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Future climate and fire interactions in the southeastern region of the United States

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ABSTRACT

Fire has a profound, though paradoxical influence on landscapes of the southeastern U.S.; it simultaneously maintains native biodiversity and ecosystem processes but also threatens silvicultural resources and human landscapes. Furthermore, since the majority of the southern landscape is heavily influenced by human activities, contemporary fire regimes are human managed disturbances within extant fire-dependent ecosystems. Though there is considerable uncertainty in climate projections for the southeastern U.S., climate change will likely impact both prescribed fire and wildfire. In this review, we synthesize climate change-fire interactions, discuss the impacts of uncertainty in a human-dominated landscape, and illuminate how both climate change projections and their uncertainties might impact our ability to manage forests in the Southeast. We define the Southeast region as consisting of the Gulf Coastal Plain, Lower Atlantic Coastal Plain, Piedmont and southern Appalachians and associated subregions. This region has the greatest area burned by prescribed fire, the highest number of wildfires in the continental U.S. and contains globally significant hotspots of biodiversity, much of which is dependent on frequent fire. The use of prescribed fire as a management tool depends on a suite of weather and fuel conditions which are affected by climate. Over the next five decades, general circulation models (GCMs) consistently predict air temperature to increase by 1.5–3 °C in the Southeast. Precipitation forecasts are more uncertain with respect to the mean; but, most models predict an increase in precipitation variability. Increases in the likelihood of severe droughts may increase wildfire occurrence while simultaneously limiting the implementation of prescribed burning by restricting the number of days within current prescription guidelines. While the Southeast has among the highest potential for C storage and sequestration, a reduction in C sequestration capacity due to increasing disturbances such as drought, insect infestations, hurricanes and fire, is possible. The potential for long-term shifts in forest composition from climate-altered fire regimes if coupled with an increased potential for wildfire occurrence could reduce quality and quantity of water released from forests at times when demand for high quality water will intensify for human use. Furthermore, any reduction in prescribed burning is likely to result in decreased biological diversity, particularly in the Coastal Plain, a global hotspot of biodiversity. Lastly, more future area burned by wildfire rather than prescribed fire has the potential to negatively influence regional air quality. Mitigating the negative effects of climate change-fire interactions would require actively exploiting favorable seasonal and inter-annual climate windows. Monitoring the type conversions of agricultural and fiber production forest will be critical for long-term projections of fire risk and watershed impacts of altered fire regimes.

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1. Introduction

In the Southeast U.S., fire both sustains many forest types and acts as a serious threat to others. Since the majority of the southern landscape is heavily influenced by human activities, even in natural areas, fire-dependent systems rely on the human application of prescribed fire, and fire-sensitive ecosystems rely on fire suppression. Changes in climate will likely add significant challenges to fire management in the near future by influencing prescribed fires and wildfires. This review synthesizes climate–fire interactions, presents projections for future climate, analyzes uncertainties

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associated with model projections, and sheds light on how those uncertainties might affect our ability to manage forests in the Southeast.

The Southeast encompasses several physiographic regions that have unique climate, vegetative composition, fire histories, fire regimes, and, consequently, current fire management. Overlain onto this complex physiography are future climate scenarios that will likely alter forest composition, species distributions, and associated fire regimes in different ways. We discuss climate–fire interactions in terms of their potential impacts on biodiversity, carbon storage, and water quality and quantity. We also discuss future fire management and potential means to manage forests under these uncertainties.

2. Physiographic region and forest types of the Southeast

We define the Southeast as consisting of the nine Level III Ecoregions shown in Fig. 1 (Omernik, 1987), that are broadly distributed across the Gulf and Lower Atlantic Coastal Plains, Piedmont and southern Appalachians. This area encompasses 96 million hectares, of which 53 million hectares is forested (Fig. 1, Table 1). The landscape is characterized by a complex arrangement of land cover, topography, and ownership. Within the forested land cover, there are extensive plantations of loblolly (*Pinus taeda* L.), longleaf (*Pinus palustris* Mill.) and slash pine (*Pinus elliottii* Engelm. var *elliotti*), and approximately one half of the region is covered in fire-dependent or fire-influenced ecosystems having a diversity of fire regimes (Drummond and Loveland, 2010). The Southeast has the greatest combined number and area of wildland fires in the U.S. (Melvin, 2012, Figs. 2 and 3).

Forest fires occur over a wide range of scales from <10 ha to 250,000+ ha; but, accurate estimates of the area burned annually are difficult to calculate due to the short duration and/or small scale of many prescribed fires that limit detection by remote sensing. Nonetheless, in 2010, there were 522,000 ha of lands managed by state and federal agencies in the Southeast reported to have been burned, though this is a small fraction of the total area burned since federal lands represent less than 8% of the region (National Interagency Coordinating Center, 2010; Melvin, 2012). The Southeast also conducts more prescribed burns than the rest of the country combined, with most of these fires occurring in the Coastal Plain and Piedmont sub-regions (Melvin, 2012). Therefore discussions of climate–fire interactions in the Southeast must include the effects on prescribed fire as well as wildfire.

The majority of the region is covered by ecosystems that tend to burn with low intensity surface fires; though there are notable exceptions (see below). Fires can recur at time scales ranging from annually (e.g., longleaf pine woodlands) to more than a century (e.g., Appalachian mountain coves and swamps); and have differing cascading ecosystem responses depending fire intensity (the amount of energy produced by the fire) and severity (a function of energy release) (Neary et al., 2005). There are four main natural forest types that occur in the region: upland pines; mixed pine and hardwoods; upland hardwoods; and swamps and forested wetlands. The pine forests in the Southeast can be divided into two subtypes that require different fire regimes that are either low intensity surface fires or intense, stand replacement fires. Forests requiring the former are much more prevalent than those requiring the latter. Within the surface fire regimes, frequency, or fire return interval, varies among forest subtypes though all occur over relatively short periods with a maximum interval of 5–10 years. Fire management in the extensive pine plantations of the region ranges from frequent surface fire regimes to the more common management without prescribed fire.

2.1. Piedmont and Coastal Plain forest types

Longleaf pine forests were the once the dominant forest type in the Coastal Plain (≈37 million ha, Frost, 1993) until widespread conversion to pine plantations, agriculture and other land uses occurred in the 20th century. Longleaf woodlands are some of the most frequently burned ecosystems in the world, with the

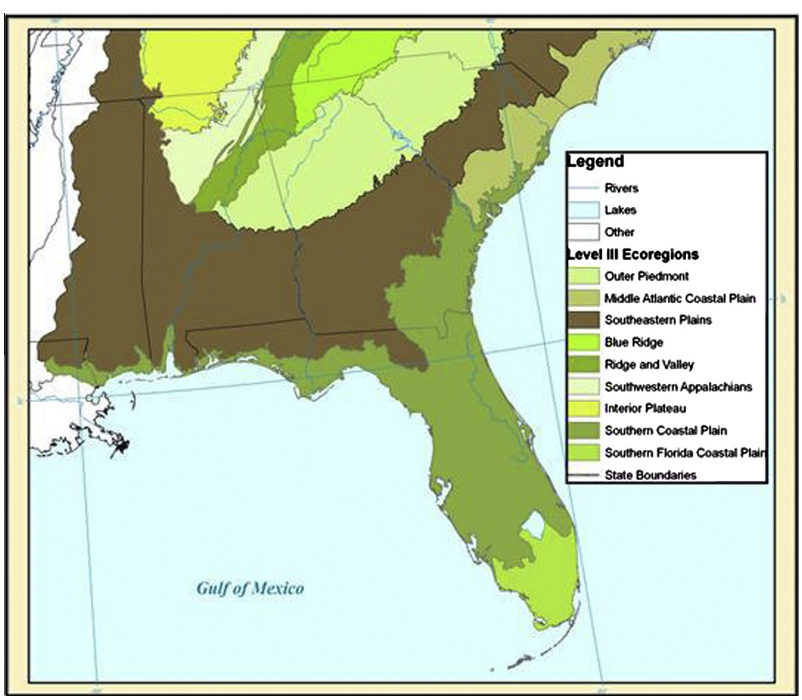

Fig. 1. Ecoregions discussed in the section on the southeastern U.S. (Bailey, 1995, http://www.fs.fed.us/land/ecosysmgmt/).

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Table 1
Forest types and acreages considered in this assessment. Data are from the Multi-Resolution Land Characteristic Consortium (MRLC) National Land Cover Database (NLCD, 30 × 30 m; 2006). Ecoregion data are from U.S. EPA (2010) revision of Omernik's Ecosystems (1987).

Ecoregion (Level III)	Land cover	Area (millions of hectares or %)
Outer Piedmont	Woody wetlands	0.36
	Deciduous forest	5.83
	Evergreen forest	3.14
	Mixed forest	0.40
	Total area	16.42
	% Forested (of total area)	59.22%
Middle Atlantic Coastal Plain	Woody wetlands	1.80
	Deciduous forest	0.10
	Evergreen forest	1.31
	Mixed forest	0.10
	Total area	6.09
	% Forested (of total area)	54.21%
Southeastern Plains	Woody wetlands	4.35
	Deciduous forest	4.27
	Evergreen forest	7.17
	Mixed forest	2.21
	Total area	31.93
	% Forested (of total area)	56.39%
Blue Ridge	Woody wetlands	0.00
	Deciduous forest	3.24
	Evergreen forest	0.30
	Mixed forest	0.16
	Total area	4.45
	% Forested (of total area)	83.21%
Ridge and Valley	Woody wetlands	0.04
	Deciduous forest	2.68
	Evergreen forest	0.49
	Mixed forest	0.31
	Total area	6.44
	% Forested (of total area)	54.71%
Southwestern Appalachians	Woody wetlands	0.03
	Deciduous forest	1.73
	Evergreen forest	0.34
	Mixed forest	0.37
	Total area	3.76
	% Forested (of total area)	65.68%
Interior Plateau	Woody wetlands	0.10
	Deciduous forest	4.11
	Evergreen forest	0.33
	Mixed forest	0.15
	Total area	10.17
	% Forested (of total area)	46.11%
Southern Coastal Plain	Woody wetlands	3.95
	Deciduous forest	0.02
	Evergreen forest	2.69
	Mixed forest	0.08
	Total area	13.73
	% Forested (of total area)	49.09%
Southern Florida Coastal Plain	Woody wetlands	0.57
	Deciduous forest	0.00
	Evergreen forest	0.00
	Mixed forest	0.00
	Total area	2.20
	% Forested (of total area)	25.72%

majority of stands burned by prescribed fire on a 1–3 year interval (Christensen, 1981; Kirkman et al., 2001). Forest structure is essentially two layers: an overstory of pine, and a species-rich understory assemblage of herbs, grasses, and shrubs. Fire exclusion results in the release of woody shrubs that then form a mid-story and eventually replace the pine overstory (Mitchell et al., 1999). The range of longleaf pine covers one of the widest edaphic ranges of any species in the Southeast, from seasonally inundated wetlands to xeric sand or clay ridges.

Pine flatwoods occur in mesic to hydric sites and have an overstory dominated by longleaf or slash pine or a mixture of the two. The understory is a mix of shrubs, palms and herbs. Fire return intervals are generally short (e.g., 3–5 years (Christensen, 1981; Stambaugh et al., 2011). Pine flatwoods are the dominant upland community in the Florida peninsula and the second most extensive forest type in the Coastal Plain. Lack of frequent fire can result in elevated fuel loads, leading to high fire intensity and severity once fires recur (McNab et al., 1978).

Pine rocklands are found on limestone outcrops in the extreme southern tip of Florida and elsewhere in the Caribbean. Structurally, they resemble the other pine forests with a lack of a mid-story and a species rich understory. Many rockland sites have low productivity and fuel loads; thus, fire return intervals are somewhat longer at 5–10 years. These forests are often found in low-lying areas and are susceptible to storm surge and sea level rise (Ross et al., 2009).

Sand pine (*Pinus clausa* (Chapm. ex Engelm.) Vasey ex Sarg.) stands occur in xeric sites in the Florida Peninsula and panhandle. The peninsula variety (*Pinus clausa* var. *clausa*) has serotinous cones and generally burns infrequently (~50 years) with high intensity and severity, stand-replacing fires (Myers, 1990; Parker et al., 2001). The panhandle variety, *Pinus clausa* var. *immuginata*, has non-serotinous cones and can regenerate under non-fire disturbance regimes.

Throughout the region, extensive pine plantations occur with monocultures of loblolly and slash pines and, to a lesser extent, longleaf pine. Many plantations are not burned intentionally for a variety of reasons, and become susceptible to stand replacement fires (though presently a rare occurrence), especially early in establishment, or after long periods of fire suppression when coupled with extreme drought (Binford et al., 2006).

Tropical hammocks are closed canopy broadleaved forests found in the southern peninsula of Florida and Caribbean with a diverse mix of evergreen and deciduous species. These forests are fire-sensitive, occurring over deep Histosols, and burn infrequently (many decades). When fires do occur, they tend to be low intensity, but high severity ground fires.

Forested wetlands occur throughout the region along rivers and in low elevations. There are many subtypes such as cypress, hardwood swamps, and hydric hammocks (Ewel, 1990). Though there are diverse species assemblages in forested wetlands, some common fire characteristics emerge. Fire frequency and severity are linked to both hydroperiod and drought, with short hydroperiod wetlands burning at higher frequencies in general, and all wetlands burning more frequently in droughts. Fire severity is typically higher in long hydroperiod wetlands that burn during droughts. In these cases, the deep Histosols can combust and alter both species composition and hydrology. Frequently-burned, short hydroperiod cypress savannas are typically both low intensity and low severity.

Mixed pine-broadleaved forests are particularly abundant in the Piedmont region, and are usually dominated by oaks, and either loblolly or shortleaf pines. These forests typically experience low intensity surface fires every 3–10 years.

2.2. Southern Appalachian mountain forest types

Much of the southern Appalachians are dominated by mixed deciduous forests. These forests are one of the most biologically-diverse temperate regions in the world (Bond et al., 2005). Fire regimes in this region vary with site moisture, elevation, aspect and slope. The shortest fire return intervals (10–40 years, Harmon, 1982) occur in mixed pine-oak and xeric pine on upper slopes and ridges; and the longest fire return intervals (many decades) occur in moist coves and high elevation, spruce-fir forests. Cove and spruce-fir forests are dominated by fire-sensitive species. When fires do occur in cove and spruce-fir forests, they are typically high severity, stand-replacing events.

3. Past fire management

3.1. Piedmont and Coastal Plain

In the past, fire return intervals were relatively frequent over much of the landscape; and for the last several thousand years, they were heavily influenced by human ignitions (Stambaugh et al., 2011). With the arrival of people into the Southeast at the end of the Pleistocene, ignitions would likely have become more frequent than lightning alone. Historical seasonality in fire frequency is poorly understood (Knapp et al., 2009); but in the Piedmont and Coastal Plain pine forests, fires likely occurred at any time during the year, and in broadleaved forests, they likely occurred in the fall through spring. Fires in forested wetlands interact with hydrology and were influenced more by patterns of droughts than rainfall seasonality as discussed above (Watts and Kobziar, 2013; Casey and Ewel, 2006). Changes in fire regimes (intentionally or accidentally) have tended to reduce fire frequency in many locations, resulting in both heavier fuels and changes in fuel types (e.g., forest floor development, fuel ladders, etc.).

3.2. Southern Appalachians

In the southern Appalachians, fire has had a long history as a prominent disturbance agent; and the forest structure and species composition of these mountain forests is reflected in its many fire-tolerant ecosystems. Fire regimes, however, have varied across the region over the last several centuries (Van Lear et al., 2000; Brose et al., 2001; Abrams, 2005) becoming much less frequent especially in the last 75 years (Fesenmyer and Christensen, 2010). Native Americans and early European settlers imposed a long period of frequent, low intensity fires, followed by a shorter period of high-intensity, stand-replacing fires during the era of heavy logging in the late 1800s (Brose et al., 2001; Guyette et al., 2002; Fesenmyer and Christensen, 2010). The forest types that burned more frequently were those dominated by oaks, table mountain, pitch (*P. rigida* Mill.), shortleaf (*P. echinata* Mill.), and Virginia (*P. virginiana* Mill.) pines. For example, many of the pine-bluestem grass woodlands and savannas were historically maintained by surface fires resulting from anthropogenic ignitions about every 3–4 years (Guyette et al., 2002); whereas mixed severity fires resulting in stand-replacement occurred about every 20 years (Guyette et al., 2006).

3.3. Fire suppression

Since the early 1900s, fires are much less frequent than they were historically due to effective fire suppression (Brose et al., 2001; Jurgelski, 2008); and as a result, forest composition consists of less fire-tolerant tree species and more fuel accumulation than was present before suppression efforts. The period of fire exclusion set the stage for large-scale tree mortality and potential loss of life and personal property from wildfires. Thus, prescribed burning has been widely used as a forest management tool for hazardous fuel reduction in the Southeast. Melvin (2012) reported approximately 2.6 million ha burned by prescription in 2011 in the Southeast—82% of the national total. The ratio of area burned by prescribed fire versus wildfire in the Southeast when contrasted with the rest of the nation (Fig. 3) provides an indication of the effectiveness of prescribed burning as the most cost-effective technique to reduce fuels and wildfire. In the Southeast, more than 2/3 of areas burned are prescribed burned, while less than 1/3 are due to wildfires whereas the ratios are reversed in the rest of the U.S. (Fig. 3). Prescribed burning also can reduce wildfire risks indirectly by maintaining health of fire-resistant species, such as longleaf pine (Sackett, 1975).

3.4. Silvicultural and agricultural landscapes

The conversion of much of the southeastern landscape to agriculture and fiber production—primarily, loblolly and slash pine—has dramatically altered the landscape for fire. Burning for agricultural purposes dominates portions of the Southeast, and can represent ignition sources for wildfire in fragmented agricultural landscapes. Paradoxically, agricultural land also reduces wildfire through the fragmentation of forested habitat in the upper Coastal Plain. These complex interactions between fire and human management are expected to change with predicted alterations in land use in the coming decades. Short rotation pine plantations are found throughout the Southeast, but dominate land use in portions of the Piedmont and the outer Coastal Plain. These high-density plantations are vulnerable to catastrophic wildfire and drought-induced beetle attacks, which further contribute to wildfire risk; more than $58 million dollars of timber were consumed on privately owned lands in the Georgia Bay Wildfire Complex alone in 2007 (Georgia Forestry Commission, 2007).

3.5. Invasive species

Fire frequency and intensity are also influenced by species composition, particularly where exotic invaders have a strong influence. In some cases, exotic species alter fuel structure and quantity, and either increase [e.g., cogon grass (*Imperata cylindrical*, Lippincott, 2000), climbing fern (*Lygodium japonicum*, Pemberton and Ferriter, 1998), Japanese brown top (*Microstegium vimineum*, Emery et al., 2011)] or decrease fire frequency and intensity [e.g., Brazilian pepper (*Schinus terebinthifolius*, Stevens and Beckage, 2009), Chinese privet (*Ligustrum sinense*, Cuda and Zeller, 2000)]. It is unclear how these species will respond to the predicted changes in climate; but, large-scale agricultural abandonment could create conditions for rapid expansion of non-native, invasive species.

4. Climate and climate change scenarios

The southern U.S. primarily exhibits a humid subtropical climate except the extreme southern portion of the Atlantic Coastal Plain (tropical), and western portion of the Gulf Coastal Plain (semiarid). Annual average daily temperature ranges from greater than 21 °C in southern FL and TX to 12.7–15.6 °C in northern parts of the region. Annual precipitation is highest in the southern Appalachians, reaching up to 2000 mm at the highest elevations, and falling to 1270–1780 mm in the Piedmont, and to 1015–1270 mm towards the Atlantic coast areas. The driest areas are found in the western areas of the Southeast, ranging 305–500 mm. Seasonal variability is characterized by hot, humid

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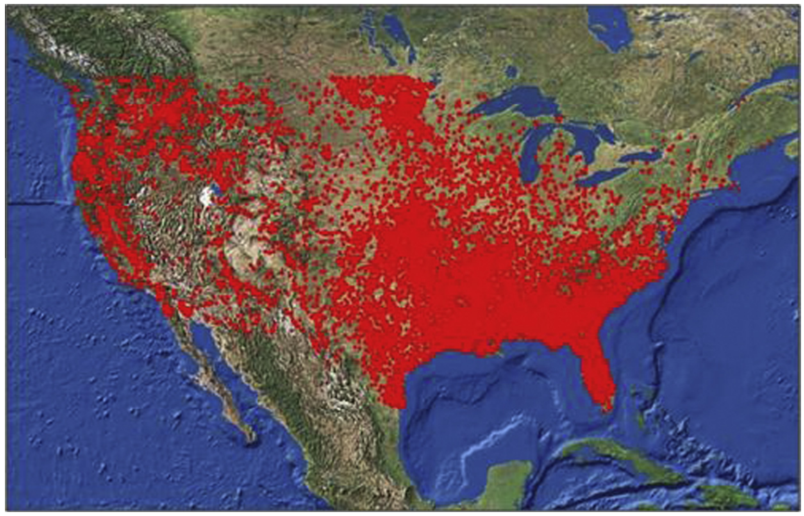

Fig. 2. Cumulative distribution of MODIS fire detections in 2010 for the continental USA. Each red point represents a single detection (http://modis.gsfc.nasa.gov/). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

summers, and mild to cool winters. The major weather and climate extremes include tornados, hurricanes, frequent lightning, and drought. Drought is the extreme climatic factor most related to large wildfires in this region (Liu et al., 2010a,b; Lawler et al., 2013).

Future temperature is projected to increase across the south, with increases ranging from less than 1.67 °C in the Atlantic coast to above 2.8 °C in northwestern Texas, under the B2 Intergovernmental Panel on Climate Change (IPCC) emission scenario projected by the HadCM3 Global General Circulation Model (GCM). The B2 emission scenario represents a smaller rate of increase than that predicted for A2, and the increasing rate seen here is generally smaller than that seen in the corresponding areas of the continental U.S. (see Rocca et al., in this issue). Future precipitation is projected to decrease in most of Texas and the western Mississippi River valley with changes exceeding 15%; but, an increase in western Texas and most areas east of the Mississippi River by an average of ∼6% (see Rocca et al., this issue).

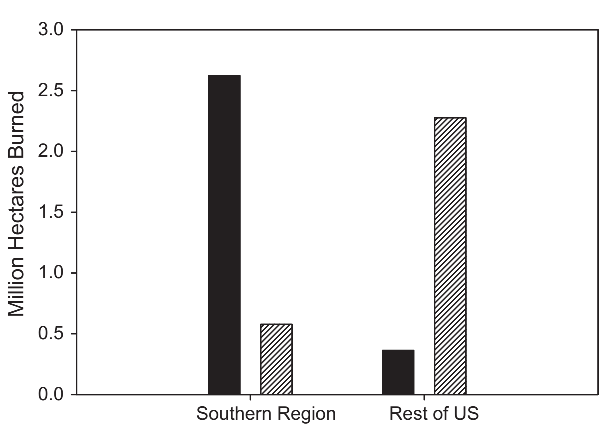

Fig. 3. A comparison in burned areas by wildfire and prescribed fire between the Southeast region and the rest of the U.S. in 2011. The solid bars indicate prescribed fires, the hatched bars indicate wildfires. Data for prescribed fires is derived from Melvin (2012), wildfire statistics from the National Interagency Coordination Center, Boise, Idaho.

4.1. Uncertainty in climate change scenarios

There are many sources of uncertainty in climate projections for the Southeast that are critical to projections of climate–fire interactions. The projection errors and bias with GCMs therefore are an important uncertainty source. With different dynamics and physics as well as simulation resolutions, the projected climate could vary significantly at regional scales among models. Though these models usually produce the same warming signals and common geographic patterns at the contiguous U.S. scale, there are considerable differences in the magnitude and direction in regional climate change patterns. For example, the Community Climate System Model (CCMS) projects summer warming at about 1 °C, while the Hadley Centre Coupled Model, version 3, (HadCM3, http://www.narccap.ucar.edu) projects 4 °C warming. Models also disagree on the direction of change: CCSM predicts a wetter Southeast while the HadCM3 projects a drier one. A further uncertainty is the effect that future climate will have on fire regimes, due in part to the spatial dependence on resolving past climate–fire relationships. For example, Morton et al. (2013) showed that the relationship between area burned and climate was lacking for small management fires, but showed a positive correlation between drier conditions on large wildfires. Because the southern fire landscape is a mosaic of fire size and ignitions, generalizations may be difficult. Nonetheless, the results of Morton et al. (2013) suggest that prescribed burned area could be independent from mean climatic conditions.

Most regional fire projections now apply high-resolution climate change scenarios downscaled from GCM projections using statistical and dynamical techniques (Bucklin et al., 2012; Misra et al., 2012). The former approach applies statistical regression based on historical meteorological measurements, and assumes historical conditions would approximate future conditions. The latter approach runs regional climate models with the boundary conditions provided by either climate modeling over a larger domain or from measurements, thus requiring more computational resources. Both approaches have limitations and uncertainties. For example, regional models used to dynamically downscale temperature and precipitation for the Southeast can often produce the opposite trends predicted at the larger spatial scale, particularly for precipitation, with variation comparable to the among-GCM variation (Bucklin et al., 2012). The CCSM and HadCM3 projections downscaled by MM5, for example, illustrated that the downscaled changes in precipitation are opposite to those of the GCM projections (http://www.narccap.ucar.edu). The regional climate model, RCM3, driven by the Geophysical Fluid Dynamics Laboratory Global Climate Model underestimates average surface temperature for some areas of the southeastern United States by about 4 °C for the daily average during the winter of the selected period (Shem et al., 2012).

4.2. Uncertainty in hurricane activity projection

Hurricanes are one of the major natural disturbances to forest ecosystems in the Southeast (Vihnanek et al., 2009), and can not only substantially increase fuel loads, but also promote wildfires when they do not coincide with strong steering currents. A single storm can convert the equivalent of 10% of the total annual carbon sequestered by forests across the United States into dead and downed biomass (McNulty, 2002). Hurricane Katrina resulted in a large loss of annual forest carbon sequestration capacity (Chapman et al., 2008). Storms occurring in the late spring and early summer typically do not interact with strong steering currents, and may remain stationary for several days. For example, the largest fire in the Southeast in more than 50 years, the Georgia–Florida Bay Fire Complex in the Okefenokee Swamp, was driven by a stationary tropical low pressure system that led directly to rapid increases in burned area driven by strong winds.

Projections in future hurricane frequency and intensity vary. Several analyses illustrate an increasing trend in hurricane frequency (Webster et al., 2005; Emanuel, 2005; Pielke et al., 2005). Other studies project less frequent but more intense hurricanes in the North Atlantic basin (Ying et al., 2012; Mallard et al., 2013) or both more frequent and intense (Emanuel, 2013). Lastly, a comparison of tropical cyclone activity in 14 Coupled Model Intercomparison Project phase 5 (CMIP5) models found no robust changes (Camargo, 2013).

4.3. Future fire potential

Currently, fire potential in the Southeast across all Ecoregions varies seasonally, with seasonal lows in the winter and spring and highs in the summer and fall. The potential is described by the Keetch-Byran Drought Index (KBDI), which averages 130 in winter, 100 in spring, 260 in summer, and 320 in fall (Liu et al., 2012). For summer and fall, fire potential is at high or upper moderate levels in the western part of the Southeast, but is low or low to moderate in the eastern part of the region. Future KBDI is predicted to increase by more than 100 in summer across most of the Southeast; but decrease by 50 in winter and spring, especially for the eastern-most Atlantic Coastal areas. As a result of this expected increase in KBDI in summer and fall, future fire potential would increase from low to moderate in the eastern sections in the Southest, and from moderate to high levels in the western portions of the Southest.

The fire seasons for the entire southern U.S. will be 2 and 3 months longer using the two criteria for fire season definition (that is, moderate level or higher, and high level or higher), respectively. Fire seasons are expected to increase by 1–5 months in the eastern eco-regions with the largest increase in the Appalachians, and by 1–3 months in the western eco-regions of the Southeast (Liu et al., 2012). This projected increase in fire season will have direct effects on how fire is managed in the future; but, uncertainty in the precipitation forecasts discussed above makes definitive statements about fire danger elusive.

Future fire will also be a function of changing species composition. As presented above, changes in climate could increase the range of areas suitable for colonization by exotic invaders, especially if conditions become warmer. While the impact of invasive plants on fire potential is species dependent, many areas of the Southeast would experience an increase in the flammability of vegetation. Additionally, the interactions among native species' responses to fire and drought will likely change the fire regime and thus the relative distribution of forest types across the landscape, with fire tolerant pines and oaks becoming more abundant under drier warmer conditions. Drier and warmer conditions may allow fire to spread into cove and spruce-fir forests more frequently than in the past (White et al., 1985).

Fuel loading is a critical factor affecting fire occurrence and emissions, and it can change in many ways in response to climate change. For example, the biomass of a given species and/or the species composition of a forest can respond uniquely to changes in climate, altering the fuel composition. Neilson et al. (2005) predicted that a large portion of the temperate deciduous forests in the Southeast would be replaced with temperate deciduous savanna in response to projected climate change, altering fuel loading and subsequent fire behavior. The chemical composition of fuels could also affect their combustion dynamics. For instance, secondary compounds in plants have been shown to both increase and decrease in response to elevated atmospheric CO_2 (Sallas et al., 2003; Mohan et al., 2006). Increasing atmospheric CO_2 concentration will likely favor an increase in fuel loading through higher productivity, especially if water is limiting (Claesson and Nycander, 2013). However, fuel loading is also dependent on other factors including decomposition, which is in turn driven by such factors as litter quality, water availability and temperature. In a recent study, Zhang et al. (2010) simulated future ecosystem dynamics across the Southeast using the contemporary fuel load map developed by the Fuel Characteristic Classification System (FCCS, Ottmar et al., 2007). Their results indicated a 12% reduction in total fuel load by the mid-21st century, as well as shifts in species composition due to climate change that could result in novel plant communities (Williams and Jackson, 2007).

4.4. Future fire management

The uncertainty surrounding climate projections will dominate planning for future fire management in the Southeast U.S. Widely varying projections, variability around precipitation, hurricane forecasts, and temperature may simply represent the inherent uncertainty with current climatic modeling or could accurately portend a more variable climatic future. This inability to distinguish model uncertainty from predicted future variability is an acute problem for Southeast climate projections; and it will likely present the greatest challenge for managed fire regimes. Climate change could bring serious limits to prescribed burning. There are only a certain proportion of days in any year that are within prescription for igniting a fire (Liu, 2012). When weather conditions are too dry, hot, and/or windy, prescribed burning has an elevated risk of escaping control and becoming a wildfire. If variability in precipitation increases, fewer burn days would likely be available since conditions too wet for fire to carry could be interspersed with periods of drought when it would be too dry to safely burn. If burn days decrease and fire return intervals increase, heavier fuel loads and changes in fuel types will further restrict the conditions where prescribed fire can be applied. For example, as fine fuels accumulate in the absence of fire, a thick humus layer begins to develop on the forest floor. When this thick layer ignites, considerable overstory mortality results from smoldering fires (Varner et al., 2007; O'Brien et al., 2010). These smoldering fires, in turn, produce excessive smoke. An additional danger of these smoldering fuels is that they can reignite surface fuels at days to weeks later causing unintentional fire spread. To burn stands with heavy fuel accumulation, a very narrow window of both weather and fuel moisture must occur simultaneously so that the litter burns but

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the humus layer does not (Varner et al., 2005). Increased variability will almost certainly decrease days available for prescribed burning in the future. The seasonality of suitable prescribed burn opportunities may also shift. Liu (2012) predicts a decrease in burning days in the summer and fall and an increase during winter and spring. Even with the potential offset due to shifts in seasonality for prescribed fire, in the face of climate variability (Morton et al., 2013), the total annual days available for prescribed fires is expected to decrease under current parameters.

Other fuel reduction and restoration treatments have been considered for the Southeast, and other regions of the U.S. (McIver et al., 2012), such as chemical and mechanical treatments (thinning and mastication). These options may become even more imperative for wildfire mitigation under future climate scenarios that limit prescribed burning. Substituting mechanical treatments for prescribed fire may be a viable alternative for fuel reduction in some cases; however, even though mechanical treatments reduce the vertical fuel component, the additional litter and woody fuels on the ground can increase wildfire risk for up to 5 years (Waldrop et al., 2010); and the accumulation of organic material in the absence of fire can still lead to a high severity burn when a low intensity wildfire occurs (Varner et al., 2005). Harvests for biomass utilization show the greatest promise as fuel reduction techniques, as biomass removal for fuel power generation can also lead to reductions in global CO_2 emissions (Jones et al., 2010). Combination treatments, such as pile and burn following cutting, or whole tree harvest, have been utilized in drier landscapes to address this potential increase in wildfire risk (McKenzie et al., 2011); but these are time consuming and are rarely cost effective. Other ecological consequences would differ between burning and fire-surrogate treatments, such as biodiversity conservation, carbon storage and sequestration (Boerner et al., 2008), biodiversity (Kirkman et al., 2001, 2004) and water quality and quantity (Ford et al., 2004). Thinning without burning can produce income and allow targeted changes in overstory composition (Agee and Skinner, 2005; Outcalt and Brockway, 2010); but chemical treatments are often necessary to control recolonization of woody species or nonnative invasive species. For example, mastication has been successful at reducing woody growth and increasing grass cover, but woody species recover quickly. Outcalt and Brockway (2010) suggest that it would be necessary to re-apply mastication on a frequency similar to prescribed fire, e.g., every 2–3 years for longleaf pine forests though this would increase the likelihood of negative effects on fuels and soils discussed above. The cumulative cost of these repeated mechanical treatments may limit their application where burning is not an option; however, these costs may be less than the cost of catastrophic wildfire.

4.5. Carbon emissions, storage and sequestration

Carbons storage and sequestration are key ecosystem services that are influenced by the structure and function of each forest type within the Southeast, and their complex interactions with fire and climate. The Southeast is among the most important regions with respect to C sequestration potential (Birdsey et al., 2006). As the region's climate continues to change, our understanding of these complex interactions becomes less clear. Currently, prescribed burning in the Southeast is conducted at higher fuel moistures and with meteorological conditions that favor low-intensity fires that reduce fuel consumption as compared to conditions typical for wildfires. Therefore, prescribed burning potentially results in lower CO_2 emissions than wildfire (Urbanski et al., 2009). Some studies have provided quantitative estimates of these comparisons in other regions. For example, Wiedinmyer and Hurteau (2010) used a regional fire emissions model to estimate daily CO_2 fire emissions over 2001–2008 for the western U.S. Wide-scale prescribed fire was found to reduce CO_2 fire emissions by 18–25% in the western U.S., and by as much as 60% in specific forest systems. Narayan et al. (2007) pointed out that prescribed burning significantly reduced CO_2 emissions in European countries with high fire occurrence. Over a 5-year period wildfire emissions were about 11 million tons of CO_2 per year, while those with prescribed burning application were only about six.

The Southeast has such a high C sequestration potential due to its relatively young age class of forests that are aggrading in biomass, large proportion of land area in forests (nearly 60%) and high rates of net primary productivity (NPP). However, regional assessments for C mitigation purposes are complex, and the impact that regional disturbances, such as insects (Gan, 2004), diseases (Birdsey et al., 2006), wildfire (Birdsey et al., 2006), and wind (McCarthy et al., 2006; McNulty, 2002) have on regional productivity are often not accounted for when scaling stand level productive capacity. For instance, Binford et al. (2006) reported that average region-wide C sequestration potential is roughly 1–2 tons $ha^{-1}\ yr^{-1}$, even though stand level measures ranged from 6 to 10 tons $ha^{-1}\ yr^{-1}$ (Birdsey and Lewis, 2003). Timber harvests, wildfire and mining contributed to reduced large scale production in the area of study (Binford et al., 2006). Disturbance impacts on regional productivity can be attenuated by management that increases ecosystem resilience to climate change (Dale et al., 2001). For instance, longleaf pine has been suggested to be a more desirable species in the Coastal Plain due to its resistance to damage from wildfire (given sufficient prescribed burning; see O'Brien et al., 2010), insects, and disease (Noss, 2001). Additionally, thinning and prescribed burning could reduce climate change interactions with major insect outbreaks such as southern pine beetle (*Dendroctonus frontalis* Zimmerman) in the Piedmont and southern Appalachians (Gan, 2004). In a simulation of productivity and hydrologic consequences of increased temperature and increased precipitation, McNulty et al. (1996) reported that increased temperature decreased NPP from less than 2% to nearly 33% depending on the water holding capacity and water balance of the site. Thus, the impact that changing climate has on C dynamics is likely to be mediated by site specific water relations. Lack of understanding of how ecohydrology and disturbances such as fire interact to regulate C storage and fluxes is currently a dominant constraint to more quantitatively predicting forest-climate impacts on C dynamics.

Our understanding of the interaction between carbon dynamics and fire in forests and their association with climate change becomes even more uncertain when we consider elevated concentration of atmospheric CO_2. Rising atmospheric concentrations of CO_2 will have direct effects on forest function and growth. Previous studies have shown that with elevated CO_2 concentrations tree species generally increase their physiological activity and production, and alter leaf chemical composition (Korner and Miglietta, 1994; Ainsworth and Long, 2005). These changes could be expected to alter litter composition and deposition increasing fuel loads. Though the carbon dynamics of southeastern forest types and the region as a whole are likely to be altered with climate change, the complexity of the ecological interactions makes precise projections impossible at this point and will require greater scientific examination. For example, a decrease in agricultural area that was followed by a subsequent increase in pine forest (either plantation or natural regeneration) might result in more carbon storage but that carbon could be at a higher risk of loss to wildfire due to increased landscape connectivity.

4.6. Fire and water interactions

The key components of watershed processes are inputs of precipitation (*P*), interactions of vegetation, soil and water including evapotranspiration (ET) and water yield (*Ro*, runoff), overland flow

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(erosion), and storage and filtering (nutrients), and outputs in stream flow. Numerous studies have been conducted on the effects of wildland fire (wildfire and prescribed) on watershed processes, particularly water quality. When a wildland fire occurs, the principal concerns for changes in water quality are delivery of sediment and chemical ions, particularly nitrate (NO_3^-), into the stream channel. Previous research in the southern Appalachians (Vose et al., 1999; Clinton et al., 2003; Elliott and Vose, 2005; Knoepp et al., 2009; Elliott et al., 2012) and Piedmont and Coastal Plain (Vose et al., 2005) has shown that wildland fire does not negatively impact water quality (stream sediment and NO_3^-) due to an intact forest floor humus (Oe + Oa) layer and rapid vegetation growth following burning. Consumption of deep humus during more extreme droughts may alter the buffering capacity of organic soil to prevent impacts to water quality.

Fire research suggests that mobilized nitrogen (NO_3^- and NH_4^+) as a result of burning is small in comparison to that lost in smoke (particulates and NO_2 and NO_x) and that any measurable response in either soil water or stream water is short-lived, and the magnitude of the response is generally small (Vose et al., 1999; Clinton et al., 2003; Elliott and Vose, 2005). However, timing of wildfire or prescribed fire may be notable. For example, Clinton et al. (2003) compared stream NO_3^- responses following various fire prescriptions including type and season of burn. They concluded that season of burning influenced the amount and duration of stream-water NO_3^- responses more than other factors such as species composition and fire type. Differences were observed between fall burns and spring burns primarily due to increased uptake of mobilized nutrients during the spring compared with the fall. Overall, stream-water NO_3^- responses across burning regimes in southern Appalachian forests are negligible.

Although the effects of fire on water quality have been well studied, surprisingly little is known about how fire will affect water quantity. No research has been conducted in the Appalachians or Piedmont and only two studies in the Coastal Plain (Bracho et al., 2008; Clinton et al., 2011) on any component of watershed hydrology (i.e., ET, transpiration (*Et*), and *Ro*) associated with wildland fire exist to our knowledge. With vegetation and water balance so closely coupled, understanding the direct and indirect feedbacks between vegetation and water quantity associated with fire becomes increasingly important, particularly under predicted climate change and altered fire regimes.

Evapotranspiration (ET) is a major component of the water balance of forested watersheds, consuming about 50–90% of the incident precipitation (Ford et al., 2011). It is also directly linked to ecosystem productivity, and the functional recovery of the hydrology of forested watersheds depends on the recovery of ET. In spite of the importance of forest ET, estimates of ET at the landscape scale have become possible only in the past few decades with use of eddy covariance, sap flux technology, and species-specific understanding of *Et* (Ford et al., 2004).

Changes in albedo, heat flux, and leaf area following fire can potentially alter *Et* demand and water use (Beringer et al., 2003; Amiro et al., 2006; Wendt et al., 2007; Rocha and Shaver, 2011; Veraverbeke et al., 2012). Even a moderate intensity fire can result in canopy scorch and leaf drop in the weeks following fire. The loss and shutdown of leaves will reduce *Et* and alter energy partitioning. One study in the Coastal Plain region (Clinton et al., 2011) examined the effects of crown scorching in longleaf pine forests. They found that while crown scorching of longleaf pine reduced leaf area by 77%, sap flow was similar between scorch and control trees due to changes in transpiration by the remaining foliage (e.g., transpiration per unit leaf area increased immediately following scorching by 3.5-fold compared to control trees).

Changes in forest composition following fire could also alter ET. For example, Bracho et al. (2008) compared two Coastal Plain ecosystems that used prescribed fire to manage vegetation. Higher annual ET at the pine flatwoods (812 mm) compared with the scrub oak (713 mm) was explained by differences in plant water availability and leaf area. Under future climate scenarios, the pine flatwoods may be at greater risk than the scrub oak community as scrub oak is more conservative in its water use than longleaf pine, regardless of precipitation amount (Bracho et al., 2008).

4.7. Fire–climate and human health

The air quality impacts due to smoke from wildfire is a critical concern for human health. Smoke is produced when wood and other organic material combust and produce a mixture of gases, solid particles, and aerosols. Smoke impacts can generally be characterized into two classes: visibility related and health related. Visibility impairments range from regional haze that obscures general visibility and degrades scenic vistas, to dramatic visibility reductions that create hazards to both air and ground transportation. Smoke can cause safety problems when it impedes local visibility to drivers of motor vehicles and creates hazardous conditions (Achtemeier, 2009). Health related impacts negatively affect human activity, especially to those with respiratory problems and other smoke-sensitive illnesses (Naeher et al., 2007). Health related impacts are regulated through the National Ambient Air Quality Standards (NAAQS) outlined in the Clean Air Act. Wildfire emissions are important sources for PM2.5 and precursors of O_3, which are two of the air pollutants subject to the NAAQS. A recent research report documented a smoke plume transported to Atlanta and other metropolitan areas during the 2007 Okefenokee wildfires in southern Georgia and northern Florida. As a result, PM2.5 concentrations exceeded the NAAQS and caused severe health problems in these areas. If wildfires are more frequent and severe in the future as is likely, the occurrence of smoke impacts will also increase and lead to more air quality concerns. There are however, ongoing improvements in atmospheric modeling to better understand smoke dynamics from prescribed and wild fires that may better guide wildfire management.

4.8. Conservation of diverse habitats

Changes in climate and the interaction with fire have a great potential for impacting biological diversity in a paradoxical way. Drier, warmer conditions could make the application of prescribed fire more difficult, lengthening fire return intervals in systems dependent on fire, such as longleaf pine and pine rocklands. This would result in a reduction in diversity in ecosystems adapted to high fire frequency and dependent on prescribed fires, while simultaneously shortening fire return intervals in wetlands and wetland ecotones because of increased susceptibility to wildfire. The net effect of both of these changes would likely be a reduction in biological diversity.

High fire frequency is crucial for the maintenance of both plant and animal diversity in many Coastal Plain ecosystems. For example, in longleaf sandhills and pine rocklands, high fire frequency is correlated with higher plant diversity (Mitchell et al., 2009; Kirkman et al., 2004, Fig. 7). Since prescribed fires are critical for maintaining high fire frequency, any changes in climate that reduce the ability to apply fire will also have a negative impact on biodiversity. Similarly, changes in fire intensity due to higher fuel loads or drier conditions will likely have a negative impact on native species diversity by driving ecosystems towards alternative stable states (Beisner et al., 2003). For example, an alternative state is created when a high severity fire kills the pine overstory in a pine flatwoods area, when subsequently either oak or palmetto shrubs are released from the understory and dominate the system.

This, in turn, excludes both pine overstory re-establishment and suppresses understory herbaceous species.

Other potential shifts could occur through a decrease in precipitation and an increase in temperature, or more frequent droughts. This could results in a shift from overstory dominance by broadleaf species to pines due to greater water use efficiency among the pines versus broadleaved overstory species. This change in dominance would drive a reduction in habitat for species requiring broadleaf habitats. More frequent droughts would also likely have a large negative impact on wetland and wetland ecotone species diversity. Fire frequency would increase in long hydroperiod wetlands with concomitant impacts on both soils and fire sensitive species. Wetland ecotones in the region that are high in biodiversity are very susceptible to changes in hydrology and temperature. Climate change could cause the wetland-upland ecotone become drier, burn more frequently, and perhaps cause wetlands to disappear. Also, fires could more easily cross the ecotone into wetlands during dry periods and cause severe ground fires and the combustion of organic soils, e.g., peat.

Given the lack of large contiguous forested landscapes, the resilience of the Southeast to dramatic changes in future climate, especially maintaining biodiversity, is dependent on careful land management. The fragmented nature of the upper Coastal Plain with large portions of the landscape in private ownership might mean that any remaining habitat will occur in scattered parcels designated for conservation. These scattered parcels would serve as the only refugia for vulnerable species that would allow for long term persistence (Lawler et al., 2013). If climate variability further limits capacity for applying prescribed burns on conservation lands, then the prospects of fire maintained biodiversity migrating in latitude or altitude is complicated by the existing landscape fragmentation. Longleaf pine dominated woodlands may be an exception and buffered against future climate impacts; given its wide edaphic gradient in the Coastal Plain (Kirkman et al., 2004) and resilient life history traits (e.g., disease and insect resistance, drought adaptation). Conversion to species like longleaf pine may offer the best long-term compromise to protecting biodiversity, meeting carbon sequestration goals, and sustaining yields for the forest products industry (Mitchell et al., 2009).

5. Conclusions

The southeastern landscape is characterized by a complex arrangement of land cover, topography, and ownership, all of which is dominated by human legacies and human-mediated disturbance regimes. The majority of the region is covered by agricultural and forested ecosystems that will respond to future climate change in unpredictable ways given current modeling uncertainties. The region also has the greatest number and area of both prescribed and wildfires in the U.S. Climate change could, however, bring serious limits to prescribed burning by altering the variability of rainfall, drought, and hurricane activity. Future drought indices that are related to wildfire danger are predicted to increase in the south, which has the potential to reduce the number of days within prescription boundaries for prescribed burns and/or shift their seasonal availability. Limitations to prescribed burning and increase in high or mixed severity fire regimes will likely have strong impacts on ecosystem services forests in this region provide. The southeastern U.S. is among the most important regions with respect to carbon sequestration potential; however, that potential is challenged by a lack of understanding of how regional disturbance patterns interact with climate and how prescribed fire cycles impact carbon storage and dynamics. Further complicating projections on C sequestration is the unknown response of agriculture to future climate change and the potential conversion rate of agriculture to forests or other land uses. The difficulty of prescribed burning in the future climate provides considerable risk to globally important sources of biodiversity, because even slightly increased fire return intervals could result in significant loss of diversity in these systems. There is an overwhelming amount of uncertainly that makes precise projections difficult, and results in a bet-hedging strategy for land managers until trends in climatic means or variability within regions are clearer.

Nonetheless, there are opportunities for mitigating some of the undesirable outcomes associated with the diminished ability to apply prescribed fire (Table 2). These suggested alterations in current activities are not meant as prescriptions, but rather as examples of how managers may be forced to alter strategies due to the impacts of the no-analog future (Williams and Jackson, 2007) on forest

Table 2
Summary of fire regimes in selected forest types where information was available with potential management adjustments to mitigate climate change scenarios discussed in this manuscript. These suggestions are not meant as prescriptions, but as considerations for exploring options for future forest management. Fire return intervals represent typical historical estimates.

Ecoregion (Level III)	Land cover	Fire return interval (years)	Severity (function of intensity and duration)	Characteristic communities	Possible management adjustments
Outer Piedmont	Mixed forest	3–10	Low severity	Oak-pine	Increase winter and early spring prescribed burns[a]
Southeastern Plains	Evergreen forest	1–3	Low severity	Longleaf pine woodlands and savanna	Maximize prescribed fire acreage and maintenance of high quality stands through burn prioritization[b]
Outer Piedmont and Southeastern Plains	Evergreen forest	0	High severity, stand replacing	Pine plantations	Increase rotation and lower density of loblolly and slash pine plantations, slowly convert to longleaf pine plantations where possible; increase thinning and prescribed burning in plantations[a,c]
Blue Ridge	Deciduous forest	20+	High severity, stand replacing	Moist coves	Lower fuel loads in surrounding forests through prescribed burning or other treatments to ease suppression of wildfire[d]
Southern Coastal Plain	Mixed forest	3–4	Mixed severity	Mixed pine-oak and xeric pine	Where sand pine is present conduct high intensity prescribed burns to meet habitat needs while reducing catastrophic fire potential. Burn as frequently as fuels allow at any time of year[c]
Southern Coastal Plain	Woody wetlands	Variable	Positively correlated with hydroperiod	Cypress, hardwood swamps, hydric hammocks	Reduce fuels in surrounding forests to ease suppression in periods of drought to combat wildfires during dry periods that cause severe ground fires and the combustion of organic soils[a,c]

[a] To minimize negative air quality effects.
[b] To maintain biological diversity.
[c] To increase C sequestration (minimize negative impacts of wildfire).
[d] To minimize negative water quality effects.

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function. Some existing yet underemployed techniques, such as burn prioritization models (Hiers et al., 2003), could increase both the effectiveness of prescribed fire programs and mitigate increased wildfire risks over large landscapes. Forest management in the Southeast will require considerable resiliency and innovation as climate change impacts begin to accumulate. Managing forests for species with wide ecological amplitudes such as longleaf pine in the Coastal Plain could increase resiliency given the uncertainty of future climate. It is also clear that research into the highly complex interactions that drive climate change effects on forest fuels, fire weather, and fire behavior must continue to improve in order to manage our future forests both in the Southeast and globally.

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