (*Butorides virescens*) (DuBowy 1996). Drastic fluctuations in annual precipitation have been shown to influence the mechanism by which watershed development impacts coastal waterbirds (Studds et al. 2012). In addition, increasing frequency and intensity of coastal storms and surges could negatively impact shorebirds, but they could also create new habitat (Cohen et al. 2009). The more intense hurricanes expected due to climate change could disturb foraging and nesting habitat for shore and marsh birds, which can have both negative and positive effects (Woodrey et al. 2012).

In addition to effecting habitat availability, climate change can shift the timing of prey availability through direct effects of climate change on prey species abundance and distribution. For example, a climate-change driven decrease in horseshoe crabs is causing a decrease in <u>ruddy turnstones*</u>, with interacting effects related to the avian influenza virus (Brown & Rohani 2012).

Raptors
Raptors are showing responses to climate change as well. Precipitation and percentage of wetland areas are the best predictors of the abundance of the <u>northern harrier*</u>. A study of six raptor species (<u>northern harrier*</u>, <u>American kestrel*</u>, <u>golden eagle*</u>, prairie falcon, red-tailed hawk, and rough-legged hawk) have shown significant poleward shifts in their wintering distributions since 1975 (Paprocki et al. 2014). Raptors also appear to be arriving earlier in the spring and leaving later in the autumn from their breeding grounds (Buskirk 2012).

Some raptors may be positively affected by climate change. A study in the western U.S. showed that <u>American kestrel*</u>migration distance decreased significantly over the last half century and that earlier nesting, and thus higher reproductive success, appeared to be driven by warmer winters (Heath et al. 2012). In addition, the <u>northern goshawk*</u> has also been shown to have high tolerance to windstorm damage (Penteriani et al. 2002), which may become more common with more intense storms in the Northeast and Midwest (Morelli et al. 2015).

Reptiles

Freshwater Turtles
Freshwater turtles will be affected by climate change in a variety of ways, mostly due to effects on water temperature and flow. For example, climate change and land conversion can act synergistically to decrease habitat for <u>bog turtles*</u> (Feaga 2010). A study of <u>wood turtles*</u> in Massachusetts showed that floods displaced nearly half of the subpopulation annually, elevated mortality rates, and decreased breeding success. Floods are expected to intensify and become more common; impervious surfaces and hardening of upstream riverbanks may be amplifying these effects (Jones & Sievert 2009). In contrast, <u>map turtle*</u> hatchlings would be expected to emerge earlier in the spring with increasing temperatures and rain events (the triggers for emergence), resulting in higher survival (Nagle et al. 2004).

Population sex ratio determination is an important consideration in turtles, as it is driven by temperature. Thus, there is concern that populations will begin to be artificially skewed toward more females or more males, depending on the life history of the particular species and location

of the population. Experimental manipulation has shown a lack of adaptive capacity to compensate for sex ratio bias due to warming nest temperatures in some species (Refsnider et al. 2013). However, other studies have pointed out that the amount of atmospheric warming required to raise nest temperatures enough to affect sex ratio is not expected until late in the century, at least for eastern box turtles* (Savva et al. 2010).

Sea Turtles

Sex ratio bias is also a concern for sea turtles. For example, the sex ratio of some sea turtle populations (e.g., green sea turtles*), is increasingly female-biased correlated with increasing temperatures (King et al. 2013). Sea turtles have shown other responses to climate change. Experiments have demonstrated that loggerhead sea turtle* hatchling survivorship and locomotive abilities are reduced when incubated at higher temperatures designed to mimic future higher sand temperatures (Fisher et al. 2014). In addition, the loggerhead sea turtle is advancing the timing of nesting as temperatures increase (Lamont & Fujisaki 2014). However, some turtles, such as leatherback turtles*, are showing the opposite pattern (Neeman et al. 2015).

Snakes

A few studies indicate that climate change could negatively affect snakes as well. Extreme precipitation events might result in negative effects on snakes. For example, after a year with exceptionally high summer rainfall, a skin infection caused significant mortality in New Hampshire's timber rattlesnake* population (Clark et al. 2011). On the other hand, higher temperatures can increase the activity patterns, and perhaps the survival rates, of ectotherms such as snakes (Sperry et al. 2010; Cox et al. 2012).

Amphibians

Amphibians are often considered indicators of ecosystem health due to their sensitivity to their surroundings, as well as their use of both terrestrial and aquatic environments. They have also been a taxon in global decline over the last decades (Adams et al. 2013). Rising temperatures alone are not the greatest climate change-related threat to this ectothermic taxa; rather, decreases in regular rain and standing water will negatively affect many amphibian species that need standing water for reproduction (Araújo et al. 2006). One study in North Carolina showed that the eastern tiger salamander* and southern leopard frog (*Rana sphenocephala*) declined with a 30-year drying trend, raising concerns for certain areas of the region by the end of the century. On the other hand, the marbled salamander (*Ambystoma opacum*) increased in abundance during this time (Daszak et al. 2005). Stream salamanders have been particularly well studied, primarily focusing on habitat fragmentation and issues other than climate change. A study at a wetland site in South Carolina showed that the marbled salamander, an autumn-breeding species, arrived at a wetland significantly later in recent years; whereas, the winter-breeding eastern tiger salamander*, arrived significantly earlier (Todd et al. 2010).

Direct effects of changes in precipitation have been studied in salamanders. For example, spring salamander (*Gyrinophilus porphyriticus*) abundance at a site in New Hampshire was negatively correlated with annual precipitation; increasing precipitation appears to be causing a decline in adult recruitment, possibly through mortality of metamorphosing individuals during spring and fall floods, which have increased in volume and frequency with the increase in precipitation (Lowe 2012). Studies of microhabitat and seasonal habitat use can indicate the probable effects

of climate change. For example, cave ambient temperature and relative humidity, factors that will be affected by climate change, were found to affect the seasonal and spatial pattern of two species of salamander in caves in Arkansas (Briggler & Prather 2006).

Climate change may also play a role in amplifying the spread of amphibian diseases such as chytridiomycosis, a disease caused by the infectious *Batrachochytrium dendrobatidis* fungus. Scientific studies have indicated that climate change may impact chytrid-related disease by shifting temperatures in regions inhabited by sensitive amphibian species towards a "thermal optimum," or a temperature at which the chytrid fungi are able to survive and reproduce (Pounds et al. 2006; Bosch et al. 2007). While research continues to develop on the subject of climate-related epidemics, scientists posit that different regions will exhibit different interactions between amphibians and chytrid-related diseases, depending on numerous climatological and environmental factors. However, the links reported so far emphasize the dangerous tendency of climate change to intensify existing threats (Lips et al. 2008).

Despite all of these changes, salamanders are expected to have some capacity to adapt to climate change. One study found that although drought negatively affected larvae, high survivorship of adult northern dusky salamanders (*Desmognathus fuscus*) during drought likely buffers this effect. Moreover, movement around the landscape in response to drought conditions allows adult salamanders to be resilient to these climate change effects (Price et al. 2012). Furthermore, adaptive capacity to respond to variability in climate has been shown in salamanders; for example, the immune system of the eastern hellbender* seems to show compensatory effects at stressfully high temperatures (Terrell et al. 2013).

Fish

There is a better understanding of how ambient temperatures affect the survival and reproduction of fishes compared to any other taxonomic group, and thus in some ways the effects of climate change are better understood for fish than for other species (Morelli et al. 2015).

Freshwater Fish

Warming water temperatures could influence activity levels, consumptive demands, growth rates, interspecific interactions, and the amount of suitable habitat available for freshwater fish. Adaptability to changing water temperature is expected to vary among species. One of the most studied species of freshwater fish in the Northeast is the brook trout*, a riverine fish adapted to cold temperatures (Shuter et al. 2012). Although there is concern that climate change will cause rivers to increase to temperatures beyond the thermal tolerance of this species, some studies show that the story is more complicated. For example, different brook trout* populations have different temperature tolerances, and refugia resulting from groundwater inputs and riparian cover can locally buffer the effects of increasing temperatures (Argent & Kimmel 2013), potentially allowing for adaptive capacity in the species (Stitt et al. 2014). The temperature sensitivity of this native trout is compounded by competition with introduced and native species. One study indicated that competition for prey and thermal refugia constrains growth (Petty et al. 2014). On the other hand, American brook lamprey* may have some ability to adapt to warming temperatures. The species was found to spawn a month earlier than the historical norm during a warm year in southeastern Minnesota (Cochran et al. 2012), although the effects of this phenomenon on the food web are unknown.

Shifting the timing of important life history events (e.g., morphological development) may disrupt temporal overlap between predators and prey (Winder & Schindler 2004). In recent years, larval yellow perch (*Perca flavescens*) in Oneida Lake, New York, attained a length of 18 mm earlier, correlated with above average May water temperatures (Irwin et al. 2009). Beyond intrinsic physiological thermal limitations, the compounding influences of habitat fragmentation and land conversion are negatively impacting some fish populations (Argent & Kimmel 2013; National Wildlife Federation & Manomet Center for Conservation Sciences 2014).

Changes in community structure can also be caused by extreme events, stemming from or exacerbated by climate change (van Vrancken & O'Connell 2010; Boucek & Rehage 2014). A population of slimy sculpin (*Cottus cognatus*), a cool water-adapted species with low mobility, declined significantly as a result of a mid-winter ice break-up and the associated flood and ice scour disturbance it caused (Edwards & Cunjak 2007).

Diadromous Fish

A future of warmer temperatures, higher salinity, lower dissolved oxygen, increasing ocean acidification, and changing water currents are all expected to strongly impact migratory fish populations (Kerr et al. 2009). These factors are expected to negatively impact food availability for catadromous eels (Knights 2003). For example, declines in the Northern Hemisphere of the larval stage of American eel* (*Anguilla rostrata*), known as glass eels, are hypothesized to be tied to a climate-driven decrease in ocean productivity and thus food availability during early life stages (Bonhommeau et al. 2008).

Changes in precipitation and stream flow are closely linked to the reproductive success of anadromous species that return from the sea to their natal rivers to breed. Atlantic coast studies have shown that water temperature and discharge affect year-class strength of American shad* populations (Crecco & Savoy 1984). Temperature appears to cue the northward movement of this species for spawning, as well as the migration of smolts; climate change is already altering migration timing (Kerr et al. 2009).

Coastal/Marine Fish

Increasing temperatures will likely act in conjunction with low dissolved oxygen and prey availability to decrease growth and reproduction in some coastal and marine fish species (Kerr et al. 2009). For instance, the winter flounder (*Pseudopleuronectes americanus*) could be negatively affected by climate change because it has poor recruitment in warm years in New Jersey, an occurrence that is potentially related to predator response to temperature (Able et al. 2014). Likewise, winter flounder growth and survival rates were lower in sites with low dissolved oxygen levels in New Jersey and Connecticut tidal marsh creeks (Phelan et al. 2000). Phenological changes and increased predation on this species have been seen in Narragansett Bay over the last century, likely in response to increased temperatures, precipitation, and sea level, and associated ecological changes (Kerr et al. 2009; Smith et al. 2010).

Changes in other Atlantic coast species have been recorded as well. The growth rate of the tautog (*Tautoga onitis*) is higher at lower temperatures (Mercaldo-Allen et al. 2006). Moreover, as a reef-based fish strongly associated with structure, distributional shifts in prey species could negatively impact the tautog, which is expected to lag behind (Kerr et al. 2009). Similarly,

although the Atlantic herring (*Clupea harengus*) is expected to shift its distribution northward, predators like the Atlantic cod (*Gadus morhua*) may not be able to follow at the same pace (Kerr et al. 2009). Some species life histories are disrupted by climate variability; increases and decreases in average temperature during the spring have been shown to negatively affect the probability of capturing spiny dogfish (*Squalus acanthias*) along the Atlantic coast, although the species became more abundant in northern sites in warm years (Sagarese et al. 2014).

Whether climate change will shift the distribution or abundance of a species in a particular location often depends on whether it is at the southern or northern edge of its range limit, or whether it is in the center of its distribution. For example, a study in Maryland found that abundance of northern puffers (*Sphoeroides maculatus*) increased in association with high winter temperatures and low flows, whereas the opposite was true for the Atlantic silverside (*Menidia menidia*), Wingate & Secor 2008).

Invasive species will interact with the effects of climate change in complex ways. Zebra mussels (*Dreissena polymorpha*) have been found to increase colonization in warmer water, thus further decreasing growth and abundance of striped bass, American shad*, alewife (*Alosa pseudoharengus*), and blueback herring (*Alosa aestivalis*) (Kerr et al. 2009). Disease may also be increasingly important in marine ecosystems. Increasing temperatures, ocean acidification, and shifting precipitation regimes may be increasing susceptibility to outbreaks and the dynamics of pathogens. For example, mortality in the longhorn sculpin (*Myoxocephalus octodecemspinoszu*) from a protozoan gill parasite increases with increasing water temperatures (Brazik & Bullis 1995). Oysters are also experiencing new disease outbreaks with warmer temperatures (Burge et al. 2014).

Invertebrates

Freshwater Mussels
Freshwater mussels (Unionidae) are one of the most imperiled wildlife groups in the Northeast and Midwest. Their habitat is already under tremendous threat from development, urbanization, and pollution. Hydropower development can have a large negative impact on freshwater mussels; many are non-migratory with limited vertical movement and rely on flood events to make large distribution shifts (Furedi 2013). In the face of climate change, dams could prevent northward and upstream migration to thermally appropriate habitat. Moreover, the increased flooding events predicted by climate change will decrease water quality, as well as displace individuals from suitable habitat. Increasing temperatures may have additional direct detrimental effects. Drought during summer could slow or eliminate critical flows (Santos et al. 2015). Additionally, mussels use fish as hosts for larval development and dispersal, often having a limited number of fish species they can parasitize. Fish hosts may themselves be negatively affected by environmental changes and will likely shift distributions at different rates than mussels. Finally, the increasing spread of zebra mussels and other invasive species will continue to negatively affect freshwater mussels (Archambault et al. 2014; Furedi 2013).

The dwarf wedgemussel* and the triangle floater* are considered extremely vulnerable to climate change. Habitat for these species is threatened by future hydropower development (Furedi 2013). The dwarf wedgemussel* populations are highly localized in areas within a

narrow band of precipitation. Thus, these populations could be disrupted by climate change, especially by the projected increased flooding in the Northeast. Dams located upstream of some triangle floater* populations could prevent movement in response to climate change. The intense precipitation predicted for the region threatens both species (Furedi 2013). Increasing stream temperatures and droughts may increase mortality, reduce burrowing capacity, and inhibit juvenile dispersal in the eastern lampmussel* (Archambault et al. 2014).

As a habitat specialist, the brook floater* is also considered extremely vulnerable to climate change. It has narrow thermal tolerances as juveniles and adults (Pandolfo et al. 2010) and is located mostly in upstream habitats; thus will have difficulty shifting in response to climate change. Increases in drought or decreases in flow will also have a detrimental impact on the species. There are similar concerns for the eastern pondmussel* along with additional concerns associated with competition from zebra mussels that may compound the impacts of climate change upon this species (Furedi 2013).

The yellow lampmussel* is considered highly vulnerable to climate change due to destruction and degradation of habitat and spreading zebra mussel populations (Furedi 2013). The green floater* is considered extremely vulnerable and is currently in decline because the calm, clearwatered upstream habitats it requires are being degraded through pollution, sedimentation, and the introduction of non-native species. Conversely, the northern lance (*Elliptio fisheriana*) seems to have higher capacity to adapt to low dissolved oxygen levels than some other species (Chen et al. 2001).

Insects

Relatively few insects that are considered species of conservation need have been studied in the context of climate change. Northeastern species thought to have high vulnerability to climate change include dragonflies like tiger spiketail* and Roger's clubtail (*Gomphus rogersi)*, (White et al. 2014). The northeastern beach tiger beetle*, federally listed as Threatened, is predicted to be negatively affected by climate change via sea-level rise and increased storm events that will lead to coastal erosion (Fenster et al. 2006). Likewise, insects associated with prairie fens like the rare butterfly, Mitchell's satyr (*Neonympha mitchellii mitchellii*), will be threatened by habitat loss due to drying of headwater streams and reduced water quality (Landis et al. 2012).

Lepidoptera will likely have particular issues with phenological mismatches in the coming decades. Caterpillars must sync their timing with food availability, which is changing. Host plants may be shifting northward in response to changing temperatures, with caterpillars potentially responding to different cues. Moreover, the food quality of leaves may be decreasing, as plants increase rates of secondary metabolites, requiring longer feeding times. Larvae could also be affected directly through increasing temperatures and changing moisture availability. Habitat specialists are expected to be most vulnerable (Keating et al. 2014).

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