CHAPTER 12

Climate Change Impacts on Florida's Biodiversity and Ecology

Beth Stys[1], Tammy Foster[2], Mariana M.P.B. Fuentes[3], Bob Glazer[4], Kimberly Karish[5], Natalie Montero[3], and Joshua S. Reece[6]

[1]Florida Fish and Wildlife Conservation Commission, Tallahassee, FL; [2]Ecological Program, Kennedy Space Center, FL; [3]Department of Earth, Ocean and Atmospheric Science, Florida State University, Tallahassee, FL; [4]Florida Fish and Wildlife Conservation Commission and Fish and Wildlife Research Institute, Marathon, FL; [5]GeoAdaptive, Boston, MA; [6]Department of Biology, California State University, Fresno, CA

Florida's rich biodiversity is the product of climatic conditions, geographic position, and underlying geology. Interactions of these factors over time have led to the state's unique biota, with Florida ranking fourth in the nation for total number of endemic species. The ability of Florida's ecosystems to support plants and animals is intimately tied to its geographic location, climatic and hydrologic variables, including timing and amount of precipitation, the frequency and intensity of storms, the range and duration of temperature extremes, and water chemistry. The ecosystems and species of Florida have adapted to past periods of climatic change. However, these ecosystems are now under stress and less resilient due to past and existing human-caused alterations and impacts, affecting their ability to withstand and adapt to additional stressors such as climate change. The overall vulnerability of some systems and species is primarily driven by the severity and extent of these non-climate stressors. Florida's biodiversity may be very different in the future, with some species and ecosystems affected to a greater extent than others. Community-level changes will occur as plant and animal species move and adapt at different rates. There are tools available to assist in determining relative vulnerability (vulnerability assessments) and potential impacts (scenario planning) that can aid in developing adaptation strategies. Awareness that change is likely to happen is critical to planning for the future and allowing for adaptation in management practices that will maximize Florida's biodiversity for future generations.

Key Messages

Climate Change Impacts on Biodiversity and Ecology

- Climate change has differential impacts on: coastal ecosystems, freshwater wetlands, and upland ecosystems. Coastal ecosystems, in particular, are subject to the "squeeze" of human impacts, changing climate, and rising sea levels.
- The Florida Keys and the Everglades are particularly vulnerable to sea level rise over the next 50 to 100 years due to their low elevation (typically less than 1 m).
- Out of 1,200 species tracked by the Florida Natural Areas Inventory, 25% are likely to lose at least half of their current habitat due to sea level rise alone.
- Florida's species have migrated and adapted to climate change in the past, but that ability is severely compromised now due largely to human modification of the landscape. Up to 76% of 236 surveyed species were deemed unlikely to be able to relocate inland in response to rising sea level.
- Several keystone species are particularly vulnerable to the impacts of climate change and the loss of these species can have cascading impacts on natural communities.
- Sea turtles are likely to respond to climate change through altered sex ratios of hatchlings, northward movements of rookeries, decreased reproductive output due to storm events, and potential shifts in foraging ground locations.

- Phenology, or the timing of life history events, are likely to change in response to climate shifts, both as the climate becomes warmer but also as it becomes more variable. This is particularly true for plants and can cause major disruptions to co-evolutionary relationships, such as those between pollinators and the plants they pollinate.

Existing Stressors and Climate Change

- Habitat loss and degradation are the leading causes of extinctions in Florida and globally. The impacts of climate change on species and natural communities are greatly magnified by decreased adaptive capacity due to habitat loss and degradation.
- Many invasive species are projected to have enhanced fitness under future climate change scenarios, potentially causing greater disruption to natural communities.
- Climate change is projected to increase the vulnerability of native species to foreign and domestic pathogens and parasites.
- Overexploited species have diminished capacity to adapt to climate change, making them especially vulnerable.

Preserving Biodiversity for the Future

- Planning for climate change involves impact assessments, adaptation scenario planning, and research and monitoring.
- While many of the ways in which species and natural communities respond to climate change are gradual, other changes can be abrupt and non-linear. These so-called thresholds, trigger points, or paradigm shifts are harder to predict, but are often more consequential than linear patterns of change through time.

Keywords

Ecosystem; Habitat; Species; Phenology; Biodiversity; Adaptation; Vulnerability Assessments; Scenario Planning

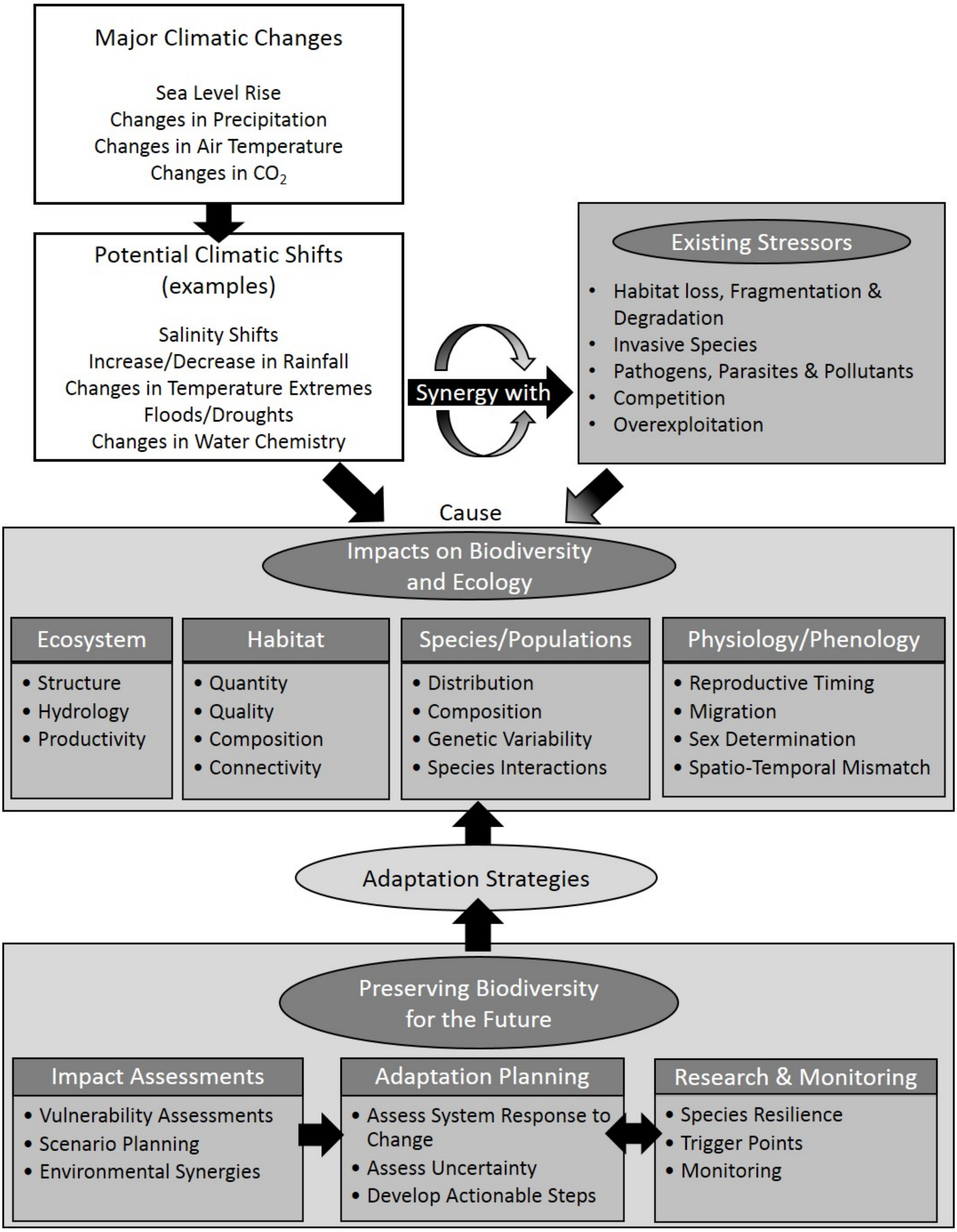

Figure 12.1. Diagrammatic illustration of this chapter showing simplified connections between major components (chapter sections). The grey boxes include overview of the chapter content, the white boxes are described in other chapters, but form the foundation of content in this chapter.

Introduction

Florida's biodiversity is extremely rich and contains a multitude of unique systems; it is identified as a "hotspot" of rare and imperiled species (Noss et al. 2015). Florida's geographic position and latitudinal range mean that the state is situated such that it encompasses both temperate and sub-tropical climate regimes, contributing to Florida's systems, communities, species diversity and distribution. Florida has the highest number of plant families, is the sixth highest in native plants species richness, has the highest number of fern species in the United States, and has the highest diversity of orchid flora and the densest concentration of carnivorous plant species in all of North America (Knight et al. 2011). Florida has more than 16,000 species of native fish, wildlife, and invertebrates, including 147 endemic vertebrate species and approximately 400 terrestrial and freshwater endemic invertebrates (Muller et al. 1989). There are currently 82 species designated as federally endangered or threatened in Florida. An additional 59 species are listed as endangered or threatened by the state, including 21 birds, eight mammals, 13 reptiles, four amphibians, nine fish, and four invertebrates (FWC 2016b). The unique scrub systems of Florida's dry, sandy ridges have the highest level of endemism for terrestrial habitats in the Southeastern United States, with more than 95 species of plants, lichens, arthropods, and vertebrates, including the iconic Florida scrub jay (*Aphelocoma coerulescens*). Coastal areas provide critical habitat for many of Florida's threatened species, including seaside sparrows, beach mice, sea turtles, beach nesting birds, and many endemic plant species. Many of Florida's rarest and most diverse communities occur as small isolated areas, such as pine rocklands, rockland hammocks, upland glades, seepage slopes, cutthroat seeps and springs (Knight et al. 2011). Florida has an extremely diverse estuarine and marine ecosystem; it is the only state in the continental U.S. with an extensive shallow reef system. The mild tropical-maritime climate of the Florida Keys provides habitats for a number of terrestrial and marine plant and animal species found nowhere else. The Florida Everglades has received international recognition and has long been recognized as one of our nation's most imperiled landscapes, included as one of 44 sites globally and one of two sites in the United States on the UNESCO List of World Heritage in Danger (Mitchell and Krueger 2011, Aumen et al. 2015). The Everglades is home to 68 threatened and endangered species (USFWS 1999). The Lake Okeechobee ecosystem is unique

Figure 12.2. Florida scrub jay. Photo by Alex Kropp

within North America, due to its large size, shallowness (the average depth is nine feet), and habitat diversity.

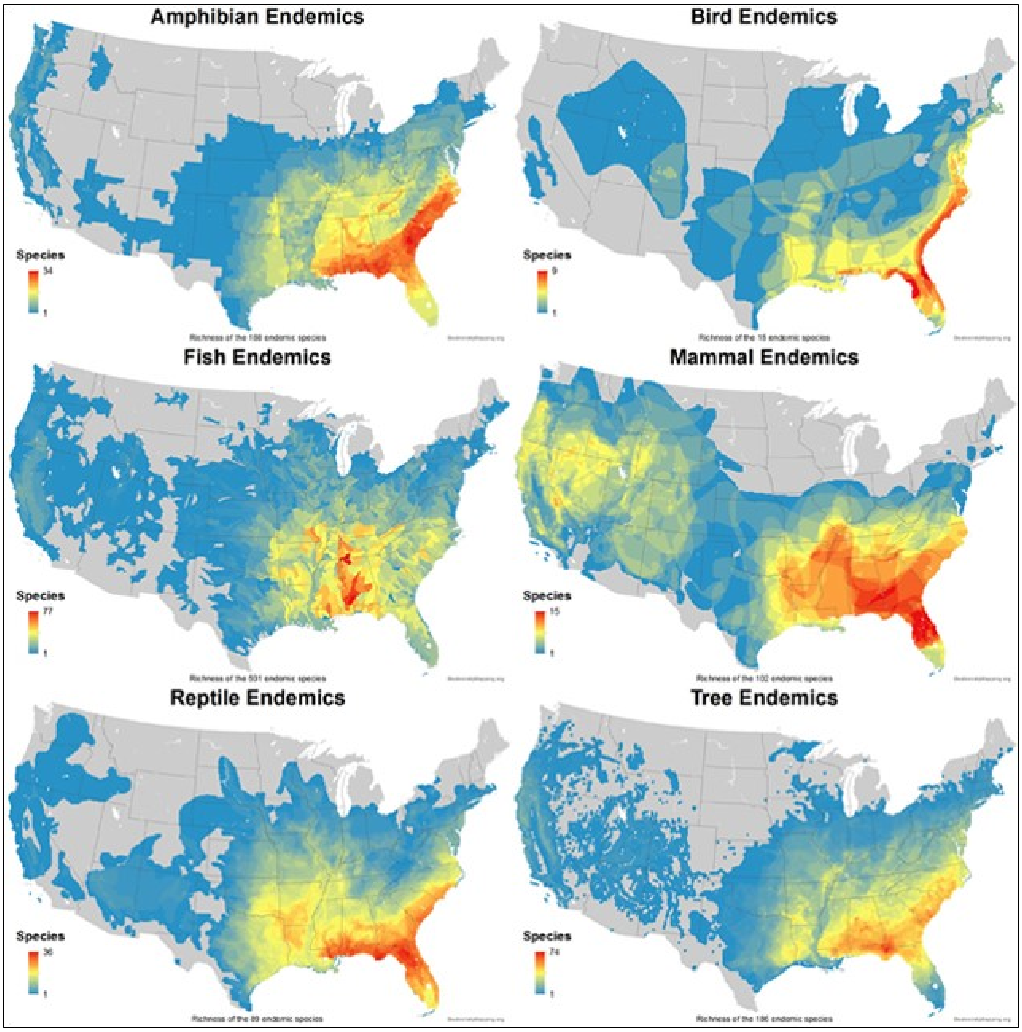

Figure 12.3. Maps of endemic species. Source: Jenkins et al. 2015.

Climate Change Impacts on Biodiversity and Ecology

Climate change is one of the most important determinants of changes in biodiversity (Sala et al. 2000; Schweiger et al. 2008). It will have impacts on biodiversity that operate at the individual, population, community, ecosystem and biome scales (Ackerly et al. 2010, Bellard et al. 2012), altering species distributions, life histories, community composition, and ecosystem function (Graham and Grimm 1990; Gates 1993; Kappelle et al.1999; Hughes 2000; McCarty 2001). The rate of climate change may become the most important feature in terms of consequences for biodiversity, potentially leading to escalating extinctions and widespread reorganizations of ecosystems, particularly where the rate of change is too fast and overwhelms the capacity of current ecosystems to adapt (Steffen et al. 2009). Those species, populations, and communities that cannot keep pace with the rate of change will be most adversely impacted (Thomas et al. 2004; Visser 2008; Ackerly et al. 2010; Bellard et al. 2012). Potential impacts on biodiversity, even under the most modest climate change scenario, will increase through most of this century (Steffen et al. 2009). Distributions of species have already been affected by climate change (Hill et al. 2001; Parmesan and Yohe 2003; Hickling et al. 2006) and it is expected that future climatic changes will have even more severe impacts (Sala et al. 2000; Thuiller et al. 2005; Araujo et al. 2006).

Climate Change Impacts on Ecosystems

The local physical geography (e.g., elevation, soil type, hydrology, climate) largely determines the type and extent of the natural communities. Florida's elevation range is extremely small, ranging from sea level to a high of approximately 107 meters. However, the subtle changes in elevation; in combination with variations in the physical geography; have led to an incredible range of ecosystems within the state. The relationships between characteristics of individual species and the surrounding environment, the role of individual species in the communities and ecosystems, the structure and function of ecosystems, and the phenomena associated with changes at all levels (genetic to biome) are important for dealing with the climate change threat to ecosystems (Steffen et al. 2009). A variety of ways exist to delineate Florida's ecosystems; for this discussion they have been divided into three groups following the divisions used by Myers and Ewel (1990): Coastal Ecosystems, Freshwater Wetlands and Aquatic Ecosystems, and Upland Ecosystems.

Coastal Ecosystems

The community structure of coastal ecosystems is governed by the tolerances of species to environmental conditions, such as light availability, temperature, moisture, disturbance, tides, water depth, salinity, and nutrient availability (Burkett et al. 2008). These systems have the natural ability to adapt to the dynamic conditions that formed and maintains them; however, these capacities are being overwhelmed by sea level rise, particularly in areas that have already been damaged by development, coastal armoring, and other activities (Anderson et al. 2016). Depending on the relative rates of sea level rise and barrier island retreat, the lagoonal area between the barrier island and the mainland may remain constant, expand, or shrink (Michener et al. 1997). Changes in wind circulation patterns and increases in wave actions due to storms will impact the interactions of sand with the pioneer grasses that build dunes. Loss of pioneer grass species and other dune vegetation likely will increase dune erosion and degradation, especially given the predicted increase in storm events. Much of the large swaths of salt marsh in Florida's Big Bend region will likely convert to open water as sea levels rise, but predicted transition of inland habitats to salt marsh will likely offset major changes in salt marsh extent. While this capacity is high in many of the undeveloped regions of the Central/North Florida Gulf Coast, that capacity is severely compromised in the heavily urbanized areas of South Florida and Florida's East Coast.

Estuarine productivity will be impacted by changes in the timing and amount of freshwater, nutrient, and sediment delivery (NFWPCAS 2012). Seagrass supports many ecological processes, including: regulation of water column dissolved oxygen; modification of the physical and chemical environments; reduction of suspended sediments, chlorophyll, and nutrients; stabilization of bottom sediments; and filtration of suspended matter (Nixon and Oviatt 1972; Short and Short 1984; Ward et al. 1984; Stevenson 1988; Koch 1996; Komatsu 1996). Changes in sea level, salinity, temperature, atmospheric carbon dioxide (CO_2), and ultra violet (UV) radiation can affect seagrass. One of the primary effects of increased temperature on seagrass will be the alteration of growth rates and other physiological functions of the plants (Short and Neckles 1999). Sea level rise and associated increases in water depth will decrease light availability and impact seagrass distribution, productivity, and structure.

The increase in sea surface temperatures (SST) associated with climate change is perhaps one of the best-documented impacts to marine ecosystems, especially in tropical coral reefs. The steady increase of global SSTs over the past century (Solomon et al. 2007) may increase susceptibility of corals to disease (Bruno et al. 2007) and often exceeds a critical threshold beyond which 'coral bleaching' occurs (Hoegh-Guldberg 1999). This phenomenon is the result of corals expelling their symbiotic zooxanthellae (algae) leading to a ghostly condition in which the coral turns white. Depending on the severity of the 'bleaching' event, corals may recover to a weakened condition, or may die altogether. Over recent years, modest SST increases have resulted in catastrophic impacts to the world's coral reefs at the global (Brown and Dunne 2016), regional (Wilkinson and Souter 2008), and Florida-wide (Manzello 2015) scales.

Freshwater Wetlands and Aquatic Ecosystems

A significant portion of Florida's landscape is covered by wetlands, ranging from expansive systems (e.g., Everglades, Big Cypress, Paynes Prairie) to isolated features located in a mosaic of upland communities (e.g., ephemeral wetlands, pitcher plant bogs). Regardless of size, wetland systems are expected to be impacted through changes in precipitation, temperature, sea level rise, and the synergisms among these factors. Annual length of soil saturation, amount of organic matter, source of water, and fire frequency all contribute to determining the major characteristics of forested wetlands in Florida. Decreased precipitation coupled with increased temperature will likely alter plant composition—allowing for encroachment of upland woody species and increased fragmentation of larger systems through reduced flow and connectivity.

The Everglades ecosystem forms the interface between temperate and subtropical biomes—creating habitats unique to Florida (Pearlstine et al. 2010). With approximately 40% of the Everglades National Park at elevations below 1 m, a potential sea level rise of more than 1 m combined with predicted temperature increases poses a significant challenge for the future ecological integrity of the park, especially in light of the disruption of the region's natural hydrology over the past century (Mitchell and Krueger 2011; Catano et al. 2014). Decreases in water quantity and quality will continue to stress the system and cause degradation; however, if the region receives more rainfall, the habitat suitability could be enhanced for aquatic prey productivity and apex predators (Catano et al. 2014). Within the Everglades ecosystem and other freshwater marshes, fire is used as a management tool to prevent mangrove and other woody vegetation encroachment into marshes, and to eliminate invasive exotics that frequently occur at the upland–marsh interface (Smith et al. 2013). Climate change effects that reduce the ability to conduct prescribed burns will contribute to shifts within the ecosystem.

The large river systems in northern Florida have the highest diversity of freshwater fish species in the state, with some watersheds having up to 100 species. The highest diversity of aquatic invertebrates is also found in northern Florida due to the higher gradient of rivers and streams, proximity to the continental landmass, and the presence of karst features such as sinkholes and caves (Knight et al. 2011). Warming water temperatures, altered stream flow patterns, and increasing storm events will impact freshwater systems (Poff et al. 2002). Additionally, sea level rise will lead to saltwater inundation of freshwater areas, groundwater contamination, and higher tidal/storm surges. Florida's karst system of sinkholes, submerged caves and springs depend upon the connection between the surface and the underground, with even slight changes in soil moisture, elevation, and temperature causing profound effects.

Upland Ecosystems

Upland ecosystems in Florida range from systems similar to those found in the Southeastern Coastal Plain to systems more commonly found in sub-tropical and Caribbean areas. The species composition of forest systems and their location and ranges are influenced by winter temperatures and other climatic factors, as well as by local factors such as fire, substrate, elevation, and species interactions. Increased temperatures will lead to increases in forest pest damage, changing fire patterns, longer growing seasons, higher evapotranspiration/drought stress, and the spread of non-native species. Crumpacker et al. (2001) found that even moderate increases in temperature (1 °C) may cause serious effects on temperate hardwood forests of northern Florida. Some of the most severe impacts indicated potential shifting of the ecosystem from forested to open woodland, scrub and savanna. Some tree species already at their southern range boundaries are predicted to have range reductions, such as southern red oak (*Quercus falcate*) and American beech (*Fagus grandiflora)* in the panhandle, and range contraction of longleaf pine (*Pinus palustris*), with the southern boundary moving northward up the Florida Peninsula. Loss of key woody species could affect forest suitability for nesting, roosting, or foraging. The majority of

Florida's upland ecosystems are dependent upon fire, with the frequency, intensity, and seasonality of fire varying between communities. The ability to maintain these systems through the use of prescribed fire will become more challenging with increased temperatures and changes in precipitation. Altered patterns of precipitation could lead to changes in the seasonality of prescribed burns, potentially altering the effectiveness of the burn for some species and systems. An increased number and intensity of extreme storm events can cause a build-up of debris leading to increases in wildfires, hotter prescribed fires, and even the inability to use prescribed fire as a management tool. Additionally, drought can alter the decomposition rates of forest floor organic materials, impacting fire regimes and nutrient cycles (Hanson and Weltzin 2000).

Habitats

The degree to which habitat conversion will favor some communities over others and how those conversions differ among areas is a major unknown factor in assessing the vulnerability of natural communities (Noss et al. 2014). Noss et al. (2014) applied the Standardized Index of Vulnerability and Value (SIVVA) framework to 30 natural communities in Florida. This assessment included quantitative model overlays of projections from sea level rise and land use change. On average, these 30 communities will lose 12% of their extent to sea level rise, as projected by high resolution statewide Sea Levels Affecting Marshes Model (SLAMM) overlays of 1 m of sea level rise by 2100. Some natural communities, such as maritime hammocks, coastal interdunal swales, and saltwater marsh will lose nearly 50% of their current extent to sea level alone. Some rare natural communities in extreme South Florida will suffer greater losses when projected changes due to land use conversion are coupled with losses from sea level rise; cactus barrens and tidal rock barrens in the Florida Keys are likely to lose 85% and 75% of their extent, respectively. These direct losses of habitat will have significant impacts on the species dependent upon them.

Coastal Habitats

An increase in storm surge associated with hurricanes could affect the sustainability of some natural coastal systems and the species that depend upon them. Loss of beaches would affect species such as sea turtles, terns, American oystercatcher (*Haematopus palliates*), and black skimmers (*Rynchops niger*), as well as critical habitat for wintering shorebirds and migrating neo-tropical migrants. Some aquatic and terrestrial species limited to coastal areas (e.g., beach mouse, Okaloosa Darter (*Etheostoma okaloosae*)) may be threatened throughout their range (Burkett 2008). Salt marshes are expected to move upslope with sea level rise (Brinson et al. 1995), but human development is likely to limit retreat and migration (Donnelly and Bertness 2001; Feagin et al. 2005; Desantis et al. 2007). The most severe loss will likely occur at sites where the coastline is unable to move inland because of steep topography or seawalls (Galbraith et al. 2002). These conditions can result in the crowding of foraging and beach-nesting birds, as

Figure 12.4. Florida Key Deer. Photo credit: USFWS Digital Library.

well as loss of crucial coastal habitat for species such as diamondback terrapin (*Malaclemys terrapin rhizophorarum*), which requires both marsh and beach habitats (Shellenbarger Jones et al. 2009). Inundation of coastal habitats will increase fragmentation as patches are divided by areas of open sea water. Sea level rise threatens small and low-lying islands with erosion or inundation (Baker et al. 2006; Church et al. 2006), many of which support high concentrations of rare, threatened, and endemic species (Baker et al. 2006). Of 40 species identified as being vulnerable to sea level rise, the mangrove diamondback terrapin, Key deer (*Odocoileus virginianus claivum*), Peninsula ribbon snake (*Thamnophis sauritus sackenii*), Lower Keys marsh rabbit (*Sylvilagus palustris heneri*), mangrove cuckoo (*Coccyzus minor*), Florida panther (*Puma concolor coryi*), loggerhead sea turtle (*Caretta caretta*), Florida brown snake (*Storeria dekayi*), and Florida bonneted bat (*Eumops floridanus*) had the highest relative vulnerability ranks when assessed using the SIVVA framework (Reece and Noss 2014).

Mangroves are one of the most productive habitats, providing integral nursery habitats for fish species; shorelines fringed by mangrove prop roots harbor diverse fish assemblages in high densities (Thayer et al. 1987). Many species of birds use the mangrove canopy as nesting sites, including wading birds, mangrove cuckoos (*Coccyzus minor*), and white-crowned pigeons (*Patagioenas leucocephala*). Relatively small changes in winter climate can result in dramatic mangrove range expansion at the expense of salt marsh; salt marsh could be reduced by 60% in Florida with only a 2-4 °C increase in annual mean minimum temperature (Osland et al. 2013). Saltmarsh-dependent bird species such as seaside sparrows (*Ammospiza maritima*) may be forced to leave the area if suitable habitat no longer exists.

Increased soil salinity in coastal uplands will lead to changes in species composition as salt-intolerant plants decline and plants with higher salt tolerances increase. Cabbage palm (Sabal palmetto) mortality on coastal islands and along the marsh/upland transition zone has already impacted coastal areas along the Big Bend region of Florida. Cabbage palm seedling mortality is correlated with tidal flooding, suggesting that salinity, flooding or the combination may be responsible for the regeneration failure of cabbage palms in low-lying coastal areas (Perry and Williams 1996).

Fire-maintained Habitats

As previously discussed, many of Florida's systems are dependent upon fire. Altered fire regimes or the absence of fire, along with other climatic changes, could lead to compositional changes to these habitats, potentially altering their suitability to the current suite of species. The absence of fire in the longleaf pine sandhill community can lead to an increase in woody vegetation, creating a dense mid-story. Species such as the red-cockaded woodpecker (*Picoides borealis*) rely on the openness of the sandhill for foraging. Florida scrub jays depend on fire to keep scrub oak habitats short and maintain plenty of open sandy areas in which to store acorns. Dry prairie provides habitat for multiple distinctive species including the crested caracara (*Polyborus plancus*), burrowing owl (*Athene cunicularia*), the Florida sandhill crane (*Grus Canadensis pratensis*), and the federally endangered Florida grasshopper sparrow (*Ammodramus savannarum floridanus*). Without appropriate fire regimes, trees and other woody vegetation move into dry prairie, creating unsuitable conditions for these and other species. In the absence of periodic fires, broadleaf plant species invade the pine rockland communities that sustain a rich diversity of plants and animals and, if left unchecked, transition to a broadleaf "hammock" (Burg 2010).

Florida Keys and Coral Habitats

Even small changes in water temperatures can have profound effects, especially in the marine environment where coral reefs, seagrasses, and mangroves predominate. In addition to the previously discussed effects of temperature on corals, reduction of ocean carbonate ion concentrations due to ocean acidification impacts their ability to build skeletons (Cooper et al. 2008). The net result of these temperature-induced impacts is the eventual loss of coral structure and a shifting community structure (Ruzicka et al. 2013). Since corals play a pivotal role in supporting biodiversity (Connell 1978), harboring the highest diversity of marine species (Carpenter 2008), impacts to their long-term survival can have devastating effects on reef-associated biodiversity. Most of Florida's sport fish species and many other marine animals spend significant parts of their lives (particularly early development stages) on or around coral reef habitats.

How changes in temperature will impact the other dominant habitat types in the Florida Keys is less well-known (Koch et al. 2015). Sea level rise will alter the landscape of the Florida Keys where elevations, with few exceptions, are between 3 and 6 ft (1–1.9 m). The Florida Keys contain approximately 75% of the state's rockland hammocks, which provide habitat for many endemic species, including 10 mammals and five reptiles (Snyder et al. 1990). Adjacent freshwater wetlands provide breeding habitat for amphibians and sources of prey for reptiles. These wetlands, as well as other important sources of fresh and brackish water, are expected to become more saline with rising sea levels and increased tidal/storm surges. In addition to these impacts, altered soil salinities will alter plant composition of the terrestrial habitats. There have already been adaptation efforts to "buy time" for the Key tree-cactus (*Pilosocereus robinii*). A project in 2015-16 relocated Key tree cactuses to higher elevations due to the species limited tolerance for saline soils (S. Traxler, USFWS, Pers. Commun.).

Freshwater Wetland and Aquatic Habitats

Herbaceous wetlands provide the foraging and nesting habitat for many species, including waterfowl, Florida sandhill crane (*Grus canadensis pratensis*), snail kite (*Rostrhamus sociabilis plumbeus*), limpkin (*Aramus guarauna),* mink (*Mustella vison*), river otter (*Lutra Canadensis lataxina*), Florida gopher frog (Rana capito), tiger salamander (*Ambystoma tigrinum*), and flatwoods salamanders (*Ambystoma cingulatum*). These wetland-dependent species will be impacted through loss and degradation of habitat when water levels and the timing of water inputs become incompatible with their foraging, nesting, or roosting requirements. Ephemeral wetland-dependent species will be affected by changes in precipitation, regardless of direction of change. Due to the typical shallow structure of ephemeral wetlands, they will be more susceptible to increased evapotranspiration rates, leading to a shorter wet period. This could lead to interrupted or terminated life stage development, as well as the replacement of herbaceous species by woody species. Increased precipitation could permanently connect these isolated wetlands to other water bodies, introducing predators. Palis (1997) found that the timing of salamanders' breeding migration is tied to precipitation and temperature, both of which could be impacted by climate change. Wading birds' nesting success is tied to appropriate nesting and foraging habitats and their proximity to one another. Nesting success is reduced when nesting sites become dry, allowing terrestrial predators easier access to the nests, and when foraging sites are located at distances too far away, beyond their physiological ability to survive and rear their young.

Figure 12.5. Flatwoods salamander. Photo by Pierson Hill.

The suitability of riverine habitats is based on variations in flow, substrate, temperature, dissolved oxygen, and other water chemistry factors. The riverine systems in the Florida Panhandle are unique in that they provide habitat for many rare fish species that are at their various range limits, either at the eastern range limit of the Mississippi River Valley system or the western range limit of the Atlantic Coastal Plain system (Bailey et al. 1954). Northwest Florida also contains 17 of the 27 first magnitude artesian springs and spring groups (Rosenau et al. 1977). Florida's fish species may be impacted by increased water temperatures, with projected decreases in precipitation and increases in temperature. Even if higher water temperatures don't cause direct mortality, they can increase the stress on the fish, leading to declines in health and increases in vulnerability to parasites and disease. Many aquatic species will be affected by bank erosion, increased siltation, and run-off caused by increased precipitation and storm events. Sea level rise will result in the inland movement of seawater, shifting the tidal influence zone of streams and rivers upstream and permanently inundating downstream riparian/coastal habitats with brackish water. Tidal and storm surges can degrade aquatic habitats through oxygen depletion, changes in salinity, and increased siltation and turbidity.

Climate Change Impacts on Species

A recent vulnerability assessment of 300 species in Florida presents some opportunities for generalizing the unique and synergistic threats among a variety of taxonomic groups from across the state (Reece et al. 2013a). As predicted by Pilkey and Young (2009), sea level rise is a major threat to many of Florida's rare and endangered species. Nearly one quarter of the approximately 1,200 species tracked by the Florida Natural Areas Inventory are projected to have at least 50% of their range lost to a sea level rise of 1 m by the year 2100. The greatest threat to species is anthropogenic habitat fragmentation (Benscoter et al. 2013), but synergisms with threats from climate change are especially dangerous for many species. Lessons learned from this assessment (Reece et al. 2013a) include: there is good data demonstrating species' risk of extinction, but insufficient data to make meaningful conservation interventions; the adaptive capacity of many species is compromised by human alterations to the landscape; and planning horizons for climate change vulnerabilities are extremely important. Reece et al. (2013a) documented a complete lack of published records or models of predicted responses to climate change or sea level rise in 88% of 300 species surveyed. Across all 300 species assessed, 30% were scored as having strong anthropogenic geographic barriers limiting their ability to shift distributions in response to threats. Sea turtles are a good example of a species with the potential capacity to shift their nesting location away from areas with inadequate incubating environment (e.g., eroded); however, shifts in nesting location may result in exposure to other threats and the use of areas that are not protected (Reece et al. 2013b). For many species, protecting existing habitats from land use change is highly likely to prevent extinction over the next 50 years; however, for nearly 25% of species assessed, that same strategy is unlikely to prevent extinction over 100-year timescales.

Climate change impacts on species will be driven by one or multiple climate-related factors acting in concert or synergistically (NFWPCAS 2012). Impacts of climate change on species can lead to changes in geographic range, species composition, risk of extinction, and species interactions (predator/prey, competition). Species with poor dispersal ability, long generation times, long time to sexual maturity, low reproductive rates, low genetic variability, narrow environmental tolerances, specialized requirements or relationships with other species, specialized habitat and/or microhabitat requirements, a narrow geographic range, or a dependence on specific triggers or cues likely to be disrupted by climate change will be the most vulnerable to climate change (Foden et al. 2008;, Steffen et al. 2009; NFWPCAS 2012). Many generalist species; such as white-tailed deer *(Odocoileus virginianus*) or feral hogs (*Sus scrofa*); are likely to continue to thrive in a changing climate (Johnston and Schmitz 2003; Campbell and Long 2009). Species, both native and exotic, with traits that assist in invading or colonizing disturbed areas will have an advantage in a rapidly changing climate (Steffen et al. 2009). Mechanisms of species' adaptation include shifting their climatic niche by adjusting their range, phenology, and physiology (Bellard 2012).

Changes in Geographic Ranges

Species distributions are influenced through species-specific temperature and precipitation thresholds and, as these thresholds are crossed, species will need to change their movement patterns, shift their ranges, or disperse further distances to reach suitable habitat as they are forced to move away from unsuitable habitat conditions (NFWPCAS 2012). Some species will be unable to relocate due to lack of suitable habitat or anthropogenic barriers obstructing their movement, Noss et al. (2014) found that 76% of 236 species threatened by sea level rise would be unable to relocate further inland. While climatic changes will lead to contraction of the range of some species, these same changes could lead to the range expansion of other species, particularly non-native invasive species (as discussed later in this chapter).

Migratory species are likely to be strongly affected by climate change. Migratory species may be impacted at multiple geographic scales, possibly experiencing alterations of habitat in their wintering grounds, breeding grounds, and along their migratory routes (Ahola et al. 2004). Mechanisms that aid in migrations, such as wind and water currents, may have positive or negative consequences depending on whether changes increase or decrease required energy expenditures to complete their migration. Altered directions of winds/currents can impact species' ability to navigate to the desired location, even delivering individuals to the wrong location. However, the ability to move and utilize multiple habitats and resources may make some migratory species relatively less vulnerable.

Due to their vulnerability to reductions in water flows and water quality, and their limited capacity to migrate to new waterways, climate change may have a strong influence on fish species distributions and abundance (Brander et al. 2003; Reid 2003). Fish species composition may change as species with lower tolerances move or suffer the impacts of rising water temperatures, as previously discussed. Some aquatic species may be able to expand their range due to increasing winter temperatures. The distribution of coastal species is closely linked with soil and water salinity (Burkett 2008). Additionally, changes in freshwater flow inputs into the estuaries may affect the distribution of suspension feeders, such as mussels, clams, and oysters (Wildish and Kristmanson 1997). There are a multitude of factors that can individually and synergistically impact marine species distributions, including changes in sea level, ocean stratification, oxygen availability, patterns of ocean circulations, storms, precipitation and freshwater input, and ocean physical and chemical conditions (NFWPCAS 2012).

Changes in Species Composition

In response to climate change, many native and non-native species may increase in abundance to such an extent that they have a transformative, and often negative, impact on other species and ecosystems (Steffen et al. 2009). As species respond to changing habitat conditions, shifts in composition are likely to alter important competitive and predator–prey relationships, which can reduce local or regional biodiversity (Parmesan and Galbraith 2004). Factors in aquatic systems, such as changes in thermal regimes, flow regimes, or salinity could alter the competitive interactions or predator–prey relations among species in ways that are detrimental to species of conservation concern (Rahel et al. 2008). The structure and function of coastal systems may change as species with a greater tolerance of increased salinity outcompete those with lower tolerance; these changes in community structure can be episodic, potentially leading to elimination of some ecosystems if thresholds are exceeded (Burkett et al. 2005).

In marine systems, climate-induced changes in community composition and food web structure resulting from the shifts in ecological niches for individual species are likely to be significant (Harley et al. 2006). Changes in temperature may influence key species interactions through which small changes in climate could generate large changes in natural communities, such as a decrease in key predator populations. Seasonal changes in freshwater inflow will be a contributing factor that may induce changes in species composition of mangrove fishes along estuarine gradients (Ley 1999).

Risk of Extinction

A review of various models predicting future biodiversity found that the majority of the models indicated significant consequences for biodiversity, with the worst case scenario models leading to extinction rates that would qualify as the Earth's sixth mass extinction (Bellard et al. 2012). Many of the species with the highest vulnerability or predicted extinction rates are species with limited or isolated populations. However, endangered species with large home range sizes and greater dispersal limitations are also associated with greater risk of extinction, possibly indicative of higher resource requirements or lower habitat quality (Benscoter et al. 2013). Both characteristics may affect their ability to adapt to rapid environmental change. Those species with low adaptive capacity will have low likelihood of finding distant habitats to colonize, ultimately resulting in increased extinction rates (Walther et al. 2002). Additionally, species with narrow geographic ranges and specific habitat requirements will be at even greater risk due to interactions of climate change and existing and future habitat fragmentation (NFWPCAS 2012).

Sea level rise will likely have a significant negative effect on species persistence, impacting the size and quality of habitat patches for coastal species through changes in the coastline and transitions among coastal habitats. Sea level rise will cause a decline in suitable habitat and carrying capacity for the Snowy Plover (*Charadrius alexandrinus*) and increase its risk of extinction (Aiello-Lammens et al. 2011). A recent vulnerability assessment (Reece et al. 2013a), evaluating sea level rise of up to 2 m and synergistic effects of climate change and anthropogenic factors identified several species as highly likely to be extinct by 2100, including the Florida grasshopper sparrow, Miami blue butterfly (*Cyclargus thomasi bethunebakeri*), Florida duskywing (*Ephyriades brunnea floridensis*), Gulf Coast solitary bee (*Hesperapis oraria*), Key deer, Florida Keys tree snail (*Orthalicus reses nesodryas*), Key tree cactus, Bartram's scrub-hairstrak (*Strymon acis bartrami*), Lower Keys marsh rabbit, and Key ringneck snake (*Diadophis punctatus acricus*). The primary threats for these species were identified as sea level rise, barriers to dispersal, storm surge, lack of freshwater, habitat loss, invasive species, disease, collection, small range size, and habitat degradation.

Keystone Species

Figure 12.6. Gopher tortoise. Photo by Jay Exum.

A keystone species is a species that has a significant effect on its environment relative to its abundance and plays a critical role in maintaining the structure of an ecological community, affecting a suite of other species in an ecosystem. Examples of keystone species in Florida include the gopher tortoise, reef building species and the American alligator (*Alligator mississippiensis*). The gopher tortoise is considered a keystone species for the sandhill community in that it "engineers" the habitat of many other species. Species that have been reported using gopher tortoise burrows include at least 36 amphibians and reptiles, 19 mammals, seven birds, and more than 300 species of invertebrates (Jackson and Milstrey 1989; Diemer 1992; Brandt et al. 1993; Kent and Snell 1994). Climatic changes that impact gopher tortoise abundance or survival, such as alterations to fire regimes, will impact a large suite of associated species.

The species that create worm reefs and coral reefs are also considered to be keystone species. Coral reef systems composed of species such as *Oculina* provide habitat for many recreational and commercially important species, such as scallop, shrimp, grouper, snapper, and amberjack. The sedentary polychaete worms (*Sabellaria vulgaris* Verrill) build tubes from sand and shells, forming colonies that attract fish, birds, and algae. Changes in circulation patterns, wave actions, SSTs, and ocean acidification may impact the coral and worm reef species and, in turn, the species that depend upon their structure as habitat.

The American alligator is considered to be a keystone species of the Everglades ecosystem and wetlands systems, creating important habitat for other species and aiding in ecological processes. The deep holes that they create in the wetland systems retain water during the dry season, providing habitat for a variety of other species. The nesting activity of the females is important for the creation of peat, as well as providing a nesting substrate for several species of turtle. Although alligators seem to be quite resilient to habitat alterations, if climate changes, particularly those changes impacting hydrological processes can cause changes in the alligator's range or nesting; multiple other species would also be impacted.

Figure 12.7. Green Sea Turtle. FWC Digital Library.

Species Highlight – Sea Turtles and Climate Change

Although sea turtles have been in existence for millions of years and have adapted to past changes in climate, it is still unsure whether they will be able to adapt to present day climate change; it is occurring more rapidly than has been observed in the past and it is accompanied by a variety of anthropogenic threats (Poloczanska et al. 2009; Fuentes et al. 2013). The cumulative impact of the various non-climatic threats sea turtles face makes their populations more vulnerable to climate threats and decreases their resilience (Fuentes et al. 2013). Sea turtles, being ectotherms, have specific thermal requirements, with their distribution often constrained by the 15 °C isotherm (Hamann et al. 2012). Therefore, shifts in ocean temperatures will likely result in distribution shifts (Weishampel et al. 2004). Indeed many populations of sea turtles worldwide have started to shift their range as a response to alterations in temperature (Witt et al. 2010). For instance, Kemps Ridley turtles (Lepidochelys kempii) have always nested on a 1000 km stretch of beach in Mexico. But over recent years, these turtles have expanded their nesting range to various beaches along the Gulf Coast of Florida, potentially as a result of changes in temperature (Pike 2013). Species distribution models for these turtles predict further expansion within the Gulf of Mexico and even along the Northern Atlantic Ocean (Pike 2013). Shifts may also occur at a more regional scale. There has been a northward shift in loggerhead sea turtle (Caretta caretta) nests along Melbourne Beach, Florida, the largest loggerhead turtle rookery in the Atlantic Ocean, likely due to warming temperatures (Reece et al. 2013b). Range shifts may be accompanied by increased exposure to other threats or, more optimistically, to areas where fewer threats exist. Availability of suitable habitat will be crucial for sea turtle adaptation in the future; however, several models predict that changes in climate and sea level rise may reduce the availability of suitable sea turtle nesting areas and the locations of where turtles nest (Fuentes et al. 2010; Katselidis et al. 2014; Pike et al. 2015). For example, it is projected that Melbourne Beach will decrease in area by 43% from 1986 to a future with 0.5 m of sea level rise; this will restrict nesting to narrow beaches, increasing risk of erosion and crowding resulting in nests overlapping with each other (Reece et al. 2013b). As temperatures and sea level rise continue to increase, protecting future suitable habitat for nesting sea turtles will greatly increase their chances of adapting to both climate change and anthropogenic impacts. However, the heavily developed coasts in the United States may hinder adaptation (Pike 2013; Fuentes et al. 2016).

Sea turtles play important ecological roles in both oceanic and terrestrial habitats (Hawkes et al. 2009). They help maintain sea grass meadows and coral reefs by grazing on sea grass plots and sponges, respectively (Bjorndal 1980), they provide transportation for epibionts, and their egg clutches and dead hatchlings provide nutrients to beach and dune vegetation (Bouchard and Bjorndal 2000; Hannan et al. 2007). Sea turtles also have important cultural, social, and economic significance (Campbell 2002; Campbell and Smith 2006). In Florida for example, residents are willing to pay \$42–\$57 per year for five years to protect sea turtle habitats from sea level rise (Hamed et al. 2016). As emblematic species, sea *turtles can help promote awareness to the threats that climate change poses to marine species (Hamann et al. 2012; Fuentes and Saba 2016).*

A sea turtle's life history, behavior, and physiology are strongly influenced by environmental temperature, which makes sea turtles particularly vulnerable to environmental changes (Fuentes et al. 2011; Hamann et al. 2012; Dudley and Porter 2014). Besides the thermal limitations that sea turtles face in their oceanic habitat, sea turtles have other strict thermal thresholds on land as well. Embryo development, hatchling sex ratio, and hatching success are all influenced by temperature and rainfall at nesting beaches (Standora and Spotila 1985; Janzen 1994; Wyneken and Lolavar 2015). Successful egg incubation typically occurs when sand temperatures are between 25 and 34 °C, with variability (Miller 1985; Howard et al. 2014) between different species; for instance, loggerheads, flatbacks (Natator depressus), hawksbills (Eretmochelys imbricata), and greens (Chelonia mydas) have been shown to tolerate nest temperatures as high as 35 °C (Howard et al. 2014). Incubation outside this range results in lower hatching success and higher morphological abnormalities in hatchlings (Miller 1985). Sea turtles also have temperature-dependent sex determination, where the sex of the hatchlings is determined by the nest temperature (Mrosovsky 1980; Yntema and Mrosovsky 1980). Temperatures above the pivotal temperature, where the result is a 1:1 sex ratio, produces more females, while temperatures below the pivotal temperature produces more males (Yntema and Mrosovsky 1980). For example, in Florida, similar to other nesting grounds worldwide, there is evidence of a bias in the production of female hatchlings (Mrosovsky and Provancha 1989; Hanson et al. 1998; Wibbels et al. 1991; Blanvillain 2007; Wibbels 2012a, b, c). Knowledge of the primary sex ratio of nestlings on nesting grounds is crucial to accurately understand the projected impacts of climate change on the reproductive output of sea turtles (Fuller et al. 2013; Marcovaldi et al. 2016). Although some knowledge does currently exist on the general sex ratio of hatchlings on Florida beaches, a systematic long-term monitoring program is still necessary to obtain data at the appropriate temporal and spatial scale.

Changes in temperature will also impact the phenology of sea turtles, including the frequency and timing of nesting (Limpus and Nicholls 1988; Saba et al. 2007; Fuentes and Saba 2016). Some populations, such as the leatherbacks (Dermochelys coriaceain) located in Costa Rica and the US Virgin Islands, have shown a delay in nesting due to increased temperatures in their foraging areas (Neeman et al. 2015). In comparison, other populations, such as the loggerheads along Florida's Atlantic Coast, have started to nest earlier due to warmer temperatures prior to the typical start of the nesting season (Weishampel et al. 2004; Pike et al. 2006). The nesting season may differ between species and populations worldwide such that earlier nesting may result in a shorter or, more optimistically, a longer nesting season. For example, SSTs resulted in loggerheads experiencing an earlier and shorter nesting season on Florida's Canaveral National Seashore, whereas loggerheads on Cape San Blas, Florida experienced a longer season as a result of earlier nesting, which is similar to more northerly rookeries (Wieshampel et al. 2004; Lamont and Fujisaki 2014). Shorter nesting seasons may cause females to lay fewer clutches in a season (Pike et al. 2006). Extended seasons may allow more individual females to nest within the season (Lamont and Fujisaki 2014); however, there is still uncertainty about the implications of nesting season lengths for sea turtle population stability.

Phenology/Physiology

Phenology is the timing of seasonal activities of an organism, which is typically highly adapted to the climatic seasonality of the environment in which it evolved (IPCC 2007). Species can cope with climate change through phenotypic plasticity and microevolution, in addition to shifting their range (Hulin et al. 2009; McGuire et al. 2016). Phenotypic plasticity is the ability of an organism to change its characteristics or traits, including morphological, physiological, and behavioral. Species with phenotypic plasticity can quickly compensate for a moderate change in environmental conditions (Jump and Penuelas 2005). Microevolution is the changes in the gene pool of a population over time that result in relatively small changes to the organism.

Microevolution can be observed over short periods of time, even between one generation and the next, and it can occur via mutation, gene flow, genetic drift, or natural selection.

The annual phenology of many species has changed in the past few years in response to modified environmental conditions (Walther et al. 2002; Parmesan 2006; Pertoldi and Bach 2007). Spring activities, such as breeding or first singing of birds, arrival of migrant birds, appearance of butterflies, choruses and spawning in amphibians, and shooting and flowering of plants, have been occurring progressively earlier since the 1960s (Walther et al. 2002).

Although migratory species are adapted to adjust their behavior with annual changes in the weather, shifts in climatic variables are beginning to result in mistimed migration (Robinson et al. 2009), with some species abandoning migration altogether and others shifting their migratory pattern (Foden et al. 2008). Changes in cues (e.g., temperatures, precipitation) for migration initiation or pathways could lead to mismatched availability of resources required for successful completion of migration or reproductive success and survival upon arriving at the spring or winter destination.

Synchrony of phenological changes in species that interact with one another, such as competitors, food species, and pollinators, will be extremely important to many species. If these timing shifts are synchronous across species that normally interact then the system is likely to remain healthy; however, if responses to change (e.g., temperature increases) vary across species then species' interactions may become out of synchrony and could lead to population declines (Parmesan and Galbraith 2004). For example, if the arrival of a migrating bird to its breeding ground and the insect it depends on for food both occur two weeks earlier, they remain in synchrony and may persist; however, if the bird arrives before the insect's hatch/emergence they become out of synchrony and the bird may experience population declines. Schweiger et al. (2008) found a pronounced spatial mismatch in future niche spaces of a butterfly and its larval host plant under three global change scenarios, suggesting that climate change has the potential to disrupt trophic interactions because co-occurring species do not necessarily react in a similar manner to global change.

There is particular interest in the effects of climate change on the population dynamics of species with temperature-dependent sex determination (Walther et al. 2002). All crocodilians (Deeming and Ferguson 1989; Lang and Andrews 1994), many turtles (Ewert et al. 1994), and several lizards (Viets et al. 1994) have temperature-dependent sex determination. Two parameters—the pivotal temperature and the transitional range of temperature—control sex determination; species with a larger transitional range of temperature are expected to be at a lower risk to climate change (Hulin et al. 2009). Ewert et al. (2005) determined that the sex ratio of the American snapping turtle (*Chelydra serpentine*) is female-biased at cool temperatures, male-biased at moderate temperatures, and only females are produced at warm temperatures. Climate change-induced shifts in thermal regimes of incubation may lead to a bias in sex ratios in populations of temperature-dependent sex determination species (Janzen 1994, Walther et al. 2002).

Plant phenology studies have generally shown earlier onset of leafing out, flowering, and fruiting as temperatures have increased (Menzel et al. 2006). As yet, few plant phenology studies have been published for Florida. Von Holle et al. (2010) used herbarium specimens and long-term climate data to assess whether the phenologies of 70 plant species varied with a changing climate; these species included 29 invasive species and 41 native species related closely to each of the invasive species. Only three species sampled were found to have flowering times that differed significantly with climate changes: two flowered later (*Albizia lebbeck* and *Sassafras albidum*) and one flowered earlier in the year (*Morus rubra*). Von Holle et al. (2010) did not find a difference in phenological response between invasive and native species. Both exhibited a trend of delayed flowering in years where minimum temperatures fluctuated.

Plant Physiology – Case Study

Plants grown under elevated concentrations of CO_2 use resources more efficiently than plants growing at ambient CO_2 (Drake et al. 1997). Photosynthesis is often stimulated while stomatal conductance and leaf nitrogen are reduced resulting in greater water-use and nitrogen-use efficiency (Drake et al. 1997; Ainsworth and Long 2005). Growth and biomass production are also often stimulated by CO_2 (Ainsworth and Long 2005). An open top chamber study at the Kennedy Space Center evaluated the impacts of elevated CO_2 (ambient +350 µmol mol-1 CO_2) in Florida scrub over an 11-year period (Hungate et al. 2013). This is the only long-term study of the effects of CO_2 on native Florida vegetation to date. Exposure to elevated CO_2 stimulated aboveground biomass accumulation in Florida scrub over the duration of the study. The biomass stimulation response was species specific: elevated CO_2 stimulated Myrtle oak (Quercus myrtifolia) and Chapman Oak (Quercus chapmanii) but had no impact on the aboveground biomass of sand live oak (Quercus geminata) (Seiler et al. 2009; Dijkstra et al. 2002). Elevated CO_2 stimulated fine root biomass following disturbance; but the effect was temporary (Day et al. 2013). Net primary production (aboveground and below ground) was stimulated by elevated CO_2 following disturbance, peaking with high availability of soil nutrients (Hungate et al. 2013). Belowground biomass was the main driver of the net primary production response. Species-specific net primary production responses were the same as for biomass; productivity of Q. geminata did not respond to elevated CO_2 (Hungate et al. 2013).

Photosynthesis was stimulated for the scrub oaks and stomatal conductance reduced with growth in elevated CO_2 (Lodge et al. 2001; Ainsworth et al. 2002; Li et al. 2003). Q. geminata was the only oak that showed consistent evidence of photosynthetic acclimation to elevated CO_2 (Ainsworth et al. 2002; Hymus et al. 2002). Q. geminata and Q. myrtifolia grown in elevated CO_2 were more nitrogen use efficient than plants grown under ambient conditions (Ainsworth et al. 2002).

Plants grown under elevated CO_2 had decreased leaf foliar nitrogen concentrations and increased C:N ratios; there was less damage from herbivores on these lower quality leaves (Stiling et al. 2003, Hall et al. 2005). Few legacy effects of elevated CO_2 were found to persist one year after exposure to elevated CO_2 concentrations was terminated; no differences remained in leaf nitrogen concentration or in herbivore densities (Stiling et al. 2013).

Long-term stomatal adaptation to increased atmospheric CO_2 may occur, which decreases water loss while maximizing carbon gain (Drake et al. 1997). There was no evidence of stomatal adaptation for oaks in the open top chamber experiments at the Kennedy Space Center: stomatal densities were similar between ambient and elevated treatments (Lodge et al. 2001). Changes in stomatal density and dimensions with increasing atmospheric CO_2 have been documented for several common Florida species by studying specimens preserved in peat and herbaria (Wagner et al. 2005; Wagner et al. 2007; Lammertsma et al. 2011). Decreases in the stomatal index of five species—water oak (Q. nigra), red maple (Acer rubrum), wax myrtle (Myrica cerifera), dahoon holly (Ilex cassine), and royal fern (Osmunda regalis)— occurred *as atmospheric CO_2 increased from 310 to 370 ppm over 60 years (Wagner et al. 2005). Lammertsma et al. (2011) identified changes in stomatal density and pore size in nine common Florida species (red maple, wax myrtle, dahoon holly, laurel oak, water oak, slash pine, longleaf pine, bald cypress, royal fern), which led to an average 34% decrease in maximum stomatal conductance per 100 ppm rise in CO_2.*

The latest IPCC assessment (2014) reported that there is high confidence (much evidence, medium agreement) that climate change-induced phenological shifts will continue to alter the interactions between species in regions with a marked seasonal cycle. Phenological changes may be the simplest process to track ecological changes of species in response to climate change (Walther et al 2002).

Existing Stressors and Climate Change

The biodiversity and ecology of Florida are already suffering from a number of existing stressors, including habitat loss, fragmentation and degradation, invasive plants and animals, altered hydrologic regimes, overexploitation, and pathogens, parasites and pollutants. In a study conducted by Wilcove et al. (1998), habitat degradation was identified as the top threat, contributing to the endangerment of 85% of the listed species analyzed; competition with or predation by alien species was the second-ranked threat, with the exception of aquatic vertebrate and invertebrate species, where pollution (including siltation) was the second-ranked threat. The ability of species and systems to adapt to climate change will be further challenged when considering the effects of these other stressors (Parmesan and Galbraith 2004). It is expected that the overall vulnerability of some ecosystems may be primarily driven by the severity of these non-climate stressors and by how they interact with climate change (NFWPCAS 2012). The synergistic effects of climate and non-climate stressors, leading to range reductions and population declines, may be severe enough to threaten some species with extinction or extirpation from significant portions of their ranges (NFWPCAS 2012). Parmesan and Galbraith (2004) found that there is a growing consensus that climate change will compound existing threats and lead to an increased rate of biodiversity loss Three key drivers of biodiversity loss include existing threats, direct effects of climate change, and the interaction between the existing threats and climate change (Driscoll et al. 2012). As described in other chapters, climate change is expected to vary regionally across Florida. This will make it even more challenging to predict how the interactions of climate change with other stressors will affect species and population responses (Noss 2011). The reduction of existing stressors is a key strategy in natural resource adaptation planning in response to climate change.

Habitat Loss, Fragmentation and Degradation

Habitat loss, destruction, and degradation are the most pervasive threats to biodiversity (Wilcove et al. 1998), with anthropogenic habitat fragmentation the greatest threat to species (Benscoter et

Figure 12.8. Habitat fragmentation. USFWS National Digital Library.

al. 2013). Habitat loss has been identified as the most significant challenge Florida's biodiversity has faced over the past century (Knight et al. 2011). These threats are expected to continue as human populations are predicted to continue to increase and lead to additional land use changes. Fragmented habitats and human land uses will hinder movement of species, further reducing their ability to shift their distributions in response to climate change (Lawler et al. 2009; Marini et al. 2009; McGuire et al. 2016). Shifting patterns of human habitation, either into new locations to accommodate new residents or away from existing locations as areas, particularly along the coast, become uninhabitable, will lead to loss and degradation of habitats and ecological processes. Additionally, as people withdraw from coastal areas impacted by sea level rise, pollution from abandoned infrastructure, such as septic tanks and underground gasoline tanks, will be a major obstacle to the maintenance of communities in terms of ecological structure and function (FWC 2012). The ability of plant and animal species to retreat in response to rising waters (both sea level rise and flood events) will be affected by barriers preventing their retreat, including human-made structures, such as buildings, bulkheads, roadways, and other obstructions. Additionally, manmade ecosystem alterations, either those already existing or those put in place in response to effects from climate change, may lead to increased habitat loss, degradation, and fragmentation. For example, the use of hardened shoreline stabilization measures coupled with more intense storms could lead barrier islands (and their habitats) to fragment and disappear. As previously mentioned, climate change is expected to impact the use of prescribed fire, an important tool for the management of Florida's pyrogenic communities. Encroachment of development into and adjacent to natural systems will further reduce the ability to use fire as a management tool.

Transportation and associated infrastructure affects the structure, function, and composition of ecosystems, causing cumulative ecological effects on landscapes, with fragmentation of the landscape being the most obvious impact since roads bisect large patches of a contiguous land cover (Coffin 2007). Trombulak and Frissell (2000) developed a framework for assessing ecological effects of roads, categorizing the impacts into seven general ways that roads affect terrestrial and aquatic ecosystems. The framework included: increased mortality during road construction, increased mortality from collision with vehicles, modification of animal behavior, alteration of the physical environment, alteration of the chemical environment, spread of exotic species, and increased alteration and use of habitats by humans (increased accessibility).

Collision with vehicles has been documented to be a significant cause of mortality for several Florida species, including the Florida black bear (Neal et al. 2003) and the Florida panther (Kautz et al. 2006, Coffin 2007), and as a limiting factor in the recovery of the endangered American crocodile in Florida (Kushlan 1988). In the case of the Florida panther, the incidence of roadkill mortality has been reduced with the installation of underpasses along Interstate 75 and State Road 29 (Kautz et al. 2006). The interactions of climate change and human population growth will increase the impacts of roads and associated infrastructure on fish and wildlife species, ecosystems, and ecological processes. The effects of roads as barriers altering natural hydrology will be exacerbated by changes in the amount of precipitation and large storm events. If precipitation patterns shift to fewer rainfall events but with larger amounts of rainfall, existing transportation infrastructure, such as bridges and culverts, may not be sufficient to accommodate the increased flow. Additionally, if the number and duration of flood events increase, the number of roadkill mortality events may increase. In low-lying areas that are frequently flooded, roads built on raised beds/berms often serve as travel corridors for wildlife, with the road shoulders frequently used as the only dry foraging sites for species such as deer. During increased storm events and floods, wildlife using the roads to escape flooded habitats will be more exposed to collision with vehicles.

In coral reef systems, local anthropogenic impacts can reduce the resilience of corals to withstand threats (including climate change), resulting in a deterioration of reef structure and the ability to sustain their complex ecological interactions (Hodgson 1999; Knowlton 2001; Gardner et al. 2003; Hughes et al. 2003; Pandolfi et al. 2003; Wilkinson 2004; Bruno and Selig 2007; Hoegh-Guldberg et al. 2007).

Invasive Species

Dispersal of species to regions beyond their normal range of dispersal (i.e. introduced or alien organisms) has been a major force shaping biodiversity (Wilson et al. 2009). Climate change is expected to exacerbate impacts from non-native invasive species (Dukes and Mooney 1999; Mooney and Hobbs 2000; McNeely et al. 2001) by facilitating the introduction of invasive species (Rahel et al. 2008) and by increasing the invasiveness (rate of spread, competitiveness) of species (Clout and Williams 2009). Biological invasion is recognized as a significant threat to biodiversity, with climate and land use changes leading to drastic range shifts of invasive species (Bellard et al. 2013). Invasive species can have significant impacts on fundamental biological processes and these will most likely increase as climate change affects the distribution, spread, abundance, and impact of the invasive species (Gritti et al. 2006). Invasive species affect native populations via competition, predation, and disease (Rahel et al. 2008), as well as by alterations of habitat structure and the food web dynamics, such as replacing natives that serve as a food source (e.g., plants providing fruits, seeds, nectar, pollen). Climate change has already enabled range expansion of some invasive species and will likely create welcoming conditions for new invaders (Dukes and Mooney 1999; NFWPCAS 2012). As noted by Hellman et al. (2008), there are five possible consequences of climate change for invasive species: (1) altered mechanisms of transport and introduction, (2) altered climatic constraints on invasive species, (3) altered distribution of existing invasive species, (4) altered impact of existing invasive species, and (5) altered effectiveness of management strategies for invasive species.

Invasions of new species are assisted by land use changes, the alteration of nutrient cycles, and climate change (Vitousek et al. 1996; Dukes and Mooney 1999; Mooney and Hobbs 2000; Hellman et al. 2008). Climate changes, including extreme climatic events (i.e., storms, floods), can enhance invasion processes from initial introduction through establishment and spread (Dukes and Mooney 1999; Walther et al. 2009; Diez et al. 2012). Human-aided transport of invasive species occurs through purposeful introductions for a variety of reasons (e.g., biocontrol, sport fishing, horticulture, agriculture, aquaculture) and through accidental introductions during the course of other economic activities. Climate change could alter these patterns of human transport (Hellman et al. 2008). Changes in the amount and timing of precipitation can alter the pathways of species introductions as new or increased flow routes transport invasive species, including animals, plants and plant propagules. Changes in precipitation may also allow for additional areas to be invaded by existing species, such as the Brazilian pepper (*Schinus terebinthifolius*), where it is restricted by inundation periods longer than three to six months (Ferriter 1997).

Figure 12.9. Brazilian pepper. USFWS National Digital Library.

Climate change can lead to the establishment of new invasive species via three mechanisms: removal/reduction of climatic constraints, tolerance of climate leading to persistent populations, and increased competitive ability or rate of spread (Hellman et al. 2008). The competitive resistance of native species may be reduced as climate change causes native species to shift out of the conditions to which they are adapted (Byers 2002). It is expected that, on average, mechanisms (e.g., dispersal) enabling invasion will allow existing invasive species to expand their ranges into newly suitable habitat more quickly than native species. Therefore, those species that have the ability to shift ranges quickly would have a competitive advantage if native populations become progressively poorer competitors for resources in a changing climate (Hellman et al. 2008). For example, some invasive species such as kudzu (*Pueraria lobataor*) may benefit when CO_2 concentrations increase or historical fire regimes are disturbed (Dukes and Mooney 1999).

In addition to facilitating the colonization of new invasive species, climate change could exacerbate the effects of existing invasive species, including selective mortality of native versus invasive species, reversals in competitive dominance, increased consumption by predators, or increased virulence of disease organisms (Rahel et al. 2008). Florida has a well-documented list of invasive plants and animals—a list that is expected to increase as temperatures warm, number of frost/freeze nights decrease, intensity and/or frequency of storm events increase, and Florida's human population increases and responds to climate change. More than 170 species of ferns and flowering plants are naturalized in southeastern Florida and hundreds of exotic plants have been introduced into the region (Austin 1978). Some of these species are not currently invasive or have not spread beyond South Florida; however, with climate change, these species may become invasive in the future or expand their current range into other regions of the state. Category I plants, defined as invasive exotics that are altering native plant communities by displacing native species, changing community structures or ecological functions, or hybridizing with natives include species such as Melaleuca (*M. quinquenervia*), Australian Pine (*Casuarina equisetifolia*), Water-hyacinth (*Eichhornia crassipes*), and old world climbing fern (*Lygodium microphyllum*). These species are invading native habitats and decreasing diversity, in some cases becoming so abundant that they interfere with species use of the area (e.g., nesting sea turtles and crocodiles) and contribute to the degradation of the habitat (e.g., erosion, clogging water bodies) (Austin 1978). There are more than 400 documented non-native animals in Florida, although not all are currently considered invasive. The Gambian pouch rat (*Cricetomys gambianus*), Burmese python (*Python bivattatus*), green iguana (*Iguana iguana*), giant toad (*Bufo marinus*), walking catfish (*Clarias batrachus*), Cuban tree frog (*Osteopilus septentrionalis*) and lionfish (*Pterois volitans*) are examples of invasive animals found in Florida. These species are known to prey upon and compete with native species. The Burmese python, native to Asia, is now found throughout much of southern Florida and has been the focus of several recent studies on impacts to native species (Dorcas et al. 2011; Dove et al. 2011; Holbrook and Chesnes 2011; Mazzotti et al. 2011, Willson et al. 2011, Dorcas et al. 2012). Many of the invasive plant and animal species found in Florida are constrained to their current extent by temperature. As temperatures increase and the number of frost/freeze nights is reduced or eliminated, many of these species will be able to migrate northward, expanding their range and potentially increasing the density of their infestations/populations.

How species respond "naturally" to the impacts of climate change may make it necessary to re-evaluate the definitions of "non-native" and "invasive" species, , as some species not currently considered native, but instead transient or occasional, expand or shift their range more permanently into Florida. For example, there is speculation that climate change is a contributing factor in the natural invasion and recent establishment in Florida of two species of tropical dragonflies from Cuba and the Bahamas (Paulson 2001). Climate change could also facilitate the movement of native species into a new area of habitat or increase its abundance in an area, and in doing so it may harm other native species in ways we typically associate with invasive species

(Rahel et al. 2008), possibly leading to localized mass extinctions, speciation, and the formation of new ecosystems (Wilson et al. 2009). Climate change impacts on the population size and scarcity of native species will influence the significance of the impact from invasive species (Hellman et al. 2008). In aquatic systems, climate change could exacerbate the effects of invasive species through selective mortality of native versus invasive species, reversals in competitive dominance, increased consumption by predators, or increased virulence of disease organisms due to increased water temperatures (Rahel et al. 2008).

Management techniques to prevent invasive plant establishment and spread include mechanical, chemical, and biological methods. Changes in temperature, precipitation, growth rates and patterns, and overall health of a particular species will affect the feasibility of these management techniques as well as the response of the species to the applied treatment. The total impact of an invasive species on a community, ecosystem, or resource includes the size of the range occupied by the invasive species (its spatial extent), its average abundance within that range, and its per capita (or per unit biomass) impact (Parker et al. 1999). Anticipating future distributions of invasive species is essential to facilitate preemptive and effective management (Bellard et al. 2013). The ability to manage invasive species due to changes in temperature, precipitation, and sea level rise will require new research, more monitoring, and a coordinated response system.

Pathogens, Parasites, and Pollutants

The climate change may result in increasing pathogen development and survival rates, disease transmission, and host susceptibility (NFWPCAS 2012). Warmer temperatures allow disease organisms to complete their life cycle more rapidly and attain higher population densities (Marcogliese 2001). Additionally, native diseases that currently only have minor effects on host organisms could have more devastating impacts under future climatic conditions (Rahel et al. 2008). Many marine and terrestrial species' pathogens are sensitive to shifts in temperature, rainfall, and humidity. As temperatures increase, many diseases are expected to become more lethal and to spread more readily (Epstein 2001; Harvell et al. 2002). There are climate-linked predictions that amphibians will decline in unusually warm years due the influence of temperature on disease dynamics (Epstein 2001; Harvell et al. 2002). A study of frogs and a pathogenic chytrid fungus (*Batrachochytrium dendrobatidis*) in Central and South America concluded that climate-driven epidemics are an immediate threat to biodiversity (Pounds et al. 2006). Changes in temperature, precipitation, soil moisture, and relative humidity can also affect the dispersal and colonization success of forest pathogens, which may impact forest ecosystem biodiversity among other important indicators of forest health (Brasier 1996; Lonsdale and Gibbs 1996; Chakraborty 1997; Houston 1998).

Increased temperatures impact parasites by increasing their growth rates, sexual maturation, mortality, and number of generations per year; higher temperatures can also promote earlier maturation, transmission, and potential maintenance of transmission year-round (Marcogliese 2001). The predicted changes in temperature and precipitation will have a serious impact on almost all environmental conditions in aquatic systems, affecting the distribution and abundance of free-living organisms, and thus by extrapolation, their parasites (Marcogliese 2001).

Alterations to temperature, pH, dilution rates, salinity, and other environmental conditions due to climate change can affect the impacts of pollutants on species and systems. The effects from these climatic changes can modify the availability of pollutants, the exposure and sensitivity of species to pollutants, transport patterns, and the uptake and toxicity of pollutants (Noyes et al. 2009). Altered transport patterns of environmental pollutants may lead to accumulations in new places thereby exposing biota in different habitats. Increased coastal flooding and inundation may result in release of contaminants from coastal soils, sediments, and infrastructure and increase exposure of fish, wildlife, and plants to these pollutants (NFWPCAS 2012). Climatic changes may lead to increased sensitivity to pollutants due to metabolic stress or inhibition of physiological processes that govern detoxification (NFWPCAS 2012).

Climate change is one of the cited causes of harmful algal blooms (Moore et al. 2008; Hallegraeff 2010), with warmer temperatures boosting the growth of harmful algae (Jöhnk et al. 2008; Paerl and Huisman 2008). The amount of runoff of phosphorus and other nutrients from farms and other landscapes currently contributes to harmful algal blooms and is expected to worsen with predicted increases in floods and other extreme precipitation events (NFWPCAS 2012).

Competition for Resources/Overexploitation

Florida's natural systems, in addition to their role in supporting biodiversity, provide a multitude of public services—supporting working landscapes, commercial and recreational activities. When well-maintained and well-managed, Florida's ecosystems can support these activities; however, overexploitation, misuse, and illegal activities can cause harm to the systems, communities, and species. Climate change can heighten species' vulnerability to overexploitation and, inversely, exploitation has made species particularly vulnerable to changes in climate (Harley and Rogers-Bennett 2004).

Activities such as hunting, fishing, wildlife viewing, hiking, biking, swimming, boating, and kayaking are popular recreational activities in Florida. Under future climatic conditions, current harvesting regimes may no longer be sustainable; furthermore, the indirect consequences of species harvest on non-target species may require special attention where a common resource base is likely to alter under climate change (Hulme 2005). Species and populations already stressed by the effects of climate change, could be pushed beyond their ability to adapt and survive—even when the natural areas they inhabit remain intact. Their environment could be degraded simply by the presence of humans as well as impacts through removal (collecting, pet trade), handling by recreationists, increased number of predators attracted by food waste, and disturbance by dogs (Gibbons et al. 2000). Due to concern about the increasing popularity of turtles for over-harvest, the Florida Fish and Wildlife Conservation Commission passed stronger rules to protect turtle species, prohibiting the taking or possession of six species of freshwater turtles from the wild (FWC 2016c). Species and populations impacted by climate change may be more vulnerable to over-harvesting if they become easier to harvest due to altered and increased movements as they react to loss or degradation of habitat, if they are forced to find alternative food sources, if their behavior is altered, or if they become stressed or diseased.

Additive and synergistic interactions between climate change and exploitation are becoming increasingly important to the dynamics of marine ecosystems and the sustainability of marine fisheries, such that stress and reduction in population size from existing fishing pressure in combination with the effects of intense events such as extreme temperature or storms may lead to increased risk of extinction of local populations (Harley and Rogers-Bennett 2004). In oceanic fish populations, human exploitation may further exacerbate the effects of oceanic warming (Walther et al. 2002). Florida is the number one destination in the US for saltwater anglers (Anderson et al. 2016). As the climate continues to change, the subtropical and tropical flats upon which species such as bonefish, tarpon, and permit depend upon, will be threatened by sea level rise. As sea level rise impacts these systems and habitats, fish stock could decrease and fishing regulations may have to change, reducing or eliminating harvest of these species.

The timber industry, cattle ranching, fishery and aquaculture industries are examples of compatible commercial use of the landscape. Climate change may impact the ability of the land to support existing levels of commercial use. For example, decreases in precipitation coupled with increases in temperature may reduce the landscape’s ability to grow the same number of trees or cattle, or affect their growth rate or health. Modifications in stand density or cattle stocking rates, or the expansion of these systems to maintain existing yields, may impact the ability of the landscape to continue to support compatible populations of fish, wildlife, and plants. Other chapters of this book contain more information on climate impacts to forestry, land use and land cover, and fisheries.

Changes in groundwater and surface water, both in the amount and quality, have significant effects on biodiversity (Knight et al. 2011). Water resources may have the highest demand for competitive uses. Reduced water availability as a result of climate change is expected to affect the greatest number of species (Robinson et al. 2009). Increases to ground and surface water withdrawal to accommodate current and increased human populations as well as potential shifts in land use could further degrade systems that are stressed by decreased precipitation and droughts. Extraction of fresh water can significantly alter natural water flows, leading to impacts on habitats and the populations and species dependent upon them. Reduced precipitation will act in concert with water extractive activities, leading to decreases in water availability and flows causing potential alterations in food/prey abundance and availability, misalignment of reproductive cycles of aquatic organisms, increased rates of disease/parasite transmission as species are crowded into fewer remaining suitable areas, and direct loss of habitat. Increased water demands for domestic, industrial, and agricultural use along with rising temperatures will lower water tables, severely impacting wetlands (Sala et al. 2000).

Preserving Biodiversity for the Future

Biodiversity conservation in a changing climate requires a re-evaluation of management goals and objectives. Compared to the rate of past environmental change, the rate of future change within natural systems could be very swift and the magnitude of change could be large. Management approaches will need to be forward-looking and focus on maintaining a diversity of well-functioning ecosystems, as it could be very difficult to maintain the current spatial arrangements and composition of systems, communities, and species under a changing climate (Steffen et al. 2009). The Climate Smart Conservation framework outlines seven major steps for climate adaptation (Stein et al. 2014). The process begins with defining the planning purpose and scope, and an assessment of climate impacts and vulnerabilities to be used to review and possibly revise the conservation goals and objectives defined in the planning purpose and scope. The next steps include identifying possible adaptation options, evaluating and selecting adaptation actions, and then implementing priority adaptation actions. Implementation is followed by monitoring to track the effectiveness and ecological response of the adaptation actions. The entire process is iterative, with each step potentially looping back to the previous one, as needed. There are tools available to assist in determining potential impacts and relative vulnerability that can aid in developing adaptation strategies. Three main practices have been proposed to identify priority areas to protect biodiversity, including: 1) focus on areas where species are predicted to have the highest loss or the highest stability (areas to serve as refugia) (Lawler et al. 2009), 2) provide connectivity to allow species to move and shift their ranges (Heller and Zavaleta 2009), and 3) maintain landscape features that control species richness (geophysical variables) (Anderson and Ferree 2010). Identification of knowledge gaps can motivate research and monitoring efforts to improve future adaptation strategies development and implementation.

Impact Assessments

Species and the natural communities that they comprise have evolved through episodes of climate change more severe and more rapid than even the post-industrial age of anthropogenic global warming (Balsillie and Donoghue 2004; Donoghue 2011). However, the adaptive capacity of species and natural communities to respond to that change has been severely compromised by human modification of the landscape (Hughes 2000; Brooks et al. 2002; Thomas et al. 2004). As such, a critical step in analyzing the potential impacts of current and future climate change is the assessment of the vulnerabilities of species and natural communities (Miller et al. 2006). These vulnerabilities may be mediated by other threats and impacts, such as land-use change.

Vulnerability assessments are a suite of tools that reflect the relative and cumulative vulnerability of populations, species, or groups of species comprising a natural community, to stressors. Vulnerabilities are typically partitioned into two components: exposure and sensitivity; often, the adaptive capacity of species or natural communities is also assessed. Inclusion of at least these three factors is important because the data typically used in the assessment process includes geographic overlays of projected conditions. In such cases, exposure can be precisely calculated through geospatial model overlays (e.g., inundation from sea level rise, conversion of natural areas to agricultural uses, etc.), while other factors such as sensitivity and adaptive capacity are determined by less empirical and more qualitative methods of assessment.

Vulnerability assessments are a suite of tools that reflect the relative and cumulative vulnerability of populations, species, or groups of species comprising a natural community, to stressors.

Land use change represents the strongest stressor on natural communities and on most species globally (Pimm and Raven 2000) and in Florida (Reece et al. 2013a). Anthropogenic climate change may exacerbate this stress through altered temperatures, precipitation, seasonality, and most importantly, sea level rise. Uncertainty of various types is an important factor to consider when implementing the results of a vulnerability assessment. For example, a high vulnerability to a particular threat, such as altered precipitation patterns, should be modulated by the relatively high uncertainty in precipitation projections relative to the more predictable change in temperature and sea level rise.

Several vulnerability assessment tools are available and have been implemented widely throughout Florida and surrounding regions. Each of the following tools focuses on a different aspect of vulnerability. Many of these tools are not equivalent and, importantly, the assessment of the same species often varies wildly depending on the choice of vulnerability assessment (Reece and Noss 2014). The Climate Change Vulnerability Index (CCVI; Young et al. 2009; Dubois et al. 2011) is widely-used and very easy to implement for rapid assessments of species. The scorer chooses a number value corresponding to a degree of exposure and sensitivity for threats, and then these are summarized into an overall assessment score. The relative importance of each of the criteria assessed is unclear, as not all vulnerabilities weigh equally on the overall assessment. The CCVI includes temperature and precipitation change as well as sea level rise and other land use-related threats exacerbated by climate change. However, the focus of this assessment is on future vulnerability to climate change, ignoring other types of threats and the current status of the species. The Conservation Status Assessment (CSA; Faber-Langendoen et al. 2012) is a widely-used system instituted by NatureServe for both species and natural communities. Similar to the CCVI, it uses a quantitative assessment system to produce a numerical score. The CSA uses a statewide and global assessment for spatial scale, and it focuses on past and present threats more than future threats. Global assessment tools such as the US

Endangered Species Act prioritization system (ESA 1973) and the International Union for the Conservation of Nature Red List system (IUCN 2010, 2015) both include quantitative assessments for species and natural communities, but do not differentiate by state or regional lines consistently enough for broad-scale prioritization or assessment efforts. The Standardized Index of Vulnerability and Value Assessment (SIVVA; Reece and Noss 2014) is a relatively recent addition to the list of vulnerability assessment tools for both species and natural communities. The SIVVA framework includes a mix of quantitative and qualitative criteria and a capacity for the user to set and manipulate the relative importance of criteria. In addition to assessing exposure and sensitivity (vulnerability) and adaptive capacity, SIVVA also includes criteria on conservation value and information availability. When the purpose of a vulnerability assessment is not only to calculate extinction risk but also to prioritize conservation efforts, the relative value of a species and the amount of information available to properly manage that species are extremely important to include (Reece et al. 2013a). This assessment has been used throughout Florida (Benscoter et al. 2013; Reece et al. 2013a), Georgia (Lowery 2016), and more broadly in the Gulf Coast (Watson et al. 2015).

There are a variety of vulnerability assessments available depending on the goals of the user. In each case, the user should, at a minimum, assess the exposure, sensitivity, and adaptive capacity of the species or natural community. It is also important to examine synergisms among threats, the spatial scale of the assessment, and the focus on past, present, and/or future threats.

Awareness that change is likely to happen is critical to planning for the future. Visualization of that awareness can be achieved through a method of study called scenario planning. Scenario planning is a discipline for developing a visual or narrative description of plausible future outcomes based on the combination of a range of complex and often intertwined factors that are projected into the future (Steinitz and Rogers 1970). It can be used to investigate the variables involved in the low controllability and high uncertainty of future states of the environment, and to determine the feasibility or likelihood of long-term biodiversity conservation in the face of climate change and resource consumption (Peterson et al. 2003). Scenario planning facilitates the comparative measurements of the rates and types of changes in biodiversity response variables, such as habitats, indices, and land cover (Gude et al. 2007). This information can then be used in support of various vulnerability assessments of natural systems or species persistence across a modeled range of future climate perturbations. Predetermined variables are applied to a series of modeled decisions over specified time steps to visualize how events or environments could look in the future. When the variables and decisions are altered, the outcomes of the scenarios change to reflect how these differences are represented or expressed, and how they

Scenario planning is a discipline for developing a visual or narrative description of plausible future outcomes.

interact with each other. By comparing multiple future scenarios, and identifying the strategic issues and causes that led to each of those particular outcomes, the potential impacts of individual decisions or modeled events can be directly visualized, evaluated, and contrasted between scenarios, thereby reducing uncertainty.

Inputs to biodiversity-oriented scenario planning models are dependent on the impacts being examined and the types of outcome information sought. Many scenario planning projects use spatial data-manipulating programs such as geographic information systems (GIS) to visually depict the locations and extent of impacts. In other studies, scenario planning can be a narrative that describes a series of decisions and policy directions and the resulting environment, including descriptive visions of the future ecosystem states. In all cases, the inputs to the planning process are directly related to the construction of the scenario framework. The framework is the set of bounding data, assumptions, and desired analysis questions that constrain the extent of the study.

There is a high degree of uncertainty as to how the extent and speed of both current and future anthropogenic alterations that will influence climate change, putting pressure on species and ecosystems to adapt, possibly rapidly and in unknown directions. By applying scenario planning to these issues, employing credible information, informed questions, robust models, and a willingness to explore a range of alternatives, the percentage of what is unknown can be reduced to a manageable range of plausible futures. This process allows for informed decision-making to the benefit of biodiversity.

There are a broad range of scenario planning models for the environmental realm that can be grouped into three subcategories: (a) "exploratory scenarios," which represent different plausible futures; (b) "target-seeking scenarios," also termed "normative scenarios," which represent an agreed-upon future target and the scenarios that provide alternative pathways for reaching this target; and (c) "policy-screening scenarios," also known as "ex-ante scenarios," which represent the outcomes of various policy options under consideration (IPBES 2016). A recent example of an "exploratory" scenario model for the state of Florida was the 2014 project: Landscape Conservation and Climate Change Scenarios for the state of Florida: A Decision Support System for Strategic Conservation. This project used scenario modeling to predict future conservation opportunities to maximize protection of biodiversity, as well as potential areas of conflict, for locations of high ecological importance that overlapped with predicted urban growth or climate change impacted areas (Vargas et al. 2014). These models used were GIS-based spatial analyses that incorporated spatial infrastructure data, population growth projections, land use categories, financial conservation allocation strategies, and sea level rise predictions to create a range of future scenarios for Florida. This information could then be reflected back to management and funding policies to inform decision-making for biodiversity conservation objectives or goals, including mandates or conservation target development. A similar "exploratory" assessment of future climate change impacts was analyzed using the same set of Florida scenarios, specifically to determine where and what would be affected by simulated sea level rise projections.

Scenario planning results are used as inputs for a range of supplementary investigations. Additional analyses that incorporate the comparative aspect of multiple futures can include the evaluation of uncertainty, degree of impacts to constructed and natural systems, risk analysis and strategic forecasting, and cost-benefit analyses, among others. In the case of the Florida scenarios example, the future scenario outputs were subsequently used in a spatial comparison with imperiled species' habitat areas. This was done to determine where critical habitat would potentially be prime targets for urban development under different growth drivers and to highlight the amounts and locations of critical lands that could be lost to inundation due to sea level rise projections. In these analyses, spatial calculations quantified the amounts of direct impacts to habitats for each scenario. This information could then be used to estimate the exposure that ecological systems might incur due to the amounts, types, and locations of loss based on each scenario.

Adaptation Planning

> Adaptation planning is a process that assesses the future change of current conditions, and adjusts management techniques and goals as needed to support positive outcomes.

Adaptation, as defined by the Intergovernmental Panel on Climate Change (IPCC 2007), is an "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities." Tools such as scenario planning give scientists and managers indications of the array of potential environmental impacts due to climate change, and vulnerability assessments identify the realistic range of changes that could be withstood before detrimental effects on biodiversity are observed. Similar to scenario planning, adaptation planning is not necessarily constrained to biodiversity conservation, but it is most often applied to impacts to natural resources and the environment.

Adaptation planning is a tool that assesses observed and forecasted impacts, acknowledges the uncertainty of future states of the environment, and develops actionable steps and a flexible implementation strategy in order to prepare for changes to the environment. It is a process that manages change, versus maintenance of existing conditions, and adjusts management techniques and goals as needed (Stein et al. 2013). Adaptation planning includes two initial processes: determining the scope of the system being planned for, and developing the strategies employed to encompass the uncertainty of climate change impacts to that system.

Conservation planning strategies related to climate change adaption can be grouped into three general categories: (a) the continuation and support of "best practice" strategies, (b) "building off of or "extending 'best practice' principles," and (c) "integrating assessments on species vulnerability to climate change into a conservation planning framework" (Watson et al. 2012).

"Best practice" strategies are those that continue current accepted or implemented conservation actions. These strategies include the identification and protection of key habitats and critical populations, habitat conservation replication and extent minimums to reduce vulnerability from stochastic events or other variables, and efficient design and management of conservation networks to maximize effectiveness and minimize existing and potential threats (Watson et al. 2012). "Best practice" strategies on their own are no longer considered sufficient to preserve biodiversity over the long term due to the static nature of their conservation techniques (Cameron-Devitt et al. 2012).

Extensions of "best practice" principles take the methods of achieving current conservation objectives and apply forward-looking assessments of how the environment will change over time to affect the existing conservation system and the diversity it supports. These extensions include strategies such as expansion and connectivity of current conservation lands to maximize the potential for populations to adapt to change within their environment, the inclusion of species refugia in conservation objectives, and management strategies that prioritize protection and maintenance of entire ecosystems versus individual species (Watson et al. 2012). These techniques incorporate potential climate change impacts into conservation planning, but are not truly adaptive because they do not set forth a system to reassess goals over time and alter or change strategies as needed.

The third category of conservation planning strategies has developed into what most scientists and managers currently consider adaptation planning (Stein et al. 2013). This form of planning incorporates species or ecosystem vulnerability assessments into the planning framework and alters conservation strategies to fit the needs of the environment. The vulnerability assessments will be altered by changing conditions over time, both climate-induced and direct anthropogenic impacts. To address future climate uncertainties, conservation planning strategies require management support in order to rerun vulnerability assessments to reassess the potential for natural resources to persist through a range of environmental changes. The incorporation of these assessments broadens the scope of the process to address both current and potential future needs under an array of scenarios. These types of supporting assessments provide data and information for the development of plausible, flexible, and effective management approaches to improve resilience, reduce vulnerability, and adapt to changing conditions.

Adaptation strategies are specific steps enacted at pre-determined times or levels to reduce risk from, or increase resilience to, detrimental climate change impacts.

Adaptation planning strategies developed specifically for biodiversity or ecological diversity preservation can be grouped into categories related to their area of application, such as habitat protection or management, species management, planning and monitoring, or law and policy (Mawdsley et al. 2009). However, effective adaptation planning should consider an array of applicable strategies, as climates and ecosystem-dependent conservation goals shift over time. Examples of adaptation planning in Florida range from a suite of all-encompassing policy actions in the Florida Energy and Climate Change Action Plan (Center for Climate Strategies 2008) and other sector-wide policy frameworks (e.g. Murley et al. 2008; Beever et al. 2010, Southeast Florida Regional Climate Change Compact Counties 2012), to specific biodiversity conservation techniques for inclusion in state wildlife action plans (Association of Fish & Wildlife Agencies 2009) or for other natural resource agencies (Cameron-Devitt et al. 2012).

The Florida Fish and Wildlife Conservation Commission recently completed their planning document, *A Guide to Climate Change Adaptation for Conservation: Resources and Tools for Climate Smart Management of Florida's Fish and Wildlife Species and Their Habitats* (FWC 2016a). The report identifies climate-related threats to species and natural communities based on impact and vulnerability assessment tools, and proposes priority conservation strategies. It also offers an approach to identifying adaptation strategies by grouping ecosystems with shared vulnerabilities and similar sets of ecological impacts, while tailoring strategies to the climate change stressors for each group. This leads to the determination of specific adaptation strategies to reduce risk that address the consequences of climate change for each natural community. These strategies form the basis of the climate change adaptation plan for Florida's natural resources. For many of the ecosystems analyzed in the document, collecting ecological values and feedback through the use of monitoring (described in detail in the next section) is specified. This element of the planning guide contributes to its function as an adaptive management plan for climate change. This information is used to alter goals, strategies, or implementation of actions and adaptation strategies as climate changes occur which shift biodiversity or natural resource targets and potential vulnerabilities.

Watson et al. (2012) described the elements of a "good adaptation strategy" as one that includes the following characteristics:

- Incorporate clear planning principles (flexibility, efficiency)
- Account for uncertainty
- Understand trade-offs
- Manage for both climate variability and long-term climate change
- Integrate human response
- Clarity of adaptation goal: resilience vs. resistance

As one of a series of climate change planning tools, adaptation planning incorporates alternative scenarios, impact and vulnerability assessments, conservation prioritization and "best practice" methodologies, and climate change predictions to produce a plan to preserve biodiversity in the face of major environmental changes. However, the step in the process that is integral to adaptation planning effectiveness is the inclusion of an element of flexibility and acceptance of uncertainty of climate variability and the resulting impacts to the environment. This adaptability can be acknowledged through updated vulnerability assessments, policy and management alterations, and modified strategies, but the ability to revise underlying conservation goals and implement adjustments will be critical to the long-term preservation of biodiversity and natural resources.

Research and Monitoring

Species Resilience

Resiliency is the ability of species or ecosystems to endure direct or indirect changes to their environment, and either recover or adapt to those changes.

In previous sections of this chapter, vulnerability assessments were mentioned as tools to evaluate the degree to which species or ecosystems can withstand perturbations and alterations to the habitats relied upon for continued existence or functioning. An assessment of species resiliency is a similar tool used in adaptation planning to predict impacts from potential shifts in future states of the environment. Resiliency is the ability of species or ecosystems to endure direct or indirect changes to their environment, and either recover or adapt to those changes. Resiliency is an attribute that allows for biological flexibility and continued existence in highly variable natural systems, and species or ecosystems with higher resiliency have the ability to 'weather the storm' more successfully. Species or systems with low resiliency may reach disturbance or variation thresholds sooner or at lower impact levels, from which there may be either no recovery or the occurrence of a regime shift (Folke et al. 2004). Regime shifts can often be to a condition or state of existence that is less productive, less stable, or threatens the survival of species. Climate change will cause unknown impacts to ecosystems and dependent species; but by employing the planning tools previously discussed, potential impacts and magnitudes of change may be possible to describe and predict. Enhanced by the inclusion of resiliency assessments, adaptive resource management and planning can be improved by taking into account the points in time or state of the environment at which species or ecosystems would be irrevocably affected.

Trigger Points

A trigger point is an event, change in status, or measureable level that indicates the system or object being monitored has reached a crucial state in advance of a critical threshold.

Adaptive management's 'early warning system' for conservation is called a trigger point: an event, change in status, or measureable level that indicates the system or object being monitored has reached a crucial state in advance of a critical threshold. A trigger point provides a preventative warning or alarm that indicates some type of action needs to be taken to prevent the state from deteriorating further and reaching a critical threshold. Trigger points are developed from potential threats deduced from scenario planning, the vulnerability of species or ecosystems from vulnerability assessments, and the determination of detrimental regime shifts or significant events from species resiliency assessments, incorporated with an understanding of the time lag needed to reassess plans and activate a management response. Trigger points enable adjustments to adaptation plans and strategies in response to new or updated information and changing circumstances (Moss and Martin 2012). It is important to note that a trigger point is not a tipping point or a critical threshold; it is a status or level identified during the planning stage that indicates a critical threshold may be imminent if actions are not taken to prevent it.

The CoastAdapt tool developed by the National Climate Change Adaptation Research Facility is an example of how trigger points can be used in adaptive management for biodiversity conservation (NCCARF 2016). This online program, partially funded by the Australian Department of the Environment and Energy, seeks to provide a tool and guidance to managers and scientists to approach climate change and sea level rise issues with an adaptive management process. In step six of their Coastal Climate Adaptation Decision Support (C-CADS) methodology, it is recommended to develop trigger points that are robust and inclusive of the range of potential climate variability (NCCARF 2016). Trigger points can be physical, environmental, social, or economic depending on the scope of the study, and should be observable, measureable, and comprehensible to all stakeholders involved (NCCARF 2016).

Monitoring

Plans that continually incorporate updated information on the status of the resources, and adapt their policies and strategies accordingly, will be more robust and responsive in the long term. Monitoring programs specific to the threatened species and ecosystems in question are essential but often overlooked components of adaptation planning. Conservation monitoring programs will be most effective when they are embedded in and inform management plans, including the necessary ability to detect spatial and temporal changes early on (Beever 2006; Lindenmayer et al. 2013). Without monitoring systems in place, system variables cannot be evaluated on a continual basis to recognize when trigger points are reached, environmental subtleties can go unnoticed, the amount of reaction time available to alter or adapt policies to extreme events is reduced or eliminated, and key indicator data for species and ecosystems is not consistent or available to other research endeavors. Equally as important, if not more so, is the necessity of using monitoring programs to assess the performance of adaptation plan efforts to determine whether strategies are effective, relevant, and efficient (NCCARF 2016).

Adaptation management monitoring programs can be scaled from local resource levels to entire countries, and the usefulness of the program depends on the objective of the study and the information it contributes to evaluation, planning, and management processes. An ongoing monitoring program established in Everglades National Park in Florida collects an array of variables associated with hydrology, climate, and salinity (Mitchell and Krueger 2011). This data contributes to evaluations of risk and resiliency of species and habitats to climate change impacts, such as sea level rise (Mitchell and Krueger 2011). The collected information is also used in conjunction with additional research and modeling efforts to understand hydrological, species, carbon, and ecosystem dynamics in and around the park, and is critical to efforts to evaluate the potential magnitude of climate change effects on the natural resources in the park (Mitchell and Krueger 2011). Without long-term monitoring programs, all research programs that inform adaptive management strategies for the park, such as habitat suitability modeling, mangrove carbon dynamics, or Florida Bay restoration planning, would not be supported.

The tools described in this section build upon each other and are integral to effective climate change adaptation planning for the long-term conservation of biodiversity. Natural resource managers and policy makers can take advantage of this wealth of information to make informed decisions when they have awareness of the range of potential impending changes to the environment, acknowledgement of the uncertainty to be faced, and access to a flexible adaptation plan with supportive monitoring programs and relevant trigger points. “The future is not predictable and as a result, adaptation depends on learning and responding effectively to lessons learnt, as well as experience, changing circumstances and new knowledge” (South West Climate Change Portal 2016).

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