CHAPTER 9

Managing Florida's Plantation Forests in a Changing Climate

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Production forestry provides substantial benefits to the state of Florida, including the provision of ecosystem services, such as regulation of water quantity and quality, provision of wildlife habitat and carbon sequestration, and supporting 80,000 jobs and $16.34 billion/year in economic activity. Climate through the end of the century in the production forestry regions of northern Florida and southern Georgia is predicted to result in substantial increases in potential loblolly pine and slash pine plantation productivity, ranging from 5–35% depending on emissions scenario, species, and location. Climate change is likely to affect the timing and frequency of abiotic disturbances, such as wildfire and windstorms, and will also change the dynamics of forest pests, pathosystems, and forest water resources. But predictions about the nature of these impacts remains uncertain. Regardless, the fact is that plantation forests have been a vital part of protecting regional water quantity and quality, and they will continue to be essential features of healthy productive landscapes, as climate changes and the potential for adverse climate impacts on water resources increases. The key to adapting forest management to changing climate will be the considered application of silvicultural tools, such as competition control, density and fertility management, and proper choice of species for each site. Keeping abreast of research advances related to these tools will be increasingly important for forest managers as climate conditions change. In addition, the development of viable policy options focused primarily on privately owned forests can help protect Florida's existing forests and the benefits they provide, and encourage investment in reforestation of existing forestland and planting new forests on previously unforested land.

Key Messages

- Production forestry provides substantial benefits to the state of Florida, including the provision of ecosystem services, such as regulation of water quantity and quality, provision of wildlife habitat and carbon sequestration, and supporting 80,000 jobs and $16.34 billion/year in economic activity.
- Climate through the end of the century in the production forestry regions of northern Florida and southern Georgia is predicted to warm from 1.5 °C to almost 3.5 °C, with small increases in annual precipitation, and elevated atmospheric CO_2 concentration. Models predict that these changes will result in substantial increases in potential loblolly pine and slash pine plantation productivity, ranging from 5–35% depending on emissions scenario, species, and location.
- Forestry is unique in that it is one of the few industries that sequesters more carbon than it emits. There are opportunities to increase carbon sequestration for mitigation of atmospheric CO_2 through retention or expansion of forested areas, altered forest management, and the use of woody biomass for power generation in place of fossil fuels.
- The frequency and intensity of abiotic disturbances, such as wildfire and windstorms, are likely to be affected by climate change; but predictions remain uncertain about the magnitude of change and their effects on the forest resource.

- Research is underway to better understand how native forest pests and pathosystems may respond to changing climate. The movement of pests or pathogens into previously non-impacted areas is of particular concern.
- Plantation forests have been a vital part of protecting regional water quantity and quality, and they will continue to be essential features of healthy, productive landscapes as climate changes and the potential for adverse climate impacts on water resources increases.'
- The key to adapting forest management to changing climate will be the considered application of silvicultural tools, such as competition control, density and fertility management, and proper choice of species for each site. Keeping abreast of research advances related to these tools will be increasingly important for forest managers as climate conditions change.
- There are several viable policy options for harnessing forests to mitigate climate change and increasing forest resilience and adaptation to climate change. However, since 71% of Florida's forests are privately owned, policy options must align well with landowner needs to have adequate impact. Broadly speaking, policies that improve market conditions, reduce burdens (regulatory and economic), and increase economic sustainability for forest landowners would help protect Florida's existing forests and the benefits they provide, and would encourage investment in reforestation of existing forestland and planting new forests on previously unforested land.

Keywords

Forestry; Natural resources; Water resources; Disturbance; Ecosystem services; Wildfire; Insects; Disease; Invasives

Introduction

Production forestry is a critically important economic resource to the state of Florida. Forests cover nearly half the state (17.3 million acres in 2013), with 15.4 million acres composed of "working forests" that are managed primarily for timber, but also for their economic benefits from other ecosystem goods and services (e.g., hunting). Nearly three-quarters of Florida's forestland is privately owned; the balance is publicly held by state and local or federal entities (FDEP 2016).

Florida is in one of the most productive tree-growing regions in the world–the Southern United States, which produces nearly one-eighth of the world's industrial roundwood and nearly one-fifth of the world's paper and pulp products. Within the U.S., this area is known as the "wood basket" of the country, generating half of the saw log and veneer products, and nearly three-quarters of U.S. pulpwood (Smith et al. 2009). Importantly, this area is expected to become even more critical to U.S. and global wood production, with significant projected increases (+25%–70%) in timber production in the region (Hugget et al. 2013) and losses of timberland elsewhere in the U.S. (e.g., due to mountain pine beetle outbreaks that have devastated western forests).

Florida is an important contributor to forest products markets, with an annual harvest of 472.5 million cubic feet of wood between 2009 and 2013, 90% from private lands (FFS 2015). The associated economic impact on the state is tremendous: forestry contributed $16.34 billion to the state's economy and provided more than 80,000 jobs in 2013 (FDEP 2016; Hodges et al. 2013).

We mostly think of forests as providing much-needed raw materials, such as timber and fiber used for wood products, heat and power generation; but forests are considerably more valuable to society for the ecosystem services that they provide. These include water availability, wildlife habitat, air quality, soil formation, recreation, carbon sequestration and biodiversity. For example, more than one-third of the water supply in the southern United States comes from forested watersheds (Lockaby et al. 2013). In Florida, water quality protection alone provides \$154–\$230 million in annual average benefits from forests (Kreye et al. 2016). A recent Florida study estimates that the typical acre of non-industrial private forestland annually provides \$5,030 of ecosystem services (e.g., timber, carbon storage, water quality, and wildlife habitat), with just 7% of that value from timber (Escobedo et al. 2012).

Florida's residents derive benefits from many types of forests, ranging from conserved forests managed primarily for ecosystem services to very intensively managed planted forests ("plantations") overseen primarily for economic benefits from tree harvesting. This chapter focuses on planted pine forests in northern Florida and southern Georgia, and provides a brief overview of predicted future climate and its likely effects on forest productivity, water quality and quantity, ecosystem services, disturbance by biotic and abiotic agents, and carbon sequestration for mitigation of atmospheric CO_2. Silviculture, the set of techniques used for managing forest structure and composition, will be an important tool for adapting forests to future climate conditions. Accordingly, we outline potential silvicultural approaches for forest management under future climate, and discuss policy options for minimizing future risks to this valuable resource.

Climate Projections for Florida

Climate projections worldwide predict an increase in air temperatures and variability in precipitation. Global circulation models predict increasing air temperatures with a high degree of certainty, with the magnitude and rate of warming varying across the globe (IPCC 2013). There is less certainty around predictions of precipitation, and much more variability in the direction and magnitude of predicted change, with future projected precipitation ranging from drier to wetter depending on region (IPCC 2013). The southeastern U.S. is predicted to have less severe warming and smaller changes in precipitation compared to other regions in North America (Carter et al. 2013). We examined climate model outputs for a range of locations in northern Florida and southern Georgia (Fig. 9.1).

Fig. 9.2 shows projected climate for 2050–2075, under two CO_2 emissions scenarios: Representative Concentration Pathway 8.5 (RCP 8.5), which assumes CO_2 emissions and associated radiative forcing continue to increase through the end of the century, and Representative Concentration Pathway 4.5 (RCP 4.5), which assumes increased CO_2 emissions through mid-century followed by reductions in emissions to approximately 1975 levels by the end of the century (see van Vuuren et al. 2011 for more details on the emissions scenarios). Changes in daily maximum air temperatures vary by emissions scenario and by latitude of location, with increases relative to the 1950–2005 baseline of 1.6 to 1.8 °C (2.9 to 3.2 °F) under the RCP 4.5 scenario, and 2.3 to 2.7 °C (4.1 to 4.9 °F) for the RCP 8.5 scenario (Fig. 9.2). Large decreases in the number of days with frost are projected as well, with reductions of 36 days to 54 days across Florida depending on location and emissions scenario. Projected changes in precipitation across the same locations and emissions scenarios are relatively small, ranging from no change in precipitation to a 4% increase (Fig. 9.2).

Simulated Loblolly and Slash Pine Productivity under Future Climate

The productive potential of planted southern pine underlies most of the economic and many of the ecological benefits derived from managed forests in Florida. To understand how productivity might change under future climate conditions, we used the forest growth model 3-PG (the Physiological Processes Predicting Growth model; Landsberg and Waring 1997), which has been parameterized for the two most important commercial tree species in the region: loblolly pine and slash pine (Gonzalez-Benecke et al. 2014, 2016). We used gridded, interpolated historical climate data (http://metdata.northwestknowledge.net/) as well as the previously described climate projections and CO_2 concentration scenarios as input for 3-PG, and simulated stem wood volume production for 25-year rotations of the two species during a baseline period (1990–2005) and for a future period (2050–2075) at the same locations used for the climate projections (Fig. 9.1). In all simulations, an initial planting density of 1,500 trees per hectare and a site index of 22 m was assumed for unthinned stands.

The 3-PG model predicted increased loblolly and slash pine productivity across all six simulated locations and emissions scenarios during the 2050–2075 time period (Fig. 9.3). This consistent increase in productivity is attributable to the combination of relatively moderate increases in temperature, continued sufficient water availability through precipitation, and increased atmospheric CO_2, which acts as a fertilizer for plants (McCarthy et al. 2010). Relative increases in productivity were largest for slash pine, ranging from about 15% at the southern sites, to greater than 35% at the more northern locations. Loblolly pine also showed greater relative increases in productivity at the more northern sites but the magnitude of increase was smaller, ranging from less than 5% at the Alachua County location to almost 20% at the Jones County site (Fig. 9.3). At each site, productivity increases tended to be larger for the RCP 8.5 scenario than for the RCP 4.5 scenario. While relative increases in productivity were generally larger for slash pine compared to loblolly pine, the absolute productivity of loblolly pine was predicted to be larger than that of slash pine, consistent with current patterns of productivity of the two species (Jokela et al. 2010). It is important to note that the modeling approach used here did not incorporate the effects of disturbances, such as insects, disease, fire, or hurricanes on forest productivity, and as such should be considered an estimate of maximum potential productivity under future climate.

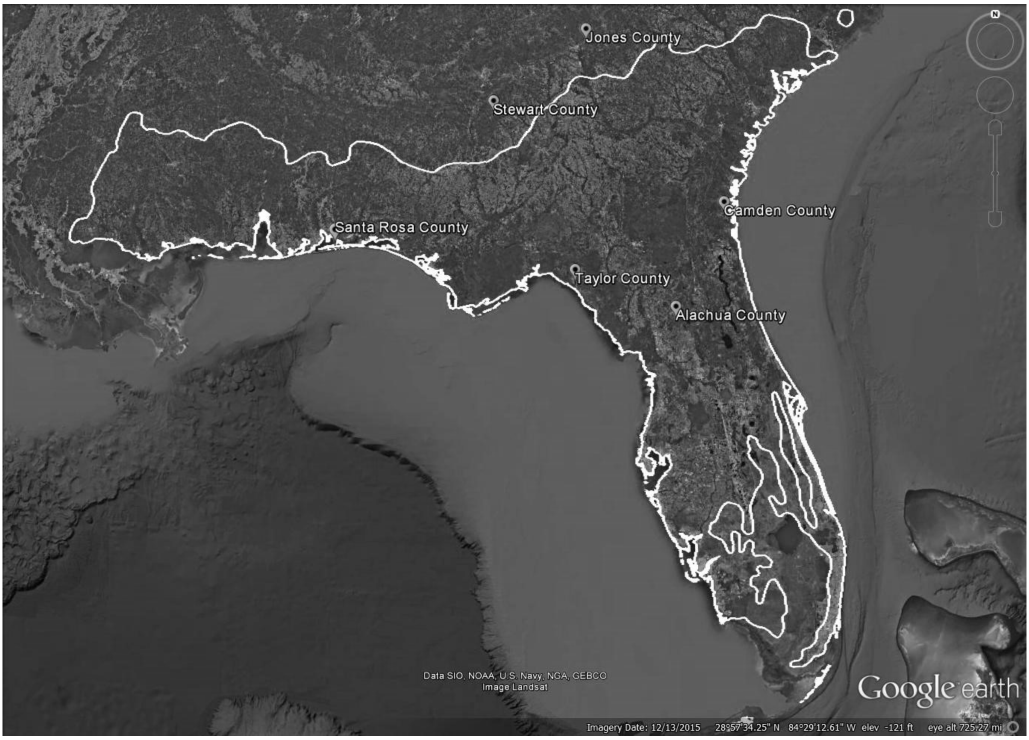

Figure 9.1. Map of the six locations (labeled by counties) in Florida and Georgia used for climate projections and productivity simulations. Current slash pine range is outlined in white.

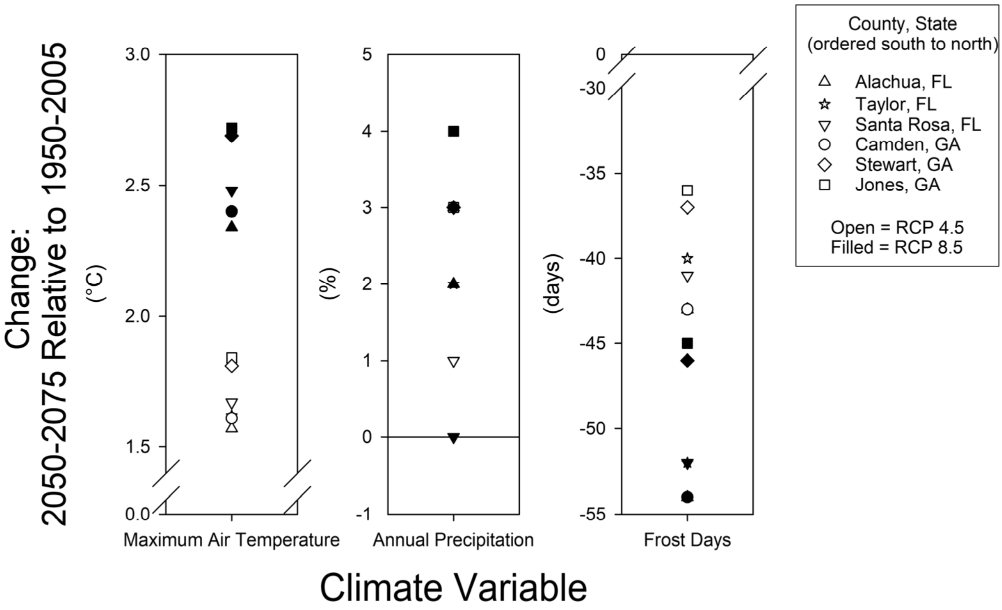

Figure 9.2. Projected change in mean maximum air temperature, annual precipitation, and annual days with frost for six locations in Florida and Georgia under two CO_2 emissions scenarios. Comparisons are for the period 2050–2075 relative to 1950–2005. Projections are the mean of output from 20 downscaled global circulation models (Abatzoglou and Brown 2012; Taylor et al. 2012).

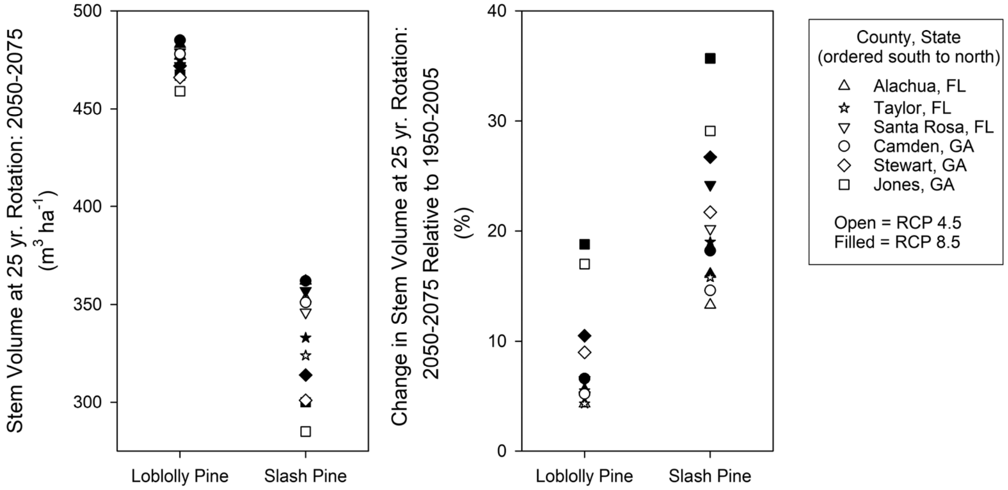

Figure 9.3. Projected stand stem volume at a rotation age of 25 years (left) and relative changes in stem volume (right) for loblolly and slash pine for six locations in Florida and Georgia under two CO_2 emissions scenarios. Stem volume was simulated with the 3-PG model (Gonzalez-Benecke et al. 2014, 2016) using as input the mean of 20 downscaled global circulation models (Fig. 9.2).

Abiotic Disturbance Effects under Future Climate

All pine species used in Florida plantations (longleaf, slash, and loblolly pines) evolved with periodic disturbances including fires, hurricanes, and droughts. These abiotic disturbances are natural components of southeastern U.S. ecosystems, and pines are adapted to survive these perturbations. Although expected to occur periodically, disturbance frequency and intensity have been projected to change in the coming decades as a result of climate change (Dale 2001; Westerling et al. 2011; Becknell et al. 2015; Johnstone et al. 2016); temperatures are rising, the growing season is becoming longer, fires and droughts are becoming more frequent and intense, and hurricane activity is expected to substantially increase. It is currently uncertain exactly how these changes will alter survival, regeneration, and other processes of pine species in plantations. We are, however, confident that current best management practices, such as maintaining proper tree spacing, attending to soil fertility, and controlling excessive competition, is likely to maintain or increase the resilience of forest plantations (Guldin 2014).

Effective understory fuel management can reduce the likelihood of intense and/or frequent fires predicted under climate change scenarios. Modern silvicultural approaches to site preparation and understory competition control using herbicides and mechanical treatments can be quite effective at controlling understory fuel loads, but these approaches can be cost-prohibitive for non-corporate landowners. Frequent, low-intensity fires every two to four years after pine establishment will reduce competing vegetation, be easier to control, and reduce the probability of catastrophic fires (Davis and Cooper 1963; Crow and Shilling 1980; Brose and Wade 2002). Pines have virtually no mortality following low-intensity fires as compared to coexisting vegetation. They survive and benefit from reduced competition as well as nutrient release after fire (Brockway et al. 1997; Mitchell et al. 2006). A large build-up of flammable fuels, which is more likely as growing seasons become longer or if fires are suppressed, increases the probability of a high-intensity fire causing crown scorch and consequentially increasing mortality of planted pines (Mitchell et al. 2009). From an economic standpoint, frequent low-intensity fires that might cause a small loss are preferable to high-intensity fires that are likely to cause a substantial loss.

Pine species are well-adapted to survive fires. Pine foliage is susceptible to fire, but unless all of the needles on a tree are completely scorched, mortality is unlikely. Furthermore, pine bark has good insulating qualities, which protects the aboveground stem from injury. Bark thickness varies considerably between and within pine species; but as a general rule, it increases with age and tree girth. Researchers have found that bark thicker than 12 mm will protect the stem cambium of most pines during prescribed fires (Fahnestock and Hare 1964). Even though pine bark is a good insulator, cambial damage can occur if the fire duration is long, which typically occurs if fuels (e.g., sloughed bark and needles) have accumulated at the base of a tree (Menges and Deyrup 2001; Varner et al. 2005). Damage to either the crown or cambium often results in death of trees months later.

Prescribed fire can be used to enhance the production of some non-timber values in planted forests. For instance, forage for wildlife and recreational opportunities, such as hunting, hiking, picnicking, and horseback riding, all benefit from periodic fires that reduce woody understory vegetation (De Ronde et al. 1990). One incentive to managing for wildlife, in particular, is the opportunity for forest landowners to participate in federal cost-sharing programs designed to offset the cost of improving habitat (Mixon et al. 2009). In addition, managing forests to improve ecosystem services, such as water yield, can be profitable if stands are well-managed and not densely planted (Susaeta et al. 2016a).

The effects of abiotic disturbances on pine plantations differ among species. By many measures, longleaf pine is the most resilient of pines planted in Florida (Wade and Johansen 1986). It can survive fires when young, has high hurricane tolerance (Johnsen et al. 2009), and can grow on dry, low-nutrition sites (Jose et al. 2007). Despite these potential advantages, longleaf pine is rarely planted for timber production because when it is a young tree its productivity is lower than that of slash pine or loblolly pine (Haywood et al. 2015).

In general, exposure time and intensity of drought and hurricane disturbances determine survival of pines, but generally small trees of a given species are easier to kill than large ones. If a disturbance, such as drought, is severe and occurs repeatedly over multiple years, pine growth will slow and some mortality is inevitable. As our climate changes, the frequency and intensity of disturbances will change as will interactions between them. It is predicted that increased drought frequency will increase fire frequency and intensity, as well as the ability of resource managers to use prescribed burns to lessen the intensity of wildfire (Mitchell et al. 2014).

Uncertainty about the future of pine plantations in Florida's disturbance-prone habitats highlights the need for research leading to predictive models that incorporate the effects of disturbance. This will help us forecast how climate change and associated changes in disturbance frequency and intensity, as well as interaction between disturbances, will affect the survival and growth of planted pines. These simultaneous changes in climate and disturbance regimes may require us to rethink how we manage pine plantations in the future (Becknell et al. 2015; Johnstone et al. 2016). Therefore, it is essential that these models help predict future trajectories of forest production and economic profit in ways that can guide policy decisions and management strategies.

Forest Health Impacts under Future Climate

Although the effects of pests and pathogens on conifers under predicted future climate are difficult to forecast, the magnitude and frequency of their impacts are predicted to increase (Garrett et al. 2009; 2013). Even if future climate scenarios are predictable in a given region, the potential effects on tree physiology and interactions with pests and pathogens are less certain (Desprez-Loustau et al. 2009). A useful framework for thinking about changes in forest health risk is the disease triangle (Fig. 9.4), which shows that host susceptibility, pathogen virulence, and conducive environments must all align for pest or disease outbreaks to occur. Climate changes may favor one factor, but not another side of the triangle–or may have counterbalancing effects. Additionally, it is difficult to predict how other exogenous variables, such as predators of pests, changes in silviculture and pesticide use, and other land use changes may influence future outbreaks in forests. Overall, perturbations to climate that challenge pine species' adaptations to current and past conditions will likely result in plant stress. Knowing the severity and duration of the stress can be useful for predicting the types of pests and pathogens that may take advantage of stressed hosts. In general, management for healthier forests in the face of climate change will need to focus on design of resilient, genetically-defined and adapted plantations (Showalter et al. 2016; Coakley et al. 1999).

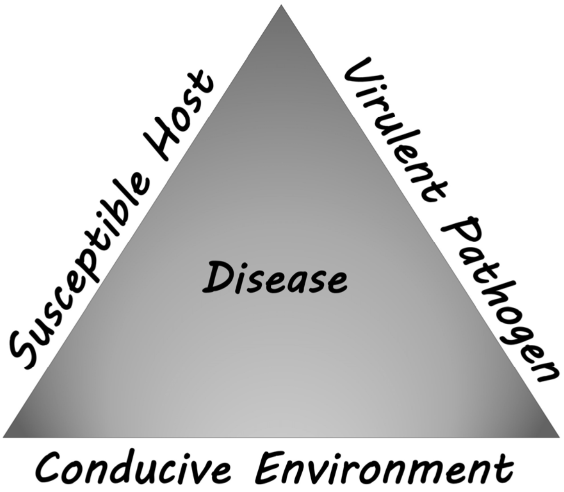

Figure 9.4. The disease triangle showing the three factors necessary for the development of disease. Note that timespans for a conducive environment are skewed for long-lived plants, such as trees.

Despite the uncertainties about how forest health will be affected by future climate, a body of empirical evidence is building that is giving us insight into what to expect. For example, Dothistroma needle blight and Swiss needle cast exemplify foliar diseases that have caused significant damage to plantation conifers worldwide as favorable conditions have aligned with disease biology to enhance the scale and severity of outbreaks. Dothistroma needle blight, caused by the fungal pathogens *Dothistroma septosporum* and *D. pini,* is a major disease of *Pinus* spp. worldwide (Bulman et al. 2013). In many areas, there have been significant increases in outbreak frequency and the disease has recently expanded into new areas (Barnes et al. 2008). Research has implicated strong El Niño Southern Oscillation (ENSO) events coincident with intercontinental disease outbreaks (Woods et al. 2016) and suggests that future climate predictions for the Northern Hemisphere will favor Dothistroma needle blight outbreaks in many areas. Although Dothistroma needle blight is not considered a major threat to southern pines, comparable pathogens occur in the region and could pose a similar threat.

Swiss needle cast, caused by *Phaecryptopus gaeumannii,* is a major foliar disease affecting plantation grown Douglas fir (*Pseudotsuga menziesii*) (Stone et al. 2008). It is particularly damaging to plantations in western Oregon and Washington in the Pacific Northwest that were previously forested with other species, such as western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*) and in New Zealand in wet coastal regions (Stone et al. 2007). The establishment of large numbers of plantations in regions favorable for disease has been a key to why these outbreaks first occurred. However, it is becoming increasingly clear that warmer winters are strongly favoring pathogen reproductive and survival processes and leading to significant increases in severity with growth losses of >50% reported (Stone et al. 2008). Although Swiss needle cast does not pose a direct threat to southern pines, similar foliar diseases, such as brown spot on longleaf pine (caused by the fungus *Mycosphaerella dearnessii*) may behave in a similar way, and with increased efforts to more broadly re-establish longleaf pine, perhaps in uncharacteristic sites at times, this disease needs to be monitored.

In general, little is known about the role climatic factors (e.g., temperature, rainfall, and humidity) play in modulating traits in trees or pathogens that might impact host susceptibility or pathogen virulence. Currently, efforts are underway to assess how pathogen and pest biology and life histories are affected by temperature and humidity. One example includes the important pine disease pitch canker. Caused by the fungus *Fusarium circinatum,* pitch canker disease affects most pine species globally and is responsible for high economic losses in the timber industry. Favored by high temperatures and humidity, the possibility of future outbreaks is high under the environmental conditions predicted for the next 50–100 years. Also, because breeding for disease-resistant trees takes many years to accomplish, it is important to understand the biology of this fungus and be able to predict which disease scenarios would be more likely to thrive under future climate conditions. Assessments of in vitro culture growth as well as sporulation and virulence of isolates collected along north–south gradients in the southeastern U.S. have illustrated isolate-specific preferences for higher or lower temperatures and appear to suggest geographic patterns (Quesada et al. 2016). This information, along with field disease phenology (spore trapping) and host spatial distribution, could be used to develop epidemiological models to predict future outbreaks (Quesada et al. 2016).

One particularly concerning mechanism by which impacts from forest pests may intensify due to climate change is the invasion by native species into new geographical areas where encounters with naïve hosts could lead to devastating effects. A very dramatic example, the mountain pine beetle (*Dendroctonus ponderosae*), has demonstrated this with devastating impacts in the western portion of North America (Carroll et al. 2003). A native species of bark beetle, the mountain pine beetle, typically affected stressed lodgepole (*P. contorta*) and ponderosa pine (*P. ponderosa*) forests in the Rocky Mountains. A combination of fire suppression, limited forest management, and decades of drought led to a massive outbreak of the mountain pine beetle that spanned from northern British Columbia to Guatemala. The effects of drought and climate change on the initial outbreak appear to be compelling, but what was unexpected was the expansion of the mountain pine beetle into previously unaffected high elevation whitebark pine (*P. albicaulis*) and high latitude jack pine (*P. banksiana*) forests (Bentz et al. 2010), presumably due to a lack of low winter minimum temperatures that previously would have kept this pest from these areas. Both host species are now considered new hosts for the mountain pine beetle, allowing the pest to move unchecked through these susceptible, non-co-evolved hosts (Bentz et al. 2009). The effect is the same as a new introduction of an alien pest. There remains uncertainty about how far the mountain pine beetle destruction will go, but there is the possibility of a trans-continental range expansion to eastern North America on jack pine, potentially threatening eastern pine forests in the future. This type of phenomenon is likely to be experienced under future climate scenarios with other native pests and should be emphasized in future efforts to establish resilient silvicultural methods and in assessments of how to manage fire on the landscape (Bentz et al. 2010).

Water Resources under Future Climate

Climate change impacts to water resources are predicted to be significant (Arnell 1999), influencing precipitation and evaporation everywhere, albeit unevenly, and sea levels in coastal areas. Coupled to growing human water demands, these changes are already altering the volume, timing, and quality of fresh water in rivers, wetlands, lakes, aquifers and estuaries, and the availability of water for human needs (Vorosmarty et al. 2000). These changes are likely to impact Florida’s commercially harvested forests in both upland and wetland settings, affecting their productive capacity (Sun et al. 2000a), their composition and resilience (Hansen et al. 2001), and their ability to sustain landscape hydrologic services (Sun et al. 2005). Plantation forestry is an extensive enterprise in Florida, however, forests can also be managed to mitigate many of the water resource challenges presented by a changing climate (Ford et al. 2011).

Forests use water (Bosch and Hewlett 1982), with rates of use impacted by composition, density, and understory management (including fire) (Powell et al. 2005). The proportion of precipitation that returns to the atmosphere via evapotranspiration can exceed 90% in Florida’s highly productive commercial forests (Gholz and Clark 2002), suggesting that Florida’s forests, and indeed forests worldwide, are important regulators of stream flow (Jackson et al. 2005). The links between forest management and landscape hydrology (e.g., streamflow and aquifer recharge) also illustrate opportunities to mitigate climate change impacts, and possibly regional water supply conflict, by connecting landowners willing to manage their plantation forests at lower density with groups willing to pay for enhanced water yield (McLaughlin et al. 2013).

Ecosystem productivity is vulnerable to changes in water availability, particularly for systems like those in Florida where rainfall and evapotranspiration are approximately in balance (Porporato et al. 2006). While forecast mean annual rainfall changes across the southeast are modest, this does not necessarily imply that the hydrologic impacts of these changes are negligible. Forests respond to patterns of rainfall, not just the annual amount (Porporato et al. 2004), potentially creating water stress in sandy soils like those common in Florida if rainfall intensity and frequency changes, even where total rainfall remains unchanged. Predictions strongly support increased incidence and altered timing of extreme rainfall (Wang et al. 2013), with drier summers, wetter winters, and more intense hurricanes (Enfield et al. 2011). Along with increased atmospheric demand for water arising from the 2 to 5 °C forecasted rise in temperature, these changing rainfall patterns can impact growth, fire and disease risk, species invasions (particularly in wetland settings), and nutrient cycling.

Compared to other land uses, plantation forests retain many of the water storage compartments present in natural landscapes, including shallow aquifers, soils with thick surface organic layers, and wetlands (Sun et al. 2000b). Low intensity management to protect soil recharge and storage functions, and best management practices that protect embedded wetlands (FDACS 2008), result in landscapes that persist in their capacity to retain rainfall. This has particularly important implications with increased incidence of extreme events (floods and droughts) since those storages serve the multiple roles of retaining floodwaters under high rainfall conditions (Lane and D'Amico 2010), attenuating downstream risks, and also sustaining flow to streams during drier periods (McLaughlin et al. 2014).

One emerging effect of ongoing carbon dioxide (CO_2) enrichment of Earth's atmosphere is improvement in plant water use efficiency, an effect that is weaker in trees than herbaceous plants (Saxe et al. 1998). With higher CO_2 concentrations, plants satisfy their carbon needs more easily, and thus lose less water for the same production (i.e., they use water more efficiently). In a retrospective modeling study of coastal plain ecosystems, water use efficiency in forests was high compared to other vegetation types but exhibited limited plasticity with rising CO_2 levels, suggesting that long-term regional increases in water use efficiency are not a result of forest CO_2 fertilization (Tian et al. 2010). One reason may be that CO_2 enrichment effects are mitigated by low nitrogen availability, a condition also impacted by increased temperatures (enhancing mineralization and denitrification rates), and reduced soil moisture (decreasing soil nitrogen mineralization rates) (Pastor and Post 1986). In short, while water use efficiency gains are possible, Florida's forests are already high efficiency systems. The implications for forest nutrition and water yield are important, but largely still uncertain.

Impacts to water quality are not frequently part of the global change narrative, except for ocean acidification effects. However, several key water quality attributes are likely to be impacted. Plantation forests are widely observed to protect downstream water quality in Florida and elsewhere (Omernik 1976, U.S. EPA 1995). High rates of primary production, generally low fertilization rates, limited use of agrochemicals, and effective best management practices to limit sediment loading or thermal impacts to streams mean that plantation forests offer a viable option that balances economic production and water quality protection. Climate change is likely to exacerbate existing water quality challenges, elevating the importance of land planning that integrates and incentivizes plantation forests. Increased incidence of extreme rainfall will likely lead to enhanced soil sediment mobilization, particularly from urban and agricultural areas, but also from plantation forests during clearcut and bedding phases (Aust and Blinn 2004). Altered flow and increased temperature are likely to alter landscape delivery of water and concentrations of key constituents, such as dissolved carbon, nitrogen and phosphorus, with some global trends already evident (Evans et al. 2004). Similarly, increased incidence of prolonged dry periods will likely impact stream dissolved oxygen and organic matter dynamics (Mulholland et al. 1997), as well as salinity in coastal forest habitats (Williams et al. 1999). The role of plantation forests in mitigating these water quality challenges follows from the general notion that plantation forests approximate a natural flow regime, that forestry operations, especially in Florida, adhere to long-standing and demonstrably effective best management practices borne of the need to protect water quality, and that flatwoods landscapes, with forests and embedded wetlands, contribute to carbon, nitrogen, and phosphorus cycling that effectively retains these elements.

Predicting the links between water resources and commercial forests in a changing climate is challenged by myriad uncertainties. The magnitude of temperature and rainfall changes, the capacity of planted trees to adjust to these changes and the attendant physiological subsidies and stresses, and the role of management (e.g., fertilization, stand density) together create a complex and contingent problem. However, it is clear that plantation forests have been a vital part of protecting regional water quantity and quality, and that they will continue to be essential features of healthy productive landscapes.

Silvicultural Approaches for Maintaining Pine Plantation Productivity in a Changing Climate

Climate change represents opportunities, threats, and a number of unknowns for land managers practicing silviculture in Florida pine plantations. As mentioned in previous sections, over the last several decades Florida has seen nominal increases in average precipitation and temperature, with most of the changes occurring during the cold season. With projected changes in average temperature and precipitation, silvicultural practices that currently improve plantation productivity will likely interact with climate or CO_2 trends to further increase productivity. Less certain is how silviculture might interact with an increase in the frequency of extreme climatic events (drought, storm events), as these are expected to also increase with climate change (Bell et al. 2016). Here we discuss critical decision points in plantation silviculture and how the importance of these decisions may be affected by climate change in Florida.

Achieving survival targets and rapid early growth in planted seedlings is the first step landowners can take to reduce climate change effects on their plantations. Plantation establishment generally includes site preparation for planting, the planting phase, post-planting release treatments from competing vegetation, and fertilization on low productivity sites. Landowners who use modern establishment and planting practices now average ~90% survival for their plantations in the Southeast (Lang et al. 2016). Land managers who consistently have seedlings survive at less than this average should consider their stand establishment approaches and identify reasons for lower effectiveness, as future conditions might alleviate or make worse the reasons for poor performance.

A stand establishment technique that may be critical for Florida in an era of rapid climate change is the continued use of raised mounds or beds on which to plant seedlings. Beds are widely used on poorly drained soils in the region, as they keep seedling roots out of saturated soil conditions that can slow tree growth or even facilitate mortality (Outcalt 1984). Bedding is likely to remain critical because one climate prediction is for the increased frequency of intense precipitation events (Bell et al. 2016). Land managers can use the geo-located 'Web Soil Survey' internet application, developed by the National Resources Conservation Service, to determine if the soil on their property has poor soil drainage characteristics. Moreover, vegetation in a pre-harvest stand may include indicator plant species (e.g. pitcher plants, wiregrass, and palmetto) that suggest impeded drainage (Jokela and Long 2012). Land managers should avoid relying solely on past experiences as to which sites they do bed or whether double-bedding is required, because a site's bedding requirements may change in response to future, extreme precipitation events or shifts in local hydrology.

Choosing which seedlings to plant is another way that landowners can mitigate potential climate change effects. For example, if bedding is too expensive but an area's soils are prone to flooding or saturation, landowners could consider planting slash pine as it is more resistant than loblolly pine to poorly drained soil conditions (Oucalt 1984). Another decision point is whether to plant bare-root (less expensive) or containerized (more expensive) seedlings. Containerized seedlings have more developed root systems and are generally more resistant to poor soil conditions (drought or saturated soils) than are bare-root seedlings (Grossnickle and El-Kassaby 2016). Containerized seedlings may also be the better choice if temperatures are warmer than optimal during planting, because their greater root density generally reflects greater nutrient reserves. In a period of rapid change, using containerized seedlings on marginal soils may justify their greater expense by reducing uncertainty in seedling survival.

Controlling competing vegetation is an important part of plantation management that could become even more critical with climate change. More intense droughts, in particular, would accentuate the inter-species competition for water that often results in reduced pine growth or even mortality (Zutter et al. 1986). Competing vegetation can also prevent fertilizer from increasing tree growth (Jokela et al. 2010), prolonging the time a plantation remains in a sensitive juvenile state. Mechanical site preparation that turns the soil or a prescribed burn after a harvest offers slight to moderate control of shrubs (e.g. gallberry and palmetto), but herbicide applications are more certain in their control and are needed for herbaceous weeds (Miller et al. 2003). An important unknown is whether competing plants will become more difficult to control in a period of rising atmospheric CO_2 and temperatures, as species may be differentially adapted to these new conditions (Manea and Leishman 2011).

Land managers who practice sound plantation management control the numbers of living trees, or stand density, throughout a rotation. Termed "stand density management," this practice begins at planting with a decision on the spacing of tree seedlings, and then occurs later when the landowner decides on whether and when to thin a stand. Pine seedlings in the southeastern United States are currently planted at an average density of 584 trees per acre (Lang et al. 2016); however, few studies are available to suggest alternative densities that might mitigate climate change effects. In general, increasing planting densities may provide a 'hedge' against increased seedling mortality. This would be particularly important for either droughty or poor drainage soils that have had little site preparation, competition control, or fertilization. However, once tree size increases and crowding causes intense inter-tree competition, pine plantations have an increased risk of suffering mass mortality from southern pine beetles (Nowak et al. 2015)—pests that might increase in virulence as tree stress from drought and heat also increases (Gan 2004). Thinning is recommended as stands approach a level of crowding associated with intense inter-tree competition; but if, for economic reasons, a land manager does not think a stand will be thinned, then planting at a lower tree density (e.g. ~200-450 trees per acre) could help protect it against pathogens later in stand rotation. However, planting at low tree densities may require manual branch pruning as the retention of branches could decrease wood quality.

On soils that have inherently low fertility, fertilization can dramatically increase pine productivity, in particular when it is coupled with inter-species competition control and appropriate site preparation techniques (Jokela et al. 2010). It is possible that future wind and drought effects on plantations could be ameliorated with forest fertilization. Recent research suggests that pine plantations fertilized at higher levels are less sensitive to wind damage than those fertilized at lower rates (Zhai et al. 2015). This may reflect faster growth, increased coarse root development, and faster canopy closure, creating a greater overall resistance to wind effects (Stanturf et al. 2007). In reference to drought, fertilized mature pine plantations apparently grow faster than unfertilized forests under reduced moisture conditions (Maggard et al. 2016). Although more research is needed, the studies currently available suggest that fertilization at recommended rates will increase plantation resistance to some of the negative aspects of climate change, and could potentially increase the positive effect that elevated CO_2 levels have on pine growth (McCarthy et al. 2010).

Perhaps more important than plantation response to climate change will be how land managers respond to the as yet unknown threats and opportunities that will affect managed forests in a rapidly changing world. Land managers who remain engaged with the research community, extension professionals, and their fellow practitioners are the ones most likely to maintain or increase the profitability of their plantations. These individuals will also be critical to reporting any climate-driven changes in plantation function to the forestry community, helping the scientific community mobilize to address threats. Maintaining communication among those invested in pine plantation management will be the key to ensuring the southern pine plantation resource continues to be productive through the upcoming period of rapid change.

Mitigating Atmospheric CO_2 by Storing Carbon in Forests and Wood Products

Plantation forests have the potential to mitigate rising atmospheric CO_2. These forests are unique among agricultural crops in that they are a substantial net sink for CO_2, meaning that they take up more CO_2 than they release during a management cycle. Because of their large production area and high productivity, southern forests are a significant portion of the U.S. carbon budget, containing 36% of the sequestered forest carbon in the conterminous United States (Turner et al. 1995). Forests in the region annually sequester 76 million metric tons of carbon, equivalent to 13% of regional greenhouse gas emissions, and have the potential to sequester more through retention and expansion of forested land area, and improved forest management, which increases productivity and resilience to disturbance (Johnsen et al. 2001, Han et al. 2007).

Forest management can be used to increase sequestration both in forest ecosystems themselves and in harvested wood products. A study by Gonzalez-Benecke et al. (2010) illustrated how forest management can influence carbon pools in slash pine, an important timber species in Florida. This study used models to examine the impacts of different management scenarios on carbon storage in different ecosystem components, as well as in "off-site" pools associated with solid wood products, such as lumber, and pulp used to produce paper and similar products.

Gonzalez-Benecke et al. (2010) showed scenarios that increased rotation length and incorporated periodic thinning accumulated greater amounts of carbon in off-site forest product pools than did scenarios involving shorter rotations and no thinning (Fig. 9.5). These sawtimber-focused scenarios produced larger trees at final harvest that, when used for long-lived products, such as structural lumber and furniture, stored carbon for longer periods and in greater quantities than scenarios that produced smaller trees and more pulpwood, which has a shorter carbon half-life off site. Importantly, this study also demonstrated that the carbon emissions associated with silvicultural activities, such as energy used for fertilizer production, fuel for planting and harvesting equipment, and fuel for transport of logs to the mill, were only a small fraction (about 2%) of the total carbon sequestered by the management system. Additional carbon benefits can be derived if harvested wood or harvest debris is used to generate electricity, since these uses offset emissions that would have been associated with the use of fossil fuel energy sources (Dwivedi et al. 2016). Wear and Greis (2012) pointed to the potential of biomass energy markets as a "game changer" for forestry in the region, which could result in increased demand for productive forests, in turn helping to prevent the conversion of forestland to other land uses while maintaining substantial carbon benefits.

Figure 9.5. Average over five rotations for carbon stock in forest ecosystem pools, off-site pulp and solid wood pools, and average carbon emissions per rotation for two slash pine silvicultural scenarios. The pulpwood scenario involved typical fertilization, no thinning, and clearcut harvest at age 22 years. The sawtimber scenario involved typical fertilization, thinning at age 14 and 22 years, and final clearcut harvest at age 35 years. Adapted from Gonzalez-Benecke et al. (2010).

Forests are dynamic systems that generate ecosystem services that can be defined as tradeoffs (i.e., managing for one service leads to the decrease in another) or bundles (i.e., both services increase). We know that different forest structures and management approaches can affect timber production, carbon sequestration, water quality, water yield, wildlife habitat, and other services in meaningful ways (e.g., Susaeta et al. 2016a-b, 2016a-c). However, the tradeoffs among multiple ecosystem services (e.g., timber, water, carbon simultaneously), which is critical from a policy and forest management perspective, have been largely unexplored, particularly in a climate change context. For instance, increased tree stocking to maximize carbon stores in areas prone to fire or attack of insects and other pests may increase ecosystem vulnerability to natural disturbances, increase water use, and decrease stream flow. Further, these tradeoffs can differ across temporal and spatial scales and depend on interactions between land use and socioeconomic conditions. It is imperative that we gain much better insight into the different management alternatives, tradeoffs, and synergies between the multiple ecosystem services provided by forests, and do so in a climate change context.

Policy Options for Florida's Future Forests

Florida's future forests face increasing pressures from land use change (e.g., due to urbanization and agricultural in-migration from the drought-stricken western U.S.), pests and disease, invasive species, policy (e.g., estate taxes, and protections for endangered species and water resources), and changes in forest ownership (e.g., fragmentation due to estate tax; Butler and Wear 2013) that affect the forest estate. Land use change is by far the largest pressure. By 2060, we expect to lose between 30 and 43 million acres of southern U.S. forest to urbanization (Wear and Greis 2012). Absent strong policy intervention, this will lead to a net reduction in forest carbon stocks by 2060 (Hugget et al. 2013).

There are several viable policy options for harnessing forests to mitigate climate change and increasing forest resilience and adaptation to climate change. However, since 71% of Florida's forests are privately owned, policy options must align well with landowner needs to have adequate impact. Broadly speaking, policies that improve market conditions, reduce burdens (regulatory and economic), and increase economic sustainability for forest landowners would help protect Florida's existing forests and the benefits they provide, and encourage investment in afforestation and reforestation.

Robust, policy-driven markets for forest-based ecosystem services are important considerations. We know that forests are highly effective at sequestering atmospheric CO_2 as biomass and long-lived forest products, and they can provide long-term solutions to offsetting greenhouse gas emissions. In the southern U.S., conservative estimates suggest that forests could offset one-fourth of the region's greenhouse gas emissions (Han et al. 2007), and in a way that is cheap relative to climate change mitigation alternatives (e.g., shuttering coal-fired power plants; Couture and Reynaud 2011; Gren and Carlsson 2013). Their valuable role in mitigating climate change is recognized by programs and policies aiming to reduce greenhouse gases, including the United Nation's Kyoto Protocol, the U.S. Environmental Protection Agency's Clean Power Plan, California's AB32, the Climate Action Reserve, the Voluntary Carbon Standard, and the American Carbon Registry (Soto et al. 2016a). However, carbon sequestration and other ecosystem services from forests are classic examples of market failure–while there exists tremendous economic value associated with the myriad ecosystem services that forests provide (e.g., Costanza et al. 2014), there are few mechanisms available to landowners to capture this value. As a result, forests are largely valued for their timber alone, which may be a relatively small portion of the overall economic value (e.g., Escobedo et al. 2012). Market mechanisms (e.g., incentives through state or federal programs, mitigation markets, and boutique contracts with private conservation groups) have been lauded as an effective class of policy interventions to fix this market failure and protect forestland.

These approaches show considerable promise. For example, payments for ecosystem services is a market-based alternative and has been suggested as a more effective strategy for offsetting landowner costs associated with ecosystem service production (Ingram et al. 2014). Studies have identified non-industrial private forest landowners as receptive to payments for carbon sequestration (Soto et al. 2016a; Dwivedi et al. 2009); but, we still know relatively little about forest landowner preferences for these policy approaches and their use has not been widely subscribed. Also, we lack an understanding of the impact of landowner participation in carbon sequestration payment schemes on jointly produced ecosystem services (e.g., Beach et al. 2005).

Cost-share programs, technical assistance programs, and changes to tax policy (e.g., lower property tax rates for conservation lands) are known to play a key role in supporting working forests, and enjoy broad public support (Kreye et al. 2016). Several existing federal and state programs (e.g., the US Department of Agriculture's Conservation Reserve Program and Environmental Quality Incentive Program, the Southern Pine Beetle Assistance and Prevention Program, and the Longleaf Landowner Incentive Program; FDACS 2016) offer effective conservation cost-share models that could be expanded with a climate change-specific focus. However, landowner enrollment in these programs lags due to perceived program inflexibility and failure to effectively address the needs of individual landowners (Hyde et al. 1996).

Likewise, both conservation easements that allow forest landowners to retain their "working forest" status while either temporarily or permanently limiting their development rights, and outright purchase of forestland by conservation organizations, are approaches to maintaining the forest estate that enjoy broad popular support. These approaches can be particularly relevant for non-industrial private forest landowners who are oriented to activities other than timber production, such as recreation, aesthetics, and wildlife, and may be highly motivated to retain forestland ownership and bequest it to future generations (Smith et al. 2009). With climate change, it may be important to grow the use of these programs to increase forest resilience and/or more fully engage forestland to mitigate climate change effects. To date, these approaches do not seem effective at slowing the pace of forestland conversion (e.g., Kramer and Shabman 1993; Stainback and Alavalapati 2002).

Policies that decrease disturbance risk or increase forest yields also contribute to the economic sustainability of Florida forestland and carbon storage. For example, policy changes to reduce the arrival of destructive forest pests through trade, and funding to provide early detection and rapid reaction to new invasive forest pests have been shown to provide a very high return on investment (e.g., Susaeta et al. 2016d). Similarly, investments in research on improved silvicultural practices and tree breeding (including through the use of genomic information) have led to substantial increases in productivity for Florida forestry (Teskey 2014), although research support has not been consistent.

Finally, more support for and emphasis on generating economic valuation data for forests and forest-based ecosystem services is needed to inform future decisions, both by landowners and policymakers. Recognizing the value of forests, including market (e.g., timber) and nonmarket (e.g., carbon sequestration) benefits, is essential for generating public and policymaker support for forest conservation, and designing durable, effective mechanisms for landowners to capture a portion of the value that their forests provide to society. Lack of adequate information and models regarding economic impacts and ecological tradeoffs associated with managing forests for climate change mitigation or increased resilience (e.g., planting longleaf pine) remains a major barrier for forest landowners in terms of participation, and for policymakers in terms of assessing programs that ensure the sustainable provision of forest-based ecosystem services. It is also essential that we work to understand the social (e.g., distributional impacts and environmental justice) and administrative (e.g., ease of implementation and administration) aspects of forest-related climate change policy, since these factors help define what is "appropriate" climate change policy action for Florida, and are significant drivers of policy choices and their ultimate success or failure (Kreye et al. 2016, Soto et al. 2016b).

Conclusion

Changing climate through the end of this century poses both risks and opportunities for plantation forest management in Florida. Risks include potential alteration in frequency and intensity of abiotic disturbances, such as wildfire and windstorms, modification of pest and pathogen dynamics, and changes in water quantity and quality. Importantly, predictions about the nature and impacts of most of these risks remain uncertain. Despite these uncertainties, changing climate also is likely to open up opportunities for Florida's plantation forests. The productivity of plantation forests is likely to increase substantially through the end of the century, due to relatively moderate changes in temperature and precipitation coupled with increases in atmospheric CO_2 fertilization. There are also important opportunities to increase the sequestration of carbon by plantation forests through retention and expansion of forestland, and appropriate alteration of forest management. These approaches can help to mitigate rising atmospheric CO_2 while simultaneously increasing the many other benefits provided by forests to the state of Florida. Application of appropriate silvicultural technology and the development of supportive public policy will be key factors in adapting future plantation forest management to the risks and opportunities of climate change.

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