TACCIMO
Template for Assessing Climate Change Impacts and Management Options

TACCIMO Literature Report

Literature Report – Annotated Bibliography Format
Report Date: April 1, 2013

Content Selections:
FACTORS – All
CATEGORIES – All
REGIONS – R8: Southern, South Atlantic, South Central

How to cite the information contained within this report

Each source found within the TACICMO literature report should be cited individually. APA 6th edition formatted citations are given for each source. The use of TACCIMO may be recognized using the following acknowledgement:

"*We acknowledge the Template for Assessing Climate Change Impacts and Management Options (TACCIMO) for its role in making available their database of climate change science. Support of this database is provided by the Eastern Forest Environmental Threat Assessment Center, USDA Forest Service.*"

Best available scientific information justification

Content in this Literature report is based on peer reviewed literature available and reviewed as of the date of this report. The inclusion of information in TACCIMO is performed following documented methods and criteria designed to ensure scientific credibility. This information reflects a comprehensive literature review process concentrating on focal resources within the geographic areas of interest.

Suggested next steps

TACCIMO provides information to support the initial phase of a more comprehensive and rigorous evaluation of climate change within a broader science assessment and decision support framework. Possible next steps include:

1. Highlighting key sources and excerpts
2. Reviewing primary sources where needed
3. Consulting with local experts
4. Summarizing excerpts within a broader context

More information can be found in the user guide. The section entitled Content Guidance provides a detailed explanation of the purpose, strengths, limitations, and intended applications of the provided information.

Where this document goes

The TACCIMO literature report may be appropriate as an appendix to the main document or may simply be included in the administrative record.

Brief content methods

Content in the Literature Reports is the product of a rigorous literature review process focused on cataloguing sources describing the effects of climate change on natural resources and adaptive management options to use in the face of climate change. Excerpts are selected from the body of the source papers to capture key points, focusing on the results and discussions sections and those results that are most pertinent to land managers and natural resource planners. Both primary effects (e.g., increasing temperatures and changing precipitation patterns) and secondary effects (e.g., impacts of high temperatures on biological communities) are considered. Guidelines and other background information are documented in the user guide. The section entitled Content Production System fully explains methods and criteria for the inclusion of content in TACCIMO.

TABLE OF CONTENTS

Effects by Source **Monday, April 01, 2013**

RESOURCE AREA (FACTOR): AIR QUALITY

ACID DEPOSITION

SOUTH ATLANTIC

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S.Environmental Protection Agency, 1-127.

"Elevated nitrogen deposition downwind of large, expanding metropolitan centers or large agricultural operations has been shown to affect forests when nitrogen deposited is in excess of biological demand (nitrogen saturation). Across the southern United States it is largely confined to high elevations of the Appalachian Mountains (Johnson and Lindberg, 1992), although recent increases in both hog and chicken production operations have caused localized nitrogen saturation in the Piedmont and Coastal Plain (McNulty et al., forthcoming)."

OZONE

R8: SOUTHERN

Mclaughlin, S., & Percy, K. (1999). Forest health in north america: Some perspectives on actual and potential roles of climate and air pollution. Water, Air, and Soil Pollution, 151-197

"A summary of the results of controlled exposure studies with seedlings and saplings of southern pines in open-topped chambers in the SCFRC (Southern Commercial Forest Research Cooperative) indicated that significant growth reductions occurred with increased ozone exposure."

SOUTH CENTRAL

Ainsworth, E. A., Yendrek, C. R., Sitch, S., Collins, W. J., and Emberson, L. D. (2012). The effects of tropospheric ozone on net primary productivity and implications for climate change. Annual Review of Plant Biology, 63, 637-661. doi:10.1146/annurev-arplant-042110-103829

"One of the few examples of observational data investigating responses to [O3, stomatal conductance, and CO2] stress combinations is that collected for a mixed deciduous forest in eastern Tennessee, United States (McLaughlin et al. 2007a). These data suggest an increase in water use under warmer climates with high [O3], with subsequent growth limitations for mature forest trees and implications for the hydrology of forest watersheds (McLaughlin et al. 2007b)."

Hanson, P.J., Wullschleger, S., Norby, R. J., Tschaplinski, T. J., Gunderson, C. A. (2005). Importance of changing co2, temperature, precipitation, and ozone on carbon and water cycles of an upland-oak forest: Incorporating experimental results into model simulations. Global Change Biology, 1402-1423.

"The majority of the tree species found on Walker Branch Watershed do not show significant growth responses to incremental increases in O3 exposure."

McLaughlin, S. B., Nosal, M., Wullschleger, S. D., & Sun, G. (2007). Interactive effects of ozone and climate on tree growth and water use in a southern Appalachian forest in the USA. New Phytologist, 174(1), 109-124. doi:10.1111/j.1469-8137.2007.02018.x

"The effects of ozone in increasing tree water use were also detectable in the surface soils in proximity to the trees for which sap flow was measured. Estimated soil moisture (% volume) ranged from 7 to 22% at Look Rock [Tennessee] in 2002. Analyses revealed increasing importance of O3 exposure on soil water status in 2002, just as was found with canopy conductance."

"Enhancement of the amplitude of the daily water-loss and recovery cycles observed in the present study [at Look Rock, Tennessee] following highest ozone exposures suggest an ozone-induced interference in whole-tree water balance. Such patterns would probably result from ozone-induced increases in daytime transpiration."

"Despite rather low levels of expected regional drought indicated for this region [southern Appalachian forests] by the PDSI [Palmer Drought Severity Index], the soils at Look Rock [Tennessee] became very dry within a period of approx. 2 wk during high ozone exposures in late summer (Fig. 3). Canopy conductance and soil-moisture analyses suggested that ozone contributed to the rapid loss of water from the rooting zone of trees, and had exacerbated water stress at this site."

"Our data [at Look Rock Tennessee] suggest that ozone uptake by vegetation in our region [southern Appalachian forests] will probably be increased both directly by higher ozone exposure, and indirectly in response to increased canopy conductance during higher-ozone episodes."

SMOKE AND FINE PARTICULATES

R8: SOUTHERN

Tai, A. P., Mickley, L. J., & Jacob, D. J. (2012). Impact of 2000–2050 climate change on fine particulate matter (PM2. 5) air quality inferred from a multi-model analysis of meteorological modes. Atmospheric Chemistry and Physics Discussions, 12, 18107-18131. doi:10.5194/acpd-12-18107-2012

"Temperature-driven changes in the southeast may reduce ammonium nitrate by ~0.2 μgm−3 due to increased volatility (Pye et al., 2009; Tai et al., 2012), but increase organic PM [particulate matter] by ~0.4 μgm−3 due to increased biogenic emissions (Heald et al., 2008; Tai et al., 2012)."

RESOURCE AREA (FACTOR): ANIMAL COMMUNITIES

AMPHIBIANS

R8: SOUTHERN

Blaustein, A. R., Walls, S. C., Bancroft, B. A., Lawler, J. J., Searle, C. L., & Gervasi, S. S. (2010). Direct and indirect effects of climate change on amphibian populations. Diversity, 2(2), 281-313. doi:10.3390/d2020281

"For many species, the "tolerance band" of acceptable developmental temperature during the embryonic stage can span 10−20 ˚C. For example, Volpe [1957] showed that normal development of Bufo valliceps [Gulf Coast Toad] embryos can occur between 20 and 33 ˚C; however, survival drops steeply on either side of this tolerance band, such that no gastrulation occurs at 36 ˚C. Thus, shifts in temperature that push a population past the tolerance band of normal development may result in years with extremely low or zero survival rates for embryos."

"Sea level rise contributes to the loss of coastal wetlands, and storm surge and its associated salt water intrusion during hurricanes can affect the abundance and species richness of amphibians in these habitats [Schriever et al. 2009]. Moreover, storm surge and freshwater sheet flooding can introduce fishes (important amphibian predators) into normally isolated, fishless wetlands [Palis et al. 2006]. In the Coastal Plain of the southeastern U.S., these coastal freshwater wetlands are important breeding sites for a highly species-rich and abundant assemblage of amphibians [Dodd et al. 2007]."

"Although mole salamanders [genus Ambystoma] and eastern newts [Notophthalmus viridescens] are not yet considered species of conservation concern, they have declined significantly over 28 yr in some areas of the Coastal Plain of the southeastern U.S. [Dodd et al. 2007]. Both of these species require intermediate to long hydroperiod wetlands for successful reproduction. If future climate change shortens the hydrology of breeding sites used by these species, there may be cascading impacts on the structure of amphibian communities in some freshwater wetlands."

Rothermel, B. B., Walls, S. C., Mitchell, J. C., Dodd Jr, C. K., Irwin, L. K., Green, D. E., ... & Stevenson, D. J. (2008). Widespread occurrence of the amphibian chytrid fungus Batrachochytrium dendrobatidis in the southeastern USA. Diseases of Aquatic Organisms, 82(3), 18. doi: 10.3354/dao01974

"Another possibility [for why amphibians in the southeastern USA are not severely affected by the amphibian chytrid fungus, Batrachochytrium dendrobatidis] is that host–pathogen interactions and environmental factors in the southeastern USA may be unfavorable for the development of clinical disease due to Bd [Batrachochytrium dendrobatidis]. For example, on the Coastal Plain, temperatures may be too high during much of the year, therefore limiting the growth and spread of Bd (Daszak et al. 2005). The question remains as to why we have not seen epidemics at cooler, higher elevations in the Piedmont and Blue Ridge physiographic regions, places where we have now documented Bd occurrence. Temperature increases due to climate warming have been proposed as contributing factors in outbreaks of chytridiomycosis in montane regions of Costa Rica (Pounds et al. 2006, but see Lips et al. 2008) and Spain (Bosch et al. 2007). However, we do not think that minimum temperatures constrain Bd growth in the southeastern USA, because die-offs attributed to chytridiomycosis have occurred in much colder montane sites, such as the Rocky Mountains (Muths et al. 2003) and Sierra Nevadas (Briggs et al. 2005)."

SOUTH ATLANTIC

Daszak, P., Scott, D. E., Kilpatrick, A. M., Faggioni, C., Gibbons, J. W., & Porter, D. (2005). Amphibian population declines at Savannah River site are linked to climate, not chytridiomycosis. Ecology, 86(12), 3232-3237.

"At Rainbow Bay, SRS [Savannah River Site], we found evidence of population declines in four species over the period 1978– 2004, including R. sphenocephala [Rana sphenocephala], in which B. dendrobatidis [Batrachochytrium dendrobatidis, the causative agent of chytridiomycosis] was present in 1981. However, our analyses of population trends suggest that these declines are attributable to an increase in the frequency of droughts at the Savannah River Site between 1978 and 2004 (Pechmann et al. 1991, Semlitsch et al. 1996). During these droughts, the length of time that Rainbow Bay had standing water was shortened to a point that was insufficient to allow for normal larval development and metamorphosis for several species (Fig. 1)."

"Our analysis showed that [amphibian] population trajectories were correlated with a species' response to hydroperiod; those that had increased frequency of recruitment failure due to insufficient hydroperiod were more likely to be declining."

Palis, J. G., Aresco, M. J., & Kilpatrick, S. (2006). Breeding biology of a Florida population of Ambystoma cingulatum (Flatwoods salamander) during a drought. Southeastern Naturalist, 5(1), 1-8. doi: http://dx.doi.org/10.1656/1528-

"During the 4-year study period [from 1999 to 2002, in the Apalachicola National Forest, Florida], the number of [Ambystoma cingulatum, Flatwoods salamanders] entering Pond 73-04 to breed dropped from 21 to one. The decline in the number of A. cingulatum migrating to pond 73-04 in 2000 and 2001 may have been due to insufficient rainfall."

"Due to several years of reduced rainfall (cumulative rainfall deficit of 94.0 cm from 1999–2001 at Wewahitchka [in the Apalachicola National Forest, Florida]), the moisture threshold for movement of most [Ambystoma cingulatum, Flatwoods salamanders] may not have been met in fall 2002 despite receiving slightly more rain in fall 2002 than fall 1999, the year when 21 immigrants were captured. Other than the proximate cues of rainfall and temperature (Palis 1997a), nothing is known regarding the environmental cues used by A. cingulatum to initiate migration to breeding sites. Further, several years of below-normal rainfall could have reduced feeding opportunities resulting in the lack of acquisition of energy reserves required for reproductive activity (Semlitsch et al. 1996)."

Ryan, T. J., & Winne, C. T. (2001). Effects of hydroperiod on metamorphosis in Rana sphenocephala. The American Midland Naturalist, 145(1), 46-53. doi: 10.1674/0003-0031(2001)145[0046:EOHOMI]2.0.CO;2

"Our results [from Carolyn's Bay, a Carolina bay located on the Savannah River Site in Aiken County, South Carolina] demonstrate that Rana sphenocephala [southern leopard frog] tadpoles accelerate development in response to pond drying; the result is early metamorphosis, which shifts the timing of metamorphosis but does not reduce overall growth."

Taylor, B. E., Scott, D. E., & Gibbons, J. W. (2006). Catastrophic reproductive failure, terrestrial survival, and persistence of the marbled salamander. Conservation Biology, 20(3), 792-801. doi: 10.1111/j.1523-1739.2005.00321.x

"Reproductive failure for the marbled salamander [Ambystoma opacum] at Rainbow Bay [an isolated wetland at the Savannah River Site near Aiken, South Carolina] was closely tied to natural variation in hydrologic conditions. A hydroperiod of insufficient duration was the main cause of complete failure. Additionally, smaller pond areas in years of short hydroperiod may have intensified density-dependent competition among larvae or resulted in mortality of eggs laid in portions of the basin that remained dry. Early filling of a pond can also diminish reproductive success if invertebrate or vertebrate predators become well established before the eggs hatch (Scott 2005)."

Todd, B. D., Scott, D. E., Pechmann, J. H. K., & Gibbons, J. W. (2011). Climate change correlates with rapid delays and advancements in reproductive timing in an amphibian community. Proceedings of the Royal Society B: Biological Sciences, 278, 2191-2197. doi: 10.1098/rspb.2010.1768

"Four of the 10 study species (three urodeles and one anuran) had significant changes in MAD [median arrival date] since 1979 (figure 1 and table 1) [Rainbow Bay, a Carolina bay wetland, Savannah River Site (SRS), South Carolina]. Both autumn-breeding species, E. quadridigitata [Eurycea quadridigitata] and A. opacum [Ambystoma opacum], arrived at the wetland significantly later in more recent years whereas two winter-breeding species, A. tigrinum [Ambystoma tigrinum] and P. ornata [Pseudacris ornata], arrived significantly earlier in later years. Estimates of the total change in breeding phenology between the first arrival year and the last arrival year for each species varied from as little as 15.3 days for A. opacum, to as long as 76.4 days in E. quadridigitata (table 1). The corresponding rates of advancement or delay varied from 5.9 to 37.2 days per decade for those species that had significant shifts in MAD (table 1)."

"Notably, later arrival of both autumn-breeding species [at Rainbow Bay, a Carolina bay at Savannah River Site (SRS), South Carolina] was positively correlated with warmer overnight temperatures during the pre-breeding season, although the correlation was only statistically significant for A. opacum [Ambystoma opacum] (table 2). For the two winter-breeding species that had significant shifts in phenology, earlier arrivals were correlated with warmer overnight temperatures during the breeding season and increased rainfall during the pre-breeding and breeding seasons (table 2). Warmer overnight temperature during the breeding season was also correlated with earlier arrival in B. terrestris [Bufo terrestris], greater rainfall during the breeding season was correlated with earlier arrival in G. carolinensis [Gastrophryne carolinensis], and greater rainfall during the pre-breeding season was correlated with earlier arrival in A. talpoideum [Ambystoma talpoideum] (table 2)."

"Here, we show that reproductive timing of four amphibian species at a wetland in the southeastern US has shifted significantly over the past 30 years."

"In addition to reporting previously unseen delays in amphibian breeding, our results underscore the ecological sensitivities of amphibians to their environment. Specifically, the estimated rates of phenological change of 5.9 to 37.2 days per decade represent some of the greatest rates of change in ecological phenomena reported to date, surpassing those of other taxa and even those reported previously for amphibians (cf. Walther et al. 2002, Parmesan 2007)."

"Our results provide important additional insights into the study of the effects of climate change on amphibians. For example, despite the broad latitudinal gradient of previous studies that found significant advancements in amphibian reproduction (ranging from 358370 N to 538120 N; Kusano and Inoue 2008 and Chadwick et al. 2006, respectively), we identified shifts in amphibian reproductive timing at the lowest latitude yet (33815.60 N)."

"Five of the species that did not change reproductive timing were normally the last to arrive at the wetland each year and were among those least likely to have arrival dates that correlated with environmental factors (tables 1 and 2). Thus, increases in temperature may have a greater effect on the timing of early breeders, whereas later breeders may rely more on other cues such as photoperiod, may be less sensitive to environmental variables overall, or may be less constrained by temperature because temperatures are more moderate when they breed."

Todd, B. D. & Winne, C. T. (2006). Ontogenetic and interspecific variation in timing of movement and responses to climatic factors during migrations by pond-breeding amphibians. Canadian Journal of Zoology, 84(5), 715-722. doi:10.1139/Z06-054

"Amphibians are highly dependent on adequate moisture to maintain water balance (Jørgensen 1997; Hillyard 1999). Desiccation risk is presumably lower during, and immediately following, rainfall, and many studies have correlated amphibian migrations with heavy rains (e.g., Semlitsch 1985; Semlitsch and Pechmann 1985; Greenberg and Tanner 2004; Greenberg and Tanner 2005). Our results [from Ellenton Bay, an isolated Carolina bay wetland located on the Savannah River Site in Aiken, South Carolina] further support this generalization and indicate that total daily rainfall is often the most important climatic factor influencing the magnitude of amphibian movements. However, some groups were less dependent on rainfall for migration than others. For example, the number of migrating recently metamorphosed [Bufo terrestris, southern toad] was poorly correlated with rainfall."

"Additionally [in addition to migrating at night to avoid predation], our results support the generalization that amphibian migrations are intimately associated with rain. However, our findings [from Ellenton Bay, an isolated Carolina bay wetland located on the Savannah River Site in Aiken, South Carolina] also demonstrate that there can be considerable variation among species in their migratory responses to climatic factors. We propose that species differ in their diel [daily] migratory patterns and responses to climatic factors, at least in part, because of differences in physiological tolerance, risk of desiccation, and risk of predation. As a result, future changes in climate and regional weather patterns may have important species-specific consequences for amphibians that rely on suitable climatic factors to successfully complete their breeding and juvenile migrations."

BIRDS

R8: SOUTHERN

Conroy, M. J., Runge, M. C., Nichols, J. D., Stodola, K. W., & Cooper, R. J. (2011). Conservation in the face of climate change: The roles of alternative models, monitoring, and adaptation in confronting and reducing uncertainty. Biological Conservation, 144, 1204-1213. doi:10.1016/j.biocon.2010.10.019

"One possible mechanism leading to population-level consequences is centered on asynchronous phenological shifts across varying trophic levels. For instance, advancement of seasonal events that affect birds, such as leaf and insect emergence, are predicted under a warming scenario (Walther et al., 2002; Parmesan, 2006). Given this prediction, we would expect birds to advance their breeding to match these shifts in vegetation and food abundance. However, migratory strategy may impede the ability to do so."

Matthews, S. N., O'Connor, R. J., Iverson, L. R., & Prasad, A. M. (2004). Atlas of climate change effects in 150 bird species of the Eastern United States (General Technical Report NE-318). Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station: 1-46.

"Bachman's Sparrow (Aimophila aestivalis) [Map section page 176]: Both CCC and Hadley [general circulation models] project increases in range and abundance for this southern species. Expansion northward is associated with the future distribution of slash pine as well as increases in average annual temperature. The only predicted decrease in abundance is associated with changes in summer drought in Florida."

Parmesan, C. (2006). Ecological and evolutionary responses to recent climate change. Annual Review of Ecology, Evolution, and Systematics, 37, 637-669.

"Warming trends at lower latitudes are associated with movements of tropical species into more-temperate areas. The rufous hummingbird [Selasphorus rufus] has undergone a dramatic shift in its winter range (Hill et al. 1998). Thirty years ago it wintered mainly in Mexico, and between 1900 and 1990, there were never more than 30 winter sightings per year along the Gulf Coast of the United States. In the early 1990s, sightings increased to more than 100 per year in the southern United States. The number of sightings has increased steadily since then—up to 1,643 by 1996, with evidence that, by 1998, resident populations had colonized 400 km inland (Howell 2002). Over this same period, winter temperatures rose by approximately 1°C (IPCC 2001b). "

Woodrey, M. S., Rush, S. A., Cherry, J. A., Nuse, B. L., Cooper, R. J., & Lehmicke, A. J. J. (2012). Understanding the Potential Impacts of Global Climate Change on Marsh Birds in the Gulf of Mexico Region. Wetlands, 32(1), 35-49. doi:10.1007/s13157-011-0264-6

"Climate change models predict that rates of SLR [sea level rise] will accelerate over the next century as warming continues (Church and White 2006; IPCC 2007), posing further threats to tidal marshes and resident marsh bird species [in the northern Gulf of Mexico]. In order to persist, these ecosystems must migrate inland or maintain surface elevations through vertical accretion and soil building at rates equal to or exceeding relative SLR (Cahoon et al. 2006; McKee et al. 2007)."

"Ultimately, any factor altering biophysical processes necessary for wetland persistence will also affect Gulf Coast bird populations."

"Over the next century, tidal marshes of the GoM [Gulf of Mexico] will be subjected to multiple, interacting climate-associated forcing factors that have the capacity to alter marsh structure and function. Of particular importance for marsh bird populations are changes to key ecological processes controlling community composition and maintenance of surface elevations relative to sea-level, as well as the direct effects that changes in sea level, temperature, precipitation, or tropical storms can have on bird population dynamics and behavior (Fig. 1)."

SOUTH ATLANTIC

Aiello-Lammens, M. E., Chu-Agor, M. L, Converino, M., Fischer, R. A., Linkov, I., & Resit Akɜakaya, H. (2011). The impact of sea-level rise on Snowy Plovers in Florida: integrating geomorphological, habitat, and metapopulation models. Global Change Biology, 17, 3644-3654. doi: 10.1111/j.1365-2486.2011.02497.x

"The SLR [sea level rise] model (SLAMM)[Sea Level Affecting Marches Model] predicted future changes in the composition of land-cover types in the coastal habitats within the range of the Snowy Plover [Charadrius alexandrines], resulting in an overall decrease in 'dry' land-cover classes and an increase in the 'open ocean' class (Figure S1; for a subset of map layers, see Supporting Information Figure S2)."

"The simulation results show that SLR [sea level rise] will likely cause a decrease in the viability of the Florida Snowy Plover [Charadrius alexandrines] populations (Fig. 4)."

"With 2 m SLR [sea level rise], the risk of extinction [of the Florida Snowy Plover (Charadrius alexandrines)] was 3.7% (0.037) more than the baseline risk of about 7%, risk of decline to 20 birds 7.6% (0.076) more, and EMA [expected minimum abundance] was 27.3 individuals less than without any SLR (Table 2), under the Medium values of all parameters. With 1 m SLR, the impacts were less: 1.9% increase in extinction risk, 6.3% increase in risk of decline, and 20.1 individuals decrease in EMA."

"In addition, there may be positive effects of climate change on this species; Snowy Plovers [Charadrius alexandrines] seem to prefer nesting in locations that recently experienced a hurricane (likely because hurricanes can create favorable Snowy Plover breeding habitat; Convertino et al., 2011). However, a shift in the timing of hurricanes toward the breeding season can also result in reduced survival and fecundity and increased variance of these rates."

Brittain, R. A., & Craft, C. B. (2012). Effects of Sea-Level Rise and Anthropogenic Development on Priority Bird Species Habitats in Coastal Georgia, USA. Environmental Management, 49(2), 473-482. doi:10.1007/s00267-011-9761-x

"Gap analysis of species [along the Georgia coast] with specific habitat requirements showed that most Acadian Flycatcher [Empidonax virescens] habitat was in tidal forest in 1999, 380 km2 in 160 patches (Table 2). In 2100, this habitat was reduced to 100–126 patches totaling 239–283 km2. Pine [Pinus spp.] (1860 km2) and oak [Quercus spp.] (416 km2) forest contained the most Yellow-throated Vireo [Vireo flavifrons] edge habitat but they decreased by 65% and 78%, respectively, under the maximum rates of SLR [sea level rise] and urban development. Northern Parula [Parula americana] habitat declined by 67% in pine forest and 37% in tidal forest under maximum SLR and development. Summer Tanager [Piranga rubra] showed the same pattern as Northern Parula with the most habitat (280 km2) and the sharpest decline (68%) in pine forest under the maximum SLR and development scenario (Table 2)."

Brooks, M. E., & Stouffer, P. C. (2010). Effects of Hurricane Katrina and Salvage Logging on Bachman's Sparrow. The Condor, 112(4), 744-753. doi:10.1525/cond.2010.100019

"As infrequent but large-scale disturbances, hurricanes are seldom studied despite their important role in coastal longleaf pine [Pinus palustris] savannas. Our results suggest that damage to trees from Hurricane Katrina may have benefited Bachman's Sparrow [Peucaea aestivalis] habitat in DSNF [De Soto National Forest, Mississippi] in three ways: by increasing song perches, by increasing escape refugia in root balls, and by thinning canopy trees. We quantify the effects of song perches and root balls for the first time. The thinning effect largely conforms to expectations from previous studies, even if thinning as a direct result of hurricanes has never been examined. Hurricanes thin trees and create patches in which trees can regenerate, helping create the uneven-aged stands characteristic of old-growth pine savannas. Tree mortality increases light penetration to the herbaceous layer, increasing plant diversity and biomass."

Bryan Jr, A. L., & Robinette, J. R. (2008). Breeding success of wood storks nesting in Georgia and South Carolina. Waterbirds, 31(sp1), 19-24. doi: http://dx.doi.org/10.1675/1524-4695(2008)31[19:BSOWSN]2.0.CO;2

"Annual variation of Wood Stork [Mycteria americana] breeding success [in Georgia and South Carolina] was linked to rainfall amounts and seasonality. There was no extensive deviation from normal rainfall in 2004, and there was apparently sufficient pre-season rainfall for prey to colonize and reproduce in foraging habitat, followed by water recession during the breeding season when adult storks were foraging for their young. In 2005, pre-breeding season rains were similar to 2004, but mid-season rains were substantially higher (six to 36 cm above normal), which likely led to prey dispersion during this critical period of nestling growth and development and ultimately led to reduced stork productivity. Also, these rains were delivered by atypical frontal systems containing severe storms, dropping high volumes of rain in very short periods of time and possibly resulting in nest loss (Coulter and Bryan 1995)."

"Storks [Wood Storks, Mycteria americana] in coastal colonies [in Georgia and South Carolina] always have tidal habitats to utilize for foraging and their presence may buffer potential negative effects of mid-breeding season rainfall. Success of inland colonies is likely affected by a combination of pre- and mid-breeding season rainfall, although the periodicity of these arbitrarily defined seasons may differ from those used in this study and could possibly be multi-year in length."

Convertino, M., Elsner, J. B., Mucoz-Carpena, R., Kiker, G. A., Martinez, C. J., Fischer, R. A., & Linkov, I. (2011). Do tropical cyclones shape shorebird habitat patterns? Biogeoclimatology of Snowy Plovers in Florida. PLoS ONE, 6(1), e15683+. doi:10.1371/journal.pone.0015683

"The plots indicate that SP [Snowy Plover (Charadrius a. nivosus)] nesting sites [in Florida] are more common during the spring following a tropical cyclone affecting the region (red points)."

"While untangling the biogeoclimatology of SP [Snowy Plover (Charadrius a. nivosus)] in Florida, we found the almost paradoxical result that SP benefits from tropical cyclones through habitat creation and maintenance."

Craft, C. B. (2012). Tidal freshwater forest accretion does not keep pace with sea level rise. Global Change Biology, 18(12), 3615-3623. doi:10.1111/gcb.12009

"Furthermore [in addition to a decline in nitrogen processing], tidal forests [along the Ogeechee, Altamaha, and Satilla, and South Newport Rivers of the Georgia coast] provide habitat for wading birds such as the wood stork (Mycteria americana) and neo-tropical migratory birds (Craft et al. 2009, Brittain and Craft 2012) that will be lost unless these wetlands are able to migrate upriver."

Schiegg, K., Pasinelli, G., Walters, J. R., & Daniels, S. J. (2002). Inbreeding and experience affect response to climate change by endangered woodpeckers. Proceedings of the Royal Society of London. Series B: Biological Sciences, 269(1496), 1153-1159. doi:10.1098/rspb.2002.1966

"In both populations [of red-cockaded woodpeckers (Picoides borealis)], the median laying date of the first egg of first clutches advanced over the study period (figure 1). In the Sandhills [of North Carolina], median laying date was significantly correlated with departure from normal temperature ($r_s = -0.43$, $p < 0.05$, $n = 19$), but not with temperature or rainfall. Departure from normal temperature increased over time, indicating that temperatures became increasingly warmer relative to the average temperature measured during the previous two decades ($r_s = 0.50$, $p < 0.05$, $n = 19$)."

"In both populations [of red-cockaded woodpeckers (Picoides borealis) in North Carolina], females that laid earlier, and females assisted by helpers, produced more fledglings from their first broods (table 1). A logarithmic transformation of laying date was used, so these results suggest that the effects of laying date were strongest early in the season."

"Individuals [of red-cockaded woodpeckers (Picoides borealis)] differed in how they altered laying date in response to climate (individual effect; table 2). Climate significantly affected laying date within individuals in both populations [in North Carolina] (climate effect), indicating that females adjusted laying date during their lifetime and hence exhibited phenotypic plasticity for this trait (table 2). There was also a strong effect of age (again using a log transformation) in both populations, with individuals laying earlier as they grew older."

"In addition to effects of climate, female age, number of helpers and individual, both inbreeding and the interaction between inbreeding and climate affected laying date [of red-cockaded woodpeckers (Picoides borealis) in North Carolina] (table 3). Inbred birds did not adjust laying date to climate, whereas non-inbred birds did (figure 3)."

"In the past two decades, egg laying has occurred increasingly earlier in two red-cockaded woodpecker [Picoides borealis] populations [in North Carolina] as the climate has changed. Because different climatic variables (i.e. departure from normal temperature and rainfall) were correlated with this shift in laying date in the two populations, we suspect that neither is the actual variable to which the birds are responding, or the actual cue used to time breeding. Temperature and rainfall may instead be surrogates for other, causal variables linked to the, as yet unknown, process governing onset of breeding."

"Our findings indicate that climate change has not disrupted the relationship between the cues used to time breeding, and temporal variation in factors that influence reproductive success, such as food availability or nest predator activity [of red-cockaded woodpeckers (Picoides borealis) in North Carolina]. It would be premature to conclude, however, that the red-cockaded woodpecker actually profits from climate change due to the benefits of breeding earlier. On the contrary, overall reproductive output decreased slightly in both populations over the study period. Whether this is due to climate change is unclear, because our models do not include other factors potentially influencing reproductive success, such as changes in habitat quality (James et al. 1997)."

"Regardless of why novice breeders and experienced females breeding with new mates are unable, or less able, to make adjustments in timing of breeding, climate change may accentuate the effects of age on reproductive success (Walters 1990) and increase selection against changing mates, which female redcockaded woodpeckers Picoides borealis] sometimes do (Daniels & Walters 2000b)."

"By unequally affecting inbred and non-inbred individuals, global climate change may represent an additional, previously unknown threat to endangered species, such as the red-cockaded woodpecker [Picoides borealis], that are largely restricted to small, isolated populations (Azevedo et al. 2000)."

Şekercioğlu, 3. H., Primack, R. B., & Wormworth, J. (2012). The effects of climate change on tropical birds. Biological Conservation, 148(1), 1-18.

"Coastal regions, which often have high bird diversity, will be affected by rising sea levels. Yet, because coastal wetlands are often bounded by agriculture and settlements, opportunities for range shifts are limited. These wetlands include Florida's Everglades and its globally important colonies of roseate spoonbills (Platalea ajaja), wood storks (Mycteria americana), and other waterbirds."

SOUTH CENTRAL

Chavez-Ramirez, F., Wehtje, W., (2011). Potential impact of climate change scenarios on whooping crane life history. Wetlands, online first, 1-10.

"Decreased precipitation in the wintering area [Texas] may lead to increased water salinities in whooping crane [Grus americana] wetland territories. Whooping cranes drink brackish marsh water when salinities are below 20 ppt (parts per thousand). If salinities increase and remain >23 ppt, all whooping cranes must leave their saltmarsh territories and fly to drink freshwater in upland sources leading to increased energy expenditure and potentially greater predation (USFWS reports, pers. Observ.)."

"Higher winter temperatures [in Texas] are likely to be positive for whooping crane [Grus americana] prey as well as making them more abundant or available to cranes. Low temperatures (<17°C), for example, cause prey (blue crab [Callinectes sapidus]) to burrow into bottom substrate (Chavez-Ramirez 1996) making them difficult to find, so fewer cold days and higher temperatures would keep blue crabs available for greater periods. Other factors, however, such as high water and crab movements could still influence availability."

"Warmer temps and northward movement of the freeze line could mean greater and more rapid growth of mangrove along coastal marshes, which are unlikely to benefit whooping cranes [Grus americana]."

"Rising sea levels will decrease the extent of saltmarsh habitat available to wintering whooping cranes [Grus americana]. Montagna et al. (2007) plotted the impact of lower and upper sea level rise estimates for Mustang Island, a barrier island just south of Aransas and Matagorda Island National Wildlife Refuges [Texas]. Even at the lowest projected sea level rise, lateral shifts of 1 to 2 km of bay-side wetland environments will occur (Montagna et al. 2007). At the high end of projected sea level rise, several upland portions of the island will be less than 200 m wide, and much of central Port Aransas, on the north end of the island, will be flooded (Montagna et al. 2007)."

Lusk, J. J., Guthery, F. S., & DeMaso, S. J. (2001). Northern bobwhite (Colinus virginianus) abundance in relation to yearly weather and long-term climate patterns. Ecological Modelling, 146(1-3), 3-15. doi:10.1016/S0304-3800(01)00292-7

"We conclude that the absolute changes in yearly weather pattern predicted by some global change models will not have as great an impact on [northern] bobwhite [Colinus virginianus] abundance [in Oklahoma] as will the magnitude of the deviations of these values from the climate bobwhites are adapted to in this portion of their range."

"As June temperature increased past ~31°C, the weather network [for Oklahoma] predicted that [northern] bobwhite [Colinus virginianus] counts will be less than the route mean (Fig. 1a). Below this temperature, counts were predicted to be slightly more than the route mean (Fig. 1a)."

"Positive deviations of July temperature from the long-term mean resulted in higher [northern] bobwhite [Colinus virginianus] counts [in Oklahoma] (Fig. 2b). Predicted counts did not fall below the mean counts until temperature deviated more than −4°C from normal (Fig. 2b). However, August temperatures below the mean resulted in increased predicted bobwhite counts and temperatures above the mean by more than 2°C resulted in below average counts (Fig. 2c)."

"Our results showed that the climate network was more parsimonious than the weather network [for Oklahoma]. Therefore, [northern] bobwhite [Colinus virginianus] population abundance may be more sensitive to the variation in weather from long-term mean climate conditions than to the magnitude of the weather variables. In other words, it may not be so much how much rain falls, as it is how much more or less rain falls than normal. The magnitude of the deviation from normal conditions may limit quail production or survival if bobwhites have a small thermal-tolerance around mean conditions to which they have adapted."

"There was a positive effect of winter precipitation on [Northern] Bobwhite [Colinus virginianus] counts [in Oklahoma]. Winter rains in excess of 50 mm and all positive deviations of winter rain resulted in higher than average bobwhite counts. Winter precipitation may enhance bobwhite production indirectly through increased spring vegetation, seed abundance, and insect densities (Swank and Gallizioli, 1954; Sowls, 1960)."

White, J. D., Gutzwiller, K. J., Barrow, W. C., Johnson-Randall, L., Zygo, L., & Swint, P. (2011). Understanding interaction effects of climate change and fire management on bird distributions through combined process and habitat. Conservation Biology, 25(3), 536-546. doi:10.1111/j.1523-1739.2011.01684.x

"Our results [from Big Bend National Park, Texas, in the northeastern Chihuahuan Desert] show potential influences of climate change on bird occurrence on the basis of a model that uses the physiological response of vegetation to climate and fire management. We identified ecological factors that may influence the occurrence of birds (Seoane et al. 2005). For example, LAI [leaf area index] often explained the relative probability of occurrence of Scaled Quail [Callipepla squamata] and Loggerhead Shrike [Lanius ludovicianus]. Because LAI is related to canopy cover and primary productivity, for these species it may indicate the availability of shelter and food."

FISH

R8: SOUTHERN

Coutant, C. C. (1990). Temperature-Oxygen habitat for freshwater and coastal striped bass in a changing climate. Transactions of the American Fisheries Society, 119(2), 240-253. doi:10.1577/1548-8659(1990)

"Stocks [of striped bass, Morone saxatilis] along the Gulf of Mexico and Florida east coast may be reduced or extirpated. Summer water temperatures there could be much in excess of those that the fish can tolerate, except where cool river waters are maintained by summer hypolimnetic discharges from reservoirs or artesian water from large springs—which seem to be major factors in survival now (Wooley and Crateau 1983; Coutant 1985)."

Waldman, J. (2011). Conservation and restoration of Acipenser oxyrinchus in the USA. In Williot, P., Rochard, E., Desse-Berset, N., Kirschbaum, F., and Gessner, J., editors, Biology and Conservation of the European Sturgeon Acipenser sturio L. 1758, 517-526. Springer Berlin Heidelberg. doi:10.1007/978-3-642-20611-5_39

"Climate change remains a threat, in particular warming experienced by Gulf sturgeon [Acipenser oxyrinchus desotoi] and southern populations of Atlantic sturgeon [Acipenser oxyrinchus] that already exist under marginal thermal conditions, as has been seen for another partly sympatric anadromous species, rainbow smelt Osmerus mordax, which has retreated from the southern portion of its Atlantic coast range (Waldman et al. 2006)."

SOUTH ATLANTIC

Coutant, C. C. (1990). Temperature-Oxygen habitat for freshwater and coastal striped bass in a changing climate. Transactions of the American Fisheries Society, 119(2), 240-253. doi:10.1577/1548-8659(1990)

"A pronounced upward shifting of estimated annual [eastern] coastal temperatures characterizes both [Goddard Institute for Space Studies and Geophysical Fluid Dynamics Laboratory] climate models (Figure 3). The South Carolina coast could be above 25°C, and avoided by striped bass [Morone saxatilis], from April to early November, during which time temperatures may peak well above 30°C."

"The [North Carolina] Roanoke River-Albemarle Sound striped bass [Morone saxatilis], which lie at the boundary between the coastal migratory habits of the more northern fish and the riverine habits of the more southern stocks, could become clearly riverine and congregate in summer in the cool dam tailwaters upriver."

GENERAL IMPACTS

Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., ... & Machmuller, M. (2008). Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. Frontiers in Ecology and the Environment, 7(2), 73-78. doi: 10.1890/070219

"Declining area of tidal freshwater wetlands, marshes, and swamp forests [via sea level rise in Georgia tidal marshes] (Table 1) may be problematic for the American alligator (Alligator mississippiensis), wood stork (Mycteria americana), and other species that depend on freshwater aquatic habitats."

Daniels, R. C., White, T. W., & Chapman, K. K. (1993). Sea-level rise: destruction of threatened and endangered species habitat in South Carolina. Environmental Management, 17(3), 373-385. doi:10.1007/bf02394680

"At the state level of analysis, 26 of the 52 endangered or threatened animal species identified as having habitat within 3 m of mean sea level are found within South Carolina (or directly offshore) and are listed in Table 1. "

"The habitats of the remaining nine [terrestrial] species [that are not extinct or near extinct in South Carolina] [i.e., American alligator (Alligator mississippienis), Bachman's warbler (Vermivora bachmanii), bald eagle (Haliaeetus leucocephalus), brown pelican (Pelecanus occidentalis), loggerhead sea turtle (Caretta caretta), piping plover (Charadrius melodus), red-cockaded woodwoodpecker (Picoides borealis), shortnose sturgeon (Acipenser brevirostrum), and wood stork (Mycteria americana)] will be threatened by saltwater intrusion, temporary flooding, inundation, or erosion if the predicted increases in sea levels come to pass. These impacts will result in the destruction of nesting and feeding areas that are currently irreplaceable, due to restrictions that have been placed on the migration paths of these species (e.g., the presence of roads such as US 17 that parallel the coast from Charleston to the North Carolina border)."

"After the gathering of the data shown in Figures 1A, 1B, and 1C, the frontage length of each habitat (i.e., the length of each habitat that opens onto the ocean or an estuary) was calculated for each [endangered or threatened] species [located within 3m of sea level in coastal South Carolina], and the total percentage of this length that was located within a high- risk area, as defined using the CVI [coastal vulnerability index], was determined (table 2). From this table, it is apparent that more than 30% of the Bachman's warbler [Vermivora bachmanii], red-cockaded woodpecker [Picoides borealis], brown pelican [Pelecanus occidentalis], and wood stork [Mycteria americana] habitat may be affected by a rise in sea level and possible increases in coastal erosion rates. The table also indicates that at the state level the piping plover [Charadrius melodus] and American alligator [Alligator mississippienis] will be relatively unaffected by changes in the coastline since a large percentage of their habitat is located on portions of the coast that are currently not at high risk to sea-level rise. These species may be at risk from other forms of habitat destruction, however."

"Of the four remaining species [those that have been cited as having current habitat in Cape Romain, South Carolina], the American alligator [Alligator mississippienis], loggerhead sea turtle [Caretta caretta], brown pelican [Pelecanus occidentalis], and wood stork [Mycteria americana] would be adversely affected if Cape Romain's current coastline were inundated. The refuge's barrier islands currently serve as nesting areas for the threatened loggerhead sea turtle and endangered brown pelican, whereas the tidal marsh in and behind Raccoon Key serves as a primary feeding area for the wood stork and as a feeding and nesting area for the American alligator. Undisturbed alligator and loggerhead turtle nesting areas, such as those currently found in Cape Romain, are rare in coastal South Carolina, and the destruction of these areas may have a significant impact on the future breeding success of these reptiles."

"The feeding grounds of the wood stork [Mycteria americana] and American alligator [Alligator mississippienis] [in Cape Romain, South Carolina] will be subject to increased shorefront erosion in response to sea-level rise and may also be subject to pond and creek enlargement due to the increased wave energies that will enter the marsh. To make matters worse, the unconsolidated and finegrained sedimentary base of Cape Romain will ensure that any new islands that may be created as Raccoon Key erodes will have low reliefs, will be subject to storm overwash, and may have marshlike characteristics. Thus, these new islands may not serve as suitable replacements for the protective barrier islands that will be lost to sea-level rise."

"In addition to the obvious reduction in marsh size that would result due to sea-level rise [in Cape Romain, South Carolina], there also would be severe repercussions on the recruitment success of larval and juvenile fish within the tidal creeks of the refuge (Thomas and others 1991). A diminished number of small fish in the coastal zone would reduce the wood stork's [Mycteria americana] and American alligator's [Alligator mississippienis] food supply and, because the feeding success of the wood stork improves with age, may increase the mortality rate of these birds (Lowe and others 1990)."

SOUTH CENTRAL

Friedenberg, N. A., Sarkar, S., Kouchoukos, N., Billings, R. F., & Ayres, M. P. (2008). Temperature extremes, density dependence, and southern pine beetle (coleoptera: Curculionidae) population dynamics in East Texas. Environmental Entomology, 37(3), 650-659. doi: 10.1603/0046-225X(2008)37[650:TEDDAS]2.0.CO;2

"Chemical control was replaced by mechanical suppression methods (cut-and remove and cut-and-leave) in east Texas in the early 1970s, allowing predator populations to recover. The loss of predators can increase the role of climate in population dynamics."

Invertebrates

R8: Southern

Mandrioli, M. (2012). Someone like it hot? Effects of global warming on insect immunity and microbiota. Invertebrate Survival Journal, 9, 58-63.

"In particular, it emerged that G. texensis [Texas field cricket, Gryllus texensis] may become more susceptible to some pathogens at higher temperatures suggesting that reproductive rate and immune function are not simultaneously enhanced at higher temperatures."

"In particular they [Adamo and Lovett, 2004] reported that elevated temperatures resulted in increased egg laying, faster egg development and greater mass gain in Gryllus texensis [Texas field crickets]. In the same experiments a reduction in the resistance to the Gram-positive bacterium Bacillus cereus was observed both above or below the average field temperature (26°C) suggesting that increased temperatures induce trade-offs between reproduction and disease resistance for some species–pathogen interactions (Adamo and Lovett, 2004)."

Mulholland, P. J., Best, G. R., Coutant, C. C., Hornberger, G. M., Meyer, J. L., Robinson, P. J, Stenberg, J. R., … & Wetzel, R. G. (1997). Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf Coast of Mexico. Hydrological Processes, 11, 949-970. doi: 10.1002/(SICI)1099-1085(19970630)11:8<949::AID-HYP513>3.0.CO;2-G

"The ratio of production to biomass (P : B) of aquatic insects is positively related to temperature, especially in the following groups: Simuliidae, Chironomidae, Odonata, Ephemeroptera, Trichoptera and Plecoptera (Benke, 1993). These groups dominate the benthos in streams, and hence increases in P : B, as well as in total productivity, are expected under a warmer climate."

SOUTH ATLANTIC

Golladay, S. W., Gagnon, P., Kearns, M., Battle, J. M., & Hicks, D. W. (2004). Response of freshwater mussel assemblages (Bivalvia: Unionidae) to a record drought in the Gulf Coastal Plain of southwestern Georgia. Freshwater Science, 23(3), 494-506. doi: 10.1899/0887-3593(2004)023<0494:ROFMAB>2.0.CO;2

"The results of our study [in the Flint River Basin of southwestern Georgia] generally concur with the observations of Johnson (2001). We observed substantial declines in mussel abundance in non-flowing streams, but substantial numbers of [Elliptio complanta/icterina], [Villosa lienosa], and [Villosa villosa] survived at some of the sites. Several of the special concern species including, [Lampsilis straminea claibornensis], V. villosa, and [Lampsilis subangulata] showed declining trends or disappeared from a number of non-flowing sites suggesting intolerance to drought stress. The drought tolerance of other mussel species in the lower FRB remains undocumented."

"Declines in mussel populations appear to be associated with unusual climatic conditions and increasing demand on the streams in the area and the regional aquifer system for irrigation water supply. Thus, infrequent disturbances, such as the 2000 drought [experienced in the Flint River Basin (FRB) of southwestern Georgia], stress the remaining populations and accelerate the loss of freshwater mussel diversity from the lower FRB."

SOUTH CENTRAL

Chavez-Ramirez, F., Wehtje, W., (2011). Potential impact of climate change scenarios on whooping crane life history. Wetlands, online first, 1-10.

"While warmer temperatures may tend to make [blue] crabs [Callinectes sapidus] more available, they may lead to decreased abundance overall. It has been theorized that the warming temperature of the Gulf of Mexico may be causing a decline in juvenile crab survival (P. Montagna pers. comm)."

Galbraith, H. S., Spooner, D. E., & Vaughn, C. C. (2010). Synergistic effects of regional climate patterns and local water management on freshwater mussel communities. Biological Conservation, 143(5), 1175-1183. doi:10.1016/j.biocon.2010.02.025

"Mussel communities in the Kiamichi River [a major tributary of the Red River in southeastern Oklahoma] changed over the 15 year period of this study, with overall abundance and species richness decreasing and relative abundance patterns shifting from assemblages dominated by thermally sensitive to thermally tolerant species. These changes corresponded with a period of very low flows in the river, which appear to have been caused by a combination of climate patterns (a regional drought; Figs. 3 and 6a) and local water management practices (reduced reservoir releases; Fig. 6b). These low flows coupled with high summer air temperatures (Fig. 3), changed the Kiamichi River in many locations from a continuously flowing river to a series of shallow, isolated pools where water temperatures sometimes exceeded 40 °C (Figs. 2, 5b; Spooner and Vaughn, 2000)."

"We believe that thermal stress associated with low water levels is one of the proximate causes underlying the declines we observed in mussel abundance and species richness [in the Kiamichi River a major tributary of the Red River in southeastern Oklahoma], and our observation that mussel mortality was related to water depth and thus temperature supports this premise (Fig. 5). In addition, we observed

that once mussels began dying in these isolated pools (Fig. 2), tissue decay led to large nutrient pulses (Vaughn et al., 2008), algal blooms, lowered dissolved oxygen levels, and thus further mussel

Spooner, D. E., & Vaughn, C. C. (2008). A trait-based approach to species' roles in stream ecosystems: climate change, community structure, and material cycling. Oecologia, 158(2), 307-317. doi: 10.1007/s00442-008-1132-9

"The magnitude, periodicity, and duration of droughts are increasing in the southern Unites States and mean summer temperatures are predicted to increase by as much as 4°C over the next 50 years (IPCC 2001; Mulholland et al. 1997). Many mussel species are already experiencing temperatures in the upper end of their thermal tolerance zone in this region [the Little River in southeastern Oklahoma], thus these increased temperatures (and associated decreased precipitation) will likely profoundly influence mussel community structure and the resulting ecosystem services in rivers in this region. For example, we detected significant effects of temperature on the physiology and ecological services provided by mussels at 35°C, and we observed mortality of three of the thermally sensitive species at 37–38°C, indicating that these temperatures are their upper limits for survival and reproduction."

"We have already observed changes in mussel community structure that are linked to stream warming. Monitoring data for ten sites in the Kiamichi River show that overall mussel abundance and species richness have declined over the past 17 years as water temperatures have increased, and that mussel beds once dominated by thermally sensitive species are now dominated by thermally tolerant species (H. S. Galbraith et al., unpublished data). Our results [from the Little River in southeastern Oklahoma] indicate that these changes in community composition will lead to changes in ecosystem function."

MAMMALS

SOUTH CENTRAL

Cameron, G. N. & Scheel, D. (2001). Getting warmer: Effect of global climate change on distribution of rodents in Texas. Journal of Mammalogy, 82(3), 652-680. doi: http://dx.doi.org/10.1644/1545-1542(2001)082<0652:GWEOGC>2.0.CO;2

"Under both 2 × CO2 climates, average size of Holdridge-modeled range [for rodents in Texas] was predicted to increase greatly relative to size of current Holdridge-modeled ranges (average ratio of 2 × CO2 range size relative to current modeled range size for CCC = 2.39, and for GFDLR30 = 3.52; Table 3)."

"When categorized by habitat, the ratio of predicted to current size of range [in Texas] under future GCC [global climate change] scenarios was larger for rodents in forests (average = 4.5-fold for CCC [Canadian Climate Centre model], 8.9-fold for GFDLR30 [Geophysical Fluid Dynamics Laboratory model]) than for those from other habitats (average = 1.4-fold for both CCC and GFDLR30; $F = 1.95$, d.f. = 3, 113, $P < 0.10$ for CCC; $F = 5.08$, d.f. = 4, 113, $P < 0.001$ for GFDLR30; Table 2)."

"Ranges of [rodent] species [in Texas] moved and changed in extent. Under CCC [Canadian Climate Centre model], ranges overlapped an average of 54% and under GFDLR30 [Geophysical Fluid Dynamics Laboratory model] ranges overlapped an average of 61% (Table 3). Species with <10% overlap (e.g., ranges under GCC were almost totally separate from current ranges) included T. canipes [Tamias canipes], P. boylii [Peromyscus boylii], P. nasutus [Peromyscuc nasutus], and N. mexicana [Neotoma mexicana]. Species with >90% overlap (e.g., little or no movement of future ranges) included Perognathus flavus, C. hispidus [Chaetodipus hispidus], R. montanus [Reithrodontomys montanus], Peromyscus maniculatus, B. taylori [Baiomys taylori], S. ochrognathus [Sigmodon ochrognathus], and M. pinetorum [Microtus pinetorum] (Table 3)."

"We assumed that rodents under 2 × CO2 climates would use new vegetation types that did not occur within Texas under the current climate. If rodents were not as flexible in using those new habitats, those species largely using new vegetation types under 2 × CO2 climates may be at risk of decline or extinction. The effect of that assumption was indicated by the proportion of the range for each species that was composed of new vegetation types under each 2 × CO2 climate (Table 3). On average, about 60% of 2 × CO2 ranges were composed of new habitat types (CCC [Canadian Climate Centre model] = 0.60; GFDLR30 [Geophysical Fluid Dynamics Laboratory model] = 0.64)."

"Terrestrial species occupied significantly fewer new vegetation associations than either arboreal or fossorial rodents [in Texas]."

"Geomys personatus and O. palustris [Oryzomys palustris] were among the species most affected by GCC [global climate change] (Table 4). The current Holdridge-modeled distribution of G. personatus, a fossorial species, was restricted to far southern Texas and a narrow portion in eastern Texas (Fig. 4). Under CCC [Canadian Climate Centre model], the range expanded to include large areas in southern, eastern, and western Texas, with penetration into the Panhandle. Under GFDLR30 [Geophysical Fluid Dynamics Laboratory model] a similar, but less extensive, distribution resulted. The majority of those range expansions were into new vegetation associations."

"[Texas rodent] Species impacted the most by GCC [global climate change] (impact index ≥ 10), included Dipodomys compactus, Geomys personatus, Liomys irroratus, Peromyscus truei, and Reithrodontomys humulis under both CCC and GFDLR30; N. Mexicana [Neotoma mexicana] and T. canipes [Tamias canipes] under CCC [Canadian Climate Centre model]; and Geomys breviceps, O. palustris [Oryzomys palustris], and Peromyscus gossypinus under GFDLR30 [Geophysical Fluid Dynamics Laboratory model] (Table 4)."

"Under CCC [Canadian Climate Centre model], highest richness shifted to the eastern part of the [Texas] Panhandle, where >40 [rodent] species occurred (Fig. 6B). Other foci of richness occurred along the border with Mexico, where areas containing 30–40 species were in the mountainous areas of western Texas, in the area around Big Bend National Park, and along the Rio Grande River into southern

"We determined that the impact of climate change on rodents would be greatest in eastern Texas if the climate becomes warmer and wetter (GFDLR30 [Geophysical Fluid Dynamics Laboratory model]), but greatest in western and southern Texas if the climate becomes warmer and drier (CCC [Canadian Climate Centre model])."

"Under either climate scenario, granivores and herbivores used fewer new habitat associations that entered the state after climate change than did omnivores and insectivores, as did terrestrial rodents compared with fossorial or arboreal rodents. In both cases, rodents used fewer new habitats if they had closer ties to particular plant types."

"For example, rodents in moist or low-lying habitats (e.g., O. palustris [Oryzomys palustris]; Fig. 5) showed marked increases in geographic range [in Texas] under GFLDR30 [Geophysical Fluid Dynamics Laboratory model], whereas rodents characteristically in drier habitats (e.g., C. hispidus [Chaetodipus hispidus]; Fig. 3) had larger geographic ranges under CCC [Canadian Climate Centre model]."

"In addition, ranges of arboreal and fossorial rodents [in Texas] contained more new vegetation types than did ranges of terrestrial species. That finding led to the conclusion that fossorial rodents such as pocket gophers were most (positively) impacted by GCC [global climate change]."

"We determined that suitable habitats for O. cousei [Oryzomys cousei] and M. mexicanus [Microtus mexicanus] would not occur in the state [Texas] under 2 × CO2 scenarios and, hence, concluded that those species would go extinct."

REPTILES

R8: SOUTHERN

Lang, J. W., & Andrews, H. V. (2005). Temperature-dependent sex determination in crocodilians. Journal of Experimental Zoology, 270(1), 28-44.

"In contrast [to previous studies], our results indicate that [in crocodilians] females are produced at both high and low incubation temperatures, with males predominating at intermediate temperatures, a FMF [female-male-female] pattern (Fig. 1). The initial transition from low-temperature females to males is relatively steep; interpolation of the TSD [temperature-dependent sex determination] curve (Fig. 1) indicates an increase from 0% to 50% males (FM [female-male] pivotal temperature) within a span of 0.8°C, from 31.5-31.8°C. Exclusively males are produced at 32.5 and 33.0°C. The transition from males to high-temperature females is more gradual; a decrease from 100% to 50% males (MF [male-female] pivotal temperature) occurs within a span of 0.8°C, from 33.0-33.8°C. Various TSD parameters are summarized in Table 3."

"With respect to TSD [temperature-dependent sex determination] patterns, five species [Alligator mississippiensis (American alligator), Caiman crocodzlus; Caiman johnstoni, Crocodylus palustrzs; Crocodylus porosus], including representatives of the two major lineages, have been examined in detail. All exhibit uniformity in TSD pattern, namely a FMF [female-male-female] pattern within a relatively restricted range of viable incubation temperatures. The relationship between temperature and sex ratios in individual species are remarkably similar. Exclusively females are produced at 31°C and below, with the FM [female-male] pivotal temperatures between 31 and 32°C. Maximum male-producing temperatures range from 32-33°C (Table 3)."

SOUTH ATLANTIC

Daniels, R. C., White, T. W., & Chapman, K. K. (1993). Sea-level rise: destruction of threatened and endangered species habitat in South Carolina. Environmental Management, 17(3), 373-385. doi:10.1007/bf02394680

"Thus, the loggerhead sea turtle [Caretta caretta] population [at Cape Romain, South Carolina] would be adversely affected if Raccoon Key and Cape, Lighthouse, and Bull islands are destroyed, reduced in size, or subject to tidal inundation. The impact of the loss of these particular islands on the loggerhead sea turtle population will be aggravated by the fact that they contain the largest undisturbed loggerhead nesting ground located outside of Florida in the United States (Cape Romain National Wildlife Refuge 1987)."

Hawkes, L. A., Broderick, A. C., Godfrey, M. H., & Godley, B. J. (2007). Investigating the potential impacts of climate change on a marine turtle population. Global Change Biology, 13, 923–932. doi: 10.1111/j.1365-2486.2007.01320.x

"In marine turtles, sex is determined by temperature in the middle third of incubation with female offspring produced at higher temperatures and males at lower temperatures within a thermal tolerance range of 25– 35 °C (Ackerman, 1997). A mixture of sexes is produced within the threshold range of temperatures (TRT, approximately 4 °C wide for the loggerhead sea turtle, Caretta caretta; Yntema & Mrosovsky, 1979) and 50% of either sex at the 'pivotal temperature' (around 29.0 °C, Mrosovsky, 1988). "

"In years with warmer spring (April and May) SSTs [sea surface temperatures], nesting [of loggerhead sea turtle (Caretta caretta)] started significantly earlier (mean April SST vs. first nest regression: F1, 22 = 4.72, P <0.05, first nest = -3.9 SST °C + 223.5, R2 = 0.18, 12 days earlier per 1 °C and mean May SST vs. first nest regression: F1, 2 2= 8.20, P <0.01, first nest = -5.2 SST °C + 265.2, R2 = 0.28, 18.3 days earlier per 1 °C, Fig. 3). This increased the duration of the nesting season significantly in warmer years (April regression F1, 22 = 7.15 P <0.05, duration = 4.8 SST °C –14.5, R2 = 0.25, 18.3 days longer per 1 °C, May regression F1, 22 = 3.47, P <0.05, duration = 5.1 SST °C – 34.8, R2 = 0.14, 36 days longer per 1 °C) but the date of last nest laid was not significantly related to any metric of

"With the predicted rise in future AT [air temperature], nests will begin to incubate at sand temperatures above the pivotal temperature (29.2 °C; Mrosovsky, 1988) for loggerheads [Caretta caretta], producing more female offspring. Simple heuristic simulation of likely hatchling sex ratios under these conditions (Fig. 5a and b) show that over 80% female hatchling production is predicted to occur in this part of North Carolina with 2 °C increase in AT. Further south, at Cape Canaveral, Florida, total feminization would occur with 2 °C of warming in AT and after 3 °C clutches would begin to incubate at temperatures above the lethal limit (35 °C; Ackerman, 1997). However, such clutch death is not likely to begin until 5 °C of warming in AT has occurred in North Carolina."

"With the maximum 7.5 °C of predicted warming in AT [air temperature], more than 40% of clutches [of loggerhead sea turtles (Caretta caretta)] at our study site and 100% of clutches at Cape Canaveral, will incubate at temperatures above the lethal limit, suggesting that nest incubation would no longer be viable at some Florida beaches during the current seasonal window of nesting."

"However, with climate warming, the actual thermal niche available to turtles for nesting will become wider (as a very simplistic example, with a mean increase of 7.5 °C AT [air temperature], the worst case scenario of warming, the suitable thermal conditions for incubation almost doubles, Fig. 6), providing [loggerhead] sea turtles [Caretta caretta] the opportunity to alter temporal nesting distribution to earlier and/or later months to mitigate increased incubation temperatures."

"Taken in concert with the environmental data sampled in this study, it appears that the primary sex ratio [of loggerhead sea turtles (Caretta caretta)] in North Carolina is not likely to become radically female biased in future years unless warming is severe."

"However, given that Florida could likely experience warming (IPCC, 2001) and is not buffered by oceanic features as in North Carolina (Boyles & Raman, 2003), there is a real possibility of further skewing or even complete feminization of the primary sex ratios [of loggerhead sea turtles (Caretta caretta)] in Florida, which holds the vast majority of nesting in the United States (Shoop & Kenney, 1992)."

"If warming occurs, [loggerhead] turtles [Caretta caretta] from northern and southern beaches could prevent extremely skewed sex ratios by (a) adapting in situ by adjusting their pivotal temperature, (b) altering nesting spatially (e.g. latitude, height on the beach, depth or substrate type, Hays et al., 2001) or (c) altering nesting temporally (e.g. nesting in cooler periods at the beginning and end of the season in order to exploit incubation environments likely to produce more males; Mrosovsky et al., 1984; Naro-Maciel et al., 1999; Hays et al., 2003; Pike et al., 2006)."

"Phenological correlations in this study and others (Mrosovsky et al., 1984; Weishampel et al., 2004; Pike et al., 2006) suggest that either changing temperatures in the future could drive adaptive phenological change to maintain current thermal conditions in [loggerhead sea turtle (Caretta caretta)] nests or that turtles may adapt the temporal spread of nesting to suit the available thermal niche. However, it should be noted that Pike et al. (2006) demonstrated that earlier seasons can also end earlier, probably because sea turtles are capital breeders (Bonnet et al., 1998), meaning that the fundamental and realised thermal niches for nesting may not necessarily be the same."

"Moreover, although [loggerhead] turtles [Caretta caretta] have evolved with continuously eroding and accreting oceanic beaches, the combination of renourishment programs, along with other anthropogenic threats such as beachfront development, and predicted sea level rise (from 0.11 to 0.43mm yr^1; IPCC, 2001) could cause a 'coastal squeeze', where landward movement of beaches is prevented by physical (anthropogenic) barriers such as beachfront development (Fish et al., 2005)."

Winne, C. T., Willson, J. D., Todd, B. D., Andrews, K. M., & Gibbons, J. W. (2007). Enigmatic decline of a protected population of eastern kingsnakes, Lampropeltis getula, in South Carolina. Copeia, 2007(3), 507-519.

"Proposed agents of reptile declines include environmental pollution, unsustainable removal (collection and road mortality), habitat loss and degradation (natural or anthropogenic), global climate change, introduced invasive species, and disease (Gibbons et al., 2000). Of these factors, environmental pollution and unsustainable removal are unlikely to be responsible for the [Lampropeltis getula, eastern kingsnakes] decline we observed because Ellenton Bay [in the Savannah River Site, South Carolina] has been protected from these factors since 1951, when it became part of a U.S. defense facility, and later, as part of a National Environmental Research Park (Shearer and Frazer, 1997)."

"Alternatively, although the habitat and prey availability at Ellenton Bay [in the Savannah River Site, South Carolina] is suitable for [Lampropeltis getula, eastern kingsnakes] in most years, periodic extreme droughts may have rendered the habitat inhospitable long enough to reduce L. getula populations. In the past three decades, Ellenton Bay has experienced two extreme droughts that rendered the wetland completely dry for two or more years (Fig. 2; Willson et al., 2006; Winne et al., 2006a). Sharp declines in the abundance of aquatic snakes (particularly Nerodia spp.) occurred at Ellenton Bay during both of these droughts (Seigel et al., 1995; Willson et al., 2006)."

RESOURCE AREA (FACTOR): CLIMATE TRENDS

GENERAL IMPACTS

R8: SOUTHERN

Biasutti, M., Sobel, A. H., Camargo, S. J., & Creyts, T. T. (2011) Projected changes in the physical climate of the Gulf Coast and Caribbean. Climatic Change, early online, 1-27. doi:10.1007/s10584-011-0254-y

"The temperature increases alone are underestimates of the extent to which it will feel warmer, as humidity will increase as well. Particularly over the oceans and coastal regions (which describes most of the Gulf coast and Caribbean), the models project little change in relative humidity. This projection—which is also robustly supported by our understanding of the physics of near-surface climate, and by observations of variability in the present climate—means that as temperature increases, there will also be significant increases in specific humidity."

SOUTH CENTRAL

Harcombe, P. A., Hall, R. B. W., Glitzenstein, J. S., Cook, E. S., Krusic, P., Fulton, M., & Streng D. R. (1998). Chapter 5: Sensitivity of Gulf Coast Forests to Climate Change (Biological Science Report USGS/BRD/BSR-1998-0002). In G. R. Guntenspergen & B.A. Vairin (Eds.), Vulnerability of coastal wetlands in the Southeastern United States: climate change research results, 1992-97. Lafayette, LA: U.S. Department of the Interior, U.S. Geological Survey, National Wetlands Research Center: 44-66.

"These climate gradients might affect the forests of the Big Thicket region [Texas] in two ways. First, precipitation ought to become increasingly limiting to tree growth from east to west. In this sense, winter may be the most critical season because it is the time when precipitation is most effective in recharging soil moisture reservoirs. In contrast, much of the summer rainfall will evaporate and will not recharge the soil reservoir. Second, the trend towards warmer summer maximum temperatures from east to west will result in higher potential evaporation demand on the trees and more frequent periods of internal moisture stress. The steep temperature increase might also be significant if a threshold effect on evapotranspiration demand is crossed for some tree species."

INTERACTIONS WITH OTHER FACTORS

R8: SOUTHERN

Sobolowski, S. & Pavelsky, T. (2012). Evaluation of present and future North American Regional Climate Change Assessment Program (NARCCAP) regional climate simulations over the southeast United States. Journal of Geophysical Research, 117(D1), D01101+. doi: 10.1029/2011JD016430

"Contributions to precipitation changes on synoptic scales will also depend on the magnitude and dynamic implications of future changes that are still poorly understood, such as widening of the Hadley circulation [Lu et al., 2007a, 2007b; Frierson et al., 2007] and northward shifting of the North Atlantic storm tracks [Yin, 2005]. The line of zero 21st century precipitation (or P – E) change bisects the Southeast latitudinally [Christensen et al., 2007; Seager et al., 2010] and a shift of this line north or south may have profound implications for the numerous large, expanding municipalities across the southeast United States."

PRECIPITATION TRENDS

R8: SOUTHERN

Biasutti, M., Sobel, A. H., Camargo, S. J., & Creyts, T. T. (2011) Projected changes in the physical climate of the Gulf Coast and Caribbean. Climatic Change, early online, 1-27. doi:10.1007/s10584-011-0254-y

"The mean rainfall response to greenhouse gas increases in the Gulf and Caribbean can be broadly described as a drying of the latitude band between 10°N and 30°N, with wetting to the south and to the north (Fig. 6 and also Fig. 12)."

Flebbe, P. A., Roghair, L. D. & Bruggink, J. L. (2006). Spatial Modeling to Project Southern Appalachian Trout Distribution in a Warmer Climate. Transactions of the American Fisheries Society, 135(5), 1371-1382. doi: 10.1577/T05-217.1

"Precipitation changes are expected, but the magnitude and direction of changes are not clear. The Hadley Centre GCM predicts increases of 20%, and the Canadian Centre GCM predicts decreases of 10% for the Southeast by 2090 (Burkett et al. 2001)."

Karl, T. R., Melillo, J. M., & Peterson, T. C. (2009). Global climate change impacts in the United States. New York, NY, USA: Cambridge University Press.

"Average autumn precipitation has increased by 30 percent for the [southern] region since 1901."

"Except for indications that the amount of rainfall from individual hurricanes will increase, (Gutowski et al., 2008) climate models provide divergent results for future precipitation for the remainder of the Southeast."

Seager, R., Tzanova, A., & Nakamura, J. (2009). Drought in the Southeastern United States: Causes, variability over the last millennium, and the potential for future hydroclimate change. American Meteorological Society, 22(19), 5021-5045.

"The median projection for the Southeast is for both increasing P [precipitation] and E [evaporation]. The balance is such that the median P - E [precipitation minus evaporation] decreases very modestly during this century; P - E drops more in the summer half-year than the winter half-year (not shown)."

"Turning to projections of anthropogenic climate change in the Southeast, models project that, in the near-future precipitation will increase year around in the Southeast north of southern Florida. However, precipitation minus evaporation (P – E) decreases modestly in the annual mean, driven by increasingly negative P - E in summer. This is in turn caused by an increase in evaporation, presumably related to atmospheric warming, that exceeds the increase in precipitation. Since P - E is positive over land, this implies a weakening of moisture convergence by the atmospheric flow; however, we have not examined how this occurs."

Sobolowski, S. & Pavelsky, T. (2012). Evaluation of present and future North American Regional Climate Change Assessment Program (NARCCAP) regional climate simulations over the southeast United States. Journal of Geophysical Research, 117(D1), D01101+. doi: 10.1029/2011JD016430

"Unlike temperature, the projected changes in precipitation [for the period 2041-2070 using North American Regional Climate Change Assessment Program (NARCCAP) simulations] are modest and vary in both sign and magnitude by location and season. Winter and spring exhibit increases of ~10% across the much of the Southeast while decreases of ~15% over the western portion of the study area are indicated for summer. During fall, increases of ~10% are projected for the coastal regions."

"Thus, the average precipitation change [in the Southeast] only exceeds background variability along the Mississippi river in summer and the Appalachian mountains in winter [for the period 2041-2070 using North American Regional Climate Change Assessment Program (NARCCAP) simulations]."

"With respect to precipitation the picture is not so clear. None of the changes shown in Figure 12 are significantly greater than background variability, and given the large intermodel spread, it is possible that a new set of NARCCAP [North American Regional Climate Change Assessment Program] simulations, even under the same forcing scenario, would yield different results. However, Figures 9 and 10 suggest that with the reduction in uncertainty due to the weighting scheme and with more realizations, the patterns of change in winter and summer may be robust though modest. The winter pattern suggests modest increases in precipitation, on the order of 10%–15%, along the northern states of the region (i.e., Arkansas, Tennessee, North Carolina, Virginia, and Kentucky). Conversely, the summer change suggests decreases as high as 20% in the western portion of the Southeast region. This decrease is mostly along the Mississippi but also extends along the Gulf coast."

SOUTH ATLANTIC

Karl, T. R., Melillo, J. M., & Peterson, T. C. (2009). Global climate change impacts in the United States. New York, NY, USA: Cambridge University Press.

"Spring and summer rainfall is projected to decline in South Florida during this century."

Seager, R., Tzanova, A., & Nakamura, J. (2009). Drought in the Southeastern United States: Causes, variability over the last millennium, and the potential for future hydroclimate change. American Meteorological Society, 22(19), 5021-5045.

"Climate model projections predict that in the near term, future precipitation in the Southeast will increase but that evaporation will also increase. The median of the projections predicts a modest reduction in the atmospheric supply of water vapor to the region; however, the mutimodel ensemble exhibits considerable variation, with a quarter to a third of the models projecting an increase in precipitation minus evaporation."

SOUTH CENTRAL

Biasutti, M., Sobel, A. H., Camargo, S. J., & Creyts, T. T. (2011) Projected changes in the physical climate of the Gulf Coast and Caribbean. Climatic Change, early online, 1-27. doi:10.1007/s10584-011-0254-y

"In the mean, models project moderate drying along the Gulf coast for most of the year, except the fall, but because the Gulf states are located at the latitude where we expect rainfall anomalies to switch from negative to positive, the outlook is uncertain."

Karl, T. R., Melillo, J. M., & Peterson, T. C. (2009). Global climate change impacts in the United States. New York, NY, USA: Cambridge University Press.

"Models project that Gulf Coast states will tend to have less rainfall in winter and spring, compared with the more northern states in the region."

TEMPERATURE TRENDS

R8: SOUTHERN

Biasutti, M., Sobel, A. H., Camargo, S. J., & Creyts, T. T. (2011) Projected changes in the physical climate of the Gulf Coast and Caribbean. Climatic Change, early online, 1-27. doi:10.1007/s10584-011-0254-y

"In all seasons, the continent warms more than the ocean [in the Gulf Coast and Caribbean], and 75% of the models project more than 2 °C (3.6 °F) of mean warming. The details of the warming vary with the seasons. During spring, the maximum warming follows the topography and is likely associated with earlier snow-melt. During summer and fall the land-sea contrast is maximum, and the warmest temperatures are in the interior of the continent."

"The increase in the number of warm nights (Fig. 4) is also widespread, but is expected to be greater in the deep tropics and Caribbean, less so over the US. Nights as warm as the 10% warmest nights of a typical year in the 60s, 70s, or 80s will be four times as frequent in the Gulf states (eight times, in Hispaniola) by the end of this century."

Karl, T. R., Melillo, J. M., & Peterson, T. C. (2009). Global climate change impacts in the United States. New York, NY, USA: Cambridge University Press.

"Since 1970, however, annual average temperature has risen about 2°F, with the greatest seasonal increase

in temperature occurring during the winter months."

"The projected rates of warming are more than double those experienced in the Southeast since 1975, with the greatest temperature increases projected to occur in the summer months."

"Under a lower emissions scenario (IPCC SRES B1), average temperatures in the region are projected to rise by about 4.5°F by the 2080s, while a higher emissions scenario(IPCC SRES A2) yields about 9°F of average warming (with about a 10.5°F increase in summer, and a much higher heat index)."

Sobolowski, S. & Pavelsky, T. (2012). Evaluation of present and future North American Regional Climate Change Assessment Program (NARCCAP) regional climate simulations over the southeast United States. Journal of Geophysical Research, 117(D1), D01101+. doi: 10.1029/2011JD016430

"The temperature change in by the middle of the 21st century is positive over the entire southeast United States [for the period 2041-2070 using North American Regional Climate Change Assessment Program (NARCCAP) simulations]. The stippling indicates grid cells where the entire 95% confidence bounds of the projected change lie outside the bounds of natural variability as defined by ϵ in section 3. $\sim\Delta T$ [average change in temperature] is generally homogeneous over the region in each season, with slight north-south, coast-inland gradients (i.e., more warming north (inland) less south (coasts))."

"The unweighted uncertainties [for average change in temperature] are over 0.5°C across most of the Southeast in all seasons. The Gulf states (spring), North Carolina and Mississippi (summer) and the northern states (fall) exhibit coherent areas with uncertainties as high as 1°C, indicating 95% confidence intervals of around 2°. This range of uncertainty sets the lower limits of change as low as 1°C in some areas during winter and spring. Conversely, the upper limits may be as high as 4.5°C–5°C over some areas during summer. While consideration of the unweighted uncertainties does not change the story of warming over the entire southeast United States by the middle of the 21st century, the range of potential warming is increased everywhere and specific seasons and locations (e.g., spring along the Gulf coast) exhibit confidence intervals that approach 2°."

"The highest uncertainties [for average change in temperature in the Southeast] occur in summer over the eastern Carolinas and the Gulf coast states [for the period 2041-2070 using North American Regional Climate Change Assessment Program (NARCCAP) simulations]."

"If the A2 SRES [IPCC Special Report Emission Scenario] assumptions prove correct, the results suggest that average temperatures across the Southeast will increase by over 2.5°[C] in summer and fall with slightly smaller increases of about 1.8°[C] in winter and spring [for the period 2041-2070 using North American Regional Climate Change Assessment Program (NARCCAP) simulations]. There is a slight northwest to Southeast gradient in all seasons with largest changes in the Northwest and smallest in the Southeast."

SOUTH ATLANTIC

Dai, Z., Amatya, D. M., Sun, G., Trettin, C. C., Li, C., & Li, H. (2011). Climate Variability and Its Impact on Forest Hydrology on South Carolina Coastal Plain, USA. Atmosphere, 2, 330-357. doi:10.3390/atmos2030330

"The anomaly of annual mean temperature for the 63-year period from 1946 to 2008 (Figure 4a) showed that the air temperature on SEF [Santee Experimental Forest, South Carolina] significantly ($P < 0.01$) increased at an average rate of 0.19 °C per decade."

"There was a significant linear increase in the annual mean daily minimum temperature at a rate of 0.26 °C per decade (P < 0.01) on SEF [Santee Experimental Forest, South Carolina] since 1946 (Figure 4b)."

Soule, P. (2005). A Comparison of 30-yr Climatic Temperature Normals for the Southeastern United States. Southeastern Geographer, 45, 16-24. doi:10.1353/sgo.2005.0018

"The statistical comparison of climate temperature normals for the two 30-yr periods by physiographic province shows that only the lower Coastal Plain [of the southeast United States] has experienced a significant change in temperature (Table 1). While the majority of stations within each physiographic province have registered increases in temperature and the change is statistically significant for all sites combined (n=104), the average increase was only 0.1 degree C."

RESOURCE AREA (FACTOR): COASTAL ECOSYSTEMS

COASTAL FORESTS

R8: SOUTHERN

Erwin, K. L. (2009). Wetlands and global climate change: the role of wetland restoration in a changing world. Wetlands Ecology and Management, 17(1), 71-84. doi:10.1007/s11273-008-9119-1

"At a freeze frequency of 12 years, mangroves replaced salt marsh. Along the Louisiana coast, freezes historically occurred about every 4 years. By the spring of 2004, however, a killing freeze had not occurred for 15 years and small mangroves occur over a large area near the coast. If this trend continues, mangroves will probably spread over much of the northern Gulf and part of the south Atlantic coast. In fact, mangroves are already becoming established and more widespread due to warming (Day et al. 2005)."

Erwin, M. R., Cahoon, D. R., Prosser, D. J., Sanders, G. M., & Hensel, P. (2006) Surface Elevation Dynamics in Vegetated Spartina Marshes Versus Unvegetated Tidal Ponds Along the Mid-Atlantic Coast, USA, with Implications to Waterbirds. Estuaries and Coasts, 29(1), 96-106.

"As with other wetland species, interspecific variation in physiological responses of different mangrove species to factors associated with climate change would be expected to lead to changes in species composition and community structure following predicted changes in sea level and atmospheric CO2 levels (Ellison and Farnsworth 1997)."

Krauss, K. W., Duberstein, J. A., Doyle, T. W., Conner, W. H., Day, R. H., Inabinette, L. W., & Whitbeck, J. L. (2009). Site condition, structure, and growth of baldcypress along tidal/non-tidal salinity gradients. Wetlands, 29(2), 505-519. doi: 10.3159/1095-5674(2005)132[411:EODSOV]2.0.CO;2

"Baldcypress [Taxodium distichum] is an extremely flood tolerant species (Hook 1984), and on our sites [across five landscape transects in coastal Louisiana, South Carolina, and Georgia], potential growth detriments provided by continuous flooding may have been countered by the overwhelming influence of salinity in what should be a functionally freshwater ecosystem."

"We suggest [using results from plots along five landscape transects in coastal Louisiana, South Carolina, and Georgia] that a threshold may exist whereby salt stressed trees lose their capacity for nutrient retention or reabsorption in tidal and non-tidal baldcypress [Taxodium distichum] swamps. Salinities approaching 2.0 ppt coincide with concentrations required to induce leaf-level ion ratio imbalances for baldcypress and promote leaf photosynthetic dysfunction (Allen et al. 1997, Krauss et al. 2000). Changes in alternating periods of wetting and drying might also affect tidal swamp soils, forest productivity, and tidal swamp persistence. Reduced capacity for nutrient conservation, especially of nitrogen, might be one way in which tidal and non-tidal baldcypress trees respond to sea-level rise and salinization. Strong links among increasing salinity, diminished growth, and increased mortality of tidal swamp trees are likely to overwhelm the more subtle processes inherent to nutrient conservation."

Osland, M. J., Enwright, N., Day, R. H., and Doyle, T. W. (2012). Winter climate change and coastal wetland foundation species: salt marshes versus mangrove forests in the southeastern U.S.. Global Change Biology, online first. doi:10.1111/gcb.12126

"Our results indicate that, within the [southeast U.S.] region, salt marshes in Louisiana, Texas, and Florida are most vulnerable to winter climate change-induced mangrove forest range expansion; for example, with a 2 to 4 degree C increase in MAMT [mean annual minimum temperature], 6820 (95% of LA state total), 1970 (100% of TX state total), and 830 (60% of FL state total) km2 of salt marsh could become vulnerable to mangrove forest replacement (Figs. 4 and 5a). Along the Atlantic coast, all of the salt marshes in Georgia (1480 km2; 100% of state total) and many of the salt marshes in South Carolina (890 km2; 63% of state total) could become vulnerable to mangrove forest replacement with a 4 to 6 degree C increase in MAMT relative to the modern climate (Figs. 4 and 5a). "

"Our 30-yr minimum [winter] temperature threshold analyses indicate that mangrove forests in the southeastern U.S. are not likely to be present in areas where minimum temperatures fall below approximately -8.9 degrees C, and mangrove forests are not likely to be dominant in areas where minimum temperatures fall below approximately -7.0 degrees C (Table 2; Fig. 3a)."

"Our analyses indicate that salt marshes in the states of Louisiana, Texas, and parts of Florida are especially sensitive to winter climate change due to their proximity to the winter climate threshold that differentiates between mangrove forest and salt marsh dominance."

"With regards to biotic interactions in newly-suitable habitats, we assume that competition between mangroves and salt marshes [in the coastal southeastern U.S.] will be most intense in areas near the poleward range limit of mangrove forests where extreme winter climate limits mangrove forest growth and development (i.e., areas where our models indicate that mangrove forests are likely to be present but not dominant), but that mangrove forests will be competitively-dominant in areas with warmer winters (Kangas & Lugo 1990; Fig. 3)."

"Interactions between sea level rise and winter climate change are particularly important [in the tidal saline wetlands of southeastern U.S.]; whereas warming is expected to enable poleward mangrove forest migration and salt marsh displacement, sea level rise is expected to result in landward mangrove forest migration and tidal freshwater forested wetland displacement (Doyle et al. 2010; Krauss et al. 2011)."

"The potential ecological effects of [poleward] mangrove forest migration and salt marsh displacement [in the tidal saline wetlands of southeastern U.S.] are likely diverse, ranging from important biota effects (e.g., changing habitat for fish and birds) to ecosystem stability (e.g., habitat loss; response to sea level rise and drought; coastal protection from storms) to biogeochemical processes (e.g., carbon and nitrogen cycling; water quality improvement)."

SOUTH ATLANTIC

Brittain, R. A., & Craft, C. B. (2012). Effects of Sea-Level Rise and Anthropogenic Development on Priority Bird Species Habitats in Coastal Georgia, USA. Environmental Management, 49(2), 473-482. doi:10.1007/s00267-011-9761-x

"Though small in area (10 km2), shrub habitat was predicted [using SLAMM5 (Sea-level Rise Affecting Marshes Model, version 5] to decline the most, 35–43% in response to SLR [sea level rise] [along the Georgia Coast] (Fig. 3). Models predicted oak [Quercus spp.] and pine [Pinus spp.] forests will decline less from SLR than shrub habitat, with 18–22% proportional losses of oak forest and 11–15% of pine forest."

Craft, C. B. (2012). Tidal freshwater forest accretion does not keep pace with sea level rise. Global Change Biology, 18(12), 3615-3623. doi:10.1111/gcb.12009

"Tidal forests are sentinels of SLR [sea level rise] because they are extremely vulnerable to saltwater intrusion. Saltwater intrusion at low salinities (e.g. 3) reduces water use, growth, height and basal area of bald cypress and tupelo gum (Pezeshki et al. 1990, Krauss et al. 2009), two of the dominant species in tidal forests. Over time, saltwater intrusion can lead to forest death and replacement by brackish marsh vegetation or open water (DeLaune et al. 1987, Hackney and Yelverton 1990, Conner et al. 2007a, Krauss et al. 2007, Krauss and Duberstein 2010). Measured rates of 137Cs and 210Pb soil accretion in tidal forests [along the Ogeechee, Altamaha, and Satilla, and South Newport Rivers] are less than the current rate of SLR along the Georgia coast (Figure 3), suggesting that these wetlands will convert to marshes or open water under current and projected future rates of SLR (Craft et al. 2009)."

"Unlike tidal forests of the Ogeechee, Altamaha and Satilla rivers, the tidal forest of the South Newport River [on the Georgia coast] receives water and sediment from a much smaller catchment (492 km2) than tidal forests on the other three rivers whose catchments are much larger, 7,348 to 35,112 km2. Here, the newly forming brackish marsh does not receive the sediment load to increase soil accretion to rates found in brackish marshes of the healthy rivers and that will be needed to compensate for SLR [sea level rise] in the future. Thus, the newly forming brackish marsh of the South Newport River is unlikely to keep up with SLR in the future and may, in fact, convert to open water."

"Though soil accretion of tidal forests [along the Ogeechee, Altamaha, and Satilla, and South Newport Rivers of the Georgia coast] is less than the recent rate of SLR [sea level rise], measurements of accretion in marshes downstream on the Ogeechee, Altamaha and Satilla rivers (Loomis and Craft 2010) suggest that conversion of tidal forest to tidal fresh or brackish marsh will be accompanied by an increase in accretion that exceeds the current rate of SLR (Figure 4)."

"Tidal fresh and brackish marshes will be better able to withstand increases in water level and salinity than tidal forest [along the Ogeechee, Altamaha, and Satilla, and South Newport Rivers of the Georgia coast] because, as sea level rises, they will sequester more C [carbon] and trap more sediment than their forested counterparts. They also will accumulate more N [nitrogen] and P [phosphorus] in soils than tidal forests (Table 3)."

"Along the Georgia coast, sea level is predicted to rise by 52 to 82 cm by 2100 according to the Intergovernmental Panel on Climate Change (IPCC), leading to a 20% decline (63 km2) in tidal forest habitat through upriver migration of tidal fresh- and brackish-water marsh (Craft et al. 2009). As marsh replaces forest, it is likely that rate of soil accretion will increase, buffering the newly developing marshes against the impacts of increased inundation and salinity. While some ecosystem services (e.g., C sequestration in soil) will be enhanced as forest converts to marsh, other services (avian habitat, N processing) may decline. Regardless, tidal forests, with their accretion rates that are considerably less than the current rate of SLR [sea level rise], and their intolerance to low levels of salinity, serve as sentinels of global warming-driven accelerated SLR along the southeastern U.S. coast and elsewhere."

Desantis, L. R. G., Bhotika, S., Williams, K., and Putz, F. E. (2007). Sea-level rise and drought interactions accelerate forest decline on the gulf coast of florida, USA. Global Change Biology, 13(11), 2349-2360. doi:10.1111/j.1365-2486.2007.01440.x

"Coastal forest stands [between 1955-2005 in Waccasassa Bay, Florida] declined in species richness with decreasing elevation ($r^2=0.43$, $P<0.05$) and increasing tidal flooding frequency ($r^2=0.68$, $P<0.001$; Table 1)."

"The 2005 census [of tree species in Waccasassa Bay, Florida] documents the disappearance of [Sabal palmetto, cabbage palmetto] >2 m tall from the most frequently flooded plot (D2) and disappearance of [Juniperus virginiana, southern red cedar] from the three plots with the most frequent tidal flooding where it was present in 2000. In other words S. palmetto remained in plots with <=26 weeks of tidal flooding, whereas J. virginiana was only present in plots experiencing <=13 weeks of tidal flooding (Table 1)."

"The chronic effects of sea-level rise on coastal forests in Waccasassa Bay [Florida] were exacerbated by the 1998–2002 La Nina-associated drought. In particular, [Sabal palmetto, cabbage palmetto] suffered greater mortality rates during 2000–2005 than 1995–2000 (paired Student's t-test: $P<0.01$, $n=13$; Fig. 6). Mortality rates of S. palmetto in plots with >=8 weeks of flooding during 2000–2005 were at least two to 15 times the 1995–2000 mortality rates (Fig. 6). [Juniperus virginiana, southern red cedar] also suffered significantly greater (paired Student's t-test: $P<0.05$, $n=6$) mortality during 2000–2005 than during 1995–2000 in all forest plots with >=1 week of flooding (Fig. 6), with mortality rates approximately 0.3–19 times greater than the earlier estimates from 1995 to 2000."

"Although [in Waccasassa Bay, Florida] [Sabal palmetto, cabbage palmetto] and [Juniperus virginiana, southern red cedar] do suffer salt damage, they may actually benefit from the presence of moderately saline source water if competition with less salt-tolerant species is, therefore, reduced, as suggested for the interactions between mangroves and fast-growing glycophilic plants (Sternberg & Swart, 1987). Above the salinity threshold at which regeneration of J. virginiana ceases, S. palmetto maintains monodominant stands that eventually die off as the salinity continues to increase. J. roemerianus is usually not present within the tree islands, but it surrounds most of them. Increased tidal inundation due to rising sea levels will continue to threaten these tree communities, as reported for tropical hardwood hammocks and pine forest in the Florida Keys (Ish-Shalom et al., 1992; Ross et al., 1994)."

"Coastal forests in Waccasassa Bay [Florida] declined during 2000–2005 at rates greater than expected from rates during the previous 8 years likely due to the synergistic effects of a drought event and sea-level rise."

"With expected increases in the rate of sea-level rise coupled with increasing drought frequencies due to global climate change, accelerated rates of coastal forests disappearance [in Waccasassa Bay, Florida] are likely and may already be evident."

Krauss, K. W., Duberstein, J. A., Doyle, T. W., Conner, W. H., Day, R. H., Inabinette, L. W., & Whitbeck, J. L. (2009). Site condition, structure, and growth of baldcypress along tidal/non-tidal salinity gradients. Wetlands, 29(2), 505-519. doi: 10.3159/1095-5674(2005)132[411:EODSOV]2.0.CO;2

"Growth of baldcypress [Taxodium distichum] in our study [across five landscape transects in coastal Louisiana, South Carolina, and Georgia] was reduced considerably in tidal and nontidal swamps at mean annual salinity concentrations above 2 ppt. Working on the Lower Cape Fear River, North Carolina, USA, Hackney et al. (2007) suggested that 2 ppt is an important threshold for conversion from swamp to oligohaline or brackish marsh. Our Waccamaw Lower (2.1 ppt salinity) and Savannah Lower (3.4 ppt salinity) sites [in South Carolina and Georgia] are both actively converting to marsh; some trees that were monitored died, while the understory marsh environment was becoming dominant."

Krauss, K. W., & Whitbeck, J. L. (2011). Soil greenhouse gas fluxes during wetland forest retreat along the lower Savannah River, Georgia (USA). Wetlands, 1-9. doi:10.1007/s13157-011-0246-8

"As tidal swamps [whose codominant tree species were baldcypress (Taxodium distichum) and water tupelo (Nyssa aquatica)] along the lower Savannah River undergo retreat, we found a modest influence of this transition on soil greenhouse gas emissions. Salinity, which ranged from 0.2 to 4.7, was not a significant driver of soil greenhouse gas emissions from these sites [Savannah National Wildlife Refuge along the border of South Carolina and Georgia]. Soil temperature, air temperature, and water level—in that order—had the greatest influence on soil CO2 emissions, but none of those factors influenced soil CH4 or N2O emissions."

Poulter, B., Christensen, N. L., and Qian, S. S. (2008). Tolerance of pinus taeda and pinus serotina to low salinity and flooding: Implications for equilibrium vegetation dynamics. Journal of Vegetation Science, 19(1), 15-22. doi:10.3170/2007-8-18410

"Our field observations [5 vegetation surveys across the Albemarle Peninsula, North Carolina] revealed that Pinus taeda [lobolly pine] and [Pinus serotina (pond pine)] were able to establish and survive in salinity conditions up to 5 ppt in semi-flooded to well-drained soils."

"We show that pine seedlings [Pinus taeda (loblolly pine) and Pinus serotina (pond pine) in Albemarle Peninsula, North Carolina] are able to establish and survive within a range of low-salinity conditions in well-drained soils contrary to the notion that discrete salinity boundaries result in either marsh or forest communities (Park et al. 1988). Under the environmental conditions experienced in Albemarle and Pamlico Sounds, pine regeneration and forest survival may continue, despite gradually rising sea level, due to physiological tolerance to low salinity levels."

"In general, the sharp boundaries between marsh and woodland communities in coastal wetlands has created the impression that the range of freshwater-species tolerance to environmental stress is small, and that gradually changing salinity and hydrology will lead to gradual plant community migration. However, in the wetlands we studied [in Albemarle Peninsula, North Carolina], low salinity shoreline gradients create conditions whereby estuarine species may tolerate gradually changing water chemistry, resulting in rates of forest migration lower than predicted by current models."

Ross, M. S., O'Brien, J. J., Ford, R. G., Zhang, K., & Morkill, A. (2009). Disturbance and the rising tide: The challenge of biodiversity management on low-island ecosystems. Frontiers in Ecology and the Environment, 7(9), 471-478. doi:10.1890/070221

"Our data showed that the area of pine [Pinus spp.] forest on Sugarloaf Key [Florida] declined from an initial 88 ha (furthest extent of pine remains) before 1935, to 30 ha by 1991 (Figure 2). The transformation of pine forest to more salt-tolerant vegetation types proceeded continuously, though at variable rates, and from low to high elevation. Live pine trees surviving in peripheral areas experienced diminished plant moisture potential and showed isotopic signs of physiological stress. The upslope recession in the pine forest border was generally consistent with a progressive salinization and rise in the groundwater associated with sea-level rise."

Ross, M. S., O'Brien, J. J., and da Silveira Lobo Sternberg, L. (1994). Sea-Level rise and the reduction in pine forests in the Florida keys. Ecological Applications, 4(1), 144+. doi:10.2307/1942124

"Our results [of the effect of sea level rise on the reduction of pine (Pinus spp.) forests] indicate that pine mortality on Sugarloaf Key [Florida] proceeded from the margins of the original forest [pre-1935] toward its center (Fig. 3), and from lower to higher elevations (Fig. 4). They further indicate that these pine forests subsequently succeeded to more halophilic vegetation types, and that the sequence advanced furthest in the areas first affected (Fig. 6). These results together signify a progressive salinization in much of the island's upland habitat during a period when sea level was rising at a fairly constant rate of ≈2.4 cm/decade (Fig. 2)."

Williams, K., MacDonald, M., & Sternberg, L. D. S. L. (2003). Interactions of storm, drought, and sea-level rise on coastal forest: a case study. Journal of Coastal

"Our previously published studies of coastal forest change in a marshy, tectonically stable region on the west coast of Florida indicated that sea-level rise affected the coastal hard-wood forest initially by eliminating the regeneration of tree species. Relict, non-regenerating stands of more sensitive species were found within healthy regenerating stands of tree species with more tolerant seedlings."

"Sabal trees [cabbage palm, Sabal palmetto] died over the course of this study [in Waccasassa Bay on the west coast of Florida] at a fairly constant rate (Figure 3), and yearly mortality rates appeared homogeneous ($X2 = 5.7$, $df = 6$, n.s.). In contrast, mortality rates of Juniperus [southern red cedar, Juniperus virginiana var. silicicola] were not homogeneous ($X2 = 57.9$, $df = 6$, $p<0.01$). Mortality rates were significantly elevated for two years after the 1993 storm (Figure 3b). Average mortality during the drought (1998-2000) appeared slightly elevated, but was not significantly different from mortality during "normal" years. The insignificance of the increase in overall Juniperus mortality during the drought can be attributed to the fact that Juniperus mortality was not elevated in plots classified as "healthy" or "intermediate" during the drought. It was only elevated in stands in the last stages of decline (Table 1)."

"Both storm and drought were associated with pulses of mortality in coastal stands at our study site [in Waccasassa Bay on the west coast of Florida]. Both selectively removed Juniperus [southern red cedar, Juniperus virginiana var. silicicola] from stands, leaving Sabal [cabbage palm, Sabal palmetto] more dominant. The overall importance of these events in causing forest loss, however, lies in their spatial relationship to effects of sea-level rise."

"Among the more salt-tolerant tree species of the forest fringe [in Waccasassa Bay on the west coast of Florida], drought-associated mortality occurred only in late stages of decline, where regeneration had ceased decades earlier."

"The pulses of mortality that occurred at our study site [in Waccasassa Bay on the west coast of Florida] in association with drought and storm caused permanent changes in forest structure primarily because sea-level rise had al-ready reduced or eliminated regeneration in these stands."

Williams, K., Ewel, K. C., Stumpf, R. P., Putz, F. E., & Workman, T. W. (1999). Sea-level rise and coastal forest retreat on the west coast of Florida, USA. Ecology, 80(6), 245-263. doi: 10.1890/0012-9658(1999)080[2045:SLRACF]2.0.CO;2

"For the four tree species that occurred in island plots [on the west coast of Florida] (Sabal, Juniperus, Quercus, and Celtis), mature individuals existed in more frequently flooded sites [indicative of future sea level rise] than did their seedlings, suggesting that regeneration failed before mature individuals were eliminated (Table 2)."

"A change in understory composition accompanied forest decline at the seaward margin of coastal forest [on the west coast of Florida]. Whereas the tree species in frequently flooded plots were a subset of those occurring in adjacent coastal forest, the understory experienced complete species turnover (Appendix)."

"Salinization of groundwater appeared to occur during early to middle stages of stand decline: shallow groundwater beneath [plot] H1, where ample regeneration of Sabal, Juniperus, and Quercus occurred, was brackish at certain times of year (up to ~15 g sea salt/L several times during 1994–1995). Groundwater salinity under plots H2 and H3, where no regeneration of Quercus occurred and that of Sabal and Juniperus was marginal, was substantially higher than under H1 when it was measured in 1997. This pattern suggests that the salinization of groundwater could be a cause of regeneration failure. However, its role in forest decline on carbonate coasts [such as on the west coast of Florida] is unclear."

"Of the species studied [on the west coast of Florida], Sabal and Juniperus were best able to maintain green leaves under conditions of continuous salt exposure, whereas Quercus could survive extremely high salt exposure by dying back and resprouting following salt removal."

"Coastal forest retreat on this relatively undeveloped carbonate coastline [in Waccasassa Bay State Preserve on the west coast of Florida], therefore, appears fully consistent with impacts of continuing sea-level rise, whereby salt exposure associated with tidal flooding eliminates tree regeneration well before mature trees die."

SOUTH CENTRAL

Krauss, K. W., Duberstein, J. A., Doyle, T. W., Conner, W. H., Day, R. H., Inabinette, L. W., & Whitbeck, J. L. (2009). Site condition, structure, and growth of baldcypress along tidal/non-tidal salinity gradients. Wetlands, 29(2), 505-519. doi: 10.3159/1095-5674(2005)132[411:EODSOV]2.0.CO;2

"For the Treasure Island (2.0 ppt) and Fleming (2.1 ppt) sites in Louisiana that are at or above the 2 ppt salinity threshold, conversion [to marsh from baldcypress (Taxodium distichum) wetlands] appears to be occurring more slowly [than at sites in coastal Georgia and South Carolina]. However, encroachment of Sagittaria lancifolia in the understory, degradation of soils to unconsolidated slurries with little root sustenance, and the unstable condition of surrounding tidal swamps suggest that these sites were also deteriorating."

Osland, M. J., Enwright, N., Day, R. H., and Doyle, T. W. (2012). Winter climate change and coastal wetland foundation species: salt marshes versus mangrove forests in the southeastern U.S.. Global Change Biology, online first. doi:10.1111/gcb.12126

"In terms of the suitability of abiotic conditions in newly-available habitat, we make the assumption that the abiotic conditions that determine the relative abundance of mangrove forests in Florida will be similar in other parts of the southeastern U.S. For most of the region, this assumption is probably appropriate; however, in areas with very low precipitation (e.g., arid parts of southwest Texas) or continuous freshwater flow (e.g., parts of Louisiana), the abundance of mangrove forests relative to unvegetated tidal flats and/or salt marshes will likely be different (Dunton et al. 2001; Montagna et al. 2007)."

Williams, K., Ewel, K. C., Stumpf, R. P., Putz, F. E., & Workman, T. W. (1999). Sea-level rise and coastal forest retreat on the west coast of Florida, USA. Ecology, 80(6), 245-263. doi: 10.1890/0012-9658(1999)080[2045:SLRACF]2.0.CO;2

"On deltaic coasts with high freshwater outflows, such as the Mississippi Delta, rising seas may boost freshwater tables, eliminating tree regeneration through increased freshwater flooding (e.g., Baumann 1987, DeLaune et al. 1987, Conner and Day 1988)."

"Regardless of the mechanism by which rising seas eliminate coastal forest, tree regeneration may be

much more sensitive to rising seas than mature-tree survival. Increases in hydroperiod in the Mississippi Delta have eliminated tree regeneration in forest stands (DeLaune et al. 1987, Conner and Day 1988, Conner and Brody 1989). Failure of tree regeneration has also been linked to saltwater intrusion (e.g., Penfound and Hathaway 1938)."

COASTAL WETLANDS

R8: SOUTHERN

Baustian, J. J., Mendelssohn, I. A., and Hester, M. W. (2012). Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Global Change Biology, 18(11), 3377-3382. doi:10.1111/j.1365-2486.2012.02792.x

"Our results [from a Louisiana salt marsh] corroborate those of Morris (2007), who found vegetation to be the driving force behind sediment trapping in a South Carolina salt marsh. This is based on the principle that vegetation slows down the movement of water on the marsh's surface, allowing suspended sediment in the overlying water to settle (Moller et al., 1999; Yang, 1999; Leonard & Croft, 2006). An increase in flooding duration should amplify this effect due to an increase in time for sediment deposition to occur (Morris, 2007). Also, greater flooding depth allows for greater sediment volume and higher sedimentation (Harter and Mitsch 2003)."

"A recent estimate of RSLR [realative sea level rise] near our study area [a Louisiana salt marsh] was 4.1 mm yr−1 between 1993 and 2006 (Morton & Bernier, 2010), with a longer term average of 9.24 mm yr−1 from 1947 to 2006 (NOAA, 2010). Under these rates of RSLR, the Planted plots [marsh areas in Louisiana affected by a sudden dieback event in 1999/2000 and planted with Spartina alterniflora in 2006] would still be able to keep pace with sea level rise, whereas the sustainability of the Reference sites [areas unaffected by the dieback event in Louisiana] would depend on their reaction to the increases in flooding. If the Reference sites react to greater flooding by increasing productivity and vertical growth (Morris et al., 2002), then the Reference marshes may survive elevated RSLR rates as well. However, if the physiological stress associated with increases in flooding overwhelms the vegetation, then marsh sustainability in the face of rising sea levels is unlikely."

Day, J. W., Christian, R. R., Boesch, D. M., Yбcaz-Arancibia, A., Morris, J., Twilley, R. R., … & Stevenson, C. (2008). Consequences of Climate Change on the Ecogeomorphology of Coastal Wetlands. Estuaries and Coasts, 31, 477-491. doi: 10.1007/s12237-008-9047-

"Not all estuarine wetlands are equally vulnerable to the consequences of climate change. For example, the northern Gulf of Mexico is particularly vulnerable to sea level rise, flooding, and erosion from storms (Hammar- Klose and Thieler 2001; Fig. 2), and the southern Gulf of Mexico is much more vulnerable to sea level rise than the Caribbean portion of Mexico (Ortiz-Perez et al. 2008)."

Kirwan, M. L., Guntenspergen, G. R., D'Alpaos, A., Morris, J. T., Mudd, S. M., & Temmerman, S. (2010). Limits on the adaptability of coastal marshes to rising sea level. Geophysical Research Letters, 37(23). doi:10.1029/2010GL045489

"Finally, our models [using simulations from five numerical models to quantify the conditions under which ecogeomorphic feedbacks allow coastal wetlands to adapt to projected changes in sea level] suggest that salt marshes are a stable ecosystem at more intermediate rates of SLR [sea level rise] and sediment concentrations. For suspended sediment concentrations greater than 20 mg/L and tidal ranges greater than 1m, conditions typical of many estuaries in the southeastern United States and western Europe [French, 2006], our models predict a critical SLR rate of about 10 mm/yr. This model observation is consistent with the broad, expansive marshes common in the southeastern United States and the rapidly accreting marshes in western Europe, where historical SLR rates are generally about 3 mm/yr."

Kirwan, M. & Temmerman, S. (2009). Coastal marsh response to historical and future sea-level acceleration. Quaternary Ice Sheet-Ocean Interactions and Landscape Responses. 28, 17-18, 1801-1808. doi:10.1016/j.quascirev.2009.02.022

"Our model experiments [which help determine the direct influence of sea level on marsh survival in salt and tidal marshes of South Carolina and the Netherlands] suggest that it takes on the order of 100 years for a marsh to adjust to an increase in the rate of sea-level rise (Fig. 1), and that during a continuous sea-level acceleration, accretion rates lag sea-level rise rates by about 20–30 years (Fig. 3b)."

Paerl, H. W., Rossignol, K. L., Hall, S. N., Peierls, B. L., and Wetz, M. S. (2010). Phytoplankton community indicators of short- and long-term ecological change in the anthropogenically and climatically impacted Neuse River Estuary, North Carolina, USA. Estuaries and Coasts, 33(2), 485-497. doi:10.1007/s12237-009-9137-0

"Hydrologic variability occurred [in the Neuse River Estuary, North Carolina] over a wide range of temporal scales. Multi-annual, seasonal, and event-induced changes in river discharge, and the resulting changes in estuarine flushing and water residence times, affected total phytoplankton biomass and differentially affected specific phytoplankton groups as a function of their contrasting growth characteristics (Figs. 1 and 5)."

"Zeaxanthin concentrations, which primarily represent cyanobacteria, exhibited seasonal fluctuations [in the Neuse River Estuary, North Carolina], with minimal concentrations during colder winter months and maximal concentrations in warmer months (Fig. 7). A multiple regression analysis of zeaxanthin on temperature, river discharge, salinity, and DIN [dissolved inorganic nitrogen] loading showed a strong positive relationship between zeaxanthin and temperature ($p=3.4\times10-13$) and a weaker negative relationship with riverine discharge ($p=4.7\times10-3$)."

"Episodic events, such as abnormal periods of high or low freshwater discharge as well as storms, can represent important drivers of phytoplankton dynamics in estuarine ecosystems. The wet spring of 2003 is an example of how short-term hydrologic forcing can profoundly affect phytoplankton biomass and community composition in the NRE [Neuse River Estuary, North Carolina]. Photopigment concentrations began to increase soon after large freshwater pulses in the spring of 2003 and continued with a rainy summer (see Figs. 1, 6, and 7)."

"The most recent decade of climatically influenced phytoplankton community data has shown highly significant shifts in composition and biomass, rivaling what was observed during the more anthropogenically influenced period of the 1970s–early 1990s, where increases in nutrient loading were the key drivers of ecological change in this community [in the Neuse River Estuary, North Carolina]. While anthropogenic stressors (nutrient over-enrichment and sedimentation) still play a fundamentally important role in shaping phytoplankton production and compositional dynamics, the impacts of these stressors have been modified by climatic changes."

"Of additional concern is how potential shifts in phytoplankton community structure due to climatic changes alter habitat range. Using geographically diverse evidence, Paerl and Huisman (2008) proposed that cyanobacterial habitats have expanded northward in the Northern hemisphere due to global warming. In addition, it was shown that longer optimal growing seasons worldwide have enabled cyanobacterial species to be more competitive in a variety of habitats, including estuaries. This was attributed to the fact that, as a taxonomic group, cyanobacteria prefer higher temperatures for optimal growth than other taxa (i.e., diatoms, chlorophytes)."

Woodrey, M. S., Rush, S. A., Cherry, J. A., Nuse, B. L., Cooper, R. J., & Lehmicke, A. J. J. (2012). Understanding the Potential Impacts of Global Climate Change on Marsh Birds in the Gulf of Mexico Region. Wetlands, 32(1), 35-49. doi:10.1007/s13157-011-0264-6

"With SLR [sea level rise], depth and duration of coastal flooding are likely to increase [in the northern Gulf of Mexico], thereby altering the extent of saltwater exposure, habitat connectivity, and nutrient and sediment subsidies to coastal marshes. Salinity and flooding represent two primary physiological stressors of coastal wetland plants (Baldwin et al. 1996; Baldwin and Mendelssohn 1998), and thus, have the potential to drive changes in plant production and community composition. For instance, changes in salinity may favor C4 graminoids such as Spartina alterniflora and S. patens over C3 species like Schoenoplectus americanus and Juncus roemerianus. However, these C3 species may be better able to tolerate flooding under certain circumstances, and often experience increased primary production or water use efficiency in response to another climate driver, elevated carbon dioxide (CO2) (Curtis et al. 1989, 1990)."

SOUTH ATLANTIC

Carr, J. A., D'Odorico, P., McGlathery, K. J., & Wiberg, P. L. (2012). Modeling the effects of climate change on eelgrass stability and resilience: future scenarios and leading indicators of collapse. Marine Ecology Progress Series, 448, 289-301. doi: 10.3354/meps09556

"[Coastal] Meadows [in Hog Island Bay, Virginia] within the bistable range from 1.6 to 1.8 m MSL [mean sea level] exhibited limited resilience such that a sequence of disturbances (years with poor light and temperature conditions) could shift a meadow into the attraction domain of the bare sediment state (Fig. 2). Thus, simulations aimed at exploring the effect of sea level rise and increasing water temperatures were expected to show that meadows initialized at 1.5 and 1.6 m MSL remain dense under an increase in MSL of 4 mm yr−1 for 30 yr (total increase of 0.12 m), whereas meadows initiated at 1.8 m MSL or deeper should show slow decline in shoot density."

"Similarly, across all water depths [of coastal meadows in Hog Island Bay, Virginia] an increase in water temperature was expected to decrease net productivity of the eelgrass [Zostera marina] meadows with catastrophic losses when summer temperature exceeded 30°C for weeks at a time."

"Increases in water temperature (Moore & Jarvis 2008) effectively increase the frequency of disturbances (e.g. years with poor growing conditions), as more years exhibit extended periods of high summer temperatures (Table 4) associated with significant [eelgrass, Zostera marina] die-offs [at Hog Island Bay, Virginia]."

"The results indicate that while [coastal eelgrass, Zostera marina] meadows shallower than 1.6 m MSL [mean sea level] for our study site [in Hog Island Bay, Virginia] are currently stable and can be expected to remain within the stable light growth environment, the onset of increased water temperatures is likely to cause significant, but reversible collapse of these meadows. The expected effect of increased sea level is to push a meadow initially located within the attraction domain of a dense meadow towards the bistable depth range where the meadows will possess limited resilience."

"Our results indicate that extant eelgrass [Zostera marina] meadows in the VCR LTER [Virginia Coast Reserve Long Term Ecological Research site] are unlikely to fail due to increases in sea-level rise alone, as rhizome branching rates and seed dispersal should be able to maintain migration of the meadows toward shallower waters. However, the results also indicate that the eelgrass meadows of the VCR LTER are likely to undergo severe die-offs due to extended summer periods with increased water temperatures."

Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., ... & Machmuller, M. (2008). Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. Frontiers in Ecology and the Environment, 7(2), 73-78. doi: 10.1890/070219

"In some coastal areas, rising sea level may result in tidal marsh submergence [as was observed by Moorhead and Brinson (1995) in the lower coastal plain of North Carolina] and habitat migration, as salt marshes transgress landward and replace tidal freshwater and brackish marshes (Park et al. 1991). Declining tidal marsh area and habitat conversion may lead to changes in delivery of ecosystem services provided by these wetlands."

"Overall, [between 1999 and 2100 in response to a 52-cm increase in sea level along the Georgia coast] there is a net loss of tidal marsh habitat (184 km2), as salt marsh habitat declines by 226 km2, while brackish marsh and tidal freshwater marsh increase by 41 km2 and 1 km2, respectively (Table 2)."

"An 82-cm increase in sea level, predicted by the A1B [IPCC climate] maximum scenario, leads to even greater reduction in tidal marsh area and delivery of ecosystem services [along the Georgia coast between 1999 and 2100]. Based on this scenario, tidal freshwater, brackish, and salt marshes decline by 39%, 1%, and 45%, respectively, by 2100"

"Under AIB [IPCC climate] mean and maximum SLR [sea level rise] scenarios, cumulative tidal marsh area declines by 11% and 33%, respectively [to increases in sea level rise of 52 and 82 cm], while cumulative reduction in delivery of ecosystem services is 4-28% lower (Table 2)."

"Although our simulation focuses on the Georgia coast, we speculate that, elsewhere, tidal freshwater and salt marshes will also be most affected by SLR [sea level rise]. Tidal freshwater marshes will decline in area as saltwater intrudes and brackish marshes migrate inland to replace them. Salt marshes will convert to open water because their low rate of vertical accretion relative to brackish and tidal freshwater marshes (Craft 2007) may prevent them from keeping pace with accelerated SLR."

Erwin, K. L. (2009). Wetlands and global climate change: the role of wetland restoration in a changing world. Wetlands Ecology and Management, 17(1), 71-84. doi:10.1007/s11273-008-9119-1

"Tropical species are living at the edge of their upper physiological limits of salinity (Walker 1985; Walker et al. 1988) and temperature (Zieman 1975; Koch et al. 2007), so further increases in salinity as a result of climate change and freshwater extraction may have significant consequences for tropical seagrasses particularly in estuaries with restricted circulation and high rates of evaporation such as Shark Bay, Baffin Bay and Florida Bay in the USA (Koch et al. 2007)."

Morris, J. T., Sundareshwar, P. V., Nietch, C. T., Kjerfve, B., & Cahoon, D. R. (2002). Responses of coastal wetlands to rising sea level. Ecology, 83(10), 2869-2877. doi: 10.1890/0012-9658(2002)083[2869:ROCWTR]2.0.CO;2

"The current equilibrium depth in regions of high RSLR [relative sea level rise] could be superoptimal (suboptimal elevation) for the marsh vegetation, which would be evidence for an unstable and deteriorating marsh community where even high rates of primary production would not necessarily ensure marsh stability. Conversely, marsh communities situated at less than optimum depths are predicted to be stable against variations in MSL [mean sea level] (Fig. 5). Our findings [using model predictions for Goat Island within North Inlet estuary, a South Carolina salt marsh] indicate that in areas of meso-tidal range and high sediment loadings, coastal wetlands could be stable against a RSLR as great as ~1.2 cm/yr, assuming a monotonic rise in MSL. However, MSL displays a number of long-period cycles and interannual variability (Fig. 1) which, when superimposed on a long-term rate of 1.2 cm/yr, would exceed the limit during ascending phases of the cycle."

"In conclusion, our model [applied to Goat Island within North Inlet estuary, a South Carolina salt marsh] demonstrates the counterintuitive result that a salt marsh at its maximum productivity (i.e., at its optimum elevation and rate of RSLR [relative sea level rise]) is not the most stable. Rather, a less productive marsh situated above its optimum elevation should be more stable because it will tolerate a higher RSLR and is less vulnerable to the variability in MSL [mean sea level]."

Poulter, B., Feldman, R. L., Brinson, M. M., Horton, B. P., Orbach, M. K., Pearsall, S. H., ... & Whitehead, J. C. (2009). Sea-level rise research and dialogue in North Carolina: Creating windows for policy change. Ocean & Coastal Management, 52(3), 147-153. doi:10.1016/j.ocecoaman.2008.09.010

"Modeling future wetland loss due to SLR [sea level rise] is sensitive to estimates of vertical accretion rates and sediment accumulation (raising surface elevation and partially mitigating inundation [Morris et al. 2002]). Recent rates of accretion in North Carolina's wetland forests are 0.26–1.0 mm yr_1 [Craft et al. 1993], while in some marshes the rates have been up to 2.0–3.0 mm yr_1 [Craft & Richardson 1998]. Vertical accretion is primarily limited by sediment transport to wetland surfaces in the Albemarle-Pamlico Sound [Wells & Kim 1989]. Recent observations of interior pond development also suggest accretion may be limited by sediment supply [Poulter 2005]. However, management practices, especially the reintroduction of fire, can strongly influence above ground organic matter accumulation and possible sediment retention [Hackney & de la Cruz 1981]."

Voss, C., Christian, R., & Morris, J. (2012). Marsh macrophyte responses to inundation anticipate impacts of sea-level rise and indicate ongoing drowning of North Carolina marshes. Marine Biology, 1-14. doi:10.1007/s00227-012-2076-5

"Employing experimental planters [in coastal North Carolina], we demonstrated remarkably similar patterns of how production metrics respond to varying inundation for two dominant macrophytes, Spartina [cordgrass] and Juncus [rushes], and for Juncus across two sites differing in inundation regime, permitting important conclusions about resilience of the coastal marsh habitat to sea level rise. Metrics of change over the growing season in total and live above-ground biomass and in shoot density all exhibited sustained and statistically significant declines with increasing inundation beyond an apparent optimal range of inundation levels (Figs. 3a–c, 4a–f; Table 2)."

"The Morris et al. (2002) model reasonably assumes that the relationship between inundation and production of a marsh macrophyte [such as Spartina (cordgrass) and Juncus (rushes) in coastal North Carolina] follows a parabolic curve in which production decreases on either side of peak production over some optimal range of inundations. If a given marsh is positioned on the ascending (left-hand) side of the curve, where inundation is below optimal levels, then rising sea levels will increase inundation, resulting in enhanced above-ground and below-ground production. Increasing below-ground production causes accretion directly by subsurface addition of organic material (bioaccumulation), while higher above-ground macrophyte biomass leads to greater baffling of tidal water flows, thereby inducing greater sedimentation. Hence, the enhancement of macrophyte production as water levels rise within this region of the parabola represents a compensatory feedback process that could allow the marsh surface accretion to equilibrate with rising sea level (Morris et al. 2002)."

"Although these feedback processes [the enhancement of macrophyte production as water levels rise] elevate the sediment surface as sea level rises, whether the marsh surface is elevated rapidly enough to match the growing rates sea-level rise and avoid ultimate physiological drowning of the macrophytes [such as Spartina (cordgrass) and Juncus (rushes) in coastal North Carolina] is unclear. Furthermore, the rate of sedimentation onto the marsh surface is also affected by other factors, such as sediment concentrations in the water column, duration and frequency of tidal flooding, and volume of water in the tidal prism."

SOUTH CENTRAL

Baustian, J. J., Mendelssohn, I. A., and Hester, M. W. (2012). Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Global Change Biology, 18(11), 3377-3382. doi:10.1111/j.1365-2486.2012.02792.x

"For marshes to survive future sea-level increases, they must be able to grow vertically at a rate great enough to offset the rate of sea level rise. Currently, the IPCC estimates eustatic sea-level rise to be 3.1 mm yr−1 (IPCC, 2007). This would indicate that the Reference plots [areas unaffected by a sudden marsh dieback event 1999/2000 in Louisiana] with an elevation change rate of 3.5 mm yr−1 would just be keeping pace with sea-level rise, but the Planted plots [marsh areas affected by the dieback event and planted with Spartina alterniflora in 2006] with a 13.3 mm yr−1 elevation increase would keep pace and even continue to gain elevation. However, the high elevation change rates in the Planted plots may not be sustainable over time as nutrients in the soil become depleted, and the marsh surface nears the upper end of the tidal prism."

Chavez-Ramirez, F., Wehtje, W., (2011). Potential impact of climate change scenarios on whooping crane life history. Wetlands, online first, 1-10.

"In a study of wetland and aquatic habitats on Texas barrier islands, White et al. (2006) found that the area of Matagorda Island, Matagorda Peninsula, and the Colorado River Delta had lost 1,842 ha of tidal flats between 1950s and 2001. Most of this habitat turned into seagrass beds, mangroves, or marsh vegetation (White et al. 2006). However, at water levels >1 m, seagrass beds become unvegetated as insufficient light penetrates to sustain this vegetation type (Montagna et al. 2007). We can expect existing saltmarsh habitats to experience significant changes in their relative abundance."

Erwin, K. L. (2009). Wetlands and global climate change: the role of wetland restoration in a changing world. Wetlands Ecology and Management, 17(1), 71-84. doi:10.1007/s11273-008-9119-1

"Increased temperature may interact with other stressors to damage coastal marshes. For example, during the spring to fall period of 2000 in the Mississippi delta, there were large areas of salt marsh that were stressed and dying (Day et al. 2005). This appears to be the result of combination of effects related to a strong La Niña event, which resulted in sustained low water levels, prolonged and extreme drought, and high air temperatures. This combination of factors apparently raised soil salinities to stressful and even toxic levels."

Purcell, K. M., Hitch, A., Martin, S., Klerks, P. L., and Leberg, P. L. (2012). The role of genetic structure in the adaptive divergence of populations experiencing saltwater intrusion due to relative sea-level rise. Journal of Evolutionary Biology, 25(12), 2623-2632. doi:10.1111/jeb.12016

"It is well established that the frequency of storm events and large storm-driven tides is increasing (Nicholls et al., 2007) and will continue to enhance saltwater intrusion into coastal marshes. Our results [from a Louisiana salt marsh] suggest that the adaptation for increased salinity tolerance reported by Purcell et al., (2008) represents an example of adaptive divergence in the face of relatively high gene flow [between brackish marshes in different regions]."

GENERAL IMPACTS

SOUTH ATLANTIC

Brittain, R. A., & Craft, C. B. (2012). Effects of Sea-Level Rise and Anthropogenic Development on Priority Bird Species Habitats in Coastal Georgia, USA. Environmental Management, 49(2), 473-482. doi:10.1007/s00267-011-9761-x

"In 2100, accelerated SLR [sea level rise] was predicted [using SLAMM5 (Sea-level Rise Affecting Marshes Model, version 5] to cause greater proportional losses of salt marsh than tidal forest [along the Georgia coast] (Fig. 2). Loss of salt marsh and tidal forest varied from 20–23%, respectively, under the A1B mean scenario, to 45–35% under the A1B maximum scenario."

Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., ... & Machmuller, M. (2008). Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. Frontiers in Ecology and the Environment, 7(2), 73-78. doi: 10.1890/070219

"In summary, our results suggest that salt, brackish, and tidal freshwater marshes of the Georgia coast will respond differently to a 52-cm increase in SLR [sea level rise], with fresh and salt marshes suffering greater losses than brackish marshes. Because brackish marshes provide ecosystem services at a rate greater than that of other marsh types, and because brackish marshes are predicted to undergo less precipitous declines in area than other marsh types, the predicted loss of ecosystem services along the Georgia coast is less than would be forecast based solely on losses in total marsh area."

Poulter, B., Feldman, R. L., Brinson, M. M., Horton, B. P., Orbach, M. K., Pearsall, S. H., ... & Whitehead, J. C. (2009). Sea-level rise research and dialogue in North Carolina: Creating windows for policy change. Ocean & Coastal Management, 52(3), 147-153. doi:10.1016/j.ocecoaman.2008.09.010

"While dead and dying coastal forests have been observed for some time [Brinson et al. 1985, 1995], only recently did aerial photograph analysis quantify the rate of overland migration of wetland habitat [Poulter 2005]. Inland coastal tree-line migration rates [in coastal North Carolina] were 1–12 m yr_1, depending on the rate of adjacent shoreline erosion and disturbance history [Poulter 2005]. Marsh habitat loss from erosion was generally mitigated by newly formed marsh further inland (replacing forest habitat), but forest formation was limited due to more intensive land-use activities in uplands [Poulter 2005]."

Ross, M. S., O'Brien, J. J., Ford, R. G., Zhang, K., & Morkill, A. (2009). Disturbance and the rising tide: The challenge of biodiversity management on low-island ecosystems. Frontiers in Ecology and the Environment, 7(9), 471-478. doi:10.1890/070221

"With the arrival of an active hurricane period due to decadal-scale variability (Goldenberg et al. 2001), the interaction between sea-level rise and storm surge will soon reach a tipping point with respect to the maintenance of local freshwater ecosystems [in the Florida Keys]. Possible acceleration in sealevel rise (Church and White 2006) and increase in hurricane intensity (Webster et al. 2005) due to global warming could bring this tipping point closer."

Ross, M. S., O'Brien, J. J., and da Silveira Lobo Sternberg, L. (1994). Sea-Level rise and the reduction in pine forests in the Florida keys. Ecological Applications, 4(1), 144+. doi:10.2307/1942124

"The physical effects of sea-level rise on terrestrial environments of the Florida Keys are likely to include changes in the position of the water table, the salinity at its surface, and the salinity of the soil solution. Our vegetation analyses [of 16 plant communities on Sugarloaf and Big Pine Keys, Florida] (Fig. 5) indicate that these three factors are very closely correlated with plant community composition and structure, and that they vary together over the landscape as a whole. Their spatial covariation is indicative of strong functional interdependence."

INTERACTIONS WITH OTHER FACTORS

SOUTH ATLANTIC

Henman, J. and Poulter, B. (2008). Inundation of freshwater peatlands by sea level rise: Uncertainty and potential carbon cycle feedbacks. Journal of Geophysical Research, 113(G1), G01011+. doi:10.1029/2006jg000395

"As expected, the range of uncertainty for total carbon emitted to the atmosphere from vegetation and peat degradation [in the Albemarle Peninsula area, North Carolina] was high, and ranged from 4.7 TgC to 128.0 TgC depending on assumptions regarding the sea level rise scenario and the fate of inundated peat entering the aquatic system (Table 5)."

"While the loss of saline wetlands [in the Albemarle Peninsula area, North Carolina] will be mitigated to some extent by internal feedback processes specific to tidal marshes [Morris et al., 2002] the combination of carbon fluxes from saline, freshwater, and low-lying terrestrial ecosystems inundated by sea level rise is likely to be globally significant."

Ross, M. S., O'Brien, J. J., Ford, R. G., Zhang, K., & Morkill, A. (2009). Disturbance and the rising tide: The challenge of biodiversity management on low-island ecosystems. Frontiers in Ecology and the Environment, 7(9), 471-478. doi:10.1890/070221

"Sea-level rise has certainly reduced fire frequency over millennia by fragmenting a continuous landmass and inhibiting fire spread from island to island [in the Florida Keys]. Moreover, within islands, the landscape has evolved into a patchwork of flammable uplands embedded within a relatively fire-resistant swamp matrix. Even within the upland patches, minor depressions intersect the shallow water table, raising fuel moisture, reducing fire intensity, and promoting hardwood shrub invasion."

"When pines [Pinus spp.] are a substantial component of the uplands in coastal areas, changes in fire regime can accelerate the impact of sea-level rise and result in a loss of fire-dependent ecosystems (eg Blackwater NWR on the Delmarva Peninsula [Kirwan et al. 2007], Swanquarter NWR in North Carolina [Poulter 2005])."

SEA LEVEL RISE

R8: SOUTHERN

Biasutti, M., Sobel, A. H., Camargo, S. J., & Creyts, T. T. (2011) Projected changes in the physical climate of the Gulf Coast and Caribbean. Climatic Change, early online, 1-27. doi:10.1007/s10584-011-0254-y

"It is clear from the correspondence between the spatial patterns of precipitation change and SST [sea surface temperature] change that the two are related. Precipitation is projected to increase strongly over the near-equatorial regions of the east Pacific and Atlantic in which SST rises the most, and to decrease over the band of minimum increase, which includes most of the Caribbean and Gulf."

"Globally averaged sea level rises by an amount of water equal to the volume of ice above an equivalent sea level. However, meltwater from rapid retreats is not distributed equally across the globe. Large changes in ice volume in Antarctica, for example, yield sea level changes 15– 30% higher than the global average for the Gulf of Mexico and Caribbean (Mitrovica et al. 2009)."

"Besides direct inundation, sea level rise increases the risk to coastal areas from storm surge associated with tropical cyclones (even if the risk that a storm of a given intensity will strike does not increase)."

Cruise, J. F., Limaye, A. S., & Al-Abed, N. (1999). Assessment of impacts of climate change on water quality in the Southeastern United States. Journal of the American Water Resources Association, 1530-1550.

"First, a number of the basins that exhibit current problems are located along the Gulf Coast where they will be significantly impacted by sea level rise during the next century as well as the decrease in fresh water inflow predicted by the Hadley Center model. If the model projections are correct, these basins and estuaries in Louisiana, Mississippi, Alabama, and Florida should see significant increases in salinity levels associated with saltwater intrusion as well as a degraded quality of the inflows that do occur. Based on these observations it is quite possible that many of these areas could exhibit brackish and eutrophic conditions throughout much of the year. These conditions may negatively impact the aquaculture and tourism industries."

Karl, T. R., Melillo, J. M., & Peterson, T. C. (2009). Global climate change impacts in the United States. New York, NY, USA: Cambridge University Press.

"Even with no increase in hurricane intensity, coastal inundation and shoreline retreat would increase as sea-level rise accelerates, which is one of the most certain and most costly consequences of a warming climate (Field et al., 2007)."

Langevin, C. D. and Zygnerski, M. (2012). Effect of sea-level rise on salt water intrusion near a coastal well field in southeastern Florida. Ground Water, online first. doi:10.1111/j.1745-6584.2012.01008.x

"As shown by Werner and Simmons (2009), [coastal aquifer] systems that are head controlled are more susceptible to salt water intrusion caused by sea-level rise than those that are flux controlled. For confined aquifers that are flux controlled, sea-level rise may not have any effect on salt water intrusion (Chang et al. 2011)."

Williams, K., Ewel, K. C., Stumpf, R. P., Putz, F. E., & Workman, T. W. (1999). Sea-level rise and coastal forest retreat on the west coast of Florida, USA. Ecology, 80(6), 245-263. doi: 10.1890/0012-9658(1999)080[2045:SLRACF]2.0.CO;2

"Whereas failure of tree regeneration in the Mississippi Delta has been linked to rising water levels and increased flooding stress (Baumann 1987, DeLaune et al. 1987, Conner and Day 1988), and failure of Sabal regeneration on sandy coasts has been attributed to erosion (Brown 1973), failure of tree regeneration in this system [on the west coast of Florida] was associated with exposure to tidal water and increasing salinity of the groundwater."

Daniels, R. C., White, T. W., & Chapman, K. K. (1993). Sea-level rise: destruction of threatened and endangered species habitat in South Carolina. Environmental Management, 17(3), 373-385. doi:10.1007/bf02394680

"Cape Romain's barrier islands will suffer from the effects of coastal erosion in addition to inundation as sea levels rise. The destruction of these barrier islands will be accelerated by the lack of a suitable supply of medium-grained sands to maintain the barrier islands in the Cape Romain area [in South Carolina]. This is primarily due to the southward direction of the longshore currents. These currents contain fine sand, mud, and silt from the South and North Santee Rivers. This sediment, although suitable for marsh accretion in coastal embayments, is easily mobilized and does not provide suitable material to allow the barrier islands, such as Cape Island, to roll over (through storm overwash) and move landward."

"Thus, the barrier islands [in the Cape Romain area, South Carolina] may become fragmented as a result of subsidence and sea-level rise. The destruction of these barrier islands will allow increased wave energies to enter and attack the refuge's marsh (Figures 3A and 3B). The increase in wave action in the refuge will cause marsh materials to be resuspended and the large tide range (i.e., mean tide range is ≈1.5 m) may flush this material back out to sea, accelerating the demise of Cape Romain's marshlands."

"The Cape Romain [South Carolina] case study demonstrates the extent to which sea-level rise would affect coastal habitats that have been identified, based on the CVI [coastal vulnerability index], as being at risk to future increases in sea level. The low sea-level rise scenario predicts a 31-cm rise in sea level and 22 cm of subsidence by the year 2100. This 53-cm is very close to, or exceeds, the estimated vertical accretion rate of the marsh (i.e., ~5 mm/yr), and as a result, may inundate 51.4% of Cape Romain."

Desantis, L. R. G., Bhotika, S., Williams, K., and Putz, F. E. (2007). Sea-level rise and drought interactions accelerate forest decline on the gulf coast of florida, USA. Global Change Biology, 13(11), 2349-2360. doi:10.1111/j.1365-2486.2007.01440.x

"Sea-level rose in Cedar Key, approximately 30 km northwest of Waccasassa Bay [Florida], at an average rate of 2.4 mm yr-1 from 1939 to 2005 (NOAA: Center for Operational Oceanographic Products and Services, 2006; Fig. 2). During our study period, MHHW [mean higher high water] actually declined by approximately 3 mm yr-1 from 1992 to 2000 and then increased at a rate of about 17 mm yr-1 from 2000 to 2005 (Fig. 2)."

Gedan, K. B., Altieri, A. H., & Bertness, M. D. (2011). Uncertain future of New England salt marshes. Marine Ecology Progress Series. 434. 229-237. doi: 10.3354/meps09084

"Using current IPCC sea level rise scenarios and a 'sea level affects marshes model' (SLAMM) of salt marsh accretion, Craft et al. (2009) predicted that 20 to 45% of salt marsh area in a Georgia estuary will be converted to low salinity marsh, tidal flat, or open water by 2100."

Guha, H. & Panday, S. (2012). Impact of sea level rise on groundwater salinity in a coastal community of South Florida. Journal of the American Water Resources Association, 1-19. doi:10.1111/j.1752-1688.2011.00630.x

"Three separate sea level rise increase simulations were conducted by increasing sea level to 0.6, 0.9, and 1.22 m. Results of the simulation clearly show significant increase in groundwater levels and relative chloride concentrations with increase in sea level [in South Florida] (Figures 16a and 16b). In well F-319 an increase of sea level from 0.34 to 0.6, 0.9, and 1.22 m results in an average of 4, 9, and 15% increase in groundwater elevation respectively. Similarly, in well G-3229 the average relative chloride concentrations would increase by 103, 310, and 639% respectively. The increase in groundwater elevations and salinity concentrations varies from location of the wells and its proximity to the coast."

Henman, J. and Poulter, B. (2008). Inundation of freshwater peatlands by sea level rise: Uncertainty and potential carbon cycle feedbacks. Journal of Geophysical Research, 113(G1), G01011+. doi:10.1029/2006jg000395

"Inundation from sea level rise [in the Albemarle Peninsula area, North Carolina] ranged from 1260 km2 under the B1 [climate] scenario to 3020 km2 under the A1FI with breach [1.38m sea level projection with collapse of barrier islands] scenario (Table 1). The eastern side of the Peninsula was most vulnerable to sea level inundation (Figure 3) with some scattered, higher-elevation peat deposits remaining in southern Dare County."

Kemp, A. C., Horton, B. P., Culver, S. J., Corbett, D. R., van de Plassche, O., Gehrels, W. R., … & Parnell, A. C. (2009). Timing and magnitude of recent accelerated sea-level rise (North Carolina, United States). Geology, 37(11), 1035-1038. doi:10.1130/G30352A.1

"The measured rate of relative sea-level rise in North Carolina during the twentieth century was 3.0–3.3 mm/a, consisting of a background rate of ~1 mm/a, plus an abrupt increase of 2.2 mm/a, which began between A.D. 1879 and 1915. This acceleration is broadly synchronous with other studies from the Atlantic coast. The magnitude of the acceleration at both sites is larger than at sites farther north along the U.S. and Canadian Atlantic coast and may be indicative of a latitudinal trend."

"Using Bayesian change point linear regression (Carlin et al., 1992), we identify a 2.2 mm/a increase in the rate of sea-level rise in excess of the background rate at Sand Point and Tump Point [North Carolina] that began between A.D. 1879 and 1915."

"Comparison of the Sand Point and Tump Point [North Carolina] records (2.2 mm/a above background rate) with these other salt-marsh studies suggests that the magnitude of accelerated RSLR [relative sea-level rise] may exhibit a latitudinal trend. Tide-gauge records support this inference (e.g., Douglas, 1991; Peltier, 2001; Wake et al., 2006); gauges north of New York City show rates (average 1.5 mm/a) lower than those to the south (average 2.5 mm/a; Douglas, 1991). Wake et al. (2006) attributed this latitudinal variation to ocean thermal expansion. In contrast, this latitudinal trend could also be a fingerprint of mass loss from the Greenland Ice Sheet because water migrates away from the ice sheet as its gravitational attraction is diminished (Conrad and Hager, 1997; Mitrovica et al., 2001)."

Langevin, C. D. and Zygnerski, M. (2012). Effect of sea-level rise on salt water intrusion near a coastal well field in southeastern Florida. Ground Water, online first. doi:10.1111/j.1745-6584.2012.01008.x

"Results of a numerical modeling analysis suggest that groundwater withdrawals [from a shallow coastal aquifer system in the Pompano Beach well-field and southeastern Florida area] were the dominant cause of a multi-decade salt water intrusion event, and that historical sea-level rise (about 25 cm for the simulation period) contributed to the extent of the intrusion by about 1 km."

Poulter, B., Goodall, J. L., & Halpin, P. N. (2008). Applications of network analysis for adaptive management of artificial drainage systems in landscapes vulnerable to sea level rise. Journal of Hydrology, 357(3), 207-217. doi:10.1016/j.jhydrol.2008.05.022

"Extensive artificial drainage networks [such as those in Dare County in northeastern North Carolina] have increased the vulnerability of low-elevation coastal landscapes to a multitude of direct and indirect impacts associated with sea level rise. Drainage networks were originally built to drain wetlands and lower water tables to encourage human settlement, agricultural use or forestry (Holden et al., 2004; Lilly, 1980). These drainage networks now have the potential to act as conduits that contribute to inland flooding during storms and salt-intrusion during episodes of sea level rise."

Poulter, B., Feldman, R. L., Brinson, M. M., Horton, B. P., Orbach, M. K., Pearsall, S. H., ... & Whitehead, J. C. (2009). Sea-level rise research and dialogue in North Carolina: Creating windows for policy change. Ocean & Coastal Management, 52(3), 147-153. doi:10.1016/j.ocecoaman.2008.09.010

"The first landscape-scale assessment of North Carolina's vulnerability to SLR [sea level rise], by Moorhead and Brinson [1995], estimated that there were 2800 km2 of land below 1.5 m elevation in northeastern North Carolina alone. This was followed by a U.S. Environmental Protection Agency (EPA) national assessment that projected a total of approximately 5800 km2 of land below 1.5 m for the entire state, using coarse resolution data with a 1.5 m contour interval [Titus & Richman 2001]. Recently, as higher resolution topographic data have become available, Poulter and Halpin [2008] mapped 5300 km2 of land at or below 1.1 m using LIDAR [Light Detection and Ranging] elevation data with a vertical resolution of ±25 cm (Fig. 1). These inundation scenarios used simplified assumptions about ecological processes and the timing of physical impacts that may either mitigate or exacerbate the effects of SLR (e.g., the scenarios do not model wetland feedbacks responding to SLR)."

"Non-linear responses to climate change are anticipated for the entire Outer Banks [North Carolina] Barrier Island system [Riggs and Ames 2003]. During episodes of SLR [sea level rise], barrier islands naturally migrate landward in response to two processes. First, storms open inlets in weak barrier segments, and island width expands through the deposition of vast flood-tide deltas. Second, overwash buries the flood-tide deltas and builds barrier island elevations. Currently, these two processes are prevented or inhibited by the construction of dune ridges and roads. Consequently, erosion along both ocean and estuarine shorelines causes islands to narrow, thus increasing their vulnerability to storms and new inlet creation. Over the long term, one or more major storms could initiate a general collapse of sediment-poor barrier segments, causing major changes to the estuarine system [Riggs 2001]."

Ross, M. S., O'Brien, J. J., and da Silveira Lobo Sternberg, L. (1994). Sea-Level rise and the reduction in pine forests in the Florida keys. Ecological Applications, 4(1), 144+. doi:10.2307/1942124

"In a scenario of rising sea level [for the Florida Keys], an increase in the level of the water table would reduce freshwater recharge capacity, leading to an overall increase in groundwater salinity. In turn, higher and more saline groundwater would contribute to an increase in soil salinity through capillary wetting from beneath. The magnitude of the effect would depend on surface elevation and whether the capillary fringe rose far enough through the limestone bedrock to intersect the bottom of the soil profile."

"Whereas the presence of a freshwater lens may temporarily buffer soil and groundwater from sea-level-derived salinity changes, an increase in the frequency and extent of tidal intrusion into interior areas during storms or spring tides may accelerate the salinization process [in the Florida Keys]."

Seneviratne, S. I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., … & Zhang, X. (2012). Changes in climate extremes and their impacts on the natural physical environment. In: Field, C.B et al. (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge, UK, and New York, NY, USA: Cambridge University Press, 109-230.

"On the North American Atlantic coast, Komar and Allan (2008) found a statistically significant trend of 0.059 m yr-1 in waves exceeding 3 m during the summer months over 30 years since the mid-1970s at Charleston, South Carolina, with weaker but statistically significant trends at wave buoys further north. These trends were associated with an increase in intensity and frequency of hurricanes over this period (see Section 3.4.4). In contrast, winter waves, generated by extratropical storms, were not found to have experienced a statistically significant change."

Williams, K., Ewel, K. C., Stumpf, R. P., Putz, F. E., & Workman, T. W. (1999). Sea-level rise and coastal forest retreat on the west coast of Florida, USA. Ecology, 80(6), 245-263. doi: 10.1890/0012-9658(1999)080[2045:SLRACF]2.0.CO;2

"Mean relative sea level at Cedar Key, Florida, rose an average of 1.5 mm/yr between 1939 and 1994, a rate consistent with most estimates of global sea-level rise (Warrick and Oerlemans 1990, Davis and Mitrovica 1996). MHHW [mean higher high water for the year] rose at a higher rate (~2.8 mm/yr, Fig. 3, Stumpf and Haines 1998). Sea level and MHHW during 1991 and 1992 were the highest on record."

Xu, S., & Huang, W. (2013). Effects of sea level rise on frequency analysis of 1% annual maximum water levels in the coast of Florida. Ocean Engineering, online first, 1-7. doi: doi:10.1016/j.oceaneng.2013.01.013

"For instance, the potential influence by SLR [sea level rise] on the hurricane storm surge hazards in Sarasota County of Florida are studied by Frazier et al. (2010). The analysis shows that SLR significantly affects storm surge impacts of future land-falling hurricanes in Sarasota County. The study also demonstrates that even if hurricanes neither become more frequent nor more intense, SLR will still increase the impacts of storm surge. If hurricanes do become more frequent or more intense, there will be more potential risks associated with storm surge damage."

"The composed 100 and 200 years extreme high water elevations in the year of 2100 by accounting SLR [sea level rise] projections are higher than those without accounting for SLR impacts. At Pensacola [Florida Gulf coast] station, the 100 years extreme high water level estimated by AMWLs [annual maximum water levels] with SLR effect in 2100 is 0.19 m higher than the one estimated by that without considering SLR effect. At Fernandina [Florida Atlantic coast] Station, the difference of estimation by accounting SLR effect is 0.17 m higher, with the AMWL at 3.46 m in 2100. Therefore, for coastal flood hazard planning and coastal engineering design, the impact of sea level rise on the extreme water levels should be included. "

SOUTH CENTRAL

Blum, M. D., & Roberts, H. H. (2009). Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nature Geoscience, 2, 488-491. doi: 10.1038/NGEO553

"Previous projections of twentieth-century land-loss trends suggest submergence of 5,700 km2 of the [Mississippi] delta plain between 1950 and 2050, mostly on the Teche, St Bernard and Lafourche deltas, with 400 km2 gained through deposition in the Plaquemines- Balize and Atchafalaya-Wax Lake deltas (Barras et al. 2003) (see Supplementary Information). We project submergence to the year 2100 using conservative subsidence rates, and sea-level rise that accelerates linearly from 3 mmyr_1 in the year 2000 to 4mmyr_1 in 2100: in the absence of sediment input, land surfaces that are now below 1m in elevation will be converted to open water or marsh (Fig. 3b). Landward of the barrier-island chains of the St Bernard and Lafourche deltas, ~7000 km2 of the delta plain already lies below sea level, with estimated submergence of an extra 10,500-13,500 km2 by the year 2100 (Fig. 3c)."

"With modern sediment loads for the combined Mississippi and Atchafalaya rivers, a trapping efficiency of 40% and sea-level rise of 1mmyr_1, the creation of accommodation outpaces sediment supply and

results in a mass deficit of ~1-5 BT [billion tons] by the year 2100: even with typical late Holocene rates of sea-level rise, further land loss would be inevitable unless the trapping efficiency approaches 100%."

"With sediment loads restored to pre-dam values of 400-500MTyr_1 [for the combined Mississippi and Atchafalaya rivers], supplies would be sufficient to sustain the deltaic landscape with rates of sea-level rise of ~1mmyr_1."

Chavez-Ramirez, F., Wehtje, W., (2011). Potential impact of climate change scenarios on whooping crane life history. Wetlands, online first, 1-10.

"Rising sea levels are an ongoing concern along the Texas coast and are likely to continue into the future. Since 1948, average sea level at the Rockport tidal gauge has risen by 4.6 mm/year, due to a combination of absolute sea level rise and local land subsidence (Montagna et al. 2007; Snay et al. 2007). By combining the rate of local land subsidence with IPCC climate models, the projected relative sea-level rise at Rockport for 2000 to 2100 is estimated at 0.46 to 0.87 m (Montagna et al. 2007)."

"Sea level rise will increase the volume of the estuaries by deepening the bays and also increasing the extent of open water. This will most likely lead to an increase in estuary salinities due to increased evaporation, greater inflows of ocean water, and decreases in freshwater inflow due to predicted changes in precipitation (Montagna et al. 2007)."

"The higher sea level will reduce the relative height of the barrier islands, making them more vulnerable to overwash by tropical storms (Montagna et al. 2007)."

RESOURCE AREA (FACTOR): EXTREME WEATHER

GENERAL IMPACTS

R8: SOUTHERN

Beckage, B., Gross, L. J., & Platt, W. J. (2006). Modelling responses of pine savannas to climate change and large-scale disturbance. Applied Vegetation Science, 9, 75-82.

"These changes to the ENSO [El Niño/La Niña-Southern Oscillation] cycle will create conditions that favor less frequent large-scale fires and decreased hurricane frequency in southeastern savannas"

"Global warming is expected to affect the frequency of ENSO [El Niño/La Niña-Southern Oscillation] events, which will influence disturbance regimes in southeastern savannas."

PRECIPITATION EXTREMES

R8: SOUTHERN

Chen, G., Tian, H., Zhang, C., Liu, M., Ren, W., Zhu, W., … & Lockaby, G. (2012). Drought in the southern United States over the 20th century: variability and its impacts on terrestrial ecosystem productivity and carbon storage. Climatic Change, 114(2), 379-397. doi:10.1007/s10584-012-0410-z

"Based on SPI [standard precipitation index], we characterized drought intensity and duration in the SUS during 1895–2007. No significant changes in drought intensity and duration were found for this time period. However, we found that the areas in the SUS [southern United States] experiencing extreme high rainfall events appeared to be increasing, which might imply an increased flooding frequency."

Karl, T. R., Melillo, J. M., & Peterson, T. C. (2009). Global climate change impacts in the United States. New York, NY, USA: Cambridge University Press.

"There has been an increase in heavy downpours in many parts of the region,(Karl and Knight, 1998; Keim, 1997) while the percentage of the region experiencing moderate to severe drought increased over the past three decades."

"The area of moderate to severe spring and summer drought has increased by 12 percent and 14 percent, respectively, since the mid- 1970s. Even in the fall months, when precipitation tended to increase in most of the region, the extent of drought increased by 9 percent."

Li, W., Li, L., Fu, R., Deng, Y., & Wang, H. (2010). Changes to the north Atlantic subtropical high and its role in the intensification of summer rainfall variability in the southeastern United States. Journal of Climate, 24(5), 1499-1506.

"Our analysis of the IPCC AR4 [Assessment Report 4] models suggests that the NASH [North Atlantic Subtropical High] system will likely intensify, expand, and move farther westward in the twenty-first century with the increase of CO2, indicating increased likelihoods of both extreme rainfall events and droughts over the SE [southeastern] United States in the future."

SOUTH ATLANTIC

Golladay, S. W., Gagnon, P., Kearns, M., Battle, J. M., & Hicks, D. W. (2004). Response of freshwater mussel assemblages (Bivalvia: Unionidae) to a record drought in the Gulf Coastal Plain of southwestern Georgia. Freshwater Science, 23(3), 494-506. doi: 10.1899/0887-3593(2004)023<0494:ROFMAB>2.0.CO;2

"There is uncertainty on whether conditions that led to the late 1990s drought [experienced in the Flint River Basin of southwestern Georgia] will become more frequent as global climate change occurs. However, the potential exists for more frequent and extended droughts in the lower FRB under some global change scenarios (Hoerling and Kumar 2003)."

SOUTH CENTRAL

Biasutti, M., Sobel, A. H., Camargo, S. J., & Creyts, T. T. (2011) Projected changes in the physical climate of the Gulf Coast and Caribbean. Climatic Change, early online, 1-27. doi:10.1007/s10584-011-0254-y

"During summer and fall, the projections of the IPCC [Intergovernmental Panel on Climate Change] models for the Gulf are moderately more significant: more than 75% of the models project dry anomalies extending over Louisiana and Mississippi in summer and positive anomalies in the northern-Gulf Coast in the fall. These projections are also confirmed by the NARCCAP ensemble, which projects more extensive dry anomalies, centered over Arkansas but also covering Louisiana and Mississippi (cf. Figs. 6 and 7)."

"The regional models (Fig. 10) support the conclusion that the average intensity of precipitation will increase over all the southeastern states, and suggest that the intensification might be largest in close proximity to the Gulf coast. The projected changes in the number of consecutive dry days and the number of heavy rainy days can again be related to the mean summertime rainfall anomalies, which, in the regional models, showed dry anomalies in the west of Mississippi and wet anomalies to the east. The maximum dry spell lengthens to the west, and is uncertain to the east. The number of days with rainfall exceeding 10 mm/day increases in the east and is uncertain elsewhere. This pattern of anomalies supports the idea that changes in warm weather convection are responsible for the changes in precipitation extremes."

SEVERE STORMS

R8: SOUTHERN

Bragg, D. C., Shelton, M. G., & Zeide, B. (2003). Impacts and forest management implications of ice storms in forests in the southern United States. Forest Ecology and Management, 186, 99-123.

"Ice storms increase potential fire risk by elevating fuel loads and limiting stand access (Irland, 2000). The Mississippi Forestry Commission (1994) estimated that the 1994 ice storm increased fuel loads 3–6 times above normal. Unless salvaged, these accumulations rapidly dry and elevate fire risk until sufficiently decomposed."

"Any disturbance that causes widespread decline in forest health and creates large volumes of dead material improves the conditions for other damaging agents, including insects, disease, and fire. These secondary events may prove at least as damaging as the original ice storm by killing injured trees and healthy survivors."

"Although ice storms are unpredictable events, we can anticipate their potential impact and plan accordingly. Since the risk of ice damage in the south grows with increasing latitude, selection of species adapted to ice loads common to the region should provide a more robust stand. The practice of low-cost forestry shows promise for reducing the economic impact of catastrophic disturbances (Straka and Baker, 1991; Haight et al., 1996). Overstocked stands suffer considerably from glazing, yet well-managed, regularly thinned forests yield fast growing, healthy, and sound trees that can survive inclement weather."

McNulty, S. G. (2002). Hurricane impacts on us forest carbon sequestration. Environmental Pollution, 116, 817-824. doi:10.1016/S0269-7491(01)00242-1

"A single storm can convert the equivalent of 10% of the total annual US carbon sequestration to dead and downed biomass."

SOUTH CENTRAL

Harcombe, P. A., Hall, R. B. W., Glitzenstein, J. S., Cook, E. S., Krusic, P., Fulton, M., & Streng D. R. (1998). Chapter 5: Sensitivity of Gulf Coast Forests to Climate Change (Biological Science Report USGS/BRD/BSR-1998-0002). In G. R. Guntenspergen & B.A. Vairin (Eds.), Vulnerability of coastal wetlands in the Southeastern United States: climate change research results, 1992-97. Lafayette, LA: U.S. Department of the Interior, U.S. Geological Survey, National Wetlands Research Center: 44-66.

"Consequently, increasing frequency of large storms may maintain uncharacteristically dense shrub populations, with detrimental consequences for canopy tree regeneration. This suppression of tree regeneration, coupled with higher storm-related mortality could result in a decline in the standing biomass (i.e., the carbon storage capacity) of southern upland forests resulting in increased emissions of CO, to the atmosphere."

TEMPERATURE EXTREMES

R8: SOUTHERN

Karl, T. R., Melillo, J. M., & Peterson, T. C. (2009). Global climate change impacts in the United States. New York, NY, USA: Cambridge University Press.

"The number of freezing days in the Southeast has declined by four to seven days per year for most of the region since the mid-1970s."

Sobolowski, S. & Pavelsky, T. (2012). Evaluation of present and future North American Regional Climate Change Assessment Program (NARCCAP) regional climate simulations over the southeast United States. Journal of Geophysical Research, 117(D1), D01101+. doi: 10.1029/2011JD016430

"Maximum ~ΔT [average change in temperature] occurs in the summer with temperatures rising over 3°C over much of the Southeast [for the period 2041-2070 using North American Regional Climate Change Assessment Program (NARCCAP) simulations]. This intense warming continues into the fall and decreases slightly in the winter and spring when ~ΔT is between 1.5°C and 2°C."

SOUTH CENTRAL

Biasutti, M., Sobel, A. H., Camargo, S. J., & Creyts, T. T. (2011) Projected changes in the physical climate of the Gulf Coast and Caribbean. Climatic Change, early online, 1-27. doi:10.1007/s10584-011-0254-y

"In the Gulf, a typical winter in the last decades of this century will be as warm as the warmest winter ever recorded and the coolest summers will be as hot or hotter than any summer in the last century; in 95% of the years, summer temperatures will be unprecedented."

TROPICAL CYCLONES

R8: SOUTHERN

Karl, T. R., Melillo, J. M., & Peterson, T. C. (2009). Global climate change impacts in the United States. New York, NY, USA: Cambridge University Press.

"The destructive potential of Atlantic hurricanes has increased since 1970, correlated with an increase in sea surface temperature. A similar relationship with the frequency of landfalling hurricanes has not been established (Emanuel, 2005; Hoyos et al, 2006; Mann and Emanuel, 2006; Trenberth and Shea, 2006)."

"An increase in average summer wave heights along the U.S. Atlantic coastline since 1975 has been attributed to a progressive increase in hurricane power.(Kunkel et al., 2008; Komar and Allan, 2007)"

"The intensity of Atlantic hurricanes is likely to increase during this century with higher peak wind speeds, rainfall intensity, and storm surge height and strength.(Meehl et al., 2007; Kunkel et al., 2008)."

McNulty, S. G. (2002). Hurricane impacts on us forest carbon sequestration. Environmental Pollution, 116, 817-824. doi:10.1016/S0269-7491(01)00242-1

"Hurricanes do not immediately change the state of carbon in downed wood. However, shortly after the biomass has been uprooted or broken off, it begins to decompose. The fine, high nitrogen content leaves are first decomposed, followed by branch, stem and roots. It is the relative proportion of the downed salvaged wood to down non-salvaged wood that will determine how much of the post-hurricane debris is lost from the carbon sequestration pool."

"Given that most of the downed wood is never salvaged, the debris and litter becomes fuel for wild fires during the following years. For example, following Hurricane Hugo, forest debris was 1.5–3 m deep in many areas (Miranda, 1996). In addition to the original damage caused by the hurricane, wildfires fueled by post hurricane slash posed a real threat to surviving vegetation."

"Following a hurricane, photosynthetic capacity can be reduced by 50% which could lead to a reduced in oleoresin flow (in pines), and increased susceptibility to insect attack (Fredericksen et al., 1995)."

"Hurricanes preferentially remove the most mature vegetation, and thus allow the potentially more productive forest understory to replace the overstory."

"Tree species with a greater proportion of total carbon biomass above ground and in leaf tissue are more susceptible to uprooting (King, 1986). The two ends of the species susceptibility to hurricane damage are loblolly pine (Pinus taeda) and Baldcypress (Taxodium distichum). Mature pines have closed, compact crown far from the ground, on stems with little taper. The pines often grow on sandy soils with poorly anchored root systems. Old growth baldcypress have a highly tapered trunk, is extremely well rooted, and has an open canopy. When both these southern Florida forest types were exposed to Hurricane Andrew in 1992, the pines experienced 25–40% damage while the bald cypress was less than 10% (Davis et al., 1996)."

Shepherd, J. M., Grundstein, A., & Mote, T. L. (2007). Quantifying the contribution of tropical cyclones to extreme rainfall along the coastal southeastern United States. Geophysical Research Letters, 34(23), L23810. doi:10.1029/2007GL031694

"The apparent increase in intense hurricane activity in the Atlantic basin is receiving considerable attention. It is reasonable to ask if more intense hurricane activity manifests itself in increased precipitation totals, which may signal an accelerated water cycle and more freshwater flux to ocean basins. However, more information is still required to understand the net contribution of tropical cyclones to ocean basins. We developed the millimeter-day (MD) as a metric to quantify the contribution of TCs [tropical cyclones] to extreme rainfall events. Our results [using satellite-derived rainfall datasets from the coastal southeastern United States] revealed extreme rainfall days or ‘‘wet millimeter days (WMDs)’’ are most likely in September and October during the peak of the hurricane season. Further, we found that major hurricanes are strongly correlated with the largest magnitude WMDs (e.g. cumulative daily rainfall event) during the TC season (1998– 2006)."

"The results [using satellite-derived rainfall datasets from the coastal southeastern United States, 1998-2006] suggest that TCs [tropical cyclones] can contribute a significant portion of rainfall in an ocean basin but an increase in major TCs may be apparent in extreme daily events rather than the cumulative seasonal totals. This may mean that a trend in TC-related rainfall may not be apparent if a weaker regime of storms like tropical depressions/storms are not increasing in frequency of occurrence."

SOUTH ATLANTIC

Johnsen, K. H., Butnor, J. R., Kush, J. S., Schmidtling, R. C., & Nelson, C. D. (2009). Hurricane Katrina winds damaged longleaf pine less than loblolly pine. Southern Journal of Applied Forestry, 33(4), 178-181.

"In a study of the Hobcaw Forest in coastal South Carolina, after Hurricane Hugo, Gresham et al. (1991) reported that longleaf pine [Pinus palustris] suffered less damage than loblolly pine [Pinus taeda]. It was noted that species native to the coastal plain are possibly better adapted to the disturbance regimes found there; for example, longleaf pine, baldcypress (Taxodium distichum), and live oak (Quercus virginiana) suffered less damage than forest species with broad distribution ranges."

SOUTH CENTRAL

Johnsen, K. H., Butnor, J. R., Kush, J. S., Schmidtling, R. C., & Nelson, C. D. (2009). Hurricane Katrina winds damaged longleaf pine less than loblolly pine. Southern Journal of Applied Forestry, 33(4), 178-181.

"Mortality [from Hurricane Katrina winds in southeast Mississippi] generally increased with mean plot height, but at any given height, mortality was greatest in loblolly pine [Pinus taeda], followed by slash pine [Pinus elliotii] and lowest in longleaf pine [Pinus palustris] (Figure 3)."

"Damage to longleaf pine [Pinus palustris] from Hurricane Katrina was clearly the least severe, followed by slash [Pinus elliotii] and loblolly pines [Pinus taeda]. As this study [in southeast Mississippi] is replicated on one site, variation among neither soil conditions nor topography was responsible for differential species mortality. Other stand attributes do not appear to be responsible for the species differences."

Warner, N. N. & Tissot, P. E. (2012). Storm flooding sensitivity to sea level rise for Galveston Bay, Texas. Ocean Engineering, 44, 23-32.

"For events leading to smaller maximum water levels [in Galveston Bay, Texas] the increase is limited by a rapid rise to a 100% probability, i.e. the events are predicted to take place every year. The largest proportional increase is computed for a 1.1 m water level, which is predicted to occur 6.5 times as often in 2100. For events leading to larger surges, the relative exceedance probability ratio decreases progressively to about a factor 1.85 for the maximum water levels generated by 2008 Hurricane Ike."

"For the faster sea level rise scenario, by 2100 the maximum water level expected every year in Galveston [Bay, Texas] is greater than the water levels of all but four hurricanes from the historical record, while the return period of an event of the magnitude of Hurricane Ike is predicted to decrease to 29 years from presently 105 years. "

"By year 2100 water level exceedance probabilities [in Galveston Bay, Texas] are expected to double for the impact of the largest storms such as Hurricane Ike, but increase by a factor over six times for the impact of smaller storm surges associated locally with the impact of storms such as Hurricanes Cindy, Alicia, and Rita for the conservative scenario."

RESOURCE AREA (FACTOR): FIRE

INTERACTIONS WITH OTHER FACTORS

R8: SOUTHERN

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S.Environmental Protection Agency, 1-127.

"Some climate scenarios project less and others more precipitation for the southern United States (Bachelet et al., 2001). Even under the wetter scenarios, however, the South is projected to experience an increase in temperature-induced drought and an increase in fires (Lenihan et al., forthcoming)."

WILDFIRE TRENDS

R8: SOUTHERN

Bachelet, D., Neilson, R. P., Lenihan, J. M., & Drapek, R. J. (2001). Climate change effects on vegetation distribution and carbon budget in the United States. Ecosystems, 4, 164-185.

"Simulated fires by MC1 [MAPSS-CENTURY1] convert large sections of the southeast to savannas and grasslands by the middle of the 21st century."

Dale, V. H., Lannom, K. O., Tharp, M. L., Hodges, D. G., & Fogel, J. (2009). Effects of climate change, land-use change, and invasive species on the ecology of the Cumberland forests. Canadian Journal of Forest Research, 39, 467-480.

"Earlier climate-change projections for a warmer and drier southeastern US produced a 30% increase in seasonal severity rating of fire hazard for the region (Dale et al. 2001). Fire can affect forests by altering nutrient cycling, killing trees, shifting successional direction, inducing seed germination, losing soil seed bank, increasing landscape heterogeneity, changing surface-soil organic layers and underground plant root and reproductive tissues, and volatilizing soil nutrients."

Heilman, W. E., Potter, B. E., & Zerbe, J. I. (1998). Regional climate change in the southern united states: The implications for wildfire occurrence. Productivity & Sustainability of Southern Forest Ecosystems in a Changing Environment, 1, 683-699.

"Because wildfire occurrence is very dependent on relatively short-term weather events along with fuel conditions, present research has partly focused on identifying the critical atmospheric circulation patterns that lead to enhanced wildfire activity in different regions of the United States., including the Southern Global Change Program (SCGP) study region. The results indicate that there are three specific circulation patterns in the middle atmosphere that are prevalent at the onset of severe wildfires in the south-central and southeastern United States. These circulation patterns produce drier-than-normal conditions over many parts of the south-central and southeastern United States during the spring and fall fire seasons. Examinations of the surface-pressure patterns associated with severe wildfire occurrence in the eastern United States and comparisons with general circulation model simulations under doubled CO2 conditions tend to suggest the future occurrence of more surface pressure and atmospheric circulation patterns that produce drier conditions in the eastern and southeastern United States."

"The relationships between the findings of Brotak and Reifsnyder (1977) and Potter (1996) and the potential atmospheric conditions associated with a changed climate are difficult to determine. However, these studies do suggest that changes in the frequency or intensity of weather systems that produce low-level jets or that move dry air masses with large surface dewpoint depressions and low relative humidity values into the southern [south central and south eastern] United States could affect the frequency of severe wildfires there."

"Changes in global and regional climates [in the southeastern US] could result in increased frequency of weather patterns associated with drought conditions, leading to enhanced fuel dryness, and thunderstorms that generate cloud-to-ground lightning strikes, leading to fuel ignition."

"For the south-central and southeastern regions of the United States, their study [Price and Rind 1994, using a general circulation model (GCM)] suggested increases on the order of 40 to 50% in the number of wildfires caused by lightning each year. Contributing to these increases is the probable decrease in the average effective precipitation (defined as precipitation minus potential evapotranspiration) over the United States under a changed climate as a result of increased atmospheric CO2 concentrations (Price and Rind, 1994)."

"In particular, the increased occurrence of high-pressure systems centered over the Gulf coast of the United States in the changed climate simulations performed by Takle et al., (1994) suggests that the southeastern United States may experience more dry days."

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S.Environmental Protection Agency, 1-127.

"On average, biomass consumed by fire is expected to increase by a factor of two or three (Bachelet et al., 2001; Bachelet et al., forthcoming)."

Liu, Y., Goodrick, S. L., & Stanturf J. A. (2012). Future U.S. wildfire potential trends projected using a dynamically downscaled climate change scenario. Forest Ecology and Management, In press. doi:10.1016/j.foreco.2012.06.049

"The length of a fire season [in the southern U.S.], measured by the number of the months with high or extreme fire potential level, will increase by 1–3 months (Fig. 13 [shows a graph of fire season length for each southern U.S. ecoregion])."

Ryan, M., Archer, S., Birdsey, R., Dahm, C., Heath, L., Hicke, J. ., . . . Schlesinger, W. (2008). Land resources. in: The effects of climate change on agriculture, land resources, water resources, and biodiversity. a report by the U.S. climate change science program and the subcommittee on global change research. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, 362.

"Flannigan et al. (2000) used two GCM [General Circulation Model] simulations of future climate to calculate a seasonal severity rating related to fire intensity and difficulty of fire control. Depending on the GCM used, forest fire seasonal severity rating in the Southeast is projected to increase from 10 to 30 percent and 10 to 20 percent in the Northeast by 2060."

SOUTH ATLANTIC

Duncan, B. W., Adrian, F. W., & Stolen, E. D. (2010). Isolating the lightning ignition regime from a contemporary background fire regime in east-central Florida, USA. Canadian Journal of Forest Research, 40(2), 286-297. doi: 10.1139/X09-193

"Generally, when it has rained, more strikes are required to ignite fires. This is especially true for July; when July is wet, it takes more lightning strikes to ignite fires, and when July is dry, fewer strikes are needed to ignite fires. July rainfall is particularly important because it corresponds to the peak in lightning incidence. This trend is clearly visible in the monthly strike to ignition ratio data. The fewest

strikes are required to ignite fires in July just after the annual dry period, and the maximum number of strikes is required to ignite fires in October after the summer wet season (Mailander 1990)."

Smith, S. M., Gawlik, D. E., Rutchey, K., Crozier, G. E., & Gray, S. (2003). Assessing drought-related ecological risk in the Florida Everglades. Journal of Environmental Management, 68(4), 355-366. doi:10.1016/s0301-4797(03)00102-6

"Although peat fire risk [in the Florida Everglades] was closely correlated with water levels, a scatterplot of water level vs. risk value (unranked) shows the effect of the secondary variables [burn history, duration of dry out, vegetation, soil type, soil total phosphorus, and soil bulk density] on the relationship. In this regard, the status of these other factors substantially lowered or enhanced risk at many locations, particularly where water levels were between -2 and -3 ft (Fig. 2)."

SOUTH CENTRAL

Harcombe, P. A., Hall, R. B. W., Glitzenstein, J. S., Cook, E. S., Krusic, P., Fulton, M., & Streng D. R. (1998). Chapter 5: Sensitivity of Gulf Coast Forests to Climate Change (Biological Science Report USGS/BRD/BSR-1998-0002). In G. R. Guntenspergen & B.A. Vairin (Eds.), Vulnerability of coastal wetlands in the Southeastern United States: climate change research results, 1992-97. Lafayette, LA: U.S. Department of the Interior, U.S. Geological Survey, National Wetlands Research Center: 44-66.

"At the dry study site [on a low, sandy ridge in Warren, Texas], the changes were relatively easily interpreted in terms of two common regional phenomena: postlogging recovery and fire exclusion. Effects of climatic changes on sites such as this will probably involve interactions between climate and fire regimes. Changes in global climate are likely to influence both within-season timing and intensity of fires, even under managed conditions, thus affecting forest composition. If fire continues to be excluded from this system, predicted increases in regional drought may aid preserve managers by retarding the invasion of mesic, shade-tolerant species into formerly fire-maintained upland habitats."

RESOURCE AREA (FACTOR): FOREST HEALTH

EXOTIC INSECT PESTS

R8: SOUTHERN

Koch, F. H. and Smith, W. D. (2008). Spatio-Temporal analysis of Xyleborus glabratus (coleoptera: Circulionidae: Scolytinae) invasion in eastern U.S. forests. Environmental Entomology, 37(2), 442-452. doi:10.1603/0046-225x(2008)37[442:saoxgc]2.0.co;2

"Each variable used in the climate matching model (Table 1) exhibited a wide range of values, which may be attributed to the approximate manner in which we defined the native geographic range for [Xyleborus glabratus, redbay ambrosia beetle] (i.e., delineating countries or large portions of countries instead of observations of the beetle's occurrence at specific point locations). Despite the coarseness of the inputs, the map resulting from the model (Fig. 4) suggests that the suitable area is largely constrained to the south eastern U.S. coastal plain, or essentially the range of redbay [Persea borbonia]. With the exception of a small area in the southern Appalachian Mountains, no other part of the conterminous United States is identified as suitable under the model."

"The restricted extent predicted for [Xyleborus glabratus, redbay ambrosia beetle] principally derives from the minimum monthly rainfall values recorded from the beetle's native range (Table 1)."

SOUTH ATLANTIC

Gramling, J. M. (2010). Potential effects of Laurel Wilt on the flora of North America. Southeastern Naturalist, 9(4), 827-836. doi: http://dx.doi.org/10.1656/058.009.0417

"The ultimate effects of Laurel Wilt may not be observed until the pathogen and vector shift from invaders to residents in a given area. Invasions of plant pathogens are often driven by the availability of a host population in the short-term, whereas their persistence may be confronted with diminished host numbers and a variety of demographic or environmental factors (Gilligan and van den Bosch 2008). As Persea spp. [laurel species] and other host plants in the Southeast are reduced in number and in average individual size, populations of the Redbay Ambrosia Beetle [Xyleborus glabratus] will likely decline. Hanula et al. (2008) demonstrated that population densities of the beetle were lower in areas in which host densities had declined due to Laurel Wilt; peak populations declined as the age of infestations increased."

NATIVE INSECT PESTS

R8: SOUTHERN

Dale, V. H., Lannom, K. O., Tharp, M. L., Hodges, D. G., & Fogel, J. (2009). Effects of climate change, land-use change, and invasive species on the ecology of the Cumberland forests. Canadian Journal of Forest Research, 39, 467-480.

"Global climate change could intensify southern pine beetle infestation risk by 2.5–5 times and could account for 4–7.5 times higher mortality than the current number of trees killed annually (Gan 2004)."

Duehl, A. J., Koch, F. H., & Hain, F. P. (2011). Southern pine beetle regional outbreaks modeled on landscape, climate and infestation history. Forest Ecology and Management, 261(3), 473-479. doi:10.1016/j.foreco.2010.10.032

"Climatic variables were ranked second in the level of importance with temperature leading precipitation in predictive power [for predicting infestations of southern pine beetle (Dendroctonus frontalis) at a regional scale]. Out of the temperature variables considered, seasonal average temperature, annual minimum temperature and relative minimum temperature were the most important variables. One management implication of our findings is that a very cold winter or a cold snap will decrease the likelihood of infestation even if there were high populations of beetles in the previous year (Ungerer et al., 1999). While average temperature likely correlated with the center SPB [southern pine beetle] geographic range, minimum temperatures strongly influence yearly population success (Ungerer et al., 1999). The seasonal focusing variables also had explanatory power, indicating the temperature influences on development are important in determining population success (Powell et al., 2000)."

"In general, high levels of fall precipitation lead to higher levels of infestation [of southern pine beetle (Dendroctonus frontalis)] the following year. In some regions this may occur because soil saturation increases root anoxia, but in others high fall precipitation may result in healthier, faster growing trees that provide beetles with a more nutritious substrate (Lombardero et al., 2000b)."

"Our analyses indicate that extreme conditions with the exception of drought, like those predicted to occur with climate change (IPCC, 2001), are less likely to lead to beetle [southern pine beetle (Dendroctonus frontalis)] success. To the north there are some susceptible hosts that have historically only experienced occasional infestations or been protected by extreme winter temperatures that could be exposed to consistent beetle populations. Beetle populations may also help regulate the distribution of certain tree species and changing climate will alter the frontiers of this relationship (Bentz et al., 2010)."

Friedenberg, N. A., Sarkar, S., Kouchoukos, N., Billings, R. F., & Ayres, M. P. (2008). Temperature extremes, density dependence, and southern pine beetle (coleoptera: Curculionidae) population dynamics in East Texas. Environmental Entomology, 37(3), 650-659. doi: 10.1603/0046-225X(2008)37[650:TEDDAS]2.0.CO;2

"Much of the complexity of the southern pine beetle's [Dendroctonus frontalis] population dynamics may be driven by climate."

Gan, J. (2004). Risk and damage of southern pine beetle outbreaks under global climate change. Forest Ecology and Management, 191, 61–71.

"Changes in temperature and precipitation would influence SPB [Southern Pine Beetle (Dendroctonus frontalis)] populations directly, through the physiological process of the insect, and indirectly, through its host trees and natural predators. Consequently, climate change could have profound effects on the distribution and abundance of SPB (Ayres and Lombardero, 2000), and thus the range (area) and intensity (risk) of SPB infestations."

"SPB [Southern Pine Beetle (Dendroctonus frontalis)] outbreak areas are projected to expand and generally shift northward as temperature increases. The expansion of the projected infestation areas would be primarily due to the shifts in the distribution of southern pines resulting from climate change (Williams and Liebhold, 2002). However, the impact of climate change on the intensity of SPB infestations, particularly in terms of economic damage, has been relatively unexplored."

"Many agree that extremes in temperature and precipitation affect SPB [Southern Pine Beetle (Dendroctonus frontalis)] populations and host trees, influencing SPB infestations. Cold winters and hot summers generally reduce SPB populations (Beal, 1929; Thatcher, 1960) while moisture deficits and surpluses could both contribute to SPB outbreaks (Kalkstein, 1974;Warning and Cobb, 1989). Of the 11 states, Alabama had the highest infestation rate and volume killed, while Florida had the lowest infestation rate and volume killed. Tennessee had the second higher SPB infestation rate, followed by South Carolina, Louisiana, Georgia, Texas, and North Carolina."

"Therefore, a warmer winter might help SPB [Southern Pine Beetle (Dendroctonus frontalis)] overwintering, leading to a higher risk of its outbreaks in the following year. But, its impact was relatively small compared to temperature changes in other seasons. For a 1% increase in the previous winter temperature, SPB outbreak risk in the current year would increase by only 0.53%."

"Warmer springs, particularly continuous warming in consecutive spring seasons, would tremendously increase the chance of SPB [Southern Pine Beetle (Dendroctonus frontalis)] outbreaks."

"The high sensitivity of SPB [Southern Pine Beetle (Dendroctonus frontalis)] infestation risk to spring temperature may be partly because warmer springs coupled with abundant food as the host trees start to grow during the season would cause SPB populations to grow earlier and more rapidly."

"Although the estimated SPB [Southern Pine Beetle (Dendroctonus frontalis)] infestations varied across the climate change scenarios, SPB infestation risk was predicted to increase under the elevated CO2 level. Under the four climate change scenarios, the risk of SPB outbreaks would increase by 2.5–5-fold from its current level."

"The estimated annual average value of timber killed by SPB [Southern Pine Beetle (Dendroctonus frontalis)] for all the 11 states would range from US$ 366 to 630 million, even without accounting for the potential expansion in pine forest areas and increases in forest productivity. Under the climate change scenarios as predicted by the four GCMs, the area of southern pine forests would increase by 25–57%. The productivity of southern pine was predicted to grow by 7.6% as atmospheric CO2 concentration doubles. When the changes in pine forest area and productivity are incorporated, the value of damage

would reach US$ 492–869 million annually, about 4–7.5 times higher than the current level."

Jianbang, G. (2004). Risk and damage of southern pine beetle outbreaks under global climate change. Forest Ecology and Management, 191, 61-71.

"Global climate change induced by doubling atmospheric CO2 concentration would intensify SPB [Southern Pine Beetle] [Dendroctonus frontalis] infestation risk by 2.5-5 times. If the changes in the area and productivity of southern pine forests due to climate change are accounted for, SPB would cause even more severe damage, 4-7.5 times higher than the current value of trees killed annually."

SOUTH ATLANTIC

Laseter, S. H., Ford, C. R., Vose, J. M., & Swift Jr., L. W. (2012). Long-term temperature and precipitation trends at the Coweeta Hydrologic Laboratory, Otto, North Carolina, USA. Hydrology Research, 43(6), 890-900. doi:10.2166/nh.2012.067

"Native insect outbreaks, e.g. southern pine beetle (Dendroctonus frontalis), are triggered by drought. The successive droughts in the 1980s and late 1990s caused widespread southern pine beetle infestations in Coweeta [Hydrologic Laboratory, Otto, North Carolina] watersheds, and throughout the southern Appalachians. As a result of these outbreaks, a decrease in pitch pine (Pinus rigida) stands and increased canopy gap area due to dead or dying snags (Clinton et al. 1993; Vose & Swank 1994; Kloeppel et al. 2003) occurred."

SOUTH CENTRAL

Friedenberg, N. A., Sarkar, S., Kouchoukos, N., Billings, R. F., & Ayres, M. P. (2008). Temperature extremes, density dependence, and southern pine beetle (Coleoptera: Curculionidae) population dynamics in East Texas. Environmental Entomology, 37(3), 650-659. doi: 10.1603/0046-225X(2008)37[650:TEDDAS]2.0.CO;2

"Minimum winter temperature also affects model 4 behavior; southern pine beetles [Dendroctonus frontalis] can only maintain outbreak levels within a discrete range of winter temperatures (Fig. 5c). Hence, different scenarios of climate change can have different long-term effects on the population."

"By influencing the prevalence of clerid predators, Monachamus competitors, or O. minus [Ophiostoma minus], extreme temperatures may affect southern pine [Dendroctonus frontalis] beetle population dynamics not only by changing the agent of regulation but by altering the lag in dominant ecological feedbacks."

PATHOGENS

R8: SOUTHERN

Runion, G. B., Prior, S. A., Rogers, H. H., & Mitchell, R. J. (2010). Effects of elevated atmospheric CO2 on two southern forest diseases. New Forests, 39, 275-285. doi: 10.1007/s11056-009-9170-7

"Despite an increase in seedling size and the amount of succulent tissue available for infection, percent infection was not significantly affected by CO2 concentration (Table 1). It should be noted that, in both runs of the experiment, growth under elevated CO2 resulted in numerically lower (14 and 5.6% for the first and second runs, respectively) percentages of loblolly pine [Pinus taeda] seedlings infected with the fusiform rust fungus [Cronartium quercuum f.sp. fusiforme]; the fact that these differences were not statistically significant was due to high chamber-to-chamber variability."

"Even though percent infection was not significantly affected by CO2 concentration, the percentage of loblolly pine [Pinus taeda] seedlings which died as a result of [fusiform] rust [Cronartium quercuum f.sp. fusiforme] infection (rust associated mortality or RAM) was generally significantly lower under elevated CO2 in both runs of the experiment (Table 1). Atmospheric CO2 concentration had no effect on measures of disease severity (fusiform rust gall length or diameter) in either run of the experiment (Table 1)."

"The percent of loblolly pine [Pinus taeda] seedlings which developed cankers following inoculation with the pitch canker [Fusarium circinatum] fungus was consistently lower ($P < 0.05$) for seedlings grown under elevated CO2 in both runs of the experiment (Fig. 3)."

"Results indicate that incidence of fusiform rust [Cronartium quercuum f.sp. fusiforme] was statistically unaffected (albeit numerically lower) by growth in elevated CO2 despite the fact that seedlings were larger (and had additional area for infection)."

"It was interesting that exposure to elevated CO2 increased the latent period (time from inoculation until sporulation) for both uredia and telia on oak [Quercus spp.] seedlings by 2 days. Fusiform rust [Cronartium quercuum f.sp. fusiforme] has a complex disease cycle and relies extensively on timing such that spore production occurs when the alternate host's tissues (oak leaves for aeciospores and pine [Pinus spp.] tissues for basidiospores) are succulent and more easily infected. A delay of 2 days, as occurred between the two runs of the oak experiment, could have a dramatic impact on this disease cycle."

Watt, M. S., Ganley, R. J., Kriticos, D. J. & Manning, L. K. (2011). Dothistroma needle blight and pitch canker: the current and future potential distribution of two important diseases of Pinus species. Canadian Journal of Forest Research, 41, 412 – 424.

"[Using the process-based niche model CLIMEX under six scenarios that include three contrasting global climate models, each with moderate and high CO2 emissions] The impact of climate change on pitch canker [Fusarium circinatum] in the southeastern United States is unclear. There is a wide variation under the three climate scenarios. The alleviation of disease pressure predicted in parts of the southeastern United States may also accompany a reduction in presence of the host. For example, the western limit for pitch canker in Texas is associated with the natural range limit of Pinus spp."

RESOURCE AREA (FACTOR): FRESHWATER ECOSYSTEMS

AQUATIC PLANTS

R8: SOUTHERN

Mulholland, P. J., Best, G. R., Coutant, C. C., Hornberger, G. M., Meyer, J. L., Robinson, P. J, Stenberg, J. R., … & Wetzel, R. G. (1997). Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf Coast of Mexico. Hydrological Processes, 11, 949-970. doi: 10.1002/(SICI)1099-1085(19970630)11:8<949::AID-HYP513>3.0.CO;2-G

"Lower baseflows and increased flow variabilities will alter plant species and competitive interactions. Among truly hydrophytic species, increased dominance of deep-rooted emergent species with well-developed aeration systems, replacement of submersed species with heterophyllous species and improved competition of deciduous species that are semi-flood tolerant would be expected. Riparian species (e.g. mesic alders) and certain conifers and hardwoods would be lost, possibly reducing shading in riparian wetlands."

FRESHWATER WETLANDS

R8: SOUTHERN

Krauss, K. W., Duberstein, J. A., Doyle, T. W., Conner, W. H., Day, R. H., Inabinette, L. W., & Whitbeck, J. L. (2009). Site condition, structure, and growth of baldcypress along tidal/non-tidal salinity gradients. Wetlands, 29(2), 505-519. doi: 10.3159/1095-5674(2005)132[411:EODSOV]2.0.CO;2

"While the distribution of water tupelo [Nyssa aquatic] in the overstory of tidal and non-tidal swamps [across five landscape transects in coastal Louisiana, South Carolina, and Georgia] was limited to salinities < 1 ppt, swamp tupelo [Nyssa biflora] occurred at salinities as high as 2.1 ppt (Waccamaw Lower [South Carolina]). This contradicts results for swamp tupelo from greenhouse studies where cessation of physiological activity and complete mortality of swamp tupelo seedlings occurred at 2 ppt salinity after only 70 d of exposure (McCarron et al. 1998). Swamp tupelo seedlings might be less tolerant to salinity than mature trees, which would indicate that salinity conditions during regeneration may have been lower on some sites than it is now. However, larger trees may also be able to escape salt stress by accessing fresher water through deeper roots."

Middleton, B. A. & McKee, K. L. (2004). Use of a latitudinal gradient in bald cypress (Taxodium distichum) production to examine physiological controls of biotic boundaries and potential responses to environmental change. Global Ecology and Biogeography, 13(3), 247-258. doi:10.1111/j.1466-822X.2004.00088.x

"Changes in climate may alter production patterns of [Taxodium distichum] swamps, and the curvilinear relationship between latitude and litterfall suggests not only that the latitudinal position of maximum production would shift with global warming, but that populations to the south and west may not be sustained."

"If two conservative temperature increases (e.g. 1.2 and 3.5 °C) are used to calculate predicted litterfall rates across latitudes, the resulting plots indicate dramatic shifts in bald cypress [Taxodium distichum] swamp production (Fig. 4). Under the more conservative temperature scenario, the southernmost swamp sites would decrease litterfall rates by 34–73% whereas northernmost sites would increase by 20–137%. With greater temperature increases, southern and some mid-latitude swamps are predicted to decrease substantially in litterfall rates (Fig. 4). However, because genetic variability of populations may vary throughout the range and influence potential responses to changes in environmental conditions (Rehfeldt et al., 1999; Davis & Shaw, 2001), the actual change in litter production with global warming may be modified by ecotypic differentiation across the range."

"Both water temperature and flooding affect bald cypress [Taxodium distichum] seed germination, seedling growth, and adult production and survivorship (McLeod & Sherrod, 1981; Scott et al., 1985; Donovan et al., 1988; Middleton, 2000) so that changes in these factors related to climate warming could ultimately affect bald cypress swamp distribution."

"Whether bald cypress [Taxodium distichum] swamps could develop at lower latitudes is not known, but decreased production within the current range (Fig. 2) and low or zero predicted production at higher temperatures (Figs 3 and 4) suggests that conditions may not support them. This question is of interest because as projected temperatures increase, populations near the lower geographical limit of the bald cypress region could become extirpated. If average temperatures increase by a few °C (IPCC, 2001), trees at the southern boundary may be unable to maintain a positive carbon balance (Fig. 4)."

"Another recent study specifically predicts the loss of T. distichum [Taxodium distichum] from swamp ecosystems in south Florida under scenarios of 2 °C annual climatic warming, based on the current distributional envelope (Crumpacker et al., 2001). The latter prediction is supported by our data indicating that production of bald cypress swamps at latitudes of 25–27° N would decrease to zero if temperatures increase by 2 °C. Additionally, our analysis shows that southern swamps with impaired hydrology are most vulnerable to temperature change (Fig. 4)."

Middleton, B. A. (2009). Regeneration potential of Taxodium distichum swamps and climate change. Plant Ecology, 202(2), 257-274. doi:10.1007/s11258-008-9480-4

"The overstory species of swamps, T. distichum [Taxodium distichum (bald cypress)], may already be experiencing physiological stress related to the higher temperatures at the southern limits of the range (Middleton and McKee 2004). With climate warming, T. distichum populations may be extirpated near the southern extreme of the range (Crumpacker et al. 2001; Middleton and McKee 2004). Any changes in the overstory composition associated with climate change would also be likely to have profound effects on the nature of regeneration from the seed banks of these forests."

Mulholland, P. J., Best, G. R., Coutant, C. C., Hornberger, G. M., Meyer, J. L., Robinson, P. J, Stenberg, J. R., … & Wetzel, R. G. (1997). Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf Coast of Mexico. Hydrological Processes, 11, 949-970. doi: 10.1002/(SICI)1099-1085(19970630)11:8<949::AID-HYP513>3.0.CO;2-G

"Higher atmospheric CO2 concentrations may also reduce leaf nitrogen content, particularly in bottomland hardwood species (Williams et al., 1986; Bazzaz, 1990). These changes, which may occur under drier soil conditions, are likely to reduce the rate of litter decomposition in streams (Webster and Benfield, 1986) and, consequently, decrease food quality for invertebrate detritivores. Thus, the net effect of increases in temperature and atmospheric CO2 on stream organic matter dynamics and detritus-based food-webs is uncertain, but potentially is substantial."

SOUTH ATLANTIC

Conner, W. H., Song, B., Williams, T. M., and Vernon, J. T. (2011). Long-term tree productivity of a South Carolina coastal plain forest across a hydrology gradient. Journal of Plant Ecology, 4(1-2), 67-76. doi:10.1093/jpe/rtq036

"The dry periods that occurred during this study [in the Waccamaw Neck area on the South Carolina coastal plain] may have contributed to understanding the complex relationship of growth to drought in southeastern rain-fed forested wetlands. On this low gradient system, response of landscape sites, that differ by <60 cm in elevation, produces vastly different communities that react differently to flooding and drought. Stem growth can be highly dependent on water table depth for flood tolerant species on wet sites, but of little significance to less flood tolerant species, and less significance to the same flood tolerant species growing on a slightly drier site. A high water table has little effect on the dry site species with that small effect being negative."

Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., ... & Machmuller, M. (2008). Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. Frontiers in Ecology and the Environment, 7(2), 73-78. doi: 10.1890/070219

"On a per-unit-area basis, tidal freshwater wetlands provide higher levels of ecosystem services than do salt marshes [in Georgia estuaries], so their decline [reduction in tidal freshwater marsh area under IPCC sea level rise models] will lead to a disproportionate decrease in delivery of ecosystem services."

Dai, Z., Trettin, C. C., Li, C., Amatya, D. M., Su, G., & Li, H. (2010). Sensitivity of stream flow and water table depth to potential climatic variability in a coastal forested watershed. Journal of the American Water Resources Association, 46(5), 1036-1048. doi: 10.1111/j.1752-1688.2010.00474.x

"The hydrology of wetland-dominated watersheds, especially first-order watersheds on the Atlantic coastal plain, is heavily dependent on precipitation and evapotranspiration (ET) (Sun et al., 2006). Therefore, climate change, including alterations in temperature and precipitation (IPCC, 2001; Wentz et al., 2007; Zhang et al., 2007), may be expected to significantly influence the hydrology of wetland-dominated watersheds (Sun et al., 2006)."

De Steven, D., & Toner, M. M. (2004). Vegetation of upper coastal plain depression wetlands: environmental templates and wetland dynamics within a landscape framework. Wetlands, 24(1), 23-42. doi:10.1672/0277-5212%282004%29024%5b0023%3avoucpd%5d2.0.co%3b2

"With respect to our first question [What local environmental factors potentially influence vegetation composition?], wetland vegetation is influenced by local environmental gradients, although in complex ways. Hydrologic regime was the strongest correlate of vegetation type [in depessional wetlands on the western half of the South Carolina Upper Coastal Plain]."

"In the Southeast, [based on our study in depessional wetlands on the western half of the South Carolina Upper Coastal Plain] the result [of future climate change] could be more forested depressions and fewer herbaceous depressions, although the potential for more fires might be a counteracting force. "

Krauss, K. W., Duberstein, J. A., Doyle, T. W., Conner, W. H., Day, R. H., Inabinette, L. W., & Whitbeck, J. L. (2009). Site condition, structure, and growth of baldcypress along tidal/non-tidal salinity gradients. Wetlands, 29(2), 505-519. doi: 10.3159/1095-5674(2005)132[411:EODSOV]2.0.CO;2

"BAI [basal area increment] of codominant baldcypress [Taxodium distichum] tended to be lower on all sites at higher flood frequencies in our study (Figure 6C). Therefore, much of the productivity in South Carolina and Georgia swamps may be restricted to sites less frequently flooded by tides (i.e., even if flooding occurs for longer durations). More frequent flooding along strongly tidal rivers tended to decrease growth (e.g., Savannah and Waccamaw Rivers), while increased flood durations associated with longerterm ponding of non-tidal sites tended to increase growth (e.g., Crabhaul Swamp [a hydrologically perched freshwater site near Georgetown, South Carolina])."

Lu, J., Sun, G., McNulty, S. G., Comerford, N. B. (2009). Sensitivity of pine flatwoods hydrology to climate change and forest management in Florida, USA. Wetlands, 29(3), 826-836.

"At the landscape scale, depressional wetlands that receive surface water and ground water from surrounding uplands are most likely sensitive to land disturbances and climate change."

Mulholland, P. J., Best, G. R., Coutant, C. C., Hornberger, G. M., Meyer, J. L., Robinson, P. J, Stenberg, J. R., … & Wetzel, R. G. (1997). Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf Coast of Mexico. Hydrological Processes, 11, 949-970. doi: 10.1002/(SICI)1099-1085(19970630)11:8<949::AID-HYP513>3.0.CO;2-G

"Florida lakes, particularly those in the northern areas, are likely to undergo significant changes with climatic warming. Warming will shift the warm temperate lakes of north Florida to subtropical conditions, resulting in a reduction in length of mixing, an increase in productivity and nutrient cycling rates, simplification and reduction of the macrozooplankton community, and an increase in protozoa and bacteria. Management problems caused by blooms of the blue-green alga Microcystis, and by growths of the exotic macrophyte Hydrilla verticillata, primarily confined to the subtropical lakes, would expand northwards with a similar shift in subtropical conditions. Many of the native, temperate fish species will be lost and replaced with exotic, subtropical species, as has occurred in southern Florida."

Mulhouse, J. M., De Steven, D., Lide, R. F., & Sharitz, R. R. (2005). Effects of dominant species on vegetation change in Carolina bay wetlands following a multi-year drought. The Journal of the Torrey Botanical Society, 132(3), 411-420. doi:10.3159/10955674(2005)132[411:EODSOV]2.0.CO;2

"In the drought period [in Carolina bays or bay-like depression wetlands located on the Savannah River Site on the Upper Coastal Plain of South Carolina], pond/meadow wetlands tended to have shorter hydroperiods than grass/sedge marshes (means of 52% and 72%, respectively); the difference was especially prominent in 2002 (Table 2). Prior to the drought, bay hydroperiods did not differ significantly between landscape positions (uplands versus terrace), but during the drought an apparent trend was for hydroperiods of upland bays to be shorter and more variable (upland mean = 50%, SE = 10; terrace mean = 70%, SE = 3; not significant). Three of the four grass/sedge marshes, which generally had longer hydroperiods during the drought, were located in terrace landscape positions (Table 1)."

"Collectively, the relative abundance of wetland species [in Carolina bays or bay-like depression wetlands located on the Savannah River Site on the Upper Coastal Plain of South Carolina] declined significantly during the drought, while the relative abundance of facultative and upland species increased significantly (Table 4). Upland species showed significantly greater increases in pond/meadow bays (mean change = 12%) than in grass/sedge marshes (mean change = 3%; Table 4). "

"Changes in vegetation composition [in Carolina bays or bay-like depression wetlands located on the Savannah River Site on the Upper Coastal Plain of South Carolina] through the drought were detectable at the level of individual bays. As a group, wetland plant species declined, whereas facultative and upland species increased. The declining species were mostly aquatic plants; few other types of wetland species consistently decreased in abundance. Rather, overall compositional change was characterized mainly by increases in the number and abundance of various emergent herbaceous and woody species."

"Our results [studying drought in Carolina bays or bay-like depression wetlands located on the Savannah River Site on the Upper Coastal Plain of South Carolina] provide some short-term evidence for two possible trajectories in herbaceous Carolina bays during drought. In ponds/meadows, drought results in establishment and expansion by additional species as a result of more open vegetation structure and a more variable hydrologic condition. Grass/sedge marshes acquire fewer species, at least in the short term, given their denser vegetation structure and somewhat longer hydroperiods."

Pyzoha, J. E., Callahan, T. J., Sun, G., Trettin, C. C., & Miwa, M. (2008). A conceptual hydrologic model for a forested Carolina bay depressional wetland on the Coastal Plain of South Carolina, USA. Hydrological Processes, 22(14), 2689-2698.

"Climatic dynamics greatly influence the hydrology of Carolina bays. Normal seasonal precipitation and evapotranspiration fluctuations and deviations from normal climate conditions greatly affect the role of surface water–groundwater interactions in the overall hydrology of these wetlands. This long-term monitoring study [at Chapel Bay, a Carolina bay in Bamberg County, South Carolina, from 1997-2003] clearly shows the climate control on the Carolina bay hydroperiod as well as surface–groundwater interactions, and thus we infer that projected climatic change may alter Carolina bay hydrology dynamics permanently; as for the exact magnitude of the impact we are not certain."

Stroh, C. L., De Steven, D., Guntenspergen, G. R. (2008). Effect of climate fluctuations on long-term vegetation dynamics in Carolina bay wetlands. Wetlands, 28(1), 17-27. doi: 10.1672/06-117.1

"However, annual hydroperiod and water depth of all [Carolina] bays fluctuated with annual rainfall variation, confirming the importance of precipitation inputs and climate variability (Schalles and Shure 1989, Lide et al. 1995, Brooks 2004, Johnson et al. 2004). Shallower bay margins experienced more frequent water-level change (see also Collins and Battaglia 2001), but even the deepest wetlands dried completely during prolonged drought. When drought conditions ended, it appeared that more than a year was required for water levels to recover completely."

"The regional climate models do not agree on whether annual precipitation will rise or decrease, but they have predicted that annual temperatures — and potentially drought frequency — will increase. Understanding how Carolina bays and similar depressional wetlands respond to current drought cycles can help predict how the systems might be impacted by future climate change."

"Similarly, in Carolina bays and other Southeastern depressions, more frequent drought would likely cause more immediate hydrologic change in small shallow bays that are naturally more prone to drying. Shifts to shorter hydroperiods would favor forest succession in more wetlands and thus alter the landscape distribution of plant community types (De Steven and Toner 2004)."

"If more flood-tolerant hardwood trees such as swamp tupelo (Nyssa biflora) or sweetgum (Liquidambar styraciflua) establish successfully [in Carolina bays] during drought, they may survive reinundation, shorten wetland hydroperiod through increased evapotranspiration, and promote further forest expansion."

Sun, G., Callahan, T. J., Pyzoha, J. E., & Trettin, C. C. (2006). Modeling the climatic and subsurface stratigraphy controls on the hydrology of a Carolina bay wetland in South Carolina, USA. Wetlands, 26(2), 567-580.

"The hydrology of southern forested wetlands such as forested Carolina bays is extremely dynamic and is affected by the balance between precipitation and evapotranspiration. Any deviation of normal precipitation will have an impact on Carolina bay hydroperiod patterns. However, ground water can be an important component of the water budgets of Carolina bays, especially during wet periods when ground water discharges into the wetland from surrounding upland [as seen in our study in South Carolina]. Carolina bays receive ground water from surrounding uplands during and following rainfall events and can then recharge the ground-water system during dry periods. However, the generalized patterns depend on the geomorphologic setting of individual wetlands."

SOUTH CENTRAL

Middleton, B. A. (2009). Regeneration potential of Taxodium distichum swamps and climate change. Plant Ecology, 202(2), 257-274. doi:10.1007/s11258-008-9480-4

"The relationship of water regime to seed germination may be critical to understanding the influence of climate change on wetland regeneration, because this study [from multiple locations along the Mississippi River] suggests that species germination would shift within a local wetland simply in response to nonflooded versus flooded conditions (Fig 5a, b). For example, in wetter northern swamps, seeds of Taxodium distichum [bald cypress] germinated in non-flooded conditions (Fig. 5a), but did not germinate from the same seed banks in flooded conditions (Fig. 5b). In wetter southern swamps, seeds of Eleocharis cellulosa [Gulf Coast spikerush] germinated in flooded conditions (Figs. 2b and 5b), but did not germinate from the same seed banks in nonflooded conditions (Fig. 5a)."

"Any climate change, which would alter hydrology, could limit the dispersal, germination, and regeneration of short lived woody species from T. distichum [Taxodium distichum (bald cypress)] swamps. Also, water flow in the Mississippi River tends to be southward, which may limit the northward migration opportunities of aquatically dispersed species. Clearly, the landscape dynamics underlying seed bank characteristics could have important influences on the climate change on Taxodium distichum swamps throughout their range."

INTERACTIONS WITH OTHER FACTORS

R8: SOUTHERN

Mulholland, P. J., Best, G. R., Coutant, C. C., Hornberger, G. M., Meyer, J. L., Robinson, P. J, Stenberg, J. R., … & Wetzel, R. G. (1997). Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf Coast of Mexico. Hydrological Processes, 11, 949-970. doi: 10.1002/(SICI)1099-1085(19970630)11:8<949::AID-HYP513>3.0.CO;2-G

"A regional analysis based on an empirical model predicts that 2-9% of streams in the southern Appalachians, and up to 55% of the streams in the north-western and north-central areas of Florida, experience episodic acidification (Eshleman, 1988). Increased clustering of storms will most likely lead to longer and/or more severe acidic episodes in these streams. This could lead to elimination of key, acid-sensitive species, particularly trout, and many of the common macroinvertebrates in the southern Appalachians, where historical acidification has been minimal (Mulholland et al., 1992)."

RESOURCE AREA (FACTOR): GENERAL BIODIVERSITY

GENERAL IMPACTS

R8: SOUTHERN

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S. Environmental Protection Agency, 1-127.

"Projected changes in temperature and precipitation suggest that southern ecosystems may shift dramatically. Depiction of the northern shift of the jet stream and the consequent drying of the Southeast (Fu et al., 2006) varies among future climate scenarios, with some showing significant drying while others show increased precipitation (Bachelet et al., 2001)."

GENETIC DIVERSITY

SOUTH ATLANTIC

Walls, S. C. (2009). The role of climate in the dynamics of a hybrid zone in Appalachian salamanders. Global Change Biology, 15(8), 1903-1910. doi: 10.1111/j.1365-2486.2009.01867.x

"My analyses lend support to the possibility that climate-induced changes in the movements of organisms may have additional consequences – those of affecting the dynamics of hybrid zones as well as the prevalence of hybridization itself (Buggs, 2007)."

INTERACTIONS WITH OTHER FACTORS

R8: SOUTHERN

McKenney, D. W., Pedlar, J. H., Lawrence, K., Campbell, K., & Hutchinson, M. F. (2007). Potential impacts of climate change on the distribution of North American trees. BioScience, 57(11), 939-948.

"There are important qualifications to these findings. First, our study examines only a sample of the approximately 700 tree species in North America, so we do not imply that the south will be devoid of trees. Furthermore, it is possible that novel climate habitats created in the southeast will be at least partially filled by species that are not currently part of the natural vegetation of the United States; exotic species expansions have been predicted for other regions and species groups under climate change (e.g.,Kriticos et al. 2003,Cumming andVanVuuren 2006)."

RANGE SHIFTS

R8: SOUTHERN

Speer, J. H., Grissino-Mayer, H. D., Orvis, K. H., & Greenberg, C. H. (2009). Climate response of five oak species in the eastern deciduous forest of the southern Appalachian Mountains, USA. Canadian Journal of Forest Research, 39, 507–518.

"Based on the positive relationship with summer PDSI [Palmer Drought Severity Index] and the negative relationship with September temperature for these five oak species [black oak (Quercus velutina), chestnut oak (Quercus prinus), northern red oak (Quercus rubra), scarlet oak (Quercus coccinea), and white oak (Quercus alba)] the increased moisture stress that is predicted to occur with global warming is likely to decrease the vigor of the extant oak trees in the southeastern US. This change in growing conditions is likely to force oak trees to establish at higher elevations, or migrate to higher latitudes, through seed dispersal. The resultant stress on living oak trees may lead to forest health decline and an increase of damage from a variety of forest pathogens."

SOUTH ATLANTIC

Ibáñez, I., Clark, J. S., & Dietze, M. C. (2008). Evaluating the sources of potential migrant species: implications under climate change. Ecological Applications, 18(7), 1664-1678. doi:10.1890/07-1594.1

"In our studied locations [in the North Carolina Piedmont and Southern Appalachians] winters will be similar to those in Central America and the Caribbean, but summers will resemble conditions in the southwestern United States. This scenario has no equivalent in the surrounding regions. Given this fact, the simple shift in species distributions from south to north predicted by climate-envelope models may not occur. Species growing at lower latitudes from our study sites could take advantage of warmer winters, but they might not be able to colonize the region under much drier conditions. In addition, most native species may experience decreasing seedling survival due to growing season aridity."

"With the current large deer populations in the Southeast, some of the herbivore pressure will shift to the species that best survive the changing climate. For example, on the basis of simple climate predictions, Coastal Plain oaks [Quercus spp.] are potential immigrants to the Piedmont (Iverson et al. 1999, Bachelet et al. 2001). However, severe herbivore pressure may be among the factors currently limiting the regeneration of the once-dominant oaks in the Piedmont."

RESOURCE AREA (FACTOR): INVASIVE SPECIES

INTERACTIONS WITH OTHER FACTORS

SOUTH ATLANTIC

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S. Environmental Protection Agency, 1-127.

"Cogongrass (Imperata cylindrica (L.) Beauv.) invasions have altered fire regimes in pine savannas in the southeastern United States (Lippincott, 2000)."

INVASIVE ANIMALS: AQUATIC

R8: SOUTHERN

Drake, J. M., & Bossenbroek, J. M. (2004). The potential distribution of zebra mussels in the United States. BioScience, 54(10), 931-941. doi:10.1641/00063568(2004)054[0931:TPDOZM]2.0.CO;2

"Turning to our projections of invasion risk in the Southeast [using a genetic algorithm for rule-set production (GARP) that includes the IPCC (Intergovernmental Panel on Climate Change) baseline climate dataset to select predictive models of species ranges], where the species richness of unionid mussels is especially high (figure 7), we observe that this region is highly susceptible to zebra mussel [Dreissena polymorpha] invasion, according to model I (with the risk of invasion approaching 100 percent). In the Southeast, unlike the western river systems, models II and III show a significantly lower invasion risk than model I, diminishing our confidence that the region is habitable by zebra mussels. However, this only reduces the risk from high (approaching 100 percent) to moderate (about 50 percent). Given the high density of endemic unionid species, even the lowest estimates of invasion risk in the Southeast are worrisome. We reiterate that even if our models suggest that a region is habitable by zebra mussels in only 50 of 100 models, this is unacceptably high in light of the high biodiversity losses to be expected from invasion by zebra mussels."

SOUTH ATLANTIC

Rahel, F. J., & Olden, J. D. (2008). Assessing the Effects of Climate Change on Aquatic Invasive Species. Conservation Biology, 22(3), 521–533. doi: 10.1111/j.1523-1739.2008.00950.x

"In freshwater systems climate change is associated with earlier breeding in amphibians (Beebee 1995), earlier emergence of dragonflies (Odonata) (Hassall et al. 2007), and compositional shifts of entire insect communities (Burgmer et al. 2007). There is speculation that the recent establishment of 2 species of tropical dragonflies in Florida represents a natural invasion from Cuba and the Bahamas that is related to climate change (Paulson 2001)."

INVASIVE ANIMALS: TERRESTRIAL

R8: SOUTHERN

Rцdder, D. & Weinsheimer, F. (2009). Will future anthropogenic climate change increase the potential distribution of the alien invasive Cuban treefrog (Anura: Hylidae)? Journal of Natural History, 43(19-20), 1207-1217. doi:10.1080/00222930902783752

"Projections of the CEM [Climate Envelope Models] of O. septentrionalis [Osteopilus septentrionalis] onto the future climate change scenarios indicate that climatically suitable areas may become more widespread overall (Figure 4). These areas include the whole Atlantic coastline from the Mexican border to North Carolina, which may connect suitable areas with today's potential distribution. In contrast the climatic suitability in its native range, as well as on the Yucatan Peninsula, will decrease."

"Our projections onto anthropogenic climate-change scenarios indicate a possible extension of the current potential distribution of the Cuban treefrog [Osteopilus septentrionalis] in Northern America. However, successful colonization of newly arising suitable areas may depend on the propagation speed of O. septentrionalis. Time series suggest that the frog was able to expand its range at about 10kmy21 in Florida (e.g., Key West– Miami, ,250 km/21y; Miami–Indian River Country, ,250 km/28y; Miami–Duval Country, 570 km/51y) and, assuming this spread rate, it could reach Louisiana and Virginia within the next 80 years."

INVASIVE PLANTS: AQUATIC & RIPARIAN

SOUTH ATLANTIC

Mulholland, P. J., Best, G. R., Coutant, C. C., Hornberger, G. M., Meyer, J. L., Robinson, P. J, Stenberg, J. R., … & Wetzel, R. G. (1997). Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf Coast of Mexico. Hydrological Processes, 11, 949-970. doi: 10.1002/(SICI)1099-1085(19970630)11:8<949::AID-HYP513>3.0.CO;2-G

"Increasing winter minimum temperatures (or more probably reduction in the frequency and severity of freezing conditions) will most likely produce a northward shift in the range of subtropical species [in Florida]. Range shifts would be expected for several recently introduced invasive species, such as the tree Melaleuca quinquenervia (Cajeput) and the shrub Schinus terebinthifolius (Brazilian pepper), that can quickly suppress native species. In central and northern portions of the state, freshwater marshes may become dominated by Melaleuca and hardwood swamps by Schinus, as has occurred in the south."

Pattison, R. R., & Mack, R. N. (2008). Potential distribution of the invasive tree triadica sebifera (euphorbiaceae) in the united states: Evaluating climex predictions with field trials. Global Change Biology, 813-826.

"The likelihood of this spread is heightened by factoring in the tree's [Triadica sibifera] occurrence near perennial sources of water because the potential unoccupied range of T. sebifera includes some of the most dissected watersheds in the USA (Thornbury, 1965). Within major watersheds, such as those of the Tennessee and Cumberland Rivers, T. sebifera could spread extensively."

Pattison, R. R., & Mack, R. N. (2009). Environmental constraints on the invasion of Triadica sebifera in the eastern United States: an experimental field assessment. Oecologia, 158(4), 591-602. doi: 10.1007/s00442-008-1187-7

"These field trials [using seeds collected from approx. 50 trees near Georgetown, SC, USA] provide evidence for the likely spread of Chinese tallow tree [Triadica sebifera] to 38°N latitude and inland along the Savannah River."

"We had earlier found evidence for potential northward and inland spread for this invader [Chinese tallow tree, Tridica sebifera], based on projections from the CLIMEX model (Pattison and Mack 2008). Our field results [using seeds collected from approx. 50 trees near Georgetown, SC, USA] largely reinforce those predictions as well as provide insight into the tree's response to different microhabitats. Spread of T. sebifera, based on both lines of evidence, appears far from complete in the United States. But the extent to which on-going global atmospheric change will influence this range occupation complicates any predictions (Pattison and Mack 2008)."

INVASIVE PLANTS: TERRESTRIAL

SOUTH ATLANTIC

Drake, S. J., Weltzin, J. F., & Parr, P. D. (2003). Assessment of non-native invasive plant species on the united states department of energy oak ridge national environmental research park. Castanea, 15-30.

"The spatial distribution of cogongrass [Imperata cylindrical] climatic habitat under 2100 climate conditions is shown in Fig. 8. Once again, all models show a northward expansion, but the Maxent models predict invasion risk under more AOGCM [atmosphere-ocean general circulation model] conditions than the MD [Mahalanobis distance] models. An ensemble of both models, variable sets, and all AOGCM projections shows that current atrisk areas along the Gulf Coast will continue to be vulnerable to invasion by cogongrass, while the invasion risk is likely to expand considerably northward into Kentucky, West Virginia, and Virginia."

RESOURCE AREA (FACTOR): PLANT COMMUNITIES

GENERAL IMPACTS

SOUTH ATLANTIC

Ibáñez, I., Clark, J. S., & Dietze, M. C. (2008). Evaluating the sources of potential migrant species: implications under climate change. Ecological Applications, 18(7), 1664-1678. doi:10.1890/07-1594.1

"Increased aridity could result in a dramatic shift from temperate deciduous forest to southern mixed forest or even savanna, with increased importance of species from lower latitudes and elevations (Iverson et al. 1999, Bachelet et al. 2001). Climate-envelope assumptions suggest that immigrants will come from warmer regions (more southerly and lower elevation). Thus, predicted immigrants to the southeastern Piedmont are situated today in the Coastal Plain, and those to the Southern Appalachians now reside on the Piedmont (Fig. 1)."

INTERACTIONS WITH OTHER FACTORS

R8: SOUTHERN

White, P. B., van de Gevel, S. L., Grissino-Mayer, H. D., LaForest, L. B. & Deweese, G. G. (2011). Climatic Response of Oak Species across an Environmental Gradient in the Southern Appalachian Mountains, USA. Tree-Ring Research, 67(1), 27-37. doi: 10.3959/2009-1.1

"High correlations between tree growth and precipitation coupled with inverse relationships between temperature and growth at each site indicated moisture availability has the greatest influence on growth of southern Appalachian oak species [Quercus spp.]."

SOUTH CENTRAL

Harcombe, P. A., Hall, R. B. W., Glitzenstein, J. S., Cook, E. S., Krusic, P., Fulton, M., & Streng D. R. (1998). Chapter 5: Sensitivity of Gulf Coast Forests to Climate Change (Biological Science Report USGS/BRD/BSR-1998-0002). In G. R. Guntenspergen & B.A. Vairin (Eds.), Vulnerability of coastal wetlands in the Southeastern United States: climate change research results, 1992-97. Lafayette, LA: U.S. Department of the Interior, U.S. Geological Survey, National Wetlands Research Center: 44-66.

"If a climate change effect were primarily to alter the competitive balance among species by differentially changing growth or recruitment rates, we would expect a slow, gradual vegetation response. Alternatively, if climate change primarily affected the disturbance regime a much more rapid response would be predicted, involving shifts in species composition (greatest shifts on dry sites, intermediate shifts on mesic sites, low shifts on wet sites)."

TEMPERATE FORESTS

R8: SOUTHERN

Beckage, B., Gross, L. J., & Platt, W. J. (2006). Modelling responses of pine savannas to climate change and large-scale disturbance. Applied Vegetation Science, 9, 75-82.

"Reductions in the frequency of fires and hurricanes associated with global warming will push southeastern pine savannas towards a forested state with an increased overstory density and reduced understory component. If decreased fire frequency is associated with a corresponding increase in fire intensity that results in an elevated level of tree mortality, this may partially offset reduced frequency of fire. However, the overall effect of reductions in fire and hurricane frequencies in the southeastern U.S., together with a CO2 fertilization effect, will be to move savanna communities towards closed forests. . If we assume that the frequency of disturbance is reduced by half, for example, with fires occurring every ten years rather than every five years and hurricanes every 40 years rather than every 20 years, then the system will move from an equilibrium at (g* , w*) = (0.46, 0.44) to one at (0.23, 0.72) in ca. 75 years (Fig. 5)."

"The transformation of savannas to a more closed forest will have large effects on species diversity in the southeastern U.S.. Savanna understories are rich reservoirs of biodiversity (Platt 1999), which will be at risk in a warmer world with fewer large-scale disturbances, as the closing of the overstory canopy leads to large reductions in species richness in these systems (Platt et al. 2004)."

Bhuta, A. A. R., Kennedy, L. M., & Pederson, N. (2009). Climate-Radial growth relationships of northern latitudinal range margin longleaf pine (Pinus palustris P. Mill.) in the Atlantic coastal plain of southeastern Virginia. Tree-Ring Research, 65(2), 105-115. doi:10.3959/2008-17.1

"Regarding the climate response of the southern yellow pines in the southeastern temperate forests of North America, loblolly pine's climate response is the best-studied. A study of loblolly pine [Pinus taeda] across its range indicates its radial growth is limited by cool January and February temperatures at its NLRM [northern latitudinal range margin] in eastern Maryland and February temperatures and as it approaches its NLRM in Arkansas (Cook et al. 1998)."

Clark, J. S., Bell, D. M., Hersh, M. H., & Nichols, L. (2011). Climate change vulnerability of forest biodiversity: climate and competition tracking of demographic rates. Global Change Biology, 17, 1834-1849. doi: 10.1111/j.1365-2486.2010.02380.x

"Whereas only Magnolia acuminata has growth sensitivity to temperature greater than 10% (Fig. 3a), many species have sensitivities this large for fecundity (Fig. 3b). Spring temperature variation has a much larger effect on fecundity than does any variable on growth. Thus, the capacity to compete for regeneration sites locally and migrate in response to climate change, which both depend heavily on fecundity (Clark et al., 2001), represent one of the most critical consequences of climate change."

"If demographic rates of a species are not tracking a climate variable now, then data do not support the interpretation that it will respond to near-term changes in that variable in the future. In contrast to P. rigida [Pinus rigida], Liriodendron tulipifera populations of the southern Appalachians are not 'tracking' current climate, as demonstrated by the wide predictive intervals in the middle panels of Fig. 5. The inability to 'predict' climate variation indicates that these variables are not influencing current growth and reproduction. Overall, Liriodendron demography 'tracks' summer drought more closely than it does spring temperature, but not with the precision of P. rigida (Fig. 5). Liquidambar populations on the Piedmont sites track summer drought, but not spring temperature (Fig. 5)."

"Our results did not support the hypothesis that responses follow simple functional-type classes. We did not find that deciduous species were more responsive to temperature than evergreens (Way & Oren, 2010), with both groups being represented in the most and least sensitive extremes (Fig. 3a). However, the hypothesis that temperature can change developmental trajectories is consistent with our finding that fecundity responded disproportionately to temperature (Fig. 3b)"

"Species in the genera Pinus, Ulmus, Fagus, and Magnolia appear strongly influenced by climate variation, with their current demographic responses being dominated by fluctuations in at least two climate variables. As climate continues to change, these species will respond. Warming springs will benefit, whereas drought will harm."

Iverson, L. R., & Prasad, A. M. (2001). Potential redistribution of tree species habitat under five climate change scenarios in the Eastern U.S. Forest Ecology and Management, 155, 205-222.

"Seven of 15 species of oak (Quercus) would increase in IV-weighted area score by more than 40% (Table 2). Pinus taeda [Loblolly pine] and P. palustris [Pinus palustris, Longleaf pine], two economically important southern pine species are also projected to expand greatly in suitable habitat."

Samuelson, L. J., Stokes, T. A., & Johnsen, K. H. (2012). Ecophysiological comparison of 50-year-old longleaf pine, slash pine and loblolly pine. Forest Ecology and Management, 274, 108-115. doi:10.1016/j.foreco.2012.02.017

"Longleaf pine [Pinus palustris] has been suggested as a species that can contribute to climate change mitigation, because of long rotations and longterm carbon storage combined with greater resistance to insects, diseases and wind damage, less energy inputs relative to the more intensively managed loblolly pine [Pinus taeda] and slash pine [Pinus elliotii] (Stanturf et al., 2007; Johnsen et al., 2009), and superior tolerance to both drought and low soil nutrition, which has been largely assumed based on success of longleaf pine on highly well-drained sandy sites."

"On well-drained soils, longleaf pine [Pinus palustris] has a large tap root (4 m beneath the soil surface for a 250-year-old tree) and wide spreading root system (up to 23 m) (Heyward, 1933) that may provide greater access to water during drought than in loblolly [Pinus taeda] and slash pine [Pinus elliottii]. However, direct comparison of root morphology and depth among species is lacking. It is possible that during severe drought typically associated with longleaf pine habitat, longleaf pine may exhibit a more conservative water use strategy."

Samuelson, L. J. & Whitaker, W. B. (2012). Relationships between soil CO2 efflux and forest structure in 50-Year-old longleaf pine. Forest Science, 58(5), 472-484. doi:10.5849/forsci.11-049

"Longleaf pine [Pinus palustris] is a species that redistributes water from deeper to more shallow soil depths, and hydraulic redistribution may reduce drought impacts on root and microbial communities. Espeleta et al. (2004) observed hydraulic redistribution of soil water by roots of longleaf pine from deeper soil depths to more shallow depths (25 and 50 cm). High sapwood-specific hydraulic conductivity in roots of longleaf pine (Gonzalez-Benecke et al. 2010) may also maintain root production and root longevity during low soil moisture."

Zotz, G. & Bader, M. Y. (2009). Chapter 7: Epiphytic plants in a changing World-Global: Change effects on vascular and non-vascular epiphytes. In: U. Lьttge, W. Beyschlag, B. Bьdel, and D. Francis (Eds.), Progress in Botany, 70(4). Berlin, Heidelberg: Springer-Verlag, 147-170. doi: 10.1007/978-3-540-68421-3_7

"Although some vascular epiphytes can tolerate at least moderate frost (Jenkins 1999), freezing constitutes a major limitation to the occurrence of epiphytes and explains, e.g. to a large part the northern limits of vascular epiphytes in the southern USA. Thus, we may observe not only altitudinal range changes, but also a poleward expansion of epiphytic taxa with a further increase in minimum temperatures. For example, we expect the northern limit of Tillandsia usneoides, which currently extends north up to Virginia, to shift further north."

"Secondly, [vascular] epiphytes may be harmed by introduced pathogens or herbivores. There is at least one well-documented case with disastrous effects for epiphytic bromeliad populations in the southern USA: the introduction of the weevil Metamasius callizona, a native of Central America (Frank et al. 2006). "

SOUTH ATLANTIC

Bhuta, A. A. R., Kennedy, L. M., & Pederson, N. (2009). Climate-Radial growth relationships of northern latitudinal range margin longleaf pine (Pinus palustris P. Mill.) in the Atlantic coastal plain of southeastern Virginia. Tree-Ring Research, 65(2), 105-115. doi:10.3959/2008-17.1

"Loblolly pine [Pinus taeda] growth at the northeastern end of its range margin has been significantly correlated to January and February minimum and maximum temperatures. This response might be caused by freezing or desiccation during these months when maximum temperatures can plummet below 10°C (Cook et al. 1998). Our results [in southeastern Virginia] indicate that February temperature contributes to limiting the radial growth of longleaf pine [Pinus palustris] at its NLRM [northern latitudinal range margin], possibly for the same reasons postulated for loblolly pine."

"Interestingly, results here [for longleaf pine (Pinus palustris) in southeastern Virginia] support a growing body of literature indicating that the radial growth of conifers in the temperate eastern U.S. is constrained by winter temperatures."

"Our data also indicate that longleaf pine [Pinus palustris] is responding to current February precipitation at their NLRM [northern latitudinal range margin] in southeast Virginia. This differs from the findings of several other longleaf pine studies that found current spring and summer precipitation has significant influence on radial growth (Devall et al. 1991; Meldahl et al. 1999; Foster and Brooks 2001; Henderson and Grissino- Mayer 2009). A potential explanation of the lack of a strong drought response at longleaf pine's NLRM is that the evaporative demand during the growing season at this northerly latitude is less than what typically causes population-level water stress. Much replication is needed to better understand water stress at longleaf pine's NLRM. The significant relationship to February precipitation found here, however, is in agreement with longleaf pine studies in South Carolina and Texas (Henderson and Grissino-Mayer 2009)."

"Similar to the prediction for loblolly pine [Pinus taeda] by Cook et al. (1998), longleaf pine [Pinus palustris] might naturally expand northward beyond its present NLRM [northern latitudinal range margin] in southeastern Virginia because of rising temperatures. However, this scenario might still require reforestation and management efforts because of the limited distribution of naturally occurring longleaf pine populations and fragmented landscape within the study region."

"If future winter temperatures increase in southeastern Virginia, winter temperature stress on the radial growth is expected to decrease and resemble the lack of positive correlation to winter temperatures in more southerly loblolly pines [Pinus taeda] (Cook et al. 1998). A potential offset to a reduction of winter temperature stress, however, could come in the form of increased drought stress during the growing season. Therefore, any gains made by warmer winter temperatures could be negated by increased drought. On the other hand, increased drought might increase the likelihood of fire and favor longleaf pine [Pinus palustris] at the expense of other conifers and hardwoods currently dominating these sites (Gilliam and Platt 1999)."

Conner, W. H., Song, B., Williams, T. M., and Vernon, J. T. (2011). Long-term tree productivity of a South Carolina coastal plain forest across a hydrology gradient. Journal of Plant Ecology, 4(1-2), 67-76. doi:10.1093/jpe/rtq036

"Severe droughts in more upland areas have caused intense mortality of oaks (Quercus sp.) and hickories (Carya sp.) in many states (Stringer et al. 1989, Clinton et al. 1993, Faber-Langendren and Tester 1993, Elliot and Swank 1994, Allen and Breshears 1998). In this study [in the Waccamaw Neck area on the South Carolina coastal plain], however, very little mortality was observed in the study sites. Stemwood productivity did seem to respond to the drought, especially in the Wet site where swamp blackgum is the major component of the tree layer. In a preliminary study of the Wet site, Busbee et al. (2003) attributed low growth rates of individual swamp blackgum [Nyssa sylvatica] trees to high stem density (1,084 stems/ha) and/or long inundation times within the site. Swamp blackgum has been reported to be a slow grower in other wetlands (Day 1985; Keeland 1994; Keeland and Sharitz 1995; Keeland et al. 1997). Although stem productivity declined on the other sites, it was not as severe as in the Wet site."

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S.Environmental Protection Agency, 1-127.

"Even under many of the somewhat wetter future scenarios, closed-canopy forests of the Southeast may revert, or in some areas, be converted to savanna, woodland, or grassland under temperature-induced drought stress and a significant increase in fire disturbance (Bachelet et al., 2001; Scholze et al., 2006)."

Pataki, D. E. & Oren, R. (2003). Species differences in stomatal control of water loss at the canopy scale in a mature bottomland deciduous forest. Advances in Water Resources, 26(12), 1267-1278. doi:10.1016/j.advwatres.2003.08.001

"The drought sensitivity of [Liriodendron tulipifera, yellow poplar] illustrated here [at Duke Forest near Durham, North Carolina] is consistent with observation that this species is more restricted in its distribution than the other species we studied [Fowells 1965]. Thus, future changes in the occurrence or duration of precipitation may affect the success of this species to a greater extent than associated species, promoting shifts in the composition and structure of deciduous forests."

"Through comparisons with other stands composed of deciduous or evergreen species, the results [studying a bottomland deciduous forest at Duke Forest near Durham, North Carolina] suggest that more frequent or lengthy periods without precipitation may reduce the length of the growing season in low-lying stands adapted to moist conditions, with strong consequences for seasonal tree water use and hydrology in bottomland deciduous forests."

SOUTH CENTRAL

Chesser, J. D., & Brewer, J. S. (2011). Factors influencing seedling recruitment in a critically endangered pitcher plant, Sarracenia rubra ssp. alabamensis. Endangered Species Research, 13, 245-252. doi:10.3354/esr00329

"Although models suggest that both populations of [Sarracenia rubra ssp. Alabamensis, Alabama canebrake pitcher plant] should be able to persist for several decades by means of ramet survival and vegetative reproduction (Chesser 2010), colonization, the rescue effect, and adaptation facilitated by sexual reproduction all depend on successful seedling establishment (Felsenstein 1974, Maynard Smith 1978, Barton & Post 1986, Menges 1990, Winkler & Fischer 2001, Agrawal 2006, Ellis et al. 2007). If continued climate change makes the currently occupied ranges of these species unsuitable, then those that are not capable of migrating or adapting will go extinct."

"This [climate change] presents particular challenges to conservationists, because the vulnerability of [Sarracenia rubra ssp. Alabamensis, Alabama canebrake pitcher plant] seedlings to environmental factors that would not have as dramatic an effect on adults (e.g. dry soils) makes the success of re-introduced populations unpredictable, even in the event that such populations can be established with adults cultivated ex situ. On the other hand, the long life span of perennials such as S. rubra spp. alabamensis, combined with the fact that short-term population viability is relatively insensitive to the seedling recruitment failure (Brewer 2001, Ellis et al. 2007, Chesser 2010), might provide sufficient time for conservation biologists to investigate ways of artificially increasing seedling recruitment and thus long-term metapopulation viability."

Haavik, L. J., Stahle, D. W., & Stephen, F. M. (2011). Temporal aspects of Quercus rubra decline and relationship to climate in the Ozark and Ouachita Mountains, Arkansas. Canadian Journal of Forest Research, 41(4), 773-781. doi: 10.1139/x11-018

"Uncommonly severe drought events that occur within the lifetime of oaks [Quercus spp.] have been proposed as initiators of decline events (Staley 1965). This unusually severe and sustained 1950s drought, a precursor to the onset of growth decline in both age classes (Fig. 2), weakening climate relationships in both age classes (Fig. 3), and increasing populations of E. rufulus [Enaphalodes rufulus] (Haavik and Stephen 2010b), was likely the initiator of this oak decline event."

"While younger Q. rubra [Quercus rubra] exhibited greater growth rates and stronger climate relationships than older Q. rubra, some individuals among each age class were affected by growth decline or mortality during the recent E. rufulus [Enaphalodes rufulus] outbreak."

Harcombe, P. A., Hall, R. B. W., Glitzenstein, J. S., Cook, E. S., Krusic, P., Fulton, M., & Streng D. R. (1998). Chapter 5: Sensitivity of Gulf Coast Forests to Climate Change (Biological Science Report USGS/BRD/BSR-1998-0002). In G. R. Guntenspergen & B.A. Vairin (Eds.), Vulnerability of coastal wetlands in the Southeastern United States: climate change research results, 1992-97. Lafayette, LA: U.S. Department of the Interior, U.S. Geological Survey, National Wetlands Research Center: 44-66.

"For the mesic stand [at Weir Woods Preserve, Texas], which may be close to a long-term steady state, the effect of the hurricane on recruitment indicates that the stand will also be sensitive to a changing climate. In such communities, one likely effect of global warming would be to increase the disturbance rate and thereby to maintain the importance of loblolly pine [Pinus taeda], water oak [Quercus nigra], and white oak [Quercus alba], as well as promote invasion by exotic woody species like Chinese tallow [Triadica sebifera]. If the decline in American beech [Fagus grandifolia] is somehow related to global warming, the response of sites like this one may be much greater."

"Direct effects of climate on [tree] recruitment and mortality were not detected, though we did find that drought strongly increased seedling mortality in the wet forest [on the Neches River Floodplain in Big Thicket National Preserve, Texas] (Streng et al. 1989). The absence of effects on trees may be the result of masking by gradual death of trees, by multiple influences on tree death and decline (Harcombe 1987; though see Clinton et al. 1993), or by indirect disturbance effects."

Samuelson, L. J., Stokes, T. A., & Johnsen, K. H. (2012). Ecophysiological comparison of 50-year-old longleaf pine, slash pine and loblolly pine. Forest Ecology and Management, 274, 108-115. doi:10.1016/j.foreco.2012.02.017

"In summary, a more conservative water use strategy in longleaf pine [Pinus palustris] defined by lower gS [stomatal conductance] and higher WUE [leaf water use efficiency] relative to loblolly pine [Pinue taeda] and slash pine [Pinus elliotii] was not supported, although leaf δ13C was higher in longleaf pine than in loblolly pine [in Harrison Experimental Forest, Mississippi]. Higher ψL [leaf water potential] in longleaf pine than in loblolly pine and slash pine suggests possible adaptation to drier environments through hydraulic changes such as in the leaf area to sapwood area ratio, allocation to root versus shoot, and rooting depth, or increases in hydraulic efficiency such as in root conductivity (Addington et al., 2006; Gonzalez-Benecke et al., 2010; Gonzalez-Benecke et al., 2011)."

"No species differences [among longleaf pine ([Pinus palustris), loblolly pine (Pinus taeda) and slash pine (Pinus elliottii)] in short-term photosynthetic response to temperature and no photosynthetic temperature optimum was evident [in our study in Harrison Experimental Forest, Mississippi] which supports the supposition that temperature interactions with other environmental factors such as drought rather than large changes in photosynthesis with temperature may dominate southern pine forest response to climate change (Dillaway and Kruger, 2010; Gunderson et al., 2010; Wertin et al., 2010)."

RESOURCE AREA (FACTOR): RECREATION

GENERAL IMPACTS

R8: SOUTHERN

Scott, D., McBoyle, G., & Schwartzentruber, M. (2004). Climate change and the distribution of climatic resources for tourism in North America. Climate Research, 105-

"With additional cities gaining climates suitable for winter sun vacations, there will be increased destination choice and competition for the short-term winter sun holiday and the seasonal 'snowbird' market. This would present new opportunities in some regions (e.g. Georgia and South Carolina), while potentially reducing the market share of leading current destinations such as southern Florida, Arizona and particularly Mexico."

SOUTH ATLANTIC

Yu, G., Schwartz, Z., and Walsh, J. (2009). A weather-resolving index for assessing the impact of climate change on tourism related climate resources. Climatic Change, 95(3-4):551-573. doi:10.1007/s10584-009-9565-7

"For Orlando [Florida], while the influence of global warming on the quality of tourism climate conditions is negative overall (cf. the "annual" column in Table 5), there are substantial differences among seasons. Tourism conditions can be expected to deteriorate in summer, but to become more favorable in some winter months."

QUALITY OF RECREATIONAL EXPERIENCES

R8: SOUTHERN

Brownstein, J. S., Holford, T. R., & Fish, D. (2005). Effect of climate change on Lyme disease risk in North America. EcoHealth, 2(1), 38-46. doi: 10.1007/s10393-004-0139-x

"Minimum temperature increase also results in the extension of suitability [for Ixodes scapularis, deer tick] into higher altitudes. Elevation is an important limiting factor for I. scapularis populations because it indirectly affects population establishment through its influence on the complex interaction among climate, physical factors, and biota (Schulze et al., 1984). As a result of increasing temperatures, the model predicts advancement of suitability into the southern Appalachian Mountains."

RESOURCE AREA (FACTOR): SOIL & GEOLOGIC RESOURCES

SOIL CARBON

SOUTH ATLANTIC

Cui, J., Li, C., & Trettin, C. (2005). Analyzing the ecosystem carbon and hydrologic characteristics of forested wetland using a biogeochemical process model. Global Change Biology, 11(2), 278-289. doi:10.1111/j.1365-2486.2005.00900.x

"The annual C [carbon] balance in wetlands is sensitive to minor changes in climatic conditions that alter

the hydrologic regime. Temperature affects the rate of a number of processes that in turn affect soil C dynamics. The higher temperature at FL [Florida] site caused a decrease in SOC [soil organic carbon] (8074 kg C ha-1 yr-1) because of a greater proportion of C was respired during decomposition of soil pools."

Noormets, A., Gavazzi, M. J., McNulty, S. G., Domec, J.-C., Sun, G., King, J. S., & Chen, J. (2010). Response of carbon fluxes to drought in a coastal plain loblolly pine forest. Global Change Biology, 16(1), 272-287. doi:10.1111/j.1365-2486.2009.01928.x

"While not all coastal plain soils are rich in organic matter, many of them have C [carbon] densities up to an order of magnitude higher than upland soils (Johnson & Kern, 2003). And even on sandy soils, intensively managed commercial forests show net productivity up to four times higher than naturally regenerated stands (Powell et al., 2008). Therefore, despite limited range, the coastal plain forests may contribute significantly to the regional and continental C cycle."

Pritchard, S. G., Strand, A. E., McCormack, M. L., Davis, M. A., Finzi, A. C., Jackson, R. B., Matamala, R., … & Orens, R. (2008). Fine root dynamics in a loblolly pine forest are influenced by free-air-CO2-enrichment: a six-year-minirhizotron study. Global Change Biology, 14, 588-602. doi: 10.1111/j.1365-2486.2007.01523.x

"Consistent (but insignificant) effects of elevated CO2 on [loblolly pine (Pinus taeda)] root production and fast turnover times of fine roots in the soil, combine to suggest that fine root turnover may be contributing to C flow into soils of Southeastern pine forests. Averaged over the 6-year study, average annual fine root mortality was 36% greater in CO2-enriched plots compared with controls. This increase in mortality (and thus C flow into soil) is partially explained by greater production (+25%) and shorter fine root lifespans (500 days in CO2 enriched and 574 days in ambient plots)."

SOIL HEALTH

R8: SOUTHERN

Iversen, C. M., Keller, J. K., Garten, C. T., and Norby, R. J. (2012). Soil carbon and nitrogen cycling and storage throughout the soil profile in a sweetgum plantation after 11 years of CO2-enrichment. Global Change Biology, 18, 1684-1697. doi:10.1111/j.1365-2486.2012.02643.x

"CO2-enrichment increased the amount of C in the fine-root standing crop [of sweetgum trees, Liquidambar styraciflua, in Oak Ridge, Tennessee], whole-soil, and POM [particulate organic matter] pools, and increased the amount of N in the fine-root, whole-soil, and MOM [mineral-associated organic matter] pools. Root and soil C and N content declined with soil depth, but there were no interactions between CO2 treatment and soil depth (Table 1)."

RESOURCE AREA (FACTOR): VEGETATION MANAGEMENT

CARBON SEQUESTRATION

R8: SOUTHERN

Aspinwall, M. J., McKeand, S. E., & King, J. S. (2012). Carbon sequestration from 40 years of planting genetically improved loblolly pine across the southeast United States. Forest Science, In Press. doi:10.5849/forsci.11-058

"Although separate from genetic improvement or intensive management, there are other factors that may have affected or may affect future C [carbon] sequestration with genetically improved loblolly pine [Pinus taeda]. For one, increases in C sequestration over time due to genetic improvement are confounded with rising atmospheric CO2 concentrations, which may have stimulated productivity and C sequestration (DeLucia et al. 1999, Hamilton et al. 2002, McCarthy et al. 2010). Therefore, genetic improvement operations may have been indirectly selecting genotypes that show enhanced capacity for sequestering C under elevated CO2. However, we have found no evidence of genetic differences in photosynthetic CO2 response curves across different levels of genetic homogeneity in loblolly pine (Aspinwall et al. 2011b)."

"Even if rising CO2 has increased productivity to some degree, nitrogen (N) limitation may have curbed the CO2 fertilization effect (Oren et al. 2001, McCarthy et al. 2010), and temporal variation in loblolly pine [Pinus taeda] C [carbon] sequestration is constrained by variations in precipitation and potential evapotranspiration (McCarthy et al. 2010). However, it is possible that under N-limited conditions and elevated CO2, the higher productivity of some loblolly pine genotypes may be the result of greater N use efficiency (Centritto and Jarvis 1999)."

"Carbon sequestration and emissions from harvested wood products is also dependent on the lifespan of the end product. In the southern United States, sawlogs and pulpwood represent about 28 and 25%, respectively, of softwood removals (Wear and Greis 2002). Nonetheless, the southern United States currently produces the majority of the world's solid wood (Wear and Greis 2002), and the physical storage of C [carbon] in wood products and landfills represents a substantial carbon sink (Birdsey and Heath 1995, Woodbury et al. 2007)."

Chen, G., Tian, H., Zhang, C., Liu, M., Ren, W., Zhu, W., … & Lockaby, G. (2012). Drought in the southern United States over the 20th century: variability and its impacts on terrestrial ecosystem productivity and carbon storage. Climatic Change, 114(2), 379-397. doi:10.1007/s10584-012-0410-z

"NPP [net primary productivity] was greatly reduced during dry years and could be more than 40% in some areas. NPP decreased in large areas of the eastern SUS [southern United States], while increasing in most areas of the west. Changes in precipitation pattern resulted in a C emission and displayed great spatial variability. Changes in precipitation induced C [carbon] sinks in most areas of the western SUS and C sources in most areas of the east. Drought impacts on NPP and C storage could be enhanced by changes in other environmental factors such as air temperature and land use change."

Hyvonen, R., Agren, G. I., Linder, S., Persson, T., Cotrufo, M. F., Ekblad, A., . . . Wallin, G. (2007). The likely impact of elevated [co2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: A literature review. New Phytologist, 173, 462-480.

"Similarly, on nutrient-poor sandy soils in the south-eastern USA, a loblolly pine [Pinus taeda] stand re-established LAI [Leaf Area Index] slowly and remained a source of C [Carbon] 6 yr after clear-cutting, whereas a fertilized stand returned to being a C sink within that time as LAI rapidly doubled (Lai et al., 2002)."

Tian, H., Melillo, J. M., Kicklighter, D. W., McGuire, A. D., Helfrich, J. V., Moore, B., & Vorosmarty, C. J. (1998). Effect of interannual climate variability on carbon storage in Amazonian ecosystems. Nature, 396(6712), 664-667.

"Changes in climate have been linked to both increases and decreases in plant growth and C [carbon] storage in terrestrial ecosystems. For instance, large-scale droughts have reduced regional [southern United States] net primary productivity and C storage (Zhao and Running 2010; Chen and others 2012)."

Tian, H., Chen, G., Zhang, C., Liu, M., Sun, G., Chappelka, A., … & Vance, E. (2012). Century-Scale responses of ecosystem carbon storage and flux to multiple environmental changes in the southern United States. Ecosystems, 15(4), 674-694. doi:10.1007/s10021-012-9539-x

"Continued regional warming [in the southern US] may result in C [carbon] loss from ecosystems through enhanced plant and soil respiration (Woodwell and others 1995; Chen and Tian 2005), but increased nitrogen (N) availability has also been associated with increased plant growth (Tian and others 1999; Melillo and others 2002) and a lengthening of the active growing season (Myneni and others 1997). Elevated atmospheric CO2 and N deposition have been shown to stimulate photosynthesis in a variety of plant species and ecosystems (Curtis and Wang 1998; Ellsworth 1999; Norby and others 2005; Luo and others 2008). However, it is not clear how long the CO2 fertilization effects will last in cases where N or other nutrients become limiting (Oren and others 2001; Luo and others 2004; Johnson 2006)."

"The impacts of tropospheric ozone (O3) concentration on regional [southern United States] C dynamics have received less attention but current studies indicate that elevated O3 concentration has significantly reduced C sequestration and net primary productivity (NPP) of terrestrial plants, particularly agricultural crops, which could offset the positive effects of elevated atmospheric CO2 and N deposition (Chameides and others 1994; Chapelka and Samulson 1998; Ollinger and others 2002; Felzer and others 2004; Ren and others 2007a, 2011a, b)."

"Simulated results indicated that multiple changes in climate, atmospheric composition, and land use and land cover resulted in a net C [carbon] sink of 0.80 ± 0.38 Pg (1 Pg = 1015 g) in the SUS [Southern United States] for the entire study period (that is, 1895 to 2007). This sink accounted for 2.7% of the total ecosystem C storage within the SUS in 1895 (Table 2). However, SUS terrestrial ecosystems were a C source of 1.20 ± 0.56 Pg from 1895 to 1950 and a C sink of 2.00 ± 0.94 Pg from 1951 to 2007 (Table 2; Figure 6A)."

"Land use, land-cover type, and precipitation were the primary determinants of C [carbon] density, which increased from west to east [of the Southern United States] (Figure 8). The highest C storage, generally greater than 25 kg/m2, was in wetland areas. Total C storage was also determined for each state (Figure 7C). During the 2007 regional drought, Texas had the highest terrestrial ecosystem C storage of any state (4.17 ± 0.39 Pg) due to its large land area. This was followed by Florida (3.81 ± 0.36 Pg), which has a large wetland area (about 18% of the total land area) (Figure 1). Kentucky had the lowest C storage (1.46 ± 0.14 Pg)."

"Among the five environmental factors [climate, land-use land-cover change, Nitrogen deposition, atmospheric CO2, and tropospheric O3] LULCC [land-use land-cover change] (including N fertilizer application and irrigation in cropland) led to a net C [carbon] source of 1.26 Pg (Figure 10B, C), accounting for 213% of the net C storage change from 1895 to 2007 [in the southern US] (Table 3). Although cropland fertilizer use (Figure 4D) greatly increased C storage (0.45 Pg C), the long-term LULCC legacy effects appear to have largely offset this C sink."

"The 30% increase in atmospheric CO2 concentrations from 1895 to 2007 contributed 1.94 Pg to the SUS [Southern United States] C [carbon] sink. The increases in the atmospheric CO2 concentrations and N deposition caused the largest contribution of the five factors and consistently increased during the study period (Figure 4C). Nitrogen deposition resulted in a net C sink of 0.48 Pg, contributing about 82% of the net change in C storage (Figure 10B, C; Table 3). Elevated O3 and climate change were less influential, reducing C storage by 0.58 and 0.40 Pg during the study period."

"The largest positive interactive effect was found between CO2 and N [nitrogen] deposition (0.35 Pg C, Table 4), indicating increasing N deposition could enhance the CO2 fertilization effect [in the southern US]. The largest negative interactive effect was found between climate warming and elevated atmospheric CO2 (-0.24 Pg C), indicating that warming might weaken the CO2 fertilization effect on C [carbon] sequestration."

"The results indicate that the CO2 fertilization effect on C [carbon] storage was obviously enhanced by N [nitrogen] deposition for all natural vegetation types [in the Southern United States] except grassland (Figure 11E), where N [nitrogen] deposition only slightly enhanced the CO2 fertilization effect. This interactive effect was less responsive at lower N deposition and atmospheric CO2 levels and increased at higher levels for all biome types except grassland."

"Our study suggests that elevated CO2 was the largest contributor to C [carbon] sequestration in the SUS [Southern United States]. However, the impacts of elevated CO2 may be constrained by other factors such as climate, land-use history, and N [nitrogen] availability (Norby and others 2005; Johnson 2006; Luo and others 2004, 2008)."

"Meta-data analysis indicated that a doubling of the CO2 concentration could stimulate NPP [net primary productivity] by a median value of 23% for forest (Norby and others 2005) and stimulate C [carbon] storage within a wide range of environmental conditions. We found that across all vegetation types, a 30% increase in the CO2 concentration from 1895 to 2007 stimulated NPP by 12% and C storage by 6%, and stimulated forest NPP by 12% and C storage by 12 and 6% in the SUS [Southern United

"Increased O3 concentrations decreased NPP [net primary productivity] [in the southern US] by 3% and C [carbon] storage 2% (0.58 Pg C), for all vegetation types, 3 and 5% for deciduous broadleaf forest, 0.5 and 0.3% for evergreen needle-leaf forest, and 7 and 5% for cropland. "

"Our simulated O3 impacts on NPP and C [carbon] storage [for the southern US] were within the range of field observational data and other model simulations in the continental US (Heck and others 1984; Pye 1988; Ollinger and others 2002; Felzer and others 2004). In addition, we found that O3 had the largest impacts on NPP and C storage of deciduous broadleaf forest and cropland, which was also consistent with previous studies (Chameides and others 1994; Chapelka and Samulson 1998; Ollinger and others 2002; Felzer and others 2004; Ren and others 2007b; Zhang and others 2007)."

SOUTH ATLANTIC

Dai, Z., Trettin, C. C., Li, C., Amatya, D. M., Su, G., & Li, H. (2010). Sensitivity of stream flow and water table depth to potential climatic variability in a coastal forested watershed. Journal of the American Water Resources Association, 46(5), 1036-1048. doi: 10.1111/j.1752-1688.2010.00474.x

"This study [on Santee Experimental Forest near Charleston, South Carolina] indicates that hurricane can substantially influence CO2 sequestration in the coastal forest ecosystems, including reducing C [carbon] storage in the stands and in- creasing soil CO2 flux within a short period. Climate variability and change can alter soil CO2 flux from this forested watershed. CO2 fluxes can increase with a decrease in water table level regulated by climate. Projecting those impacts to future climate change, soil CO2 flux can increase due to temperature rise without bringing more precipitation to this forest, leading to an increase in evapotranspiration demands that incurs a decrease in water table level."

Noormets, A., Gavazzi, M. J., McNulty, S. G., Domec, J.-C., Sun, G., King, J. S., & Chen, J. (2010). Response of carbon fluxes to drought in a coastal plain loblolly pine forest. Global Change Biology, 16(1), 272-287. doi:10.1111/j.1365-2486.2009.01928.x

"The loblolly pine [Pinus taeda] plantation in the lower coastal plain of North Carolina, USA, acted as a strong C [carbon] sink, sequestering 360–835 gCm_2 yr_1 through the 3 years of study."

"Even though the GWT [ground water table] was generally high [at our site on a loblolly pine (Pinus taeda) plantation in the lower coastal plain of North Carolina], there were indications of moisture limitation on C [carbon] sequestration, including (i) sensitivity of gc_max [Daily maximum canopy conductance] to VPD [vapor pressure deficit] at low VWC [volumetric water content] (<50% of total

extractable water), and (ii) decreasing plant hydraulic conductivity Ktree [Whole tree hydraulic conductance] during drought."

Stoy, P. C., Katul, G. G., Siqueira, M. B. S., Juang, J. -Y., Novic, K. A., McCarthy, H. R., … & Oren, R. (2008). Role of vegetation in determining carbon sequestration along ecological succession in the southeastern United States. Global Change Biology, 14, 1-19. doi: 10.1111/j.1365-2486.2008.01587.x

"NEEA [annual net ecosystem exchange] at OF [old-field] was near zero, PP [planted pine] was the most productive of the three ecosystems under ideal conditions, and NEEA at HW [hardwood forest] was highly resistant to climatic variability (Table 1, Figs 1–3). These results largely followed expectations based on the 'Strategy of Ecosystem Development' of Odum (1969), which hypothesizes that GPP [gross primary productivity] rapidly increases with ecological succession, then decreases as forests age, while RE [ecosystem respiration] increases monotonically due to the increase in autotrophic biomass."

"Odum (1969) additionally hypothesized that early successional ecosystems maximize productivity, while late successional ecosystems maximize 'protection' against (i.e. resistance to) environmental variation. Indirect evidence of this characteristic can be identified in the NEE [net ecosystem exchange] measurements: NEEA [annual net ecosystem exchange] at PP [planted pine] was highest under ideal conditions, but was also highly variable in response to environmental variability, while the interannual variability of NEEA at HW [hardwood forest] was small (Table 1, Figs 1–3)."

"The result that the hardwood forest (HW) was insensitive to drought compared with the adjacent coniferous forest (PP) contrasts with previous results in Canada and Europe (Kljun et al., 2006; Granier et al., 2007), which have found coniferous forests to be generally less drought sensitive (Baldocchi, 2008). Our results agree instead with flux research, demonstrating that more mature forests are less drought sensitive (Law et al., 2001)."

SOUTH CENTRAL

Norby, R. J., Ledford, J., Reilly, C. D., Miller, N. E., & O'Neill, E. G. (2004). Fine-root production dominates response of a deciduous forest to atmospheric CO2 enrichment. Proceedings of the National Academy of Sciences, 101(26), 9689-9693. doi: 10.1073/pnas.0403491101

"The additional C taken up and converted to organic matter by trees [planted sweetgum, Liquidambar styraciflua] in CO2-enriched plots (average 22% increase in NPP [net primary productivity]) was allocated primarily to fine-root production (Fig. 2D). After the first year of treatment, there was no significant increase in aboveground woody dry matter production (stem growth). Because fine-root turnover is much faster than turnover of woody stems, the preferential allocation to fine roots should significantly reduce the potential for additional C sequestration in trees in elevated CO2 (Norby et al. 2002)."

FACTORS LIMITING PRODUCTIVITY

R8: SOUTHERN

Bachelet, D., Neilson, R. P., Hickler, T., Drapek, R. J., Lenihan, J. M., Sykes, M. T., . . . Thonicke, K. (2003). Simulating past and future dynamics of natural ecosystems in the United States. Global Biogeochemical Cycles, 17.

"Under CGCMI [Canadian Global Coupled Model 1], both LPJ [Lund-Potsdam-Jena] and MC1 [MAPSS - CENTURY 1] suggest a rapid, drought-induced decline in southeastern forests, indicated by a reduction in vegetation density."

Runion, G. B., Entry, J. A., Prior, S. A., Mitchell, R. J., & Rogers, H. H. (1999). Tissue chemistry and carbon allocation in seedlings of Pinus palustris subjected to elevated atmospheric CO2 and water stress. Tree Physiology, 19(4-5), 329-335. doi:10.1093/treephys/19.4-5.329

"An increase in biomass in response to elevated CO2 in well-watered longleaf pine [Pinus palustris] plants, with no interactions between CO2 and water supply [shown in our study using containerized saplings exposed to elevated CO2 in open-top chambers for 20 months], is similar to results from other studies examining effects of water stress and elevated CO2 on tree seedlings (Samuelson and Seiler 1993, Tschaplinski et al. 1993). Elevated CO2 tended to decrease tissue N concentration, whereas water stress increased tissue N concentration, a finding similar to that reported for loblolly pine (Tschaplinski et al. 1993). Seedlings grown in elevated CO2 and subjected to water stress partitioned more biomass below ground or into fine roots than well-watered seedlings grown in ambient CO2, but there were few significant changes in allocation of C compounds in response to either the CO2 or water treatment, suggesting that functional relationships and balances among plant organs were not greatly altered by the treatments."

"Our findings that elevated atmospheric CO2 concentration and plant water status influenced longleaf pine [Pinus palustris] tissue chemistry [shown in our study using containerized saplings exposed to elevated CO2 in open-top chambers for 20 months] indicate potential alterations in susceptibility to insect and disease attack and rates of decomposition."

SOUTH ATLANTIC

Bracho, R. G., Starr, G., Gholz, H., Martin, T. A., Cropper, Jr., W. P., and Loescher, H. W. (In press). Controls on carbon dynamics by ecosystem structure and climate for southeastern U.S. slash pine plantations. Ecological Monographs. doi:10.1890/11-0587.1

"Water deficits during the growing season actually had two effects on LAI [leaf area index] [of Pinus elliottii]: i) early needle drop as compared with wet years, and ii) a reduction in needle growth. Two pulses of needle fall were recorded during drought years (data not shown), a smaller one in late spring and early summer, in addition to the normal more major event in the late fall, as observed for similar stands by Gholz et al. (1991)."

"However, if low precipitation extends through the growing season during severe and extreme drought conditions, elongation of newly formed needles is also reduced, as observed for Pinus radiata by (Linder et al. 1987) and (Sands and Correll 1976) and in our stands [of Pinus elliottii] in 2006-2007."

"After canopy closure, the annual variability in NEE of these [Pinus elliottii] sites was most closely related to the departure of growing season precipitation from long-term averages ($r2 = 0.54$, $P<0.01$; Fig. 7a)."

Shugart, H., Sedjo, R., & Sohngen, B. (2003). Forests & global climate change potential impacts on U.S. forest resources. Pew Center on Global Climate Change.

"The Southeast, which is currently a dominant region for forestry, is likely to experience net losses, as tree species migrate northward and tree productivity declines."

SOUTH CENTRAL

Norby, R. J., Ledford, J., Reilly, C. D., Miller, N. E., & O'Neill, E. G. (2004). Fine-root production dominates response of a deciduous forest to atmospheric CO2 enrichment. Proceedings of the National Academy of Sciences, 101(26), 9689-9693. doi:10.1073/pnas.0403491101

"Microbial N cycling and N availability have not responded to elevated CO2 in this [planted sweetgum (Liquidambar styraciflua) stand] or other forest stands (Zak at al. 2003); therefore, the N needed to meet the requirement for increased NPP [net primary productivity] must be met through increased access to soil N."

"The CO2-induced increase in fine-root standing crop in summer could also be an important mechanism for conferring increased resistance to late-season droughts. Because leaf area index of this stand did not respond to CO2 enrichment (Norby et al. 2003), there was a large increase in the ratio of fine-root length to leaf area. This result implies a reduction in hydraulic resistance at the rhizosphere, making more soil water available (Sperry et al. 2002). The stimulation of root growth in deeper soil could be particularly important in buffering trees against seasonal droughts. However, we have not observed any interactions between CO2 and drought in this stand."

GENERAL IMPACTS

R8: SOUTHERN

Sohngen, B., & Sedjo, R. (2005). Impacts of climate change on forest product markets: Implications for North American producers. Forestry Chronicle, 81, 669-674.

"Within North America, existing studies suggest that producers [of forest products] in northern regions are less susceptible to climate change impacts than producers in southern regions because many climate and ecological models suggest that climate become dryer in the U.S. South."

GROWTH AND YIELD

R8: SOUTHERN

Huang, J., Abt, B., Kinderman, G., Ghosh, S. (2011). Empirical analysis of climate change impact on loblolly pine plantations in the southern United States. Natural Resource Modeling, 24(4), 445-476. doi: 10.1111/j.1939-7445.2011.00098.x

"Across all four climate scenarios, the percentage change in GSV/ha [growing stock volume per hectare] [of loblolly pine (Pinus taeda) plantations] ranges from −31% to 16%. The prediction under the A1 scenario is slightly lower and the prediction under the B2 scenario is slightly higher than for other scenarios. Recall that the Hadley III A1 model predicts the largest increase in temperature and B2 predicts the smallest increase in temperature. The SGM results imply that a less warm climate would be preferable to a warmer climate for loblolly pine plantations in the southern United States. Although the magnitude of the prediction varies for different scenarios, the spatial pattern of the growth change is consistent across the four scenarios. Georgia, South Carolina, North Carolina, Arkansas, and eastern Texas are projected to experience a larger increase in loblolly pine growth. A larger decrease in the GSV is projected to occur in Florida, southern Louisiana, and southern Alabama. "

"The average site productivity across all managed loblolly pine [Pinus taeda] plots was assumed for the current growth curve. Then the change in the site productivity due to climate change was added to the current site productivity to generate the future growth curve. Similar to the SGM [static growth model] results (Figure 3), the DGM [dynamic growth model] results shown in Figure 7 indicate that the regional impact of climate change on the growth of loblolly pine stand is quite small, although the impact at a smaller scale can be significant. "

"We observed a similar spatial pattern [in loblolly pine (Pinus taeda) plantations]; that is, the southern counties in the study area are likely to experience a decrease in GSV [growing stock volume] or site productivity, while some northern counties may obtain an increase in GSV or site productivity under future climate scenarios. This spatial variation in the change of GSV and site productivity indicates that climate change has the potential to affect the future growth of loblolly pine in the southern United States locally (i.e., at small scales). "

"Both Figures 3 and 7 show that climate change may benefit the South as a whole (i.e., the mean GSV [growing stock volume] is estimated to increase across the study area under future climate scenarios, although the increase is quite small). Given that loblolly pine (Pinus taeda) stands in some counties may lose volume while others may gain, it is plausible that the overall impact across the region is marginal. "

"By combining our growth models with potential future climate change scenarios over the next 50 years, we found only minor overall impacts on [lobloly pine (Pinus taeda)] species growth in the South but significant spatial variation, with northern counties benefiting from climate change and southern counties experiencing growth declines. The overall pattern is consistent across the growth models and climate scenarios. This trend implies that the loblolly pine plantations might expand northward in the future, which is consistent with the projection derived by the U.S. Forest Service (http://www.nrs.fs.fed.us/atlas/tree/RFtreemod˙131.html#)."

McNulty, S. G., Vose, J. M., & Swank, W. T. (1996). Potential Climate Change Effects on Loblolly Pine Forest Productivity and Drainage across the Southern United States. Ambio, 25(7), 449-453.

"The MCC Scenario [historic site climate + combined increases in air temperature and precipitation] predicted that NPP [net primary productivity] [of loblolly pine (Pinus taeda] at the VA [Virginia] site would increase, while predicted NPP at the three other sites decreased. The MCC Scenario for the VA site did not increase average growing season air temperature beyond optimal levels for photosynthesis (Strain et al. 1976), and increased precipitation reduced water stress. Conversely, the effects of increased temperature at the FL [Florida] and TX [Texas] sites were not offset by increased precipitation, so NPP decreased. Finally, the MS [Mississippi] site, which had the highest precipitation and intermediate air temperature, showed the smallest increase in NPP when precipitation was increased by 20% and exhibited a moderate reduction in NPP under the MCC Scenario."

"Climate change could significantly reduce NPP [net primary productivity] and increase drainage across many forested areas in the southern US. Forests located in the warmest sections of the present range of loblolly pine [Pinus taeda] are more susceptible to changes in productivity and hydrology than forests located in wetter or cooler areas."

Moore, D. J., Aref, S., Ho, R. M., Pippen, J. S., Hamilton, J. G., & DeLucia, E. H. (2006). Annual basal area increment and growth duration of Pinus taeda in response to eight years of free-air carbon dioxide enrichment. Global Change Biology, 12, 1367–1377. doi: 10.1111/j.1365-2486.2006.01189.x

"Exposure of a Pinus taeda [loblolly pine] forest to elevated CO2 for 6 years caused an increase in basal area (BA) growth and productivity (DeLucia et al., 1999; Hamilton et al., 2002; Scha¨fer et al., 2003; Finzi et al., 2006). However, there has been no corresponding increase in the rate of nitrogen mineralization in plots exposed to elevated CO2 (Finzi et al., 2002; 2006) and nitrogen has become increasingly immobilized in biomass and organic soil (Finzi et al., 2006), suggesting that the growth stimulation may decline in the future."

"Annual BAI [basal area increment] [of loblolly pines (Pinus taeda)] varied among years and was on average higher in trees exposed to elevated CO2 (Table 1; Fig. 3a). There was a significant stimulation of annual BAI in each year of the experiment that varied between 13.2% and 27.4% (Fig. 3). "

"Although a significant crown class by treatment interaction could not be resolved (Table 3), it appeared that the relative stimulation was greater for emergent (19%) and dominant [loblolly pine (Pinus taeda)] trees (24.5%) than for the subcanopy individuals (11.4%; Fig. 4), suggesting that the smaller suppressed trees may not have been able to take full advantage of the extra CO2 provided by the treatment."

"While basal area growth ceased in the winter (Figs 1 and 2), P. taeda [loblolly pine (Pinus taeda)] needles are physiologically active throughout the year (Hymus et al., 1999). We might expect photosynthetic enhancements during the winter to provide more carbohydrate to pines in elevated CO2 and perhaps allow them to commence growth earlier, during slightly colder conditions."

"In this study, elevated CO2 had no effect on the relationship between tree growth and rainfall or soil moisture. Stomatal conductance and transpiration in P. taeda [Pinus taeda (loblolly pine)] are unresponsive to elevated CO2 (Teskey, 1995; Pataki et al., 1998; Ellsworth, 1999; Scha¨fer et al., 2002) so for this species it is not likely to have a disproportionate effect on growth during times of low rainfall."

"Because P. taeda [Pinus taeda (loblolly pine)] trees grew more in elevated CO2 and consequently used more nutrients (Finzi et al., 2002) it is possible that the suppressed individuals would be more competitively disadvantaged in elevated CO2 than in ambient CO2."

"The initial stimulation in above ground stem growth diminished substantially in a Liquidambar styraciflua forest after 3 years of CO2 exposure, as trees allocated new carbon to the production of fine roots (Norby et al., 2004)."

"Based on analyses up to 2002, trees grown in elevated CO2 accumulate nitrogen in biomass at a faster rate than their ambient grown counterparts, and depending on future changes in ecosystem C:N ratio and net nitrogen mineralization rates, the CO2 effect on growth and productivity may diminish in coming years (Finzi et al., 2006). However, for the first 8 years of this experiment there has been a consistently positive effect of CO2 on P. taeda [Pinus taeda (loblolly pine)] growth."

Norby, R. J., Ledford, J., Reilly, C. D., Miller, N. E., & O'Neill, E. G. (2004). Fine-root production dominates response of a deciduous forest to atmospheric CO2 enrichment. Proceedings of the National Academy of Sciences, 101(26), 9689-9693. doi: 10.1073/pnas.0403491101

"These results contrast with those from the similar FACE [free-air CO2 enrichment] experiment in a loblolly pine [Pinus taeda] stand (Hamilton et al. 2002). There, the enhancement in NPP [net primary productivity] was allocated primarily to aboveground stem increment. The C in pine fine roots has a 3-fold-higher MRT [mean residence time] than in sweetgum [Liquidambar styraciflua] roots (Matamala at al. 2003) (similar to the difference in MRT of the evergreen vs. deciduous canopy); therefore, annual fine-root production and mortality rates are much lower than in our sweetgum stand, and the pine root system is less responsive to elevated CO2 (Matamala & Schlesinger 2000)."

Runion, G. B., Prior, S. A., Rogers, H. H., & Mitchell, R. J. (2010). Effects of elevated atmospheric CO2 on two southern forest diseases. New Forests, 39, 275-285. doi: 10.1007/s11056-009-9170-7

"In both runs of the experiment, 6-weeks of growth under elevated CO2 resulted in significantly taller loblolly pine [Pinus taeda] seedlings (Table 1). Since seedlings were assigned to open top chambers at random, there was no difference in seedling height before placement into the chambers. Therefore, the increase in height was due to an increase in size of the new, succulent, apical growth (candles). Seedling groundline diameters were also statistically larger (run 2) or tended to be larger (run 1) when exposed to elevated CO2 (Table 1)."

Shugart, H., Sedjo, R., & Sohngen, B. (2003). Forests & global climate change potential impacts on U.S. forest resources. Pew Center on Global Climate Change.

"The results imply a reduced presence and performance of loblolly pine [Pinus taeda] in the southeastern United States and a shift into Kentucky and northward, where it now does not occur."

Wagner, R. J., Kaye, M. W., Abrams, M. D., Hanson, P. J., & Martin, M. (2012). Tree-ring growth and wood chemistry response to manipulated precipitation variation for two temperate Quercus species. Tree-Ring Research, 68(1), 17-29. doi:10.3959/2010-6.1

"We expected 13 years of altered precipitation to affect the annual ring growth of two dominant oak species [white oak, Quercus alba, and chestnut oak, Quercus prinus] in the southeastern US; however neither species was sensitive to a ~30% increase or decrease in throughfall. We found interannual responses to seasonal precipitation and temperature and the inherent variation in growth between species to be the most significant variables influencing observed patterns in annual ring growth."

"The impact of changing climate on the development of the mixed oak {Quercus] forests of the Southeastern United States is largely unknown. Although the results of this study imply a possible resilience of oak trees to climate stressors, the trees sampled for the study were growing at a relatively favorable site, leaving the possibility that these results may not hold true for sensitive species growing on more stressed locations."

Wertin, T. M., McGuire, M. A., van Iersel, M., Ruter, J. M., & Teskey, R. O. (2012). Effects of elevated temperature and [CO2] on photosynthesis, leaf respiration, and biomass accumulation of Pinus taeda seedlings at a cool and a warm site within the species' current range. Canadian Journal of Forest Research, 42(5), 943-957. doi:10.1139/x2012-

"Two studies have reported that an increase in mean growing season air temperature caused a decrease in tree growth (Norby et al. 2000; Wertin et al. 2011). Both studies were at sites near the southern (warmer) geographic limit of the species' range, suggesting that increased temperatures at these sites may have been supra-optimal for net carbon gain and growth. In one study, seedlings of sugar maple (Acer saccharum Marsh.) had reduced stem height (21%) and stem diameter (16%) with an increase in air temperature of +3.5 °C (Norby et al. 2000). In the other, seedlings of northern red oak (Quercus rubra L.) had 18 and 36% less biomass in +3 and +6 °C elevated air temperature treatments, respectively, compared with seedlings grown at ambient temperature (Wertin et al. 2011)."

Woodbury, P. B., Smith, J. E., Weinstein, D. A., & Laurence, J. A. (1998). Assessing potential climate change effects on loblolly pine growth: A probabilistic regional modeling approach. Forest Ecology and Management, 107(1), 99-116.

"Based on a climate change scenario derived from the results of four GCMs [General Circulation Models], our model estimated that loblolly [pine] [Pinus taeda] growth will likely decrease slightly throughout its 12-state range."

"We also determined which climatic factors and components of [Pinus taeda] tree growth had the most influence on the predicted growth rate. The most influential factor at all locations was the relative change in C assimilation. Of climatic factors, CO, concentration was found to be the most influential factor at all locations. Substantial regional variation in estimated growth was observed, and was probably due primarily to variation in historical growth rates and to the importance of historical growth in our model structure."

SOUTH ATLANTIC

Kallarackal, J. & Roby, T. J. (2012). Responses of trees to elevated carbon dioxide and climate change. Biodiversity and Conservation, 21, 3127 – 1342. DOI 10.1007/s10531-012-0254-x

"A study on the extreme drought and acute heat wave that impacted ecosystems across the southeastern USA in 2007 including a 19-year-old sweetgum (Liquidambar styraciflua) tree plantation exposed to long-term eCO2 [elevated CO2] or ambient CO2 treatments was done by Warren et al. (2011). According to the study, in the eCO2 exposed plantation, sap flow got reduced by 28% during early summer, and by up to 45% late in the drought during record-setting temperatures. Modelled canopy conductance declined more rapidly in eCO2 plots during this period, thereby directly reducing carbon gain at a greater rate than in ambient CO2 plots. Consequently, premature leaf senescence and abscission increased rapidly during this period, and was 30% greater for eCO2. While eCO2 can reduce leaf-level water use under droughty conditions, acute drought may induce excessive stomatal closure that could offset benefits of eCO2 to temperate forest species during extreme weather events."

Nedlo, J. E., Martin, T. A., Vose, J. M., & Teskey, R. O. (2009). Growing season temperatures limit growth of loblolly pine (Pinus taeda L.) seedlings across a wide geographic transect. Trees, 23, 751-759. doi: 10.1007/s00468-009-0317-0

"Mean growing season temperature had a very large effect on [loblolly pine (Pinus taeda)] seedling biomass accumulation in this study. Total biomass accumulation was highest at the Athens [Georgia] site, and it was 18% less at the Macon [Georgia] site, 43% less at the Gainesville [Florida] site and 48% less at the Coweeta [North Carolina] site."

"The provenance used in this study was from the middle of the loblolly pine range [Pinus taeda]. The amount of growth reduction at the northern and southern sites might have differed if genotypes from those locales had been selected. Significant genotype and temperature interactions have been reported for Pinus sylvestris families (Sonesson and Eriksson 2000). However, results from loblolly pine family plantings in different geographic locations have shown that there is little change in the ranking of the relative growth performance of most, but not all, loblolly pine families in different environments (McKeand et al. 1997)."

"From the regression equation of biomass and temperature, a 1 °C change in mean annual temperature from the growth optimum (which we assume was approximately the Athens [Georgia] site temperature) produced about a 10% change in biomass growth [of loblolly pine (Pinus taeda)]."

"Even in the presence of thermal acclimation of respiration, the large and linear response of [loblolly pine (Pinus taeda)] biomass growth to temperature, as demonstrated by the 18% difference in growth across a 1.4 °C change in mean growing season temperature, suggests that future changes in temperature may have substantial effects on growth of this species. However, we expect that the effect of increasing temperature can be negative or positive, depending on whether the plants are located in supra- or sub-optimum portions of their range."

Pritchard, S. G., Strand, A. E., McCormack, M. L., Davis, M. A., Finzi, A. C., Jackson, R. B., Matamala, R., … & Orens, R. (2008). Fine root dynamics in a loblolly pine forest are influenced by free-air-CO2-enrichment: a six-year-minirhizotron study. Global Change Biology, 14, 588-602. doi: 10.1111/j.1365-2486.2007.01523.x

"There was a trend (P = 0.15) suggesting an increase in [loblolly pine (Pinus taeda)] fine root length standing crop in FACE [free-air carbon enrichment] plots compared with controls (Table 1; Fig. 1a and b). Averaged over all 6 years of the study, CO2-enriched plots maintained 23% more fine root length than control plots."

"Shifts in [loblolly pine (Pinus taeda)] root length density from shallow to deeper soils over the course of the study are reflected by a significant horizon x year interaction (P = 0.0001; Fig. 1c). Although we found no significant CO2 x horizon effect, the modest (and insignificant) stimulation of fine root length standing crop by CO2 enrichment appeared to shift from shallow to deeper soil with increasing duration of the experiment (Fig. 1c)."

"Yearly cumulative [loblolly pine (Pinus taeda)] root length mortality was 36% greater in CO2-enriched compared with control plots averaged over the entire 6-year-study (P = 0.04; Table 1; Fig. 2b and Fig. 3). The effect of CO2 enrichment on cumulative yearly mortality varied considerably from year to year (Table 1; Fig. 3)."

"Exposure to CO2-enriched air did not influence [loblolly pine (Pinus taeda)] root turnover index (cumulative yearly root length production/ average yearly standing crop) (P = 0.58; Table 2). Turnover index in CO2-enriched plots was 0.61 compared with 0.58 in ambient plots."

"In general, [loblolly pine (Pinus taeda)] fine root NPP [net primary productivity] was positively related to the amount of rainfall over the period of active stem growth and was negatively related to average ambient air temperatures over this same period (rainfall data and temperature data from Moore et al., 2006) (Fig. 6b and c)."

"The increase in [loblolly pine (Pinus taeda)] standing root crop observed here mirrors the 23% increase in ecosystem NPP [net primary productivity] reported for four forest FACE [free-air carbon enrichment] experiments implemented across a broad range of productivity (Norby et al., 2005)."

"The 23% increase in [loblolly pine (Pinus taeda)] fine root standing crop resulting from CO2-enrichment in this experiment is mirrored by a 24% increased in midday soil respiration reported for the same plots (Bernhardt et al., 2006)."

"The increase in [loblolly pine (Pinus taeda)] fine root diameter observed in CO2- enriched plots in 1998 and 1999 did not persist. Stimulation of root diameters resulting from CO2 enrichment decreased in a linear fashion with increasing duration of the experiment (from 0.7mm in 1998 roots down to <0.5mm in 2004 roots)."

Valentine, H. T., Amateis, R. L., Burkhart, H. E., Gregoire, T. G., Hollinger, D. Y., & MacFarlane, D. W. (1999). Projecting the growth of loblolly pine in a changing atmosphere. Southern Journal of Applied Forestry, 23(4), 212-216.

"In conclusion, growth rates of loblolly pine [Pinus taeda] are expected to increase with the rise in atmospheric CO2 in coming decades. For stands planted today in Buckingham County, VA, a 5.7% gain in woody dry matter (or woody volume) is expected in 20 yr as a result of an annual increment of 1.6 ppm/yr in the concentration of atmospheric CO2. After 30yr, the expected gain increases to 7.2%. More importantly, in 20 yr, the amount of woody dry matter in a 20-yr-old stand is expected to be, on the average, 9.8% greater than the amount of woody dry matter in a 20-yr-old stand today. Similar increases in yield should be expected throughout the range of loblolly pine. Consequently, many yield tables and models will be rendered inaccurate unless adjustments are made to account for changing atmospheric conditions."

Wang, F., Xu, Y. J., & Dean, T. J. (2011). Projecting Climate Change Effects on Forest Net Primary Productivity in Subtropical Louisiana, USA. AMBIO, 40, 506-520. doi: 10.1007/s13280-011-0135-7

"McNulty et al. (1996) pointed out that increasing monthly minimum and maximum temperature by 2 °C, NPP of loblolly pine [Pinus taeda] forests decreased 30% in the Florida site."

Ward, E. J., Oren, R., Bell, D. M., Clark, J. S., McCarthy, H. R., Kim, H. S., & Domec, J. C. (2013). The effects of elevated CO2 and nitrogen fertilization on stomatal conductance estimated from 11 years of scaled sap flux measurements at Duke FACE. Tree Physiology, 33(2), 135-151. doi:10.1093/treephys/tps118

"In [Pinus taeda, loblolly pine] [at the Duke Free Air CO2 Enrichment (FACE) site in Durham, North Carolina], we do not find support for a direct effect of eCO2 [elevated (+200 ppm) atmospheric CO2 levels] on GS [stomatal conductance], but rather an indirect effect where decreases in AH [hydraulic allometry index] were related to decreases in GS in some time periods. While the mean GSRef [a reference conductance] was lower in the EC [elevated CO2, unfertilized] treatment than in the AC [ambient CO2 unfertilized] treatment, ~45% of the study period (Figure 5, top panel), we see that it is actually higher than expected based on AH alone in the spring and growing season (Figure 11, Table 4). A direct leaf-level effect of eCO2 would be expected to result in more consistent decreases in GS between these treatments."

"Unlike [Pinus taeda, loblolly pine], our analysis of sap flux in [Liquidambar styraciflua, sweetgum] [at the Duke Free Air CO2 Enrichment (FACE) site in Durham, North Carolina] is consistent with a direct effect of eCO2 [elevated (+200 ppm) atmospheric CO2 levels] on GS [stomatal conductance] in this species. The GS estimates are lower in EC [elevated CO2, unfertilized] than in AC [ambient CO2 unfertilized] for 76% of the months studied, as well as in EF [elevated CO2 with nitrogen fertilization] versus AF [ambient CO2 with nitrogen fertilization] in 2006–08 (Figure 5, bottom panels)."

Wertin, T. M., McGuire, M. A., van Iersel, M., Ruter, J. M., & Teskey, R. O. (2012). Effects of elevated temperature and [CO2] on photosynthesis, leaf respiration, and biomass accumulation of Pinus taeda seedlings at a cool and a warm site within the species' current range. Canadian Journal of Forest Research, 42(5), 943-957. doi:10.1139/x2012-

"We hypothesized that at the cooler northern site [near Blairsville, Georgia], both elevated [CO2] and elevated temperature would cause an increase in growth [in loblolly pines, Pinus taeda], while at the warmer southern site [near Tifton, Georgia], elevated [CO2] would increase growth but elevated temperature would decrease it. With regard to the effects of elevated [CO2], our hypothesis was supported: seedlings grown in elevated [CO2] had a higher rate of photosynthesis and accumulated more biomass at both sites compared with seedlings grown in ambient [CO2]. However, contrary to our hypothesis, seedlings grown in elevated temperature accumulated more biomass at both the cool and warm sites. "

"Elevated [CO2] increased biomass accumulation [in Pinus taeda] at both sites (Fig. 5). At final harvest, biomass was 11% greater ($P = 0.001$) in the elevated [CO2] treatments at the warm site [near Tifton, Georgia] and 13% greater ($P = 0.041$) at the cool site [near Blairsville, Georgia] compared with the ambient [CO2] treatments. The elevated temperature treatments had a similar effect. Seedlings grown in the elevated temperature treatments, averaged across both [CO2] treatments, accrued more biomass compared with seedlings grown in the ambient temperature treatments, although the effect was significant only at the final harvest (12% at the warm site, $P = 0.001$; 30% at the cool site, $P = 0.001$)."

"However, contrary to our hypothesis, seedlings [of loblolly pine, Pinus taeda] grown in elevated temperature accumulated more biomass at both the cool [sites near Blairsville, Georgia] and warm sites [near Tifton, Georgia]. The positive effect of an increase in temperature on growth at the warm site was especially interesting given that the growing season temperature was comparable with, or exceeded, temperatures at many locations along the southern-most edge of the species' range. This result suggests that temperatures within the current range of P. taeda [Pinus taeda] are lower than the optimum for growth. The strong relationship between temperature sum and growth, regardless of treatment or site, provides additional evidence that we did not reach the thermal limit for growth of this species in this study."

"Our findings [from experiments in Georgia] also suggest that, in nonlimiting water and soil nutrient conditions, predicted future climate conditions are likely to increase growth throughout the range of P. taeda [Pinus taeda], at least of seedlings, and provide an indication that the species may be growing in conditions below its optimum temperature (Topt) throughout its current range."

Wertin, T. M., McGuire, M. A., & Teskey, R. O. (2012). Effects of predicted future and current atmospheric temperature and [CO2] and high and low soil moisture on gas exchange and growth of Pinus taeda seedlings at cool and warm sites in the species range. Tree Physiology, 32(7), 847-858. doi:10.1093/treephys/tps051

"We found that [Pinus taeda, loblolly pine] seedling growth responded positively to the combination of elevated temperature and elevated [CO2] across a large spatial and thermal range (345 km north to south, 4.1 °C difference in mean air temperature during the growing season [between the Blairsville, Georgia (mountain) and Tifton, Georgia (coastal plain) sites]). This result suggests that, for this species, a substantial change in future atmospheric CO2 and temperature conditions is not likely to result in a negative change in seedling growth for this species. However, the low water treatment significantly reduced biomass production at both sites, indicating that soil moisture availability is a stronger determinant of growth than elevated temperature and [CO2]."

"Our findings [studying loblolly pine (Pinus taeda) seedlings at sites in Blairsville, Georgia (mountain) and Tifton, Georgia (coastal plain)] suggest that precipitation and the availability of soil moisture will have a greater effect on the growth than atmospheric temperature and CO2 conditions across the species range. However, the potential change in future precipitation in the southeastern USA is highly uncertain. Our results suggest that if precipitation decreases, low soil moisture is likely to be the dominant environmental factor limiting carbon gain and growth. On the other hand, our results also suggest that an increase in precipitation, along with elevated temperature and [CO2], is likely to provide conditions favorable for the growth of loblolly pine."

SOUTH CENTRAL

Harcombe, P. A., Hall, R. B. W., Glitzenstein, J. S., Cook, E. S., Krusic, P., Fulton, M., & Streng D. R. (1998). Chapter 5: Sensitivity of Gulf Coast Forests to Climate Change (Biological Science Report USGS/BRD/BSR-1998-0002). In G. R. Guntenspergen & B.A. Vairin (Eds.), Vulnerability of coastal wetlands in the Southeastern United States: climate change research results, 1992-97. Lafayette, LA: U.S. Department of the Interior, U.S. Geological Survey, National Wetlands Research Center: 44-66.

"Early gap models (Shugart 1984) assumed a direct relationship between range limits of taxa and the growth rates of adult trees that is not supported by available data (Prentice et al. 1991; Bonan and Sirois 1992). Our sites [in Texas] include several taxa growing very close to their range limits for which growth rates are as high as any recorded in the interiors of the geographic ranges."

Norby, R. J., Ledford, J., Reilly, C. D., Miller, N. E., & O'Neill, E. G. (2004). Fine-root production dominates response of a deciduous forest to atmospheric CO2 enrichment. Proceedings of the National Academy of Sciences, 101(26), 9689-9693. doi: 10.1073/pnas.0403491101

"CO2 enrichment began to have an effect on root productivity [of sweetgum, Liquidambar styraciflua] during the third year, and the response was strongest in midsummer (June to August). The CO2 effect on annual production (Fig. 2A) was highly significant, with production 2.2-fold higher in CO2- enriched plots from 2000 to 2003."

"Peak standing [root] crop [of sweetgum, Liquidambar styraciflua] in ambient CO2 varied from June to early September in different years, but the peak in elevated CO2 always occurred later by 15–42 days. The effect of CO2 on peak standing-root mass was highly significant (Fig. 2C)."

"The absence of an effect of CO2 on turnover rate from the first two methods [of calculating root turnover in planted sweetgum, Liquidambar styraciflua] indicates that the increase in root mortality and concomitant input of root C into the soil was a direct result of increased root production and not an alteration of root physiology."

"Our results suggest that CO2 enrichment significantly increased peak-standing root crop [of sweetgum, Liquidambar styraciflua] by altering allocation such that the potential for root occupancy of the soil volume was increased. This response was manifested especially in the deeper distribution of roots in the soil profile (Fig. 3)."

Wang, F., Xu, Y. J., & Dean, T. J. (2011). Projecting Climate Change Effects on Forest Net Primary Productivity in Subtropical Louisiana, USA. AMBIO, 40, 506-520. doi: 10.1007/s13280-011-0135-7

"Across Louisiana, the projected 10-year average NPP during periods of 2001–2010, 2021–2030, and 2041–2050 showed a distinctly increasing trend from North to South but small changes from East to West (Fig. 3)."

"The modeling results of this study suggest that projected forest NPP in Louisiana will differ with the various greenhouse gas emission scenarios."

"We think the slight increasing temperature in Louisiana during 2000–2050 does not rise to a level to limit forest growth but may increase photosynthesis rates to an optimum as suggested by Saxe et al. (2001)."

"Minimum temperature has also been projected to increase in Louisiana for 2000–2050 under the three climate scenarios (Fig. 6c), implying a longer growing season."

"The modeling results showed that forest NPP would positively respond to the medium (A1B) and high (A2) greenhouse gas emissions (CO2 concentration of 850 and 1,250 ppm in the atmosphere in 2100, respectively). The response of Louisiana forests NPP to the low greenhouse gas emission (B1, CO2 concentration of 600 ppm in the atmosphere in 2100) was mixed: an initial increase through 2018 followed by a sharp decrease through 2030 before a relatively stable period through 2050."

INTERACTIONS WITH OTHER FACTORS

SOUTH CENTRAL

Harcombe, P. A., Hall, R. B. W., Glitzenstein, J. S., Cook, E. S., Krusic, P., Fulton, M., & Streng D. R. (1998). Chapter 5: Sensitivity of Gulf Coast Forests to Climate Change (Biological Science Report USGS/BRD/BSR-1998-0002). In G. R. Guntenspergen & B.A. Vairin (Eds.), Vulnerability of coastal wetlands in the Southeastern United States: climate change research results, 1992-97. Lafayette, LA: U.S. Department of the Interior, U.S. Geological Survey, National Wetlands Research Center: 44-66.

"For example, the high rates of natural turnover indicate that these [Gulf Coast] forests will respond rapidly to climate change, and if hurricanes and floods increase in frequency and intensity as a result of global warming, forest turnover rate may be even more rapid. If higher mortality is not offset by higher growth, standing biomass of the forests may decline."

TIMBER PRICE AND SUPPLY

R8: SOUTHERN

Perez-Garcia, J., Joyce, L. A., McGuire, A. D. & Xiao, X. (2002). Impacts of climate change on the global forest sector. Climatic Change, 54, 439 – 461.

"The U.S. South illustrates a different effect of climate change on the forest sector. The South is the major producer of forest products supplying wood products for its own regional needs and shipping its excess to the North and other regions. Producer welfare is lower for the timber sector under climate change with losses between $5.4 and $4.2 billion. The mill processors benefit in part since they see lower log costs, but lower product prices offset these gains resulting in slightly negative changes in the RRR [‘reference’ set of parameters and assumptions in the Integrated Global System Model] and LLH [based on lower CO2 emissions from the Emissions Production and Policy Analysis model]scenarios."

RESOURCE AREA (FACTOR): WATER RESOURCES

GENERAL IMPACTS

R8: SOUTHERN

Mulholland, P. J., Best, G. R., Coutant, C. C., Hornberger, G. M., Meyer, J. L., Robinson, P. J, Stenberg, J. R., … & Wetzel, R. G. (1997). Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf Coast of Mexico. Hydrological Processes, 11, 949-970. doi: 10.1002/(SICI)1099-1085(19970630)11:8<949::AID-HYP513>3.0.CO;2-G

"With a warming of 4°C, the thermal regime of a stream will become similar to that presently characteristic of streams 640 km to the south (Sweeney et al., 1992). For example, the thermal regimes of streams in Virginia, North Carolina and Tennessee would become similar to those now in southern Alabama, southern Georgia and northern Florida."

SOUTH ATLANTIC

Dai, Z., Amatya, D. M., Sun, G., Trettin, C. C., Li, C., & Li, H. (2011). Climate Variability and Its Impact on Forest Hydrology on South Carolina Coastal Plain, USA. Atmosphere, 2, 330-357. doi:10.3390/atmos2030330

"The observations and simulations show that there may be substantial hydrologic alterations induced by climate change in forested watersheds on the lower coastal plain. The long-term climate observations indicate that there hasn't been a substantial increase in annual precipitation in this area, but that air temperature has increased. Due to the large variability in precipitation, we could not detect change in stream flow over the period. The coastal plain watersheds are subject to tropical storms that can alter the hydrology by affecting forest composition and structure."

Dai, Z., Trettin, C. C., Li, C., Amatya, D. M., Su, G., & Li, H. (2010). Sensitivity of stream flow and water table depth to potential climatic variability in a coastal forested watershed. Journal of the American Water Resources Association, 46(5), 1036-1048. doi: 10.1111/j.1752-1688.2010.00474.x

"The simulation of multiple temperature and precipitation scenarios shows that the hydrology of the forested coastal plain watershed [in Santee Experimental Forest, South Carolina] is sensitive to climate change. The proportion of precipitation allocated to streamflow is projected to correspond to increases or decreases in precipitation. Similarly, the projected effect of climate change on water table depth is substantial. Changes in water table depth are significant with either an increase or decrease in precipitation and an increase in temperature. The impact of drought on the water table depth in the watershed is projected to be large."

"The results from climate change scenarios indicate that the hydrological regime of forested watersheds on coastal plains is highly sensitive to changes in annual precipitation and temperature. Those hydrological effects are particularly critical to ecological functions of the upland and wetland forest ecosystems within the watershed. For example, watershed predicted reduction in water table depth under some scenarios would significantly shrink or end the existence of wetlands within the watershed [in Santee Experimental Forest, South Carolina]."

GROUNDWATER

SOUTH ATLANTIC

Dai, Z., Trettin, C. C., Li, C., Amatya, D. M., Su, G., & Li, H. (2010). Sensitivity of stream flow and water table depth to potential climatic variability in a coastal forested watershed. Journal of the American Water Resources Association, 46(5), 1036-1048. doi: 10.1111/j.1752-1688.2010.00474.x

"Water table depth on WS-80 [in Santee Experimental Forest, South Carolina] was sensitive ($R2 > 0.99$, $p < 0.01$) to the climate change scenarios (Figure 6a). The annual average water table level was higher for scenarios of increased precipitation (PIN1-PIN5) and lower when precipitation decreased (PDE1-PDE3) as compared to the current condition (CCC) yielding a quadratic polynomial function (Figure 6a). However, the magnitude of changes in water table depth within the watershed corresponded to the relative topographic position. The upland positions tended to exhibit larger changes in water table depth as compared to riparian or wetland areas."

"Annual average water table depth [in Santee Experimental Forest, South Carolina] decreased linearly with increasing temperature (scenarios TIN1-TIN6) (Figure 6b), exhibiting a reduction of 1.9 cm per °C temperature increase, within the simulated range of 0-6°C."

"Since most climate change scenarios predict an increased temperature regime, it is likely that the shallow water table characteristics of coastal forests will be affected (Lu et al., 2009)."

Lu, J., Sun, G., McNulty, S. G., Comerford, N. B. (2009). Sensitivity of pine flatwoods hydrology to climate change and forest management in Florida, USA. Wetlands, 29(3), 826-836.

"The coastal plain region may be more susceptible to disturbances due to its unique hydrology that is dominated by shallow ground-water tables (Amatya and Skaggs 2001). The shallow ground-water tables reflect the dynamic balances between evapotranspiration (ET) and precipitation (Sun et al. 2002). About 70–80% of annual precipitation returns to the atmosphere as ET in coastal watersheds (Gholz and Clark 2002, Lu et al. 2003, 2005). Therefore, any changes to ET and precipitation will have direct impacts on the ground-water table fluctuation patterns, and potentially the biotic functions."

"When temperature increased 2°C or precipitation decreased 10%, the water table dropped deeper than the base line scenario. "

"An increase in air temperature by 2°C increased PET [potential evapotranspiration], and thus increased water loss [in a pine flat-woods site in Florida]. An increase in water loss resulted in a further drop of the water table level."

"However, during the dry periods when the water table was well below the ground surface, impacts were stronger, which suggests that the water table is more sensitive to climate change during dry periods."

SNOW AND ICE

R8: SOUTHERN

Karl, T. R., Melillo, J. M., & Peterson, T. C. (2009). Global climate change impacts in the United States. New York, NY, USA: Cambridge University Press.

"Heavy snowfall and snowstorm frequency have increased in many northern parts of the United States. In the South however, where temperatures are already marginal for heavy snowfall, climate warming has led to a reduction in heavy snowfall and snowstorm frequency. These trends suggest a northward shift in snowstorm occurrence (Gutowski et al., 2008)."

SURFACE WATER

R8: SOUTHERN

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S.Environmental Protection Agency, 1-127.

"However, even in wetter regions (e.g., the southeastern United States), hot temperatures and high evapotranspiration rates cause only 50% of annual precipitation to be available for streamflow (Sun et al., 2005)."

"Future scenarios of climate and land-use change indicate that the water yield for this [southeast] region will become increasingly variable (Sun et al., 2005)."

McNulty, S. G., Vose, J. M., & Swank, W. T. (1997). Regional hydrologic response of loblolly pine to air temperature and precipitation changes. Journal of the American Water Resources Association, 33(5), 1011-1022. doi: 10.1111/j.1752-

"Using the GCM scenarios across the region, predicted annual drainage may decrease by 1 percent to 66 percent (when predicted forest death was assumed to have no species replacement). Most of the increase in drainage associated with the MCC scenario was due to a 20 percent increase in total annual precipitation. The GISS scenario is most closely aligned with the expectations of future climate change (Cooter et al., 1993). Using this scenario, predicted total annual regional drainage would not be significantly different from historic rates, because of increased evapotranspiration per unit leaf area and reduced total leaf area."

SOUTH ATLANTIC

Dai, Z., Trettin, C. C., Li, C., Amatya, D. M., Su, G., & Li, H. (2010). Sensitivity of stream flow and water table depth to potential climatic variability in a coastal forested watershed. Journal of the American Water Resources Association, 46(5), 1036-1048. doi: 10.1111/j.1752-1688.2010.00474.x

"The simulated linear increase of 2.4% in streamflow corresponding with 1% increase in precipitation [in Santee Experimental Forest, South Carolina] was comparable to the response in the Trend River basin in North Carolina where a 23% increase in streamflow corresponded to a 10% increase in precipitation (Qi et al., 2009)."

"Compared to current climate conditions (scenario CCC), the annual average streamflow [in Santee Experimental Forest, South Carolina] decreased at a rate of approximately 5% per °C temperature increase, within a 0-6°C range (scenarios CCC and TIN1-TIN6) (Figure 5b). The monthly streamflow decreased by 1.0-11.6% per °C in the five-year period, and the decrease was not related to monthly precipitation ($R2 = 0.06$, $n = 60$, $p > 0.05$)."

"In a pine plantation in eastern North Carolina, Sun et al. (2000b) reported an 8.7% increase in ET [evapotranspiration] due to a 1.9°C temperature increase. That change in ET relative to temperature (1:4.6) is similar to the predicted change in streamflow on WS-80 [in Santee Experimental Forest, South Carolina], which is also strongly affected by ET."

"The results from the two-factor scenarios (PNT1, PNT2, and PNT3, which combined temperature increase by 2°C with precipitation increase by 5, 10, and 15%) showed that streamflow [in Santee Experimental Forest, South Carolina] increased by 3.0, 12.5, and 28.7%, respectively. This result suggested that the increase in streamflow was likely to be larger, if global warming would increase precipitation at a rate higher than the 6-7% per °C reported by Wentz et al. (2007) and Lambert et al. (2008)."

"If the temperature increased by 2°C and precipitation decreased by 10% (scenario TVP, see Table 3), the streamflow [in Santee Experimental Forest, South Carolina] would decrease by 23.9% in wet years to as much as 38.5% in dry years."

"Compared to current climate conditions (scenario CCC), streamflow response to increasing or decreasing precipitation intensity in this watershed [in Santee Experimental Forest, South Carolina] was very significant ($R2 = 0.997$; $p \ll 0.01$), and that reduced precipitation or drought would substantially decrease the streamflow."

Qi, S., Sun, G., Wang, Y., McNulty, S. G., & Myers, J. M. (2009). Streamflow response to climate and landuse changes in a coastal watershed in North Carolina. Transactions of the ASABE, 52(3), 739-749.

"Streamflow [in the Trent River Basin, eastern North Carolina] was found to be very sensitive to the prescribed precipitation changes (fig. 6). When compared to the baseline, a 10% change in precipitation resulted in a mean change of 20% in annul streamflow, ranging from 2% to 55% over the 10-year simulation period (1992-2001). A 20% change in precipitation resulted in a mean streamflow change of 45%, ranging from 31% to 60% (fig. 6). A strong nonlinear response was observed, suggesting that the Trent River basin may be more responsive to large increases in precipitation, such as those seen with the 20% scenario."

"Annual streamflow and ET [evapotranspiration] values [in the Trent River Basin, eastern North Carolina] showed an increasing trend under the HadCMSul2 scenario. Changes in water yield varied from -34% to 238%, and changes in ET varied from -21% to 37%. The increasing trend was largely due to the increase in precipitation associated with the HadCMSul2 scenario (fig. 9). In contrast, under the CGC1 scenario, both streamflow and ET showed a decreasing trend (fig. 10). Compared to baseline conditions, annual streamflow varied from -93% to 45%, and ET varied from -37% to 21% of baseline. The decreasing trends in both ET and streamflow were due to a decrease in precipitation (fig. 10)."

"Simulated streamflow responses [in the Trent River Basin, eastern North Carolina] to climate change scenarios of the HadCMSul2 and CGC1 GCMs [general circulation models] suggest that precipitation may overwhelm the effects of increased air temperature alone. Increase of precipitation frequency and intensity will likely affect streamflow response as well. This is one important aspect of the hydrologic changes for the coastal region, where the hydrologic processes are dominated by the "saturation excess" flow generation mechanisms (Sun et al., 2001)."

SOUTH CENTRAL

Loáiciga, H. A. (2009). Long-term climatic change and sustainable ground water resources management. Environmental Research Letters, 4, 035004 (11pp). doi:10.1088/1748-9326/4/3/035004

"The climate-change scenario (scenario 2) increased spring flows at Comal and San Marcos springs [Texas] by approximately 160% and 17%, respectively, relative to the baseline scenario (scenario 1)."

"The ground water use impact and climate-change scenario (scenario 4) decreased spring flows by 73% and 1% at Comal and San Marcos springs [Texas], respectively, relative to the baseline scenario."

WATER QUALITY

R8: SOUTHERN

Mulholland, P. J., Best, G. R., Coutant, C. C., Hornberger, G. M., Meyer, J. L., Robinson, P. J, Stenberg, J. R., … & Wetzel, R. G. (1997). Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf Coast of Mexico. Hydrological Processes, 11, 949-970. doi: 10.1002/(SICI)1099-1085(19970630)11:8<949::AID-HYP513>3.0.CO;2-G

"Changes in climate that produce longer periods of low flow in summer also reduce stream water quality. Summer low flows are currently the periods of poorest water quality in many south-eastern rivers and streams (Meyer, 1992). Not only is there less dilution of anthropogenic additions of nutrients, organics and toxic substances, but also the warm temperatures and biomass accumulations (resulting from longer periods between episodes of scouring) increase community respiration rates resulting in lower dissolved oxygen concentrations."

WATER SUPPLY

R8: SOUTHERN

A'Bear, A. D., Boddy, L. & Jones, T. H. (2012). Impacts of elevated temperature on the growth and functioning of decomposer fungi are influenced by grazing collembola. Global Change Biology, 18, 1823 – 1832.

"Traditionally water stressed areas [in the southeastern US] with little precipitation or regions with large irrigated areas or large water usage from thermoelectric facilities had more stress with increased population and global warming. Less populated areas that had little water shortage problems in the past may also face water stress issues under changes in global and regional climate. However, future changes in precipitation patterns remained uncertain, especially in the eastern U.S., and thus realistic prediction of future water stress remains challenging."

Karl, T. R., Melillo, J. M., & Peterson, T. C. (2009). Global climate change impacts in the United States. New York, NY, USA: Cambridge University Press.

"Because higher temperatures lead to more evaporation of moisture from soils and water loss from plants, the frequency, duration, and intensity of droughts are likely to continue to increase."

McNulty, S. G., Vose, J. M., & Swank, W. T. (1996). Potential Climate Change Effects on Loblolly Pine Forest Productivity and Drainage across the Southern United States. Ambio, 25(7), 449-453.

"Using the GCM scenarios across the region, annual drainage [in loblolly pine (Pinus taeda) forests] may increase by 10% to 240% (when predicted forest death is assumed to have no species replacement), as ET [evapotranspiration] is altered."

Shugart, H., Sedjo, R., & Sohngen, B. (2003). Forests & global climate change potential impacts on U.S. forest resources. Pew Center on Global Climate Change.

"Many of the GCM [General Circulation Model] simulations over the past decade or longer have indicated significant drying in the Southeast, despite moderate increases in precipitation, because of higher temperatures."

Sun, G., McNulty, S. G., Cohen, E., & Myers, J. (2005). Modeling the impacts of climate change, landuse change, and human population dynamics on water availability and demands in the southeastern u.s. The Society for Engineering in Agriculture, Food, and Biological Systems.

"Combined climate change (drying) and population growth will reduce water supply and increase water demand, thus generally causing increased water stress"

Sun, G., McNulty, S. G., Moore Myers, J. A., & Cohen, E. C. (2008). Impacts of multiple stresses on water demand and supply across the southeastern United States. Journal of the American Water Resources Association, 44(6), 1441-1457. doi:10.1111/j.1752-1688.2008.00250.x

"Compared to historic (1985-1993) hydrologic conditions [for the southeastern US], annual precipitation and evapotranspiration in 2020 were projected to either slightly increase, or decrease dramatically depending on the GCM [general circulation model] used. Simulations suggested a large regional decrease in water yield using the CGC1 scenario due to a large increase in air temperature and moderate decrease in precipitation, but a large increase in water yield using the HadCM2Sul over the eastern part of the region due to a large increase in precipitation and a moderate increase in air temperature. This contrast between the two scenarios was most pronounced in the Piedmont and mountain regions that generally had higher runoff than the coastal zones"

"Across the study region [the southeastern US], average water stress was predicted to decrease slightly by 5% under the HadCM2Sul climate scenario, but increase greatly (34%) under the CGC1 climate change scenario (Table 2) (Figure 7). As in other impact studies (Jha et al., 2006), the two GCMs predicted different future precipitation patterns for the study region, resulting in different hydrologic conditions and distinctly different water stress patterns."

"Basins [in the southeastern US] with large population saw a dramatic increase in water stress under the CGC1 scenario, but most of the watersheds east of the Mississippi Valley saw decreased water stress under the HadCM2Sul (Figure 11). However, large cities such as Raleigh, Atlanta, and northern Virginia that receive 10-20% more precipitation still showed increased water stress due to large population growth."

"Across the region [the southeastern US], CGC1 climate change and population change caused an increase in water stress by 48%, which was a more severe effect than the HadCM2Sul and population combination (Table 2) (Figure 7)."

"Overall, land use/land cover change played a minor role in shaping water availability from the point of water quantity, thus its impact on water stress [in the southeastern US] was limited. In contrast, precipitation patterns and population growth had a huge impact on water availability and water stress patterns locally and across the region."

SOUTH ATLANTIC

Aldous, A., Fitzsimons, J., Richter, B., & Bach, L. (2011). Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies. Marine and Freshwater Research, 62, 223-231. doi: 10.1071/MF09285

"Similar to the regions of the United States where the river hydrograph is dominated by rainfall, the Savannah River basin is expected to experience increasingly severe and frequent droughts, increased winter and decreased summer rain, and a change in the seasonality of peak events (Neff et al. 2000; Bates et al. 2008)."

Bracho, R. G., Starr, G., Gholz, H., Martin, T. A., Cropper, Jr., W. P., and Loescher, H. W. (In press). Controls on carbon dynamics by ecosystem structure and climate for southeastern U.S. slash pine plantations. Ecological Monographs. doi:10.1890/11-0587.1

"In the southeastern U.S., severe droughts over the past century occurred with a frequency of ~ 15 years, with a second year of dry weather often following the first (Gholz and Boring 1991). Projections for the region, although uncertain, are that rainfall will increase but evaporation will also increase due to atmospheric warming, producing a negative water balance (Twilley et al. 2001, Held and Soden 2006 , Christensen et al. 2007, Bates et al. 2008, Seager et al. 2009). Climate change may also lead to increased drought frequency (Breshears et al. 2005). "

Dai, Z., Amatya, D. M., Sun, G., Trettin, C. C., Li, C., & Li, H. (2011). Climate Variability and Its Impact on Forest Hydrology on South Carolina Coastal Plain, USA. Atmosphere, 2, 330-357. doi:10.3390/atmos2030330

"The changes in seasonal precipitation [on Santee Experimental Forest, South Carolina] were extremely small in the last six decades with only a slight upward trend in falls and winters, but there was a downward trend in springs and summers. Therefore, the warming is likely to potentially bring more spring and summer droughts to this area, which are detrimental to forests (Mulhouse et al. 2005), especially for those summer droughts due to high evapotranspiration demands in summers."

"Based on the projections of the hydrologic changes of this forested watershed, using the synthesis of the observations and simulations, the extent of areas with wetland hydrology, dependent on shallow water table in this study catchment, will either shrink or disappear in the future; this is because the climate change may substantially raise the air temperature but may not bring an adequate precipitation increase to this watershed containing both wetlands and uplands to compensate for the increase in ET [evapotranspiration] demands caused by temperature increase."

Griffin, M. T., Montz, B. E., & S Arrigo, J. (2013). Evaluating climate change induced water stress: A case study of the Lower Cape Fear basin, NC. Applied Geography, 40, 115-128. doi: 10.1016/j.apgeog.2013.02.009

"The central watersheds [of the Lower Cape Fear River basin in eastern North Carolina] show the biggest decrease in available water, which, in turn, could play a significant role in increasing the risk of water stress in the region. The difference in the baseline to worst case IPCC predictions (Fig. 4c) is substantial throughout the basin. However, the values in the southern watersheds surrounding New Hanover County indicate drastic decreases in water availability (runoff), by as much as 50%. The implications of this in the future as population grows in and around New Hanover County are ominous."

"Regions [of the Lower Cape Fear River basin in eastern North Carolina] highlighted in Fig. 7 represent areas experiencing water stress or areas that could experience water stress in the future under mean IPCC [intergovernmental panel on climate change] climate change predictions and steady population growth. Results indicate that the region, which has historically been water rich, is transitioning to one facing potentially major water resource issues, due to both climate and population changes. Even when removing the population factor and just looking at the available water (runoff) within each watershed, water availability is expected to decline, as runoff values are decreasing across the basin in each scenario except for that of the best case climate prediction."

"Total yearly water deficits [in the Lower Cape Fear River basin in eastern North Carolina], calculated as the difference between potential evapotranspiration and actual evapotranspiration, increase in the mean and worst case scenarios, due to the highly seasonal pattern of the water balance fluxes and the predicted seasonal shifts in climate forcings. The fall and winter are usually periods of recharge as the temperature is decreasing, which in turn decreases evapotranspiration. The opposite is true for the spring and summer when temperatures are high. Temperature is the primary determining factor in this region as the precipitation is distributed fairly evenly throughout the year. However, with the mean and worst case climate predictions, precipitation decreases in summer months while the temperature is increasing, therefore causing the yearly deficits to increase. Such a shift could increase the frequency or severity of summer droughts, and likely would affect seasonal water demand as well."

Qi, S., Sun, G., Wang, Y., McNulty, S. G., & Myers, J. M. (2009). Streamflow response to climate and landuse changes in a coastal watershed in North Carolina. Transactions of the ASABE, 52(3), 739-749.

"As the air temperature was increased or decreased by 1.11°C each day, water yield [in the Trent River Basin, eastern North Carolina] showed a decrease or increase of approximately 6% of the baseline values, with a variation of 3% to 11%. Similarly, when temperature increased by 2.78°C, water yield decreased by an average of 15% with a larger variation of 9% to 31% (fig. 6). The effects of air temperature on water yield are due to its effects on evapotranspiration (ET); the effects of precipitation on water yield are propagated through both ET and other water fluxes in the watershed."

"When temperature was increased by 1.11°C, the average ET [evapotranspiration] increase [in the Trent River Basin, eastern North Carolina] was 2.7%, while the water yield decreased by 5.7% (fig. 6). When temperature was increased by 2.8°C, ET and water yield changes were more than doubled, with increases and decreases of 6.2% and 13.9%, respectively."

SOUTH CENTRAL

Harcombe, P. A., Hall, R. B. W., Glitzenstein, J. S., Cook, E. S., Krusic, P., Fulton, M., & Streng D. R. (1998). Chapter 5: Sensitivity of Gulf Coast Forests to Climate Change (Biological Science Report USGS/BRD/BSR-1998-0002). In G. R. Guntenspergen & B.A. Vairin (Eds.), Vulnerability of coastal wetlands in the Southeastern United States: climate change research results, 1992-97. Lafayette, LA: U.S. Department of the Interior, U.S. Geological Survey, National Wetlands Research Center: 44-66.

"These increases in saplings at the wet site [on the Neches River Floodplain in Big Thicket National Preserve, Texas] may be due to a change in the long-term flood pattern (Fig. 5-1); the period 1975-89 was the longest period of low flooding observed since recording began in 1921. The implication is that frequency of long-duration floods strongly controls sapling recruitment in floodplains by limiting regeneration to infrequent flood-free intervals and to areas of high light availability in gaps."

"In the wet forest [on the Neches River Floodplain in Big Thicket National Preserve, Texas], global change effects are harder to predict, since they might involve increases in frequency and intensity of both floods and droughts. It seems likely that the flooding effect would prevail, however, possibly reversing the changes set in motion by human alteration of the hydrologic regime."

Poff, N. L. (2002). Ecological response to and management of increased flooding caused by climate change. Philosophical Transactions of the Royal Society of London A, 360, 1497 – 1510. 10.1098/rsta.2002.1012

"In a historical reconstruction of flood histories for upper Mississippi River tributaries over the last 7000 years, Knox (1993) found that small shifts in temperature (1-2 °C) and precipitation (10-20°) caused sudden changes in flood magnitude and frequency. Knox (2000) also concluded that flood chronologies from several regions suggest that more frequent occurrences of large and extreme floods tend to be associated with periods of rapid climate change."