Chapter 11

The Effects of Climate Change on Natural Ecosystems of the Southeast USA

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This chapter examines those ecosystems not covered by other chapters in this report, focusing primarily on ecosystems of the southeast that are either aquatic or experience soil water saturation and flooding on a regular, annual basis. Agricultural and forest systems are discussed in separate chapters of this report. We were unable to be exhaustive in our ecosystem coverage, which means that several very important natural ecosystems of the Southeast (SE) are not discussed anywhere in this report.

Our approach was to broadly cover the impacts of key elements of climate change in the Southeast, including temperature, precipitation, storms, and ocean acidification. Hydrology and the water budget play a critical role in how the ecosystems covered in this report will be impacted by climate change, because of the close connection between temperature and precipitation with ecosystem evapotranspiration (ET). The interaction between the physical aspects of climate change and the feedbacks from biotic communities will affect the vulnerability and sustainability of natural ecosystems of the Southeast. Because of the possibility of rivers, reservoirs, and wetlands totally drying out because of climate change and human engineering of terrestrial and river systems, we find the aquatic systems of the Southeast to be perhaps the most susceptible to climate change. If our grandchildren are to be able to appreciate these natural ecosystems in their lifetimes, it is essential that we fully understand the complex linkages and feedbacks between the combined effects of climate change, land use change, and human engineering of the landscape.

Key Findings

Three very different aspects of climate change are very likely to affect natural ecosystems of the Southeast. Those aspects are (1) warming and hydrology (rainfall and evapotranspiration) (2) sea level rise (SLR), especially for tidal fresh to saline marshes and swamps, and (3) ocean acidification, especially for hard bottom reefs and coral reefs.

For all the natural ecosystems considered in this chapter, it is difficult to isolate the effects of climate change from the many other threats to these systems, including, for example, invasive species and disease, land use change, water withdrawals, and atmospheric deposition. A unique characteristic of many natural wetland ecosystems of the SE is that the combined effects of sea level rise, associated increase in salinity, increased interannual variability, and altered dry-wet cycles (see Chapter 2) likely will enhance the fluxes of potent greenhouse gases (GHGs), especially methane (CH_4) and nitrous oxide (N_2O), into the atmosphere. This increase in GHG emissions has implications for the USA carbon balance and its net contribution to the global increase in effective CO_2 concentrations in the atmosphere.

- For aquatic ecosystems in the SE an important aspects of climate change will be warmer water temperatures that are expected to put organisms closer to the threshold temperature for their thermal tolerance and exacerbate low dissolved oxygen conditions, which already characterize many of the blackwater streams draining the SE coastal plain.

- In parts of the Southeast, more frequent droughts coupled with increasing water demands from greater evapotranspiration (ET) and growing human consumption may result in more frequent stream drying, even in systems historically considered perennial, which may in turn increase the frequency of local species extirpations.
- Non-native, invasive species will increase due to less frequent and shorter durations of cold temperatures caused by climate change.
- Climate change is expected to have major harmful impacts in the increasingly rare longleaf pine savannas of the SE.
- Some parts of the SE are projected to experience more frequent droughts and higher rates of ET, which is expected to worsen the fire risk that is already the greatest threat to millions of acres of freshwater peat wetlands. CO_2 emissions during fire can reverse centuries of CO_2 sequestration and ultimately convert these systems from being net C sinks to significant C sources.
- In the SE tidal wetlands, the higher predicted rates of SLR are likely to outpace the ability of wetlands to accrete sediment and increase their elevation. As a result, wetlands are expected to become vulnerable to coastal erosion and increased inundation, eventually converting to open water. Such changes have been apparent in coastal Louisiana for several decades, where loss is exacerbated by high rates of land subsidence as well. With the loss of tidal wetlands, upland human settlements will lose important protection from storm surges, which could result in significant economic loss to coastal communities.
- Coral reefs and other hard-bottom reefs of the SE are also susceptible to climate change, especially due to warming waters, acidification, and sea level rise. Effects of ocean acidification and warming can be exacerbated when present with other stressors in reef systems, such as disease, coastal runoff, overexploitation, vessel damage, marine debris, and exotic species.

Climate effect on hydrology in the SE will be perhaps the single most important impact on natural ecosystems during the coming century. This aspect may also have the greatest policy relevance because society has the ability to control or regulate precipitation runoff, river flow, water storage, and water use. To some extent, warming of aquatic systems can be moderated by water management that insures adequate flow during summer months. Likewise, salinity intrusion and the upstream shifting of brackish habitats can be controlled, though not prevented, by water management that buffers the effects of droughts. Loss of river and noncoastal wetlands might also be moderated or controlled by water management policy that limits drainage, maintains connection to the river network, and meets minimal flow requirements of the various types of wetlands of the SE.

How natural ecosystems of the SE will respond to climate change is the subject of ongoing research. How climate changes will interact with other anthropogenic activities, such as land use change and human water use, are also important avenues of study. Available research suggests that future policy and management activities may need to be adaptive by design and changed as knowledge expands.

11.1 Background

In this chapter, the major ecosystems of the SE and Caribbean region are discussed, excluding those discussed in other chapters, namely natural and managed forests, agriculture, and the systems supporting major commercial fisheries and mariculture operations. This review begins with the aquatic systems of the SE, the lakes, reservoirs, streams, and rivers. The chapter then transitions down elevation to review the effects of climate change on savannas, then freshwater wetlands and swamps, tidal wetlands and swamps, and finally offshore coral reefs and hard-bottom reefs.

Not all natural ecosystems of the SE are discussed, only those that are considered to be most vulnerable to changes in the hydrologic cycle as a result of changes in temperature, precipitation, and evapotranspiration. Two types of systems that are uniquely vulnerable to other aspects of climate change, sea level rise and ocean acidification, are also discussed. Important systems not examined include maritime forests on barrier islands (Figure 11.1), other barrier island ecosystems, such as dunes (Greaver and Steinberg 2010), and southern Appalachian bogs. These should be included in future assessments of climate change in the SE.

Climate projections considered in this chapter were developed for the 2012 Southeast Climate Assessment report (Konrad et al. 2012), and are based on regional downscaling of the National Climate Assessment using the IPCC A2 and B1 scenarios for climate projections. The A2 scenario is somewhat pessimistic in that it assumes many nations will change behaviors only modestly. For the SE, it assumes population will triple by 2100. The B1 scenario in contrast is optimistic that nations will mitigate human activities that can further warm the planet. For the SE, it assumes population will increase about one-third by 2100. With respect to climate, all scenarios suggest there will be marked warming across the SE, especially during summer. Temperature is likely to increase 1.2°C to 2.2°C in the Caribbean to as much as 4.4°C in interior regions of the SE. Warming will be pronounced in urban areas, because of the urban heat island effect (see Chapter 5). There likely will be increases in annual net precipitation across much of the SE, but with decreased rainfall during summers. There is increased likelihood for the number of extreme precipitation events to increase throughout the region especially across the lower Mississippi River Valley and along the northern Gulf coast. Interannual variability is projected to increase with greater likelihood of drought across the lower Mississippi River and Gulf Coast but fewer droughts across the northern tier of the SE region and in the mid-Atlantic. Thus we can expect to see increased frequency and severity of drought with consequent effects on hydrology and river flow. Sea level rise is expected to increase between 0.2 m and 2 m by the end of the century.

11.2 Southeastern Freshwater Aquatic Ecosystems

The aquatic systems of the SE are diverse and include the largest river system of the USA, the Mississippi and Atchafalaya Rivers; first-order mountain streams of the Smokey Mountains in Tennessee and North Carolina; manmade ponds and reservoirs so common on farms and throughout the Tennessee River Valley; the blackwater rivers of coastal Georgia, Florida and South Carolina; and the freshwater Everglades of Florida.

Figure 11.1 Maritime forests on some of the few remaining, relatively intact barrier islands of the Southeast, for example on Ossawbaw Island, GA, are vulnerable to climate change through the devastating impact of winds, surge, salt spray, and shoreline erosion from hurricanes and sea level rise. This artistic rendering by Philip Juras (*Passing Storm*, 2009, oil on canvas) shows remnants of the maritime forest now in the intertidal beach zone.

Streams, Rivers, Lakes and Reservoirs

Many freshwater ecosystems in the SE increasingly are subject to changing climatic conditions (Cook et al. 2007, Karl et al. 2009, Kaushal et al. 2010). Warmer waters, the potential for more frequent and severe droughts in some regions, and floods from more extreme storm events such as major hurricanes, will continue to alter freshwater ecosystems and will stress a wide range of freshwater species (Emanuel 2005, Gibson et al. 2005, Elsner and Jagger 2006, Shepherd et al. 2007, Parisi and Lund 2008, Kaushal et al. 2010, Dai 2011). Long-term (more than 100 years) decreases in rainfall have been observed for warmer months of the year for Georgia, North Carolina, and South Carolina (Alexandrov and Hoogenboom 2001). In some SE coastal plain regions, decreases in summer rainfall combined with increased groundwater withdrawals for irrigation are resulting in significant decreases in stream discharge (Rugel et al. 2012). These declines have been linked to decreased exports of carbon as suspended organic matter to coastal areas and with potential increases in local mineralization rates and corresponding release of CO_2 from streams (Mehring 2012).

Where long-term trends of increasing temperatures and extremes in rainfall (droughts and floods) occur, these are likely to alter distributions and abundance of freshwater algae, zooplankton, benthic invertebrates, and fish as well as ecosystem

processes. In general, the effects of increased temperatures will decrease dissolved oxygen concentrations and increase rates of respiration for freshwater species. For example, many cold-water fish such as trout in southern Appalachian headwater streams are currently near their upper thermal limits during extreme summer heat waves (see Chapter 10). Even warm water species can be limited by extremely high water temperatures in shallow ponds and pools where cool, deep waters or spring-fed inflows are not available as thermal refugia. Of particular concern are largemouth bass, a large component of the multimillion-dollar recreational fishing industry in southeastern waters (Boyle et al. 1998, Hay 1988).

There are many direct and indirect ways in which warming can impact aquatic systems of the SE. Higher temperatures in shallow lakes and reservoirs can increase growth rates for warm-water species but only to thresholds of thermal tolerance (Rypel 2009). Higher water temperatures are also expected to exacerbate low dissolved oxygen conditions, which already characterize many blackwater streams that drain the southeastern coastal plain (Mulholland et al. 1997,Utley et al. 2008). Moreover, the prolonged droughts often associated with these warmer waters can also lower water levels and eliminate essential habitats for completion of life cycles and effective foraging. Fishes that disperse within large drainage basins can adjust to warmer temperatures by moving northward to find cooler waters if their routes for dispersal are unimpeded by dams, diversions, or dry-river channels (Matthews and Marsh-Matthews 2003, Ficke et al. 2007). However, the potential combination of record warm temperatures with possible increased frequencies and intensities of droughts (see Chapter 2) may place many species at risk over wide regions. Warmer waters also increase the exposure of freshwater fish and other species to diseases and parasites that diminish survivorship (Ficke et al. 2007). The increase in risk from toxic cyanobacteria that are extending their geographic ranges and causing massive fish kills is also associated with warmer waters where high nutrient loading can provide a competitive advantage to these harmful algae (Paerl et al. 2011). Warmer waters associated with droughts and floods are also linked to increases in various species of mosquitoes. Expanding ranges and pulsed population increases in these vectors that reproduce in temporary waters and wetlands can result in disease outbreaks among wildlife and humans (Shaman et al. 2002).

Impacts on rare species of fish and mussels are of particular concern in a changing climate. For example, freshwater mussel life-history connections can be disrupted by habitat loss for specific fish hosts (Box and Williams 2000). In addition, high densities of invasive bivalves such as zebra mussels (*Dreissena polymorpha*) and corbicula (*Corbicula fluminea*) may cause declines of native species of freshwater mussels during periods of low water (McMahon and Bogan 2001, Cherry et al. 2005). The Atlantic and Gulf sturgeon (*Acipenser oxyrinchus oxyrinchus, A. oxyrinchus desotol*) grow large by using both marine and estuarine habitats as adults and reproduce in coastal rivers along the Atlantic and Gulf of Mexico (Freeman et al. 2003, Grunwald et al. 2008). Their populations have declined previously due to overfishing, reduction in spawning sites by dam construction, and river pollution. These large, slow growing species require specific water depths, temperatures, and substrata for spawning in the remaining coastal waters available for sustaining their complex life histories. However, reduced flows from groundwater, lower river-water levels, and generally warmer waters during drought

are additional stresses. These fish historically supported fisheries but are now considered imperiled. Shortnose sturgeon (*A. brevirostrum*), which remain in rivers their entire life, are also of particular concern as their southern range, limited by temperature, is likely to shift northward out of Georgia as warming proceeds in this century. This species is also vulnerable to impacts associated with salt water intrusion, as oligohaline tidal waters are a critical habitat during their multidecadal adult years.

The SE has the highest aquatic diversity of any temperate system; however, the ecological relationships and life histories of many SE species are not yet well understood within the constraints of current climatic variability (Golladay and Battle 2002, Golladay et al. 2004). In addition, sustaining this exceptionally high regional biodiversity is difficult because emerging cumulative effects are creating novel habitats and dynamics that have not previously been observed. Currently, many species declines are associated with widespread alteration of stream habitats and flow regimes, and these effects are expected to be exacerbated by climate change (Box and Williams 2000). Specifically, some areas may experience more frequent droughts coupled with increasing water demands. In these areas, the heightened water demand is expected to result in more frequent stream drying, even in systems historically considered perennial, and thus increasing the frequency of local species extirpations (McCargo and Peterson 2010, Peterson et al. 2011).To the extent that greater short-term flow variability occurs, particularly during warmer seasons, there will be expected lower reproductive success of many fish that require periods of stable flow during nesting, spawning, and juvenile development. Decreased base flows will reduce habitat availability and lower survival for species requiring flowing-water habitats. Freshwater mussel reproduction may fail if temperatures exceed tolerance levels or if low flows limit the effectiveness of mechanisms for attracting host fish. Decreased base flows in combination with nutrient loading from agricultural and urban areas may result in algal blooms that alter food webs and benthic habitats, shifting biotic communities as well as threatening water supplies. Where more frequent drought and unpredictable flow alter steam systems, these conditions are expected to result in faunal homogenization, in which communities become dominated by species most capable of re-colonizing or surviving in such conditions. Faunal homogenization is currently seen in the spread of the invasive red shiner (Walters et al. 2008), loss of highland endemic fishes from southern Appalachian streams (Scott and Helfman 2001, Scott 2006, Walters et al. 2003), and reduced diversity in fragmented and flow-altered systems.

Climate change is also expected to facilitate establishment of non-native and invasive species by lessening constraints imposed by frequency and duration of cold temperatures. Non-native subtropical and tropical species, including many species already established in Florida, and potentially spread by unintended release from aquaculture (e.g., Tilapia, *Oreochromis* spp.), aquaria, or live fish markets (e.g., swamp eel, *Monopterus* spp.) may increase with warmer and milder winters (Collins et al. 2002, Nico et al. 2011). Higher stream temperatures and greater streamflow variability may also favor invasive species, which often have wider environmental tolerances than native species (Rahel and Olden 2008). The spread of invasive zooplankton such as *Daphnia lumholtzi* is expected to increase in response to warmer waters (Fey and Cottingham 2011).

In every region, it is difficult to isolate the effects of climate change from the other

aspects that threaten freshwater species. For example, accelerated erosion from climate change, or from flooding induced from land-use changes, diminishes habitat quality for many species. Although rivers and reservoirs fill with sediment during floods and water levels decline during droughts, the subsequent dredging of rivers to maintain shipping channels can have a longer-lasting effect on many freshwater species than the shorter term climate-related impacts. Additionally, warmer summers and growing populations increase societal demand for freshwater. Heat waves require more cooling waters for energy production to meet the increased use of air-conditioning and for pumping water to irrigate crops. The rapid increase in construction of water storage reservoirs and ponds in the SE has created relatively permanent changes in the region's hydrology. Reservoirs are also associated with increased introductions of invasive species (Rahel and Olden 2008). Freshwater habitats have lost critical characteristics of their natural flow regimes (Gibson et al. 2005, Poff et al. 2007). In many cases, the past connectivity among headwater streams, groundwater, rivers, and their floodplains has been modified or lost completely (Freeman et al. 2007). These changes and losses of habitats may continue or even increase as solutions are devised for increasing water storage to meet growing demands, mitigate droughts, and regulate floods.

11.3 Southeastern Savannas

Fire-dependent longleaf pine (*Pinus palustris*) savannas historically covered much of the southeastern Coastal Plain, but are now less than 5% of the landscape (Christensen 2000, Keddy 2009). Remnant examples of these savannas (Figure 11.2) classified hydrologically as wet, mesic (moist), or dry--are some of the most species-rich terrestrial communities ever measured at small spatial scales, ranging to more than 50 species per square meter (Walker and Peet 1984). Diversity is particularly high on frequently burned mesic and wet savannas, and is exemplified by abundant orchids and carnivorous plants such as pitcher plants (*Sarracenia* spp.), sundews (*Drosera* spp.), and the native range of Venus fly trap (*Dionaea muscipula*). East of the Mississippi River, longleaf pine savannas contain abundant wiregrass (*Aristida* spp.) in the understory; west of the Mississippi wiregrass is replaced by little bluestem (*Schizacharium scoparium*), a grass also common in the tallgrass prairies of the Midwest. A recent study in the western Gulf Coastal Plain using fire scars on longleaf pine trees growing in mesic longleaf-bluestem savannas suggested an average fire frequency of 2.2 years during the period from 1650 to 1905 CE—one of the most frequent fire histories ever documented (Stambaugh et al. 2011). These fires typically occur in the growing season, with important consequences for plant reproduction. Wiregrass and other savanna species only flower after growing season fires and not after managed fires set in the dormant season (Platt et al. 1988). In wet savannas, abundant *Sphagnum* peat moss and dead peat have accumulated and currently store significant amounts of carbon.

With warmer temperatures, diminished summer precipitation, and an increase in frequency and severity of drought predicted for parts of the Southeast over the remainder of the century, the likelihood of fire will increase as well (Mearns et al. 2003, Liu et al. 2010). The combined effects of drought, warmer temperatures, and higher fire probability likely will increase the flow of carbon to the atmosphere by the decomposition

Figure 11.2 Longleaf pine savanna of the southeastern Coastal Plain. This forest is actively managed through controlled burns on the Fort Stewart Military base in Georgia. Species diversity is particularly high in these ecosystems. While warmer winter temperatures may benefit the longleaf pine ecosystem in the northern range margin, the majority of longleaf pine savannas likely will fare less well due to increasing summertime droughts. (*Photograph by Charles Hopkinson.*)

and burning of drier vegetation and peat, as in other peatland ecosystems throughout the world (Ise et al. 2008, Taylor 2010, Hergoualc'h and Verchot 2011).

In addition to fire, the composition and function of these ecosystems are strongly influenced by drought frequency. In most of the longleaf pine range, spring and summer precipitation are the most important climatic variables associated with growth. While warmer winter temperatures may benefit the longleaf pine ecosystem in the northern margin of its range, most longleaf pine savannas will likely fare less well if future conditions include increasing summertime droughts (See Chapter 2).

Wet longleaf pine savannas often grade into swamps dominated by cypress tree species (*Taxodium distichum* and *T. ascendens*) and swamp gums (*Nyssa biflora* and *N. aquatica*). A 10year study in coastal South Carolina analyzed tree growth and ecosystem productivity in forests across a range of soil moisture types and found that severe drought affected wet swamp forests more than mesic oak-pine forests or dry longleaf ecosystems (Conner et al. 2011). Another study found that spring and summer

precipitation and temperatures were the most important environmental variables explaining tree growth in swamps of the Congaree National Park (Doyle 2009). In both cypress-gum swamps and longleaf pine savannas, predicted increases in the frequency of major hurricanes (see Chapter 2) likely will increase forest damage and create biophysical feedbacks to climate through temporary changes in surface albedo (reflectivity) and reductions in evapotranspirative cooling (Juárez et al. 2008).

11.4 Southeastern Freshwater Marshes and Swamps

Freshwater marshes and swamps of the SE are found throughout the region, but they are especially prevalent along low gradient river systems (e.g., Mississippi and Atchafalaya Rivers) and the extensive coastal plain physiographic province that lies between the Atlantic and Gulf coasts and the fall-line adjacent to the Piedmont province. While many of these wetlands are perennially connected to the river network, others are continually isolated or connected via ephemeral streams. Land use changes for urbanization or agriculture significantly affect the integrity of these systems and must be considered along with climate change for future assessments.

As with the stream, river, lake, and reservoir aquatic systems of the SE, freshwater marshes and swamps are also highly vulnerable to warming, changes in precipitation quantity and severity of storms, and the frequency and severity of drought. The combined effects of warming and changes in precipitation likely will alter overall hydrology including increased evapotranspiration and reduced stream base flows (IPCC 2001, Mulholland et al. 1997, Schindler 1997, Vörösmarty et al. 2000). In general, temperature regimes of freshwater ecosystems are projected to change in parallel with shifts in air temperature because of the tight relationships between air and water temperature (Mohseni and Stefan 1999, Mohseni et al. 2003, Allen et al. 2005). Alterations of regional and catchment hydrology predicted by global climate models include increasing frequency and intensity of extreme precipitation events driven by increased temperature (Easterling et al. 2000), although increased water inputs may be offset by increased evapotranspiration and runoff, and these effects may exhibit high regional variability (M.C. Todd et al. 2010 and 2011). Resulting impacts of climate change on riverine wetland ecosystems are predicted to include increased periods of water drawdown, greater frequency and intensity of high flow events, and increased water temperature (IPCC 2001, Alcamo et al. 2003, Carpenter et al. 2005, Webster et al. 2005, IPCC 2007, Erwin 2009, Mulholland and Sale 1998).

Wetland ecosystems will play a critical role in determining climate change feedbacks, as shifts in hydrology and increased soil temperature will enhance GHG emissions at catchment and regional scales (Erwin 2009) further contributing to climate change. The vast amount of carbon stored in the peat soils of the pocosins and Everglades makes them especially important due to the danger of an autocatalytic reaction between climate change and drought: as climate change leads to more drought, it also leads to more oxidation of peat soil, which releases GHGs and further speeds the rate of GHG induced atmospheric warming and more drought. Drainage of these wetlands has also caused large carbon losses from soil and slower rates of carbon storage, contributing to global climate change (Bridgham et al. 2006).

Ecosystem fluxes of greenhouse gasses, including CO_2, N_2O, and CH_4, depend not only on hydrologic position and flow paths within wetland complexes (Pennock et al. 2010), but also exhibit considerable temporal variation with changes in hydroperiod, including hydrologic pulsing from surface water inputs (Altor and Mitsch 2008, Mander et al. 2011). The responses of biogeochemical cycling of carbon and nitrogen to climate change impacts in southeastern wetlands ecosystems are particularly understudied, and represent a critical source of uncertainty in projecting future climates (Clough et al. 2007). The types of wetlands addressed in this assessment represent known and predicted climate change effects on freshwater wetlands in the southeastern USA. They include the Carolina Bays and Pocosins, mountain bogs, riverine floodplain swamps, coastal wetland forests, and the Florida Everglades.

Fire is the greatest threat to these wetland ecosystems under climate-induced drought. For example, a recent study estimated carbon emissions for a large peatland fire in North Carolina using remote sensing to reconstruct burn severity and topographic Light Detection and Ranging (LiDAR) to estimate peat burn depths (Poulter et al. 2006). This study estimated that total carbon emissions for a 40,000-ha (98,842-acre) 1985 fire was from 1 to 3.8 Tg (1.1 to 4.2 million tons), with spatially heterogeneous patterns of carbon fluxes from 0.2 to 11 kg C m^{-2} (4.7 to 258 lb C ft^{-2}) depending on vegetation type, peat burn depth, soil substrate (mineral or organic), and fire severity. A more recent fire in the Pocosins Lakes Wildlife Refuge during the severe drought of 2008 burned 16,785 ha (41,549 acres) of abandoned drained peatlands, releasing an estimated 10 million metric tons (11 trillion tons) of carbon from the peat soil to the atmosphere. These two events show the potential for massive releases of carbon from fires in Pocosin peatlands under lower water tables resulting from climate-induced droughts.

Carolina Bays

Southern wetlands are vulnerable to changes in precipitation frequency and warmer temperatures, especially as these changes are likely to result in more frequent droughts and higher rates of evapotranspiration (Mulholland and Sale 1998). Wet and dry cycles are thought to drive plant community dynamics in Carolina Bay wetlands, with wet periods characterized by larger areas of aquatic and emergent species and dry periods leading to the expansion of grasses and woody species. The potential increase in drought frequency would be likely to drive a shift to communities dominated by less flood tolerant woody species, especially in smaller bays that are more prone to drying (Stroh et al. 2008). Future cycling between wet and dry conditions likely will be driven by a balance between changes in precipitation, and increased evapotranspiration by increased temperature (Pyzoha et al. 2008). In southern mountain bogs, predicted increases in evapotranspiration in concert with anthropogenic increased nitrogen deposition might lower water tables and accelerate peat decomposition leading to a shift to alternative ecosystems (such as ephemeral wetlands or dry land ecosystems) and local extinction of several bog species (Schultheis et al. 2010).

Pocosins

Pocosins, also known as southeastern shrub bogs, are characterized by a very dense growth of mostly broadleaf evergreen shrubs with scattered pond pines. The typically

thick layer of peat soils, 1 m to 3 m (histosols), underlying pocosin soils store nearly 300 Mt (330.7 million tons) of carbon in North Carolina alone (Richardson 2012). Under normal saturated hydrologic conditions, decomposition in organic soils is minimized due to a lack of oxygen, allowing for accumulation of organic carbon. Bridgham and Richardson (1992) incubated peat from pocosins in anaerobic conditions and found very low CH_4 production potentials relative to other peatlands. However, they also found that CO_2 increased greatly in aerobic soils under drought conditions--a climate scenario projected to happen in parts of the southeastern USA under climate change (IPCC 2007, also see Chapter 2). A recent field study by Morse et al. (2012) in restored and natural Pocosin soils also found very low levels of CH_4 release to the atmosphere in comparison with CO_2 and N_2O under dryer conditions. Morse found increases in CH_4 gas under higher water levels, more CO_2 release from dryer soils and seasonal fluxes of CO_2 to the atmosphere, further supporting the earlier findings of Bridgham and Richardson (1992) and suggesting that climate-induced drought could change the magnitude and form of GHG fluxes. Further research is needed to establish how these GHG fluxes will change.

Southern Bottomland Swamp Communities

In southern bottomland swamp communities, alteration of growing season length and water regime could influence the ability of dominant canopy species to regenerate. Middleton (2009) found a distinct shift in species that germinate under flood and nonflood conditions within bald cypress (*Taxodium distichum*) swamps, and concluded that with the already low regeneration potential of dominant tree species, the range of bald cypress swamps may be compressed from the South in future climate scenarios. Stallins et al. (2010) found the interplay of lower baseflow on Apalachicola River, floodplain geomorphology, and canopy gap dynamics was associated with shifts in species composition of the floodplain forest canopy. This trend was most pronounced in backwater swamps where obligate wetland tree species, such as water tupelo (*Nyssa aquatica*), ogechee tupelo (*N. ogeche*), and Carolina ash (*Fraxinus caroliniana*), have undergone marked reductions in stem densities and there has been a muddling of the compositional contrasts between plant communities along the wet to dry gradient that typifies riparian floodplains.

The hydrology of coastal forested wetlands is expected to be very responsive to changes in both precipitation and temperature with declines in floodplain water table elevations and stream base flows expected under many future model scenarios (Dai et al. 2010, Dai et al. 2011). Similar results are seen in pine flatwoods where these effects are expect to be most pronounced in depression wetlands during dry cycles (Lu et al. 2009). Conner et al. (2011) examined the effects of drought on ecosystem productivity along a moisture gradient within coastal plain wetland forests in South Carolina and found that, both in terms of trunk diameter and above ground net primary productivity, wet sites were more sensitive to drought conditions than drier sites.

Everglades

The successional dynamics of the Everglades are mainly controlled by the interaction of climatic patterns (droughts and rainfall) and human alterations of hydroperiod, which

in turn influence fire frequency and the degree of fire intensity as well as the transfer and release of carbon and nutrients on the landscape (Richardson 2008). In the Everglades, the dominant sawgrass (*Cladium mariscus,* spp. *jamaicense*) communities (Figure 11.3) growing typically on one to three meters of peat are thought to be resilient to a wider range of inundation durations and depths than other species, although prolonged periods of flooding cause problems (Richardson 2008). However, other communities such as pine savanna, red mangrove scrub, bay-hardwood, and muhly grass have more pronounced physiological limitations to inundation depth, duration, or both, and are more restricted in their distribution (Richardson 2008, MJ. Todd et al. 2010). Within the context of more extreme cycling between wet and dry conditions, this suggests that these plant communities may undergo a contraction of spatial extent under future climate scenarios. Knowledge of long-term climatic patterns is important to understand changes within the Everglades. With impending sea level rise due to global climate change, saltwater becomes even more of a factor as it invades farther into the southern Everglades and alters freshwater communities (Bartlett et al. 1995). It is unclear whether freshwater flow can counteract or prevent saltwater intrusion associated with sea level rise. A sudden change from freshwater to saltwater conditions may accelerate oxidization of organic substrate leaving large areas of thin substrate or bare limestone bedrock with a greatly reduced potential for plant community shifts in response to climate change (Pearlstine et al. 2010, Willard and Bernhardt 2011).

Figure 11.3 *Nymphaea* open water slough surrounded by Sawgrass (*Cladium jamaicense*) in the central Everglades. The peat depths are 1.8 m at this site. Wetland prairies such as these are highly vulnerable to changes in the hydrologic cycle. While these systems are currently strong carbon sinks, under a warmer and drier climate they could become carbon sources emitting powerful greenhouse gases such as CH_4, in addition to CO_2. (*Photograph by Curtis J. Richardson.*)

11.5 Southeastern Tidal Marshes and Swamps

The greatest expanse of tidal wetlands in the continental USA is found in the Southeast. More than half of all tidal marshes are associated with the Mississippi River delta in coastal Louisiana. Because of their location at the land-sea interface, these areas are impacted by changes occurring in the sea as well as throughout the upland watersheds that drain to the coast. The magnitude of ecosystem services provided by these systems is among the highest of all ecosystems. They provide water quality amelioration benefits, high rates of carbon sequestration, and nursery grounds that support the vast majority of recreational and industrial fisheries in the SE region, and storm surge abatement that protects hundreds of billion dollars of coastal real estate (Barbier et al. 2011).

Coastal wetlands, sentinel ecosystems for environmental change and human-induced degradation of natural systems, are predicted to disappear at an accelerating rate (Nicholls et al. 1999, Nicholls et al. 2007). The distribution of coastal wetland habitats is determined predominantly by land elevation relative to sea level, freshwater, and climate. Climate change is predicted to cause widespread degradation of the coastal wetlands of the southeastern USA due to sea level rise (SLR), changes in freshwater flows, and increased frequency of extreme weather events (Meehl et al. 2007, Karl et al. 2009). Human activities, including hydrologic alterations (e.g., dams and levee construction), coastal development, and pollution will likely interact with climate change and further degrade coastal systems (Gedan et al. 2009). The most pressing issues for wetlands facing climate change and how they will alter the coastal landscape are discussed in the following paragraphs.

Sea level is the overriding factor determining the existence of tidal wetlands (Figure 11.4). Tidal wetlands have existed in a state of equilibrium with sea level rise (~0.2 mm/year) over the past 4,000 years by accumulating mineral sediment and organic matter produced by marsh vegetation (Morris et al. 2002, Mudd et al. 2009). Rates of SLR along the southeastern Atlantic and Florida coasts (2.5 mm/year) are comparable to the current global average of 2 to 3 mm/year (Meehl et al. 2007, NOAA 2011). Rates of SLR in the Louisiana Gulf Coast are much higher (9.5 mm/year) due to a combination of human activity and tectonic subsidence (NOAA 2011). Climate change is predicted to accelerate SLR in the coming century resulting in a sea level increase of up to 2 m or more by 2100 (see Chapter 2), Meehl et al. 2007, Rahmstorf 2007, Rahmstorf et al. 2007, Richardson et al. 2009, Vermeer and Rahmstorf 2009). As rates of SLR outpace the ability of wetlands to build elevation, they will become vulnerable to coastal erosion and increased inundation rates, eventually resulting in the conversion of coastal wetlands to open water (Day and Templet 1989, Donnelly and Bertness 2001, Craft et al. 2009, Kirwan et al. 2010).

Anthropogenic activities will reduce the ability of coastal wetlands to adapt to SLR. Increased freshwater and fossil fuel withdrawals increase local subsidence rates (Yuill et al. 2009). The construction of dams and other freshwater control devices reduce sediment delivery to the coast (Slattery et al. 2002, Graff et al. 2005). Large scale disappearance of wetlands in Louisiana has already been observed as sea level rises and sediment supply is restricted by large scale river alterations (Blum and Roberts 2009). At the same time, development has restricted the ability of coastal wetlands to migrate

inland and upland with SLR via shoreline hardening and the placement of fill in the immediate coastal zone (Feagin et al. 2010).

The Atlantic Multidecadal Oscillation (AMO) and El Nino–Southern Oscillation (ENSO) cycles are closely linked to regional climate and ocean temperatures (see Chapter 2 Konrad et al. 2012). Increasing average sea temperatures over the past 40 years have been correlated with increased intensity of hurricanes, which in turn have been correlated with an increase in average summer wave heights in the Atlantic (Komar and Allan 2008, Kunkel et al. 2008). Increased storm and wave intensity cause erosion and shoreline retreat of coastal wetlands. Coastal wetlands are important for dissipating storm energy and their loss leads to the increased vulnerability of human structures on coastlines to wave erosion (Gedan et al. 2011). Storm surges can also introduce saltwater into sensitive freshwater ecosystems increasing wetland degradation.

Climate models predict greater interannual variability in temperature and precipitation with the potential for greater frequency of droughts and floods that, in combination with increased temperatures and accelerated rates of evapotranspiration across terrestrial landscapes, will alter the availability of freshwater to the coast. Increased human demands for freshwater and changes in seasonal precipitation patterns have and likely will continue to alter the timing and magnitude of freshwater delivery to the coast. Changes in precipitation regimes, storms and anthropogenic alterations of freshwater flows are predicted to compound the effects of SLR, resulting in saltwater intrusion into freshwater wetlands (Smith et al. 2005, Hilton et al. 2008, Craft et al. 2009).

Figure 11.4 Tidal salt water marshes and swamps, such as this *Spartina alterniflora* marsh near Sapelo Island, GA, are particularly vulnerable to sea level rise. If they are unable to build in elevation as rapidly as sea level rises, they will revert to open-water areas. Salt marshes are critical habitats for most of the commercial fisheries of the SE USA. (*Photograph by Christopher Craft.*)

Saltwater intrusion into coastal freshwater wetlands will accelerate the release of organic carbon by stimulating microbial decomposition, especially sulfate reduction, and negatively affect plant productivity and alter species composition (Craft 2007, Weston et al. 2006, Spalding and Hester 2007, Neubauer and Craft 2009, Neubauer 2011, Weston et al. 2011). Increased decomposition will lead to a reduced capacity to sequester carbon, increased greenhouse gas production (CO_2 and CH_4), and a reduced capacity to build elevation against SLR (Neubauer and Craft 2009, Neubauer 2011). Nitrogen cycling (e.g., denitrification, nitrification, and nitrogen accumulation) will be negatively affected by salinity, reducing nitrogen removal from coastal waters and increasing coastal eutrophication (Rysgaard et al. 1999, Giblin et al. 2010, Weston et al. 2010).

Plant metabolic processes will be stressed by the interaction of increased flooding and salinity as well as increased temperature. Saltwater intrusion and increased evapotranspiration caused by elevated temperatures will elevate soil salinities, thus coastal wetland plant communities will shift towards species with greater salinity tolerance (Craft et al. 2009, Neubauer and Craft 2009). Increased inundation can stimulate plant growth at limited water depths (40 to 60 cm below mean high tide), beyond which it will cause mortality (Morris et al. 2002, Kirwan et al. 2010). Increased temperatures and longer growing seasons might increase net primary productivity (Kirwan et al. 2009). Though increased productivity may help coastal wetlands build elevation against SLR via the addition of organic matter to soils (Pendall et al. 2004, Langley et al. 2009), increased rates of decomposition due to higher temperatures, saltwater intrusion, and coastal eutrophication may limit or negate this effect (Langley and Megonigal 2010, Kirwan and Blum 2011). Increased CO_2 concentrations also favor plants with a C3 metabolism over those with a C4 metabolism, indicating that large-scale shifts in plant community compositions may occur, which will have implications for habitat use and food resources for fish, birds, and other fauna (Rasse et al. 2005). The complex interactions between these factors are poorly understood, but will determine how plant communities respond to climate change.

Unpredictable nonlinear interactions may increase susceptibility of marsh ecosystems to drought and increased salinity. For example, Silliman et al. (2005) found that drought and salinity induced die-off of salt marsh vegetation was exacerbated by herbivore grazing. Large-scale diebacks of salt marsh vegetation, called "brown marsh," occurred along the southeastern and Gulf coasts between 2002 and 2004, affecting more than 250,000 acres (McKee et al. 2004, Silliman et al. 2005). These diebacks may accelerate salt marsh conversion to open water (McKee et al. 2004).

Tidal freshwater forests are extremely vulnerable to climate change (Figure 11.5). More than 80% of tidal wetland forests occur in the SE USA and dieback and retreat of these systems has been observed over the past several decades (Connor et al. 2007). Saltwater intrusion stunts the growth of the dominant species, such as bald cypress (Krauss et al. 2009), and extended periods of chronic saltwater exposure caused by SLR lead to forest dieback (Connor et al. 2007). These systems are also sensitive to increased flooding associated with SLR, not just salt water exposure as rising sea levels will cause river water to backup and increasingly flood oligohaline wetlands (Connor et al. 2007). While herbaceous marshes can adapt to climate change by building elevation and rapid community shifts, tidal freshwater forests are less able to adapt via vertical accretion

or migration due to their slow growth and development, low sedimentation rates, and adjacency to upland areas. They are often replaced by herbaceous freshwater and brackish marshes that alter habitat and decrease overall potential for carbon sequestration as woody biomass (Connor et al. 2007). Desantis et al. (2007) report that exposure to salinity stress as little as a few times a year reduces species diversity in Florida Gulf Coast tidal freshwater forests, converting communities with more than 20 species to low-diversity stands of cabbage palm (*Sabal palmetto*) and southern red cedar (*Juniperus virginiana*). At low elevations, increased frequency of saltwater intrusion causes these systems to convert to herbaceous marsh (Desantis et al. 2007, Geselbracht et al. 2011).

Climate change will facilitate the expansion of invasive species by altering climatic constraints and transport of invasive species (Hellmann et al. 2008). Cold weather is one of the primary factors limiting the abundance of the invasive semi-aquatic rodent nutria (*Myocastor coypus*; Dedah et al. 2010 and references therein). Nutria burrowing and feeding activities destroy root systems and depress soil accretion leading to erosion and submergence of wetlands (Gedan et al. 2009). The invasive tree Chinese tallow (*Triadica sebifera*) is predicted to move 300 to 700 km north of its current range with a 2°C increase in temperature (Pattison and Mack 2008, Wang et al. 2011) and *Melaleuca quinqueneria* is predicted to similarly expand its range northward. Hurricanes and other storm events may aid in the spread of invasive propagules, and repeated hurricane disturbance has been shown to favor certain invasive species over their native counterparts, for instance *Iris pseudocorus* over *I. hexagona* (Pathikonda et al. 2009). Direct

Figure 11.5 Tidal freshwater forest along the Satilla River in coastal Georgia. These forests are particularly vulnerable to salt water intrusion that occurs with sea level rise. Vegetation likely will be replaced by salt tolerant marsh species, such as *Zizaniopsis* sp. During the transition these environments can emit high rates of greenhouse gases, including CO_2 and CH_4. (*Photograph by Christopher Craft.*)

human actions could also enhance invasive potential for two highly productive and aggressive invasive species, *Arundo donax* and *Phalaris arundinacea,* which are being explored for biofuel production (Hellmann et al. 2008).

Warming may also facilitate the expansion of certain native species at the expense of others. Mangrove wetlands are limited by periodic freezes to southern Florida and the Louisiana and Texas coasts (Sherrod and Mcmillan 1981 and 1985, Mcmillan and Sherrod 1986, Sherrod et al. 1986, Pickens and Hester 2011). Multiple observations confirm the northward advance of mangrove species over the last 20 years due to the lack of freezes in the Gulf and South Atlantic regions (Zomlefer et al. 2006, Michot et al. 2010). Sea level rise is facilitating mangrove encroachment on the salt marsh dominant species *Spartina alterniflora* and allowing mangroves to move inland with saltwater intrusion to replace freshwater marshes on the Florida coast (Doyle et al. 2010, Krauss et al. 2011). Though there is some evidence that mangroves may build elevation in response to SLR more readily than salt marsh and may be more resilient to storm surges (McKee et al. 2007, Kumara et al. 2010), increased mangrove dominance has implications for coastal food webs, economically important fisheries (e.g., fish, shrimp, and other shellfish) and recreational activities.

Changes in the extent and productivity of wetland plant communities will have cascading impacts on fisheries, migratory birds, and bird breeding habitat (Craft 2007, Craft et al. 2009). Wetlands provide refuge and food for many post-larval and juvenile fish, crustaceans, and mollusks that are important to the maintenance of viable commercial and recreational fisheries (UNEP 2006). These systems provide habitat for resident and migratory water birds that are important to hunters and bird watchers. Many of these species rely on the preservation of an entire estuarine landscape because they feed in salt marshes but breed and nest preferentially in freshwater wetlands or upland edge habitat (e.g., the wood stork, painted bunting) (Winn et al. 2008, Brittain et al. 2011). Other species (e.g., rails) select nesting locations in relation to tide levels, putting them in danger as sea level rises and storm surges intensify (Rush et al. 2010, van de Pol et al. 2010). Delivery of ecosystem services associated with water quality improvement and carbon sequestration likely will decline as tidal wetland habitat is lost or altered (Craft et al. 2009).

Recent model simulations suggest the combined impacts of accelerated SLR and saltwater intrusion will drastically alter the estuarine landscape over the next century through submergence and landward migration of estuarine systems (Craft et al. 2009, Neubauer and Craft 2009). The greatest losses likely will occur at both ends of the estuarine spectrum, namely salt marshes and tidal freshwater forests (Donnelly and Bertness 2001, Craft et al. 2009, Geselbracht et al. 2011). Climate change impacts on both terrestrial and marine systems also affect wetlands, the future survival of which will depend on management of an entire continuum of landscapes from the headwaters of rivers to the ocean.

11.6 Coral Reefs of the Southeast USA

Coral reefs and hard bottom reefs are some of the most biologically diverse ecosystems in the temperate, subtropical, and tropical oceans (Veron 2000). In the southeast-

ern USA, stony corals exist in the shallow waters of the western Atlantic, the Gulf of Mexico, as well as US territories in the Caribbean including Puerto Rico, the US Virgin Islands, and Navassa Island (Figure 11.6). Most of these reefs are within managed areas including three national parks (Biscayne, Dry Tortugas, and Virgin Islands); national monuments and national historical parks (Buck Island and Salt River Bay); national marine sanctuaries (Flower Garden Banks, Florida Keys, and Gray's Reef); and a state park (John Pennekamp in Florida). Other coral reefs are found along the SE coast of Florida from Martin County to Dade County, Florida. Middle Grounds and Pulley Ridge in the Gulf of Mexico contain some of the deepest stony corals in the USA. Detailed assessment and status reports for coral reefs in the USA have been produced by NOAA, Global Coral Reef Monitoring Network, and Reef and Rainforest Research Center. In the following section, some aspects of these reports are summarized as they relate to the effects of global climate change (Waddell and Clarke 2008, Wilkinson 2008, Wilkinson and Souter 2008).

Figure 11.6 Location of coral reefs in the SE USA including Flower Garden Banks (FGB), Florida Middle Grounds (FMG), Pulley Ridge (PR), Dry Tortugas (DT), Florida Keys (FK), Biscayne (B), southeast Florida reefs (SEFL), Gray's Reef (GR), Navassa Island (NI), Puerto Rico (PRR), and US Virgin Islands (USVI). Orange areas are coral reefs from ReefBase (http://reefgis.reefbase.org/).

Coral reefs worldwide are in decline as a result of multiple stressors, including climate change (Wilkinson 2008). The Florida Keys and US Caribbean reefs, once structurally complex, have declined with few reefs exhibiting a mean live coral coverage greater than 10% (Waddell and Clarke 2008) and with 21% of the reefs destroyed are unlikely to recover (Wilkinson 2008). The largest changes documented since the 1970s indicate that the most prevalent branching corals, the acroporid corals, have experienced population declines of greater than 90% (Acropora Biological Review Team 2005). Two of these corals, *Acropora palmata* and *A. cervicornis*, were listed in 2006 as threatened under the Endangered Species Act (Hogarth 2006). In 2010, the National Marine Fisheries Service found sufficient evidence to list 82 additional coral species as threatened, including eight Caribbean species (NOAA 2010). The majority of coral reefs in the Caribbean-Atlantic-Gulf of Mexico region are reported to be in poor or fair condition with Flower Garden Banks having the fewest threats (Waddell and Clarke 2008). However, the 2010 Deepwater Horizon oil leak occurred to the east of Flower Garden Banks and monitoring continues to assess any impacts from the accident.

The major direct climate change threats to coral reefs are increases in water temperature, ocean acidification, and sea level rise (IPCC 2007). Effects of ocean acidification and warming can be exacerbated when coupled to other stressors in reef systems, including disease, coastal runoff, overexploitation, vessel damage, marine debris, and exotic species (Carilli et al. 2009). In 1983, 93% of a sea urchins species, *Diadema antillarum,* died in the Caribbean (Lessios 1988). Sea urchins are important because they graze on algae thereby providing suitable habitat for coral settlement. Diseases of coral reef organisms can be expected to increase in the future as climate change stressors increase (Richardson 1998, Waddell and Clarke 2008). Coral diseases include coral bleaching, black-band disease, dark-spots disease, red-band disease, white-band disease, white-plague disease, white pox, and yellow-blotch disease (Richardson 1998).

There is active investigation and research of climate change impact on corals and their capacity to adapt. While some studies report declining coral growth rates (De'ath et al. 2009, Cantin et al. 2010, Manzello 2010), others show some species having greater extention rates but with decreased skeletal density (Helmle et al. 2011). Additionally some studies suggest that changes in temperature may offset changes in pH for some corals (Cooper et al. 2012, McCulloch et al. 2012), while others suggest the opposite (Rodolfo-Metalpa et al. 2011). There has been concern that high CO_2 levels (Veron et al. 2009, Veron 2011) may lead to the demise of corals, but some studies suggest corals may adapt or survive in refugia (Hughes et al. 2003, Fabricius et al. 2011, Howells et al. 2012, Karnauskas and Cohen 2012).

Prolonged events of abnormal water temperatures lead to coral bleaching, when corals expel the symbiotic zooxanthellae that provide the coral with nutrients (Muscatine 1973, Jokiel and Coles 1977). Corals can recover from short duration bleaching events (i.e., days); however, prolonged or drastic temperature changes for weeks can result in bleaching that leads to coral death (Jokiel and Coles 1977). Such events were unheard of before the 1970's and are now occurring in some locations with increased frequency (3 to4 years) and currently bleaching events take place each summer somewhere in the USA coral reef system (Wilkinson and Souter 2008). A massive regional coral bleaching event affected virtually the entire Caribbean basin in the late summer and fall of 2005.

Following this bleaching event, a coral disease epidemic resulted in about a 50% decline in live coral cover and in places up to 90% mortality (García-Sais et al. 2006, Miller et al. 2006, Wilkinson and Souter 2008). Conversely, cold water events can also lead to bleaching and coral death, such as the anomalous cold event in 2010 that killed numerous near-shore corals in the Florida Keys and southeast Florida (NOAA 2011, Colella et al. 2012).

Tropical storms can have damaging effects on coral reefs by overturning colonies, altering the habitat, increasing turbidity, and increasing nutrient concentrations from land runoff (Wilkinson and Souter 2008). During the 2005 hurricane season, extensive damage to coral reefs occurred in the Flower Garden Banks, the Dry Tortugas, and the Florida Keys; however, these reefs were spared from bleaching because the passing hurricanes reduced water temperatures (Stone et al. 2005, Gierach and Subrahmanyam 2008, Wilkinson and Souter 2008). An increase in the frequency of intense tropical storms predicted by climate models (Trenberth and Shea 2006, Bender et al. 2010, Mousavi et al. 2011, see Chapter 2), would result in more wave damage to coral reefs while scouring some areas and accumulating sediments and rubble in others thus altering the coral reef habitat (Wilkinson and Souter 2008).

Much remains to be learned concerning the effects of ocean acidification in coral reef systems from the physiological scale to ecosystem level (Fabricius et al. 2011, Pandolfi et al. 2011). Decreases in pH reduce growth rates of organisms that have calcified skeletons, such as corals; mollusks; and some plankton, echinoderms, and crustaceans (Veron et al. 2009). Changes in ocean pH have been documented for the Caribbean and Gulf of Mexico (Gledhill et al. 2008, Gledhill et al. 2009) and ocean acidification models predict pH may drop another 0.3 pH units by 2100 with business-as–usual climate change scenarios (Caldeira and E.Wickett 2003, Feely et al. 2009, National Research Council of the National Academies 2010). Future projections that model continued warming and ocean acidification show increased coral bleaching and coral disease resulting in widespread morality (Hoegh-Guldberg et al. 2007, IPCC 2007, Veron et al. 2009, Pandolfi et al. 2011).

Sea level rise is a concern in reef systems primarily as it affects water depth and light penetration (IPCC 2007). Coral reefs can respond to slow rates of sea level rise as they have during past glacial-interglacial cycles (Lidz 2006); however, coral reefs may not be able to keep up with the rates of sea level rise that are possible by the end of the 21st century, especially when considering other stressors on coral health.

Finally, increased precipitation associated with climate change may impact coral reefs by increasing runoff of contaminants, sediments, and nutrients into oceans thus further reducing coral health and contributing to the decline of coral reefs (Weber et al. 2006, Deslarzes and Lugo-Fernández 2007, Waddell and Clarke 2008).

11.7 Summary

For all the natural ecosystems considered in this chapter, it is difficult to isolate the effects of climate change from the many other threats to these systems, including for example invasive species, disease, land use change, water withdrawals, and atmospheric deposition.

Sea level rise and ocean acidification are two additional aspects of global climate change that uniquely affect the natural ecosystems considered in this chapter, especially coastal tidal wetlands and coral reefs. It is likely that acidification effects also will be experienced in freshwater stream, lake, reservoir, and river systems. Another unique aspect of many natural ecosystems of the SE is that the combined effects of sea level rise, associated increase in salinity, and alternating wet and dry cycles likely will enhance the fluxes of potent GHGs, CH_4 and N_2O, into the atmosphere.

In the SE, higher water temperatures are expected to put organisms closer to their thermal temperature limits and exacerbate low dissolved oxygen conditions, which already characterize many blackwater streams draining the southeastern coastal plain. Fish that disperse within basins can adjust to warmer temperatures by moving northward to find cooler waters, but only if their routes for dispersal are unimpeded by dams, diversions, and dry-river channels. Freshwater mussel reproduction may fail if temperatures exceed tolerance levels or if low flows limit the effectiveness of mechanisms for attracting host fish.

More frequent droughts coupled with increasing water demands, from of greater evapotranspiration (ET) and growing human consumption, likely will result in more frequent stream drying, even in systems historically considered perennial, which will increase the frequency of local species extirpations. The net result is faunal homogenization, in which communities become dominated by a smaller number of species that are most capable of recolonizing or surviving in stream systems affected by more frequent drought and unpredictable flow conditions.

Climate change is expected to further the establishment of non-native, invasive species by lessening constraints imposed by frequency and duration of cold temperatures.

Climate change is expected to have major impacts in the increasingly rare longleaf pine savannas of the SE. The combined effects of drought, warmer temperatures, and fire probability will increase the flow of carbon to the atmosphere by the decomposition and burning of drier vegetation and peat. While warmer winter temperatures may benefit the longleaf pine ecosystem in the northern range margin, the majority of longleaf pine savannas will likely fare less well due to increasing summertime droughts.

Southeastern freshwater wetlands are vulnerable to climate driven changes in precipitation and temperature, where more frequent droughts and higher rates of ET are predicted. Most of the SE freshwater wetlands experience shifts in seasonal fluxes of greenhouse gases, with more CH_4 under wet conditions, and more CO_2 and N_2O under dry conditions.

Fire is the greatest threat to millions of acres of freshwater peat-based wetlands in the SE under climate-induced drought. CO_2 emissions during fire can reverse centuries of CO_2 sequestration and ultimately convert these systems from being net C sinks to important C sources. Wet and dry cycles drive plant community dynamics in freshwater wetlands and where increased drought frequency occurs, it is likely to drive a shift to communities dominated by less flood tolerant woody species.

For tidal wetlands of the SE, rates of sea level rise could outpace the ability of wetlands to build elevation. As a result wetlands likely will become vulnerable to coastal erosion and increased inundation rates, eventually converting to open water, as has been experienced in coastal Louisiana for several decades now. The construction

of dams and other freshwater control devices reduce sediment delivery to the coast further exasperating wetland loss. Increased storm and wave intensity cause erosion and shoreline retreat of coastal wetlands. Tidal freshwater forests are less able to adapt either via vertical accretion or migration due to their slow growing time, low sedimentation rates and their adjacency to upland areas.

Warming will likely facilitate the expansion of certain native species at the expense of others. For example mangrove wetlands, which are limited in their northern limits by periodic freezes, are advancing northward in the Gulf and South Atlantic coastal regions of the SE.

Coral reefs and other hard bottom reefs of the SE are also susceptible to climate change, especially because of warming waters, acidification, and sea level rise. Effects of ocean acidification and warming can be exasperated when coupled to other stressors in reef systems, including disease, coastal runoff, overexploitation, vessel damage, marine debris, and exotic species. Warm water temperatures lead to coral bleaching and when prolonged can lead to death of corals. Changes in tropical storm frequency and intensity will impact coral reefs as many forms of coral are susceptible to wave damage.

Much remains to be learned about the effects of acidification on coral reef systems, from the physiology to the entire ecosystem. Sea level rise affects light transmission to the reef, especially so if the reef has limited ability to build vertical elevation. In addition most reef building is via calcification, which is highly sensitive to ocean pH.

Southeast aquatic and coastal systems are also sensitive to climate changes that may increase freshwater runoff from land as well as carry contaminants and nutrients that can degrade these environments.

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