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Southern Forest Outlook

FIRE

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An Analysis to Support the Southern Forest Outlook

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Abstract

This report in support of the *Southern Forest Outlook* assesses current and future risks associated with wildfire and smoke in the Southern United States, through a synthesis of literature review and new analysis. Key questions concern wildfire risk management and resilience-building efforts in the face of a changing climate, risks to forest ecosystem services, the potentially disproportionate impacts of fire and smoke on socioeconomically vulnerable populations, and how the growing wildland-urban interface, changes in fire regimes, and changes in safe prescribed burning conditions are likely to impact future management efforts. Results portray the regional geography of wildfire and smoke risks to people and ecosystem services, and where high return on fuel reduction investments can be achieved. Modeled future changes suggest shifts towards forests more prone to hazardous fire, with changes in risks to people and ecosystem services varying geographically and among different future scenarios. Results also suggest that preemptive forest management efforts including prescribed fire can offset future changes in wildfire and smoke risks. Ongoing and future changes in climate, forests, and society present complex wildfire risk challenges, but pathways exist to build forest resilience and mitigate risk.

Keywords: Wildfire risk, climate change, prescribed fire, smoke emissions, social vulnerability, risk management, ecosystem services.

Contents

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Photo: USDA Forest Service

Preface

The *Southern Forest Outlook* (SFO) adds to the regional landscape-level Southern Forest Assessment library. The South has a long history of regional assessments to address uncertainties within the forestry sector. Wheeler published *The South's Third Forest* in 1970, which evaluated trends and synthesized the peer-reviewed literature to examine the future of timber supply given increasing demand and concerns of underinvestment in private forest land. That report was followed by *The South's Fourth Forest* in 1988 (USDA Forest Service 1988), which focused on re-evaluating many of the same questions. However, research for *The South's Fourth Forest* relied on using timber market models and policy analyses to examine alternatives for reversing underinvestment in nonindustrial private forests. By the late 1990s, growth in forest management and timber production largely anticipated by those reports, coupled with the emergence of satellite chip mills, raised concerns about the sustainability of forests in the South, which motivated the *Southern Forest Resource Assessment* (SFRA) in 2002 (Wear and Greis 2002). *The Southern Forest Futures Project* (SFFP) (Wear and Greis 2013) was completed in 2013; it updated and expanded the analysis conducted for the SFRA. The SFFP was driven by increasing urbanization, land ownership dynamics, and markets and included integrated change scenarios based on population, economic factors, and climate change.

Analyses and results detailed in the Southern Forest Assessment library have been used to support planning and policy discussions for decades. *The South's Third Forest* identified strategies to encourage planting and increase management on private forests; protect forests from insects, diseases, and fires; and build stronger institutions for forestry training, technology transfer, and research. Its forecasts of population-driven urbanization and expansion of tree planting and timber production have been realized in the South. *The South's Fourth Forest* anticipated the growth in timber production realized through 2000 and informed a suite of programs and policies to encourage reforestation, management, and forest protection. The SFRA led to improved best management practices monitoring, helped to expand the Forest Inventory and Analysis Program, provided a wealth of information for the first State Forest Action Plans, and led to broader engagement across the forestry community. Findings from the SFFP helped set research priorities at the U.S. Department of Agriculture, Forest Service, Southern Research Station; provided motivation for a high priority regional working forest conservation initiative known as Keeping Forests; and increased emphasis on understanding socioecological systems related to water resources.

In 2019, the Forest Service and Southern Group of State Foresters (SGSF) leadership recognized a need to update the Southern Forest Assessment library with a new regional assessment—the SFO. Recent changes in land use, forest disturbances, forest management, and forest product markets have led to increasing uncertainty about the future of the sector. Though much of the assessment library remains relevant, new data, research results, and projection models allow for new insights into critical issues facing the South.

The SFO is a four-part synthesis of the following issues: (1) timber market conditions and futures, (2) water and forest interactions, (3) fire in a changing ecological and social landscape, and (4) forest dynamics and land-use change. These issue areas each leverage the work of the 2020 Resources Planning Act Assessment in terms of overall drivers (climate, population, and income), land-use change, forest condition (dynamics), and markets. The Southern Research Station and Southern Region, along with the SGSF, led the SFO with the objective of informing forest sector decisionmakers and the interested public about observed trends, anticipated futures, and critical issues based on authoritative synthesis and interpretation of existing science, data, and 50-year projections.

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Photo: USDA Forest Service

Key Messages

- Modeled future changes in forest landscapes of the Southeastern United States suggest shifts towards conditions like those in the western and southern parts of the region by mid-century, with a warmer climate and forests more prone to hazardous fire. These findings are consistent with expectations for more frequent fire return intervals and shorter prescribed burn windows, at least within traditional burn seasons in the South.
- Most areas with projected increases in wildfire risk by mid-century are where risk is already high, but parts of the southern Piedmont and forests west of the Mississippi River with moderate risk also show strong projected increases. Areas where different possible futures show the most agreement that risks will increase are in northern, upland subregions and Florida.
- Projected changes in specific risk factors show regional variability. Risk of direct exposure of people and structures to wildfire shows the strongest, and most consistent, increase across the region. The southern Appalachian Mountains, Ozark Mountains, and isolated areas along the coastal plain also consistently show increase in risk of smoke emissions sent to populated areas, forest carbon loss, and potential impacts to important watersheds.
- Enhanced fuel treatment programs could offset projected climate-related increase in risks associated with wildfire and smoke emissions from wildfire. The degree to which this is possible varies across the region and among different plausible future projections.
- Accounting for community differences in socioeconomic vulnerability—beyond population and structure densities alone—can lead to local and subregional shifts in emphasis of wildfire and smoke risks. Understanding changes in socioeconomic factors such as wealth, mobility, housing, and household composition will be important for anticipating and managing risks into the future.

Introduction

Fire in a Changing South: Forests, Society, and Climate

Fire is an intrinsic component of Earth's ecosystems, playing an important role in nearly all ecosystems in the Southeastern United States (the South). This includes both wildfire and fire used by people as a tool for shaping ecosystems and landscapes (Greenberg and Collins 2021, Kelly et al. 2020, Mitchell et al. 2014, Ryan et al. 2013, Wade et al. 2000). Much of the forest land base in the South comprises systems that are, or were before European colonization and land conversion, dependent to varying degrees on recurrent fire to maintain characteristic system structures and functions. Fire plays a particularly important role in pine-dominated ecosystems and other Southern Coastal Plain landscapes for sustaining system processes and biodiversity (Glitzenstein et al. 2021, Noss 2018).

Contemporary fire regimes in the South can be considered human fire regimes, being governed primarily by management decisions, land-use patterns, human ignitions, and other human influences (Balch et al. 2017, Bowman et al. 2011, Kobziar et al. 2024). Prescribed fire has historically been widely used to manage forest ecosystems, playing a more important role than in other North American regions, with 6 to 10 million acres burned annually in the South in recent decades (Cummins et al. 2023, Liu et al. 2014, Melvin 2021, Mitchell et al. 2014, Wade et al. 2000). As in other regions, prescribed fires help slow the development of hazardous fuel conditions while achieving a variety of social, economic, and ecological benefits (Brose and Wade 2002, Ryan et al. 2013, Stephens et al. 2012, Wade et al. 2000). However, prescribed fire history and current practice coexist in a complex relationship with a parallel history of fire suppression in the South. Resulting disruption of fire cycles has increased fuel loads and promoted shifts away from high-frequency, low-intensity fire regimes towards low-frequency, high-intensity regimes—a shift that is implicated in ubiquitous changes in forest structure, function, and composition (Greenberg and Collins 2021, Ryan et al. 2013).

These changes, together with a changing climate, rapidly growing populations, and attendant land-use changes including an expanding wildland-urban interface (WUI), have strongly shaped the risks associated with wildfire. As a result, alongside the benefits fire provides for sustaining healthy forests, wildfires also pose an increasing threat to people, infrastructure, and some ecosystem services, with the potential to be socially and economically catastrophic. Climate change in particular poses challenges throughout the South, as it does globally. Warmer temperatures and changes in precipitation patterns will alter the frequency and intensity of wildfires (Abatzoglou and Williams 2016, Smith et al. 2020). These changes will have significant implications for public health and safety, because elevated wildfire risk coupled with changes in our ability to manage fuels with prescribed fire could lead to more frequent, extensive, and intense wildfire and smoke events (Bowman et al. 2020, Gao et al. 2021, Kupfer et al. 2022, Liu et al. 2016, Prestemon et al. 2016).

Confronting the threats posed by wildfire while sustaining the positive roles of fire in Southern forests will challenge forest management in the coming decades. Prescribed fire will likely remain the most practical tool for reducing wildfire risks while improving forest conditions and maintaining ecosystem services. Wildfires occurring in areas with a recent history of prescribed fire can burn at lower intensity and extent, be easier to control, generate less smoke, and cause less damage than in other areas (Addington et al. 2015, Brose and Wade 2002, EPA 2021, Fernandes 2015, Stephens et al. 2012).

At the same time, the use of prescribed fire is likely to become increasingly constrained by ongoing changes in weather patterns, more strict air quality regulations, concerns about escaped fire into expanded WUI landscapes, and the availability of trained personnel (Kobziar et al.

2015, Kupfer et al. 2020, Stanturf and Goodrick 2013). Climatic shifts in particular will change the frequency and seasonal timing of environmental conditions that allow for safe and effective prescribed fires (Abatzoglou and Kolden 2013). Thus, fully capitalizing on the growing importance of prescribed fire for building resilience to wildfire will present unique management challenges into the coming decades (Liu et al. 2014, Vose et al. 2021).

Setting the scene: recent influential events

Events in recent years have greatly changed the fire management landscape for programs across the country. Soon after the catastrophic 2020 wildfire season in the Western United States, key documents emerged framing the growing wildfire crisis and societal implications and responses. These included the U.S. Department of Agriculture, Forest Service's 10-year strategy for confronting the wildfire crisis (USDA Forest Service 2022a, b) and the Wildland Fire Mitigation and Management Commission's Report to Congress (Wildland Fire Mitigation and Management Commission 2023). The 10-year strategy and the Commission Report both emphasize expanding the use of beneficial fire and other vegetation management practices to reduce wildfire risk and promote forest health. They also share an emphasis on integrative, cross-boundary collaboration to advance efforts to build community and ecosystem resilience, such as the development of community wildfire protection plans. This approach recognizes that managing risk requires coordinated effort across a range of stakeholders, including government agencies, private landowners, and local communities.

These guiding documents build on the National Cohesive Wildland Fire Management Strategy (the Cohesive Strategy), particularly in their renewed emphases on expanding prescribed fire and community collaboration (WFLC 2014, 2023). The Cohesive Strategy's emphasis on risk as a crucial concept for understanding what values are at stake, and for managing fire at landscape scales, is also carried forward in these documents. A social and ecological risk perspective helps expand from reactive fire response to proactive mitigation and resilience building (Wildland Fire Mitigation and Management Commission 2023).

All of these efforts identify social vulnerability and investment in underserved communities as priorities for addressing the risks posed by wildfire (USDA Forest Service 2022a, WFLC 2023). The vulnerability of people to impacts from fire depends on the location of communities and infrastructure and how they are situated in the WUI. But multiple additional socioeconomic factors can heighten the potential for harm, or conversely, enhance community resilience, including household and community economic status, mobility, language spoken, educational attainment, and housing type (Coughlan et al. 2019, Kondo et al. 2022). Research also suggests that primarily Black, Hispanic or Latino, and Native American communities experience greater vulnerability to wildfires than other communities (Davies et al. 2018, Palaiologou et al. 2019). Accounting for these factors is necessary for a full understanding of wildfire risk and formulating management responses, but standard assessments have not typically integrated them in the estimation of wildfire vulnerability and risk.

The priorities expressed in the 10-year strategy, the Commission Report, and the Cohesive Strategy are highly relevant in the South. Socioeconomic disparities in the region influence community vulnerability to wildfire and smoke (Afrin and Garcia-Menendez 2021, Gaither et al. 2015). Prescribed fire remains the most important tool for maintaining and expanding fuel treatment efforts in landscapes across the region, and community-based approaches to wildfire management in the South have been shown to be effective in reducing wildfire risk and improving community resilience (Nelson et al. 2004). These guiding documents make clear the new challenges entailed in confronting the wildfire crisis, and the principles they espouse also align well with existing approaches to wildfire risk and forest management in the South.

Another key event occurred on May 20, 2022, following a prescribed fire escape in New Mexico, when the Chief of the Forest Service ordered a pause on all prescribed fire activities, pending a 90-day program review, to ensure that the agency's prescribed burn program is anchored in the most contemporary science, policies, and practices. The pause and review were seen as essential for ensuring that the agency had the resources, tools, and support needed to carry out the aggressive goals outlined in the 10-year strategy, while also strengthening public confidence and understanding of the role of prescribed fire in managing forest ecosystems. The leading recommendations from the review were of a tactical nature targeted at increased program oversight. Another common thread throughout the report was the need for strategic assessment of fuel treatment investments, including prescribed fire (USDA Forest Service 2022c). This brings attention to growing needs for science-driven tools that can support efficiency, transparency, and accountability in risk management decision making—needs that are also emphasized by the Commission Report (Wildland Fire Mitigation and Management Commission 2023).

Key questions framing the Outlook

The heightened focus on prescribed fire and other fuel treatments brought about by the ongoing wildfire crisis has broadened our view of the *Southern Forest Outlook*. The fire chapter of *The Southern Forest Futures Project*, the predecessor to the Outlook, focused primarily on the consequences of climate change for fire in the South (Stanturf and Goodrick 2013). For the current analysis we took a broadened approach, reflected in these questions:

- Where are the greatest wildfire risks, and how are they likely to change as climate, forests, and society change in the coming decades?
- How do we significantly increase the scale and pace of prescribed fire and other fuel treatments to manage wildfire risk in the face of a changing climate?
- How do we do this while accounting for forest carbon management as a key climate mitigation tool, and the impact of severe fire on public water supplies, a key ecosystem service?
- Where is wildfire most likely to produce smoke that exposes people at harmful levels, and how can fuel treatments address this risk?
- How does the reality that socioeconomically vulnerable populations are disproportionately affected by fire and smoke, influence our fire management priorities?
- How do we demonstrate efficiency of investments in risk management, as well as effectiveness in achieving resilience-building objectives?

We paired our analysis with a review of recent scientific literature to further address related questions about ongoing and future changes in climate, forests, and society that can be expected to impact how wild and prescribed fire are managed. These questions were:

- How are expansion of the WUI, changes in fire regimes, and changes in seasonal availability of safe prescribed burning conditions likely to impact management efforts?
- What opportunities exist to improve wildfire risk management even as these and other factors may place new constraints on the implementation of prescribed fire?

Assessing Fire in Southern Landscapes

Knowledge and tools that anticipate changes in climate, forests, and society can aid strategic planning of investments in prescribed fire and other management practices, helping to build forest resilience and reduce current and anticipated wildfire risks. To this end we undertook an analysis of plausible trajectories of change over the coming few decades for a broad suite of factors relevant to understanding wildfire risks, and opportunities for managing risks through fuel reductions. We used a two-tiered approach to (1) characterize current and future landscapes with respect to fire, communities, forests, and forest management; and (2) quantify current and future risks, and likely impacts of fuel management, in that landscape context. These steps, summarized in the next two sections, allowed us to address our research questions and produce large-scale spatial data products that can provide support for risk management planning and decision making.

Firescapes: a social and ecological context for managing fire

Our first objective was to provide a landscape-level context for understanding the factors that shape wildfire and its impacts, and that also shape appropriate management responses. To achieve this, we integrated a large body of spatial data to delineate firescapes across the region. Firescapes can be understood as recurring landscape types with particular social, built, biophysical, and ecological properties with respect to fire. Different firescapes carry distinctive implications for wildfire, prescribed fire, and their consequences for people and resources, providing an important broad-scale management context (Smith et al. 2016). Firescapes should not be confused with firesheds, which are intended to delineate areas within which fire is likely to spread from ignition points to structures or other resources (USDA Forest Service 2022b). Firescapes serve a broader purpose of characterizing the social and biophysical landscape contexts that shape fire and its consequences.

Our approach to firescape delineation is consistent with the landscape and community classification approach of the Cohesive Strategy (WFLC 2014) although modifications for the present application include new data, finer scale analysis, and future projections (Gould et al. 2023). To classify and map firescapes across the South, we used a spatial data synthesis approach that takes full advantage of social, ecological, and biophysical data available from a wide variety of sources. We used statistical methods for data reduction to generate key variables with intuitive interpretations in terms of fire dynamics and history, forest characteristics, climate, conservation values, social and ecological vulnerabilities, and landscape change. We then used those attributes to classify landscapes into firescape types, and mapped these across the region. Our delineation of present-day firescapes is described elsewhere (Gould et al. 2023), and we include summary results in this report. For this analysis, we extended the approach to quantify possible future changes in firescape distributions across the South, under a variety of climate models and scenarios representing plausible climate and forest changes.

Risk assessment

Our second objective was to quantify risks and the potential effectiveness of risk management under current landscape conditions and plausible future conditions. Specifically, we evaluated (1) risks posed by wildfire and smoke to people and ecosystem services; (2) the potential for prescribed fire to reduce risk through forest fuel load reduction; and (3) plausible future changes in both. We developed a spatially explicit assessment that quantifies risk as an interaction between the potential for hazardous fire and the vulnerability of people and resources that could be exposed to hazardous fire. Our risk assessment is intended as a decision-support tool for planning ecosystem management investments in a way that achieves objectives efficiently, even under considerable uncertainty (Scott et al. 2013, Thompson and Calkin 2011).

Our assessment model accounted for biophysical, ecological, and socioeconomic dimensions of risk, utilizing spatial information from the firescapes analysis together with additional spatial data (Nepal et al. 2023). With the model, we mapped spatial variation across the region for four values: (1) risk to people and structures from direct wildfire exposure; (2) health and safety risks to people from smoke (an exposure that occurs even distant from fire locations); (3) risk to forest carbon stocks potentially lost during severe fire; and (4) risk to surface-derived drinking water

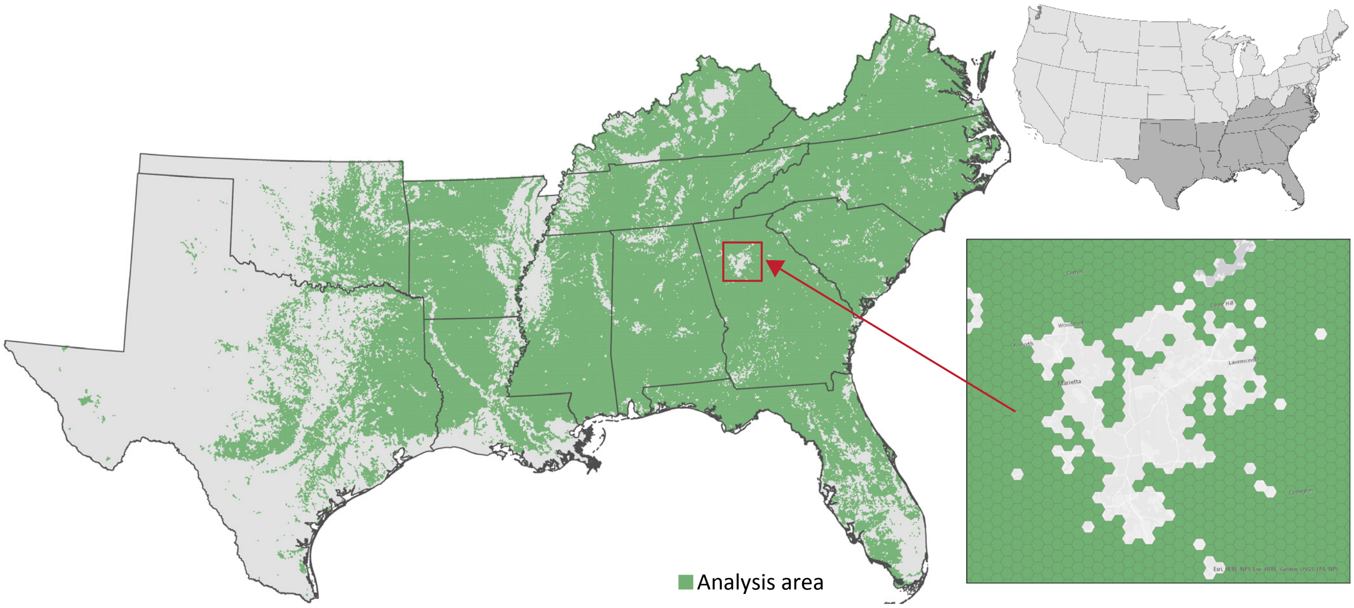

Figure 1—Study area in the Southeastern United States. The landscape analysis used a 2,470-acre (1000-ha) hexagonal landscape grid, restricted to hexagons with at least 25 percent forest cover (e.g., inset).

originating in forested watersheds. We assessed these risks under two management scenarios: one assuming existing fuel loads, and the other assuming enhanced landscape-level investment in fuel reduction activities. Comparing the relative value of risk outcomes under these two scenarios provides a way to identify strong return-on-investment opportunities for risk reduction across the region.

The details of our modeling approach are presented elsewhere (Nepal et al. 2023), and we summarize the methods and results in this report. For this analysis, we extended the model to examine both management scenarios under a range of plausible climate and forest futures. Supplementing present-day assessment with comparable information about plausible future risks—despite the greater uncertainty—enriches planning information by suggesting areas where investing now to build forest resilience can mitigate the most pressing future risks.

What's at Risk in the Southern Region

Our study area included the 13 States in the Southern United States that comprise the Southern Region administrative unit of the Forest Service (fig. 1). We limited our analysis to landscapes with at least 25 percent forest cover. Forests in this region are among the most productive and biologically diverse in North America, sustaining a wide range of conservation values and ecosystem services that support a large and rapidly growing population and economy. We briefly review the social and ecological vulnerabilities included in our regional assessment. Though the values at stake extend to nearly any area affected by fire, we highlight the roles they play in forest landscapes.

Direct impacts on people and structures

Losses of life, property, and community infrastructure are the most immediate and important impacts resulting from direct exposure to wildfire. The vulnerability of populations in the South to these impacts, as elsewhere, is determined partly by the location and density of communities relative to lands with potential for hazardous fire, including the spatial situation of communities relative to the WUI (U.S. Fire Administration 2022). The South has experienced rapid population growth and housing development in recent decades, resulting in rates of WUI expansion that are among the highest in the Nation (Radeloff et al. 2018, 2023). Public and private land ownership are highly fragmented, with private lands accounting for 86 percent of forest land; as a result, most wildfire, prescribed fire, and WUI expansion occur on private lands (Hoover and Riddle 2021, Melvin 2021).

Vulnerability is also a product of additional socioeconomic factors that make wildfire more likely to result in disaster for some people than for others (Coughlan et al. 2019). These include housing type and condition, and the preparation of housing and other infrastructure for resistance and resilience to wildfire, all of which can depend in turn on multiple socioeconomic factors (Calkin et al. 2014, U.S. Fire Administration 2022). The potential for harm to people and infrastructure, and the capacity for recovery, can vary with economic status, minority status, mobility, household composition, language spoken, educational attainment, and additional factors (Kondo et al. 2022). Socioeconomic disparities affecting vulnerability are prevalent in the South at small and large spatial scales, both within and among communities (Afrin and Garcia-Menendez 2021, Davies et al. 2018, Emrich and Cutter 2011, Gaither et al. 2015).

Health and safety risks from smoke exposure

Smoke from wildfires poses significant risks to public health and safety that can extend far beyond the immediate area of wildfire impacts. These risks are of growing concern in the context of a changing climate that is expected to increase the frequency and intensity of wildfires in the South. Despite most large fires occurring in the Western United States, most mortality and adverse health impacts attributable to smoke appear to occur in the Eastern United States, and the South in particular, due to higher densities of exposed populations (O'Dell et al. 2021). Risks can vary depending on a range of factors, including proximity and duration of smoke exposure, type of vegetation burned, and weather conditions during the fire (Fann et al. 2018, Reid et al. 2016). Smoke from wildfires contains a complex mixture of gases and particulate matter, including carbon monoxide, nitrogen oxides, volatile organic compounds, and fine particulate matter (PM2.5) (Liu et al. 2016, 2017; Reid et al. 2016). Exposure to these pollutants can cause a range of adverse health effects, including respiratory and cardiovascular problems, headaches, and eye and throat irritation (Cascio 2018, Rappold et al. 2012). Vulnerable populations such as children, older adults, and those with pre-existing health conditions may be especially at risk (Reid et al. 2016).

Prescribed fires can also generate smoke and pose risks to public health and safety (Navarro et al. 2018, Resnick et al. 2015). In the South, these risks are heightened for more socially vulnerable populations (Afrin and Garcia-Menendez 2021). However, prescribed fires are typically smaller and less intense than wildfires, and are conducted under controlled conditions intended to minimize impacts to public health and safety (Black et al. 2017, Chen et al. 2021, Resnick et al. 2015). The tradeoff between the impact of smoke from prescribed fire, and prescribed fire's role in reducing the likelihood of more severe wildfire smoke, is an important area of management concern and research need.

Forest carbon stocks

Landscapes in the South store unusually large amounts of carbon at the continental scale due to substantial forest cover in the region. Rapid forest growth rates also result in active carbon sequestration that has largely compensated for disturbance-induced losses in recent decades (Coulston et al. 2015). Increased wildfire frequency, severity, and size under a changing climate nonetheless may challenge carbon stability, in combination with other climate-influenced forest disturbances, and in the context of aging forests with slowing sequestration potential (Coulston et al. 2015, 2023; Liu et al. 2014). Fire produces carbon emissions from combustion of dead and live biomass in forest vegetation and soils, and additional emissions can occur in the long run from changes in soil properties and other factors (EPA 2021, Mayer et al. 2020). Release of carbon to the atmosphere during wildfire typically outpaces release during prescribed fire by large margins, due to differences in fuels consumed (Mayer et al. 2020). More frequent low-intensity prescribed fires that primarily consume surface litter, understory vegetation, and some ladder fuels, can also promote forest carbon storage in the long run by protecting carbon in the soil and large trees from more severe fire impacts (Flanagan et al. 2019, Hurteau et al. 2019, Krofcheck et al. 2019, Wiedinmyer and Hurteau 2010).

Important forest watersheds

Surface water stressors from fire in Southern forests are normally overshadowed by more pervasive impacts to watersheds from forest conversion, urbanization, and direct climate effects (Lockaby et al. 2013). Effects of fire can nonetheless be locally severe, depending on topography, vegetation, and fire intensity and spatial extent. Ash and other contaminants from burned sites may accumulate locally in water bodies affecting water quality. Loss of vegetation from severe wildfire can create surface runoff conditions conducive to erosion and flash flooding, which can affect water quality and, in extreme cases, threaten lives and property in nearby communities. Pronounced impacts on forest lands in the Eastern United States are typically confined to cases of large and severe fires, often associated with extreme drought (Caldwell et al. 2020). Low intensity fire, including prescribed fire, normally has little impact on forest water quality or quantity in the South (Hallema et al. 2018, 2019; Liu et al. 2014). Increased frequency, extent, and severity of wildfire driven by climate change would be expected to result in locally impaired streamflow regulation and increased transport of sediments and nutrients, in turn potentially impacting aquatic ecosystems, recreational water use, and drinking water supplies (Caldwell et al. 2020, Loiselle et al. 2020, Mitchell et al. 2014). Our analysis assessed the potential for at least temporarily compromised surface water within watersheds that are important for surface-derived drinking water. Though these impacts can be very local, we examined the potential for local vulnerabilities within broader watersheds to assess regional risk patterns.

Methods

The first step in our analysis was to compile relevant spatial variables with complete regional coverage. Selected variables represented aspects of fire history and dynamics, forest composition and structure, fuel load, carbon storage, biodiversity, land use/land cover, forest ownership, important watersheds, population and structure densities, WUI, socioeconomic vulnerabilities, and climate. Details and data sources are listed in table A.1 and Gould et al. (2023). In addition, we generated spatial data for potential smoke exposure from wildfire by modeling smoke exposure.

The spatial unit for all analyses was a 2,471-acre (1000-ha) hexagon representing a landscape size with general relevance for fire behavior, resource distributions, land use, and management activities in the South. We attributed a continuous grid of these hexagons across the region with values for the 73 variables selected for the analysis, and restricted the hexagons to only those with at least 25 percent forest cover. Details of data selection and their spatial harmonization are in Gould et al. (2023).

In the following sections we first summarize methods for using the compiled spatial dataset to model smoke exposure, firescapes, and wildfire risk. We then describe methods for projecting future conditions by combining these models with projections from climate models and socioeconomic scenarios.

Smoke Exposure Modeling

Spatial data estimating the potential for forests to send smoke to populated areas at unsafe levels of exposure, if wildfire occurs, were not available for the region. We therefore generated two such variables by using methods detailed in Gould et al. (2023) and summarized here. We estimated (1) population potentially exposed given existing fuel loads; and (2) population potentially exposed under a scenario of reduced fuels. The modeling approach used forest fuel loads and weather patterns to estimate smoke plume characteristics and intersected the plumes spatially with population density. Population was also adjusted for socioeconomic characteristics that may heighten vulnerability to smoke exposure.

We used smoke plume data from the National Oceanic and Atmospheric Administration's (NOAA) Hazard Mapping System (HMS), an interactive processing system wherein satellite analysts integrate data from a number of satellites to produce a quality-controlled daily dataset of detected fires and significant smoke plumes (Gaither et al. 2015). We applied the HMS data to generate potential smoke plume information for every forested 1000-ha hexagon in our regional analysis. To accomplish this, the coordinates of each HMS plume were transformed into coordinates relative to the source point, then these source-relative plumes were assigned to each hexagon based on an inverse distance-squared interpolation process. This provided each hexagon with a collection of potential plume pathways. In addition, we used a simple gaussian plume model (Lavdas 1996) to estimate at what distance the surface smoke concentration decays below a threshold given by the Environmental Protection Agency’s level associated with conditions unhealthy for sensitive individuals. This provides a means of estimating smoke concentrations at ground level. The use of the gaussian plume model allowed for flexibility in adjusting the screening distance based on changes in fuel conditions under projected future scenarios and fuel management scenarios (Vargo 2020).

For a fire in a given source hexagon, we accumulated the human population of all hexagons intersecting the smoke plume (not only those with forest), for an estimate of the total number of people potentially exposed. Population was adjusted by social vulnerability by multiplying by the overall vulnerability index from the Socioeconomic Data and Applications Center and the Centers for Disease Control, the same social vulnerability data used in other aspects of our analysis (table A.1). The vulnerability index ranges from 0 to 1.0 where 1.0 indicates the highest vulnerability, so this adjustment reduced the value of our final metric for less vulnerable populations.

Our final metric for smoke exposure, the potential population exposed to smoke (PPES), is expressed as the logarithm of the mean sum of population, or vulnerability-adjusted population (VPPES), in the hexagons intersecting each smoke plume from the collection of plumes assigned to a hexagon.

Key inputs for the plume model were emission rate, transport wind speed, mixing height, and stability class. The emission rate was based on the available fuel loading within the hexagon and an assumed 80 percent consumption for current climatic conditions. Transport wind speed and mixing height values were extracted from the Ventilation Climate Information System (Ferguson et al. 2003) and a constant stability class of moderately unstable, sometimes labeled as class B or 2, was assumed (e.g., fig. A.1).

Fuel load estimates for each hexagon were the same as those used elsewhere in this study (table A.1). In addition to using the estimated existing fuel load, we also ran the analysis under a scenario wherein fuels were reduced by approximately 50 percent from the existing level. This produced two outputs, one estimating potential smoke exposure from wildfire that occurs under existing fuel load conditions, and one assuming that fuels management prior to wildfire occurrence had reduced available fuels.

Firescape Analysis

Detailed methods for the present-day firescapes analysis are provided by Gould et al. (2023). Briefly, we implemented a factor analysis that included all 73 landscape description variables (table A.1), summarized to the spatial analysis hexagons. Factor analysis uses the correlation structure among variables to model a smaller number of unobserved, latent variables known as factors (Costello and Osborne 2005, Tabachnick et al. 2013). The factors can be considered as a representation of fundamental dimensions of the data, usually having straightforward interpretations based on the variables with high loadings for a given factor. We used this approach to identify a set of factors that (1) explained much of the spatial variation in the original variables; and (2) had strong relevance for the social and ecological dimensions of interest relevant to fire and fire management (Gould et al. 2023).

We then implemented a nonhierarchical cluster analysis to identify and describe recurring firescapes across the South, wherein hexagons belonging to the same firescape had shared properties (Hargrove and Hoffman 2004, Mayer et al. 2014, Romesburg 2004, WFLC 2014). The factor analysis outputs were the inputs for the cluster analysis, so each resulting firescape was defined in terms of its centroid values for the factors. We assigned factor values and cluster (firescape) memberships to all analysis hexagons, and then mapped the resulting firescapes for the region.

Risk Assessment

Risk can be assessed in terms of the interaction between exposure and vulnerability to stressors, where vulnerability (or sensitivity) indicates an expected response to a given level of exposure (Thompson and Calkin 2011, Turner et al. 2003). We used a Bayesian network (BN) modeling approach set up with an exposure-vulnerability structure to quantify wildfire risks, as well as the potential risk reduction consequences of fuel reduction decisions. Details of the model and its use to assess present-day risks are in Nepal et al. (2023); we provide a summary here.

A BN is a graphical model that quantifies probabilistic relationships among variables deemed important in a system of interest (Conroy and Peterson 2013, McCann et al. 2006). BNs can be useful tools at the interface between science and management to help bring into focus the most important aspects of a problem, quantify uncertainties, and explore the possible outcomes of key decisions (Merritt et al. 2010). These properties make BNs well-suited to risk assessment in general, and wildfire risk assessment and related management problems in particular (Carriger et al. 2021, Moe et al. 2021). The two main components of a BN are a graphical structure that captures qualitative knowledge about how variables in a system are related, and conditional probabilities that quantify causality in those relationships. Conditional probabilities can be drawn from expert knowledge, derived empirically from data, or combinations thereof (Conroy and Peterson 2013, Moe et al. 2021).

In our model (fig. 2), probabilistic estimates of risk and the potential for risk reduction through management decisions were conditional on the

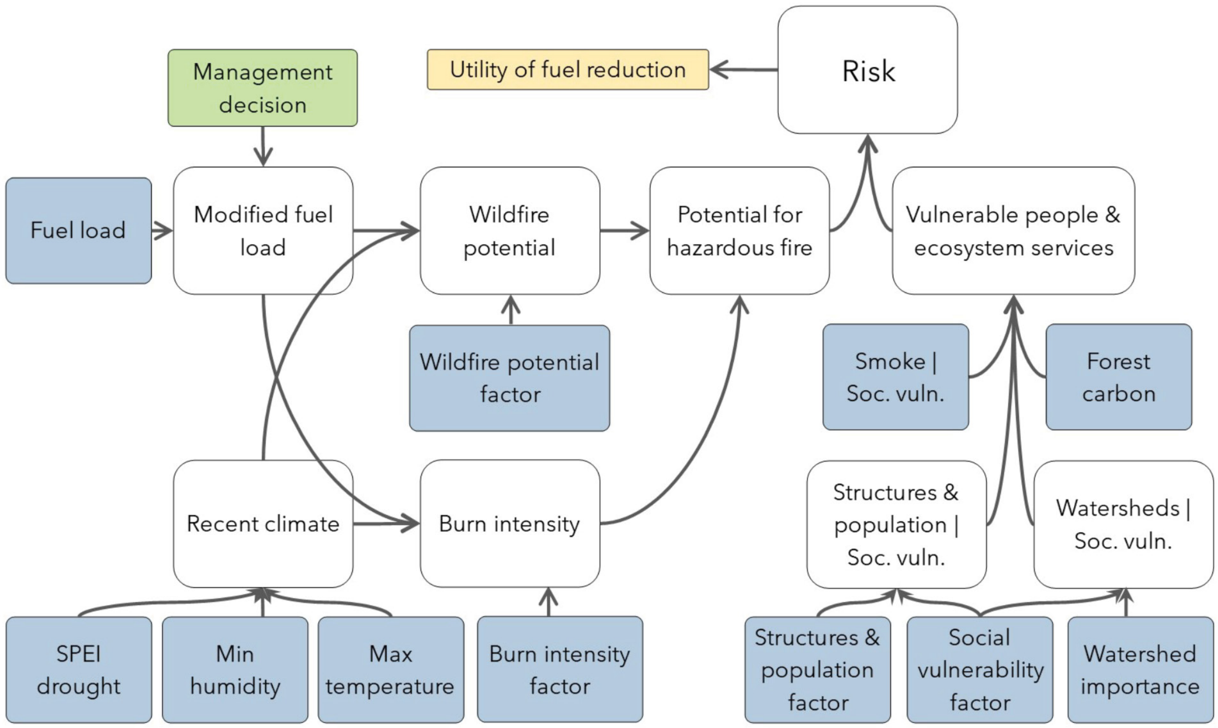

Figure 2—Flow chart showing structure of the Bayesian network model quantifying wildfire risk and the utility of fuel reductions for reducing risk. Blue boxes represent data inputs (also see table 1). Inputs labeled as factors (e.g., burn intensity factor) were generated in the firescapes analysis. White boxes represent probabilistic outcomes influenced by the data, which in turn influence risk. The green box influences fuel load under different fuel management scenarios, and the yellow box quantifies preferences for different risk outcomes based on alternative management decisions. Model versions were generated for each vulnerability (direct risk to people and structures; indirect risk from smoke exposure; risk to forest carbon; risk to important watersheds), and for all vulnerabilities combined. SPEI = Standardized Precipitation Evapotranspiration Index. From Nepal et al. (2023).

various landscape and climate characteristics represented in the model structure (table 1). The potential for hazardous fire was conditional on burn probability and intensity, which in turn depended on fuel load, climate variables, and related variables that helped to define burn probability and intensity. Specifically, the wildfire potential and intensity and fire-prone forests factors (table 1) from the firescapes analysis had their highest loadings for variables directly representing burn probability and intensity, but they also included loadings for additional variables including forest types, forest tree diameter size classes, and long-term climate variables (Gould et al. 2023). The model also captured the influence of climate anomalies and drought for the most recent 3 years. Based on expert elicitation (Nepal et al. 2023), we included the Standardized Precipitation Evapotranspiration Index (SPEI), a standard drought index (Vicente-Serrano et al. 2010), and anomalies for minimum monthly humidity and maximum monthly temperature. Drought had twice the weight of the humidity and temperature anomalies in the model. We used climate data from the statistically downscaled MACAv2 dataset, selected for use in the 2020 Resources Planning Act (RPA) Assessment and archived by the Forest Service (Joyce and Coulson 2020b), updated to the most recent years. We used total available fuels from the Fuel Characteristic Classification System of the LandFire program (USDA Forest Service and USDOI 2024) to represent fuel load, estimated for the year 2022 (tables 1, A.1).

Vulnerabilities of people and ecosystem services were quantified as (1) the social vulnerability-adjusted human population and infrastructure directly exposed to wildfire, represented by the structure and population density factor from the factor analysis; (2) social vulnerability-adjusted human population exposed to smoke, by using the smoke exposure modeling procedure described above; (3) forest carbon stocks potentially lost during wildfire, represented by a modeled variable for total forest carbon (Wilson et al. 2012, 2018); and (4) social vulnerability-adjusted important areas for surface-derived drinking water represented by

Table 1—Input variables for the Bayesian network model quantifying wildfire risks to people and ecosystem services

Variable	Description	Unit
Structure and population density	Factor variable with high loadings for housing-unit density, population density, and wildland-urban interface	Factor index value
Social vulnerability	Factor variable with high loadings for vulnerability indices: socioeconomic status, housing type, transportation, household composition, and disability	Factor index value
Watershed importance	Importance of HUC12 watersheds for surface-derived drinking water to receiving populations	Importance index value
Potential hazardous smoke emissions	Potential for unsafe emissions to reach populations (vulnerability weighted)	Log of summed population exposed, vulnerability weighted
Forest carbon	Total forest carbon stocks	Tons per acre
Wildfire potential	Factor variable with high loadings for burn probability, risk to potential structures, and wildfire hazard potential	Factor index value
Wildfire intensity and fire-prone forests (burn intensity)	Factor variable with high loadings for flame length exceedance, forest types, forest tree size classes, and hot and dry climate	Factor index value
Fuel load	Total available fuels in the forested area of the hexagonal landscape unit	Tons
SPEI drought index	3-year drought index, leading up to and including December 2021	Drought index value
Minimum relative humidity anomaly	3-year anomaly, relative humidity in the month with the lowest value in the year, 2019–2021	Z-score; departure from 30-year normal
Maximum temperature anomaly	3-year anomaly, maximum temperature in the month with the highest value in the year, 2019–2021	Z-score; departure from 30-year normal

HUC12 = 12-digit hydrologic unit code; SPEI = Standardized Precipitation Evapotranspiration Index.

These variables are shown in blue in figure 2. Factor variables are from the firescapes analysis described in the text. Additional information for variables and data sources is in table A.1. Table from Nepal et al. (2023).

the Forest to Faucets 2.0 model (Mack et al. 2022). Social vulnerability in the BN model used the social vulnerability factor from factor analysis (table 1). The BN model was implemented to quantify risk for each of these four vulnerabilities separately and combined. For combined risk, the conditional probability of the vulnerable people and ecosystem services model node (fig. 2) reflected the following weights based on partner elicitation: population and structures (3.0); smoke exposure (2.0); forest carbon (1.0); and important forest watersheds (1.0).

The management decision model node (green node in fig. 2) implemented two alternative scenarios: (1) business as usual, for which the estimated fuel load was not altered; and (2) investment in an enhanced fuel reduction program, which hypothetically reduces available fuels by approximately 50 percent. The fuel reduction scenario was designed to represent broad investment in prescribed fire in the forest landscape, rather than the effect of a single prescribed burn. Though highly generalized, this was considered appropriate in expert elicitation for aiding investment prioritizations at the regional scale. The expected utility of fuel reduction in the model (yellow node in fig. 2) was based on the management value of the estimated risk outcome under either scenario. Lower risk was a higher value outcome, and reducing risk if it was high had greater value than reducing risk where it was already low. Finally, the relative utility (the ratio of the utilities under the two management scenarios) quantified the degree to which the outcome under the fuel reduction scenario outweighed the alternative.

Projecting Future Change

Scenarios and climate models

The *Southern Forest Outlook* relies on the same core scenarios as the 2020 RPA Assessment, representing a range of plausible potential socioeconomic and climate futures (USDA Forest Service 2023). Within the RPA Assessment, a set of core scenarios was developed from the Intergovernmental Panel on Climate Change (IPCC) scenarios. The IPCC provides a global context for a range of potential futures, with the climate futures defined in terms of differing representative concentration pathways (RCPs) (IPCC 2014). The RCPs are defined by radiative forcing (W/m^2). In simple terms, radiative forcing is the difference between energy being absorbed by the Earth and the energy being reflected and emitted back into space. When the balance is greater than zero, warming occurs. For the 2020 RPA Assessment, RCP 4.5 and RCP 8.5 were selected. RCP 4.5 has a radiative forcing of 4.5 W/m^2 at stabilization (after year 2100), with a carbon dioxide (CO_2)-equivalent concentration of approximately 650 ppm. RCP 8.5 has a radiative forcing of more than 8.5 W/m^2 in 2100, with a CO_2-equivalent concentration of >1370 ppm (Moss et al. 2010).

Scientists are challenged to align socioeconomic paths that are consistent with RCP paths (van Vuuren et al. 2014). Shared socioeconomic pathways (SSPs) were developed after the RCPs, and the SSPs offer economic and demographic storylines at a global scale that generally align with the RCP levels (O'Neill et al. 2017). The four SSPs used in the RPA Assessment (SSP1, SSP2, SSP3, and SSP5) include a wealthy and increasingly economically equal world that has a focus on climate change mitigation and slowing population growth (SSP1), an economically wealthy world with more focus on adaptation and high U.S. population growth but slower global population growth (SSP5), a less wealthy world with continued inequality and low U.S. population growth and high global population growth (SSP3), and an intermediate case intended to roughly replicate current rates of economic and population change (SSP2).

The RPA scenarios are based on combining RCPs and SSPs (fig. 3). Langner et al. (2020) provides a description of the scenarios for the United States. These scenarios were also evaluated as part of the *Southern Forest Outlook*. The LM scenario (low warming-moderate U.S. growth) is based on the combination of RCP 4.5 and SSP1 and describes a future with medium growth (3.0 times current) in U.S. real gross domestic product (GDP), medium population growth (1.5 times current), and lower global emissions. The HL scenario, combining RCP 8.5 and SSP3, suggests low U.S. population growth (1.0 times current) and low growth in U.S. real GDP (1.9 times), but high emissions. The HH scenario, the combination of RCP 8.5 and SSP5,

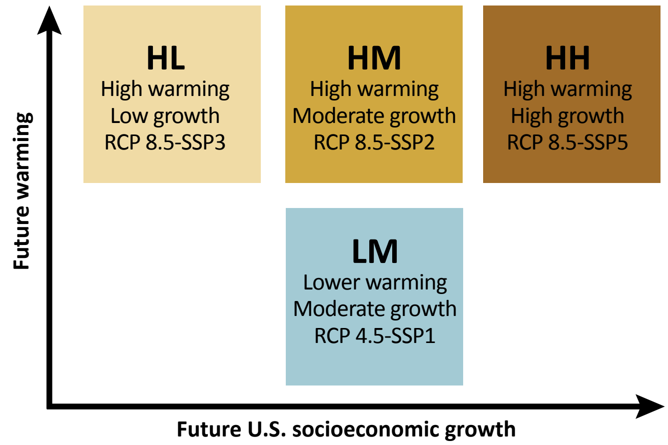

Figure 3—Scenarios developed for the 2020 Resources Planning Act Assessment. Source: USDA Forest Service (2023: 3-3).

describes a future with high warming and high U.S. socioeconomic growth: U.S. real GDP increases 4.7 times current levels, and population growth increases by 1.9 times. Under the HH scenario, these high levels of GDP and population growth are coupled with high global emissions. Between the HL and HH scenarios is the HM scenario (RCP 8.5 and SSP2), which has high global emissions and, consequently, high warming. Under the HM scenario U.S. growth is moderate: a 2.8 times increase in U.S. real GDP and a 1.4 times increase in U.S. population growth. More information about these scenarios is available in Langner et al. (2020).

RCPs were designed to capture the range in plausible projected radiative forcing (W/m^2) found in the scientific literature. Radiative forcing is also used as an input into general circulation models (GCMs), which are used to model future climates. There are numerous competing GCMs; for the RPA Assessment and the *Southern Forest Outlook*, five GCMs were selected to pair with each scenario. The five GCMs can generally be classified into least warm, hot, dry, wet, and middle climate futures for the United States (table 2). It is important to note that the GCM classification into least warm, hot, dry, wet, and middle is based on long-term average departures (1971–2000 versus 2041–2070) over the entire United States. This classification is relevant to the South (fig. 4). In the South, under the least warm model, average annual temperature is projected to increase 1.1 °C (RCP 4.5) to 2.75 °C (RCP 8.5). The hot model suggests average annual temperature will increase by between 2.6 and 3.9 °C. Under the dry model, average annual precipitation will decrease by between 9 and 13 percent. The wet model suggests a future where average annual precipitation will increase by between 7 and 8 percent. The middle climate model represents a future where the departures are relatively close to the average departures for mean annual temperature and precipitation. These averages indicate the representativeness of the selected GCMs relative to the larger set of candidate GCMs, recognizing that there is also important variability across the region within any given projection (Joyce and Coulson 2020a).

The four different RPA scenarios are combined with the five different climate models (table 2) to produce 20 different scenario-climate futures. When specified, these are denoted with a RPA scenario-climate model format. These scenario-climate futures represent a broad range of socioeconomic futures, warming futures, and temperature and precipitation futures. Together, these futures create an envelope under which the forests of the Southern United States might exist.

Climate variables and projections

We used modeled historical and future projected climate data from the downscaled MACAv2 dataset (Abatzoglou 2013, Abatzoglou and Brown 2012), selected for use in the 2020 RPA Assessment and archived by the Forest Service (Joyce et al. 2018, Joyce and Coulson 2020a). Of the 20 scenario-climate futures, we used 16 to model risk changes from current (1992–2021) to mid-century (2041–2070) in our firescape and risk assessment analyses. The four futures that used the

Table 2—General Circulation Models used with each Resources Planning Act Assessment scenario

	Least warm	Hot	Dry	Wet	Middle
General circulation model	MRI-CGCM3	HadGEM2-ES	IPSL-CM5A-MR	CNRM-CM5	NorESM1-M
Source institution	Meteorological Research Institute, Japan	Met Office Hadley Centre, United Kingdom	Institut Pierre Simon Laplace, France	National Centre of Meteorological Research, France	Norwegian Climate Center, Norway

Source: Langner et al. (2020).

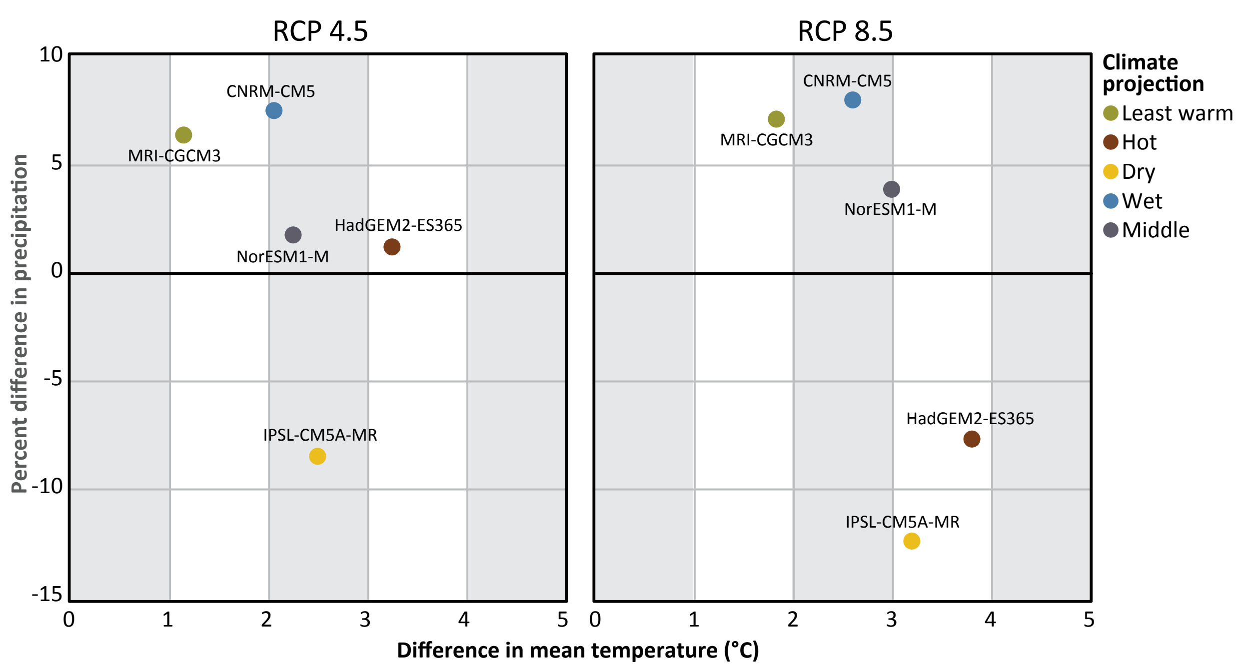

Figure 4—Comparison of the climate projections used in the *Southern Forest Outlook* for two representative concentration pathways (RCP, emissions future), showing differences in mean annual temperature and percent differences in mean annual precipitation between the 1971–2000 and 2041–2070 time periods in the U.S. South. General circulation model names corresponding to the projections are listed under each colored dot. The descriptive names of the projections are in the legend. Source: Joyce and Coulson (2020a: 84).

NorESM1-M GCM were excluded because relative humidity, an important variable for our fire risk modeling, was not available for that GCM in the MACAv2 dataset. Excluding this GCM was unlikely to have a strong influence on cross-GCM findings because it is considered a middle-of-the-road model (table 2) (Joyce and Coulson 2020a).

We calculated 30-year climate normals for five modeled climate variables used in our analyses: minimum monthly relative humidity (RHmin), maximum monthly solar radiation (SRADmax), maximum monthly temperature (Tmax), maximum monthly potential evapotranspiration (PETmax), and minimum monthly accumulated precipitation (PRmin). We also included the SPEI drought variable, calculated from monthly precipitation and PET. The SPEI index measures drought severity in terms of intensity and duration by using a multiscalar approach that is sensitive to temperature and precipitation, through the incorporation of PET (Vicente-Serrano et al. 2010). We calculated SPEI for 3-year periods for each month (i.e., that month and the 35 preceding months).

We calculated approximate 30-year climate normals (mean and standard deviation [stdv] among years) for all variables under all scenarios, by using MACAv2 modeled projections for three time periods. We used 1979–2005 as the normal (baseline) period against which to reference modeled climate anomalies. This was also the reference period for modeled SPEI. We aimed to be consistent with the RPA observed baseline period 1979–2008, while recognizing the transition at 2006 from historical modeled to projected climate under RCPs in the MACAv2 datasets. Modeled climate normals were also calculated for the current period (1992–2021) as the basis of comparison to evaluate future change, and for the future mid-century period (2041–2070).

The risk model also incorporated short-term climate anomalies to account for the influence of recent extremes of heat and dryness. We calculated these as the departure from the modeled reference period 1979–2005 normals during each of 10 consecutive 3-year periods within both the current and future 30-year periods. We treated these 10 periods as modeled anomaly realizations, providing 10 realizations for each of the 16 broader scenarios. We calculated anomalies for Tmax and RHmin as proxies for heat and dryness departures from normal. Anomalies were z-score variables using the equation:

Anomaly = [recent – mean(normal)]/stdv(normal)

This yielded standardized values, with values between -1.0 and 1.0 considered within the typical range of variability for the reference period, and more extreme values considered beyond typical variability, as estimated by standard deviation (Jones and Hulme 1996). We also included the 3-year SPEI as a recent departure variable, for the same 3-year periods as the Tmax and RHmin anomalies. Values of SPEI outside the -1.0 to 1.0 range are considered atypical drought or wet conditions, respectively, in comparison to variability during the reference period.

Projecting forest-type group, size class, fuel load, and smoke exposure

Changes in forest-type group and size-class data (table A.1) were projected under the RPA scenario-climate model futures by using the method detailed in Brooks et al. (2020). The simplified type groups and size classes used in our analysis are shown in blue in figure 5. The 90-m, pixel-level type group and size-class assignments were projected at decadal intervals. We calculated the proportional cover of the type groups and size classes within analysis hexagons for each decade. To estimate values for the mid-century period (2041–2070), we used the mean value of 2050, 2060, and 2070. We used the 2020 values for the current period, against which to evaluate future change.

Under all scenarios and both time periods, we also modeled forest fuel load (total available fuels) by using these projected forest data. We did this by using a BN submodel, with forest fuel load conditional on forest-type group composition (i.e., the collection of proportional cover values), forest size-class composition, and the proportion of total forest cover (fig. 5). The network learned the conditional probabilities directly from the current forest and LandFire fuel load data. We then used

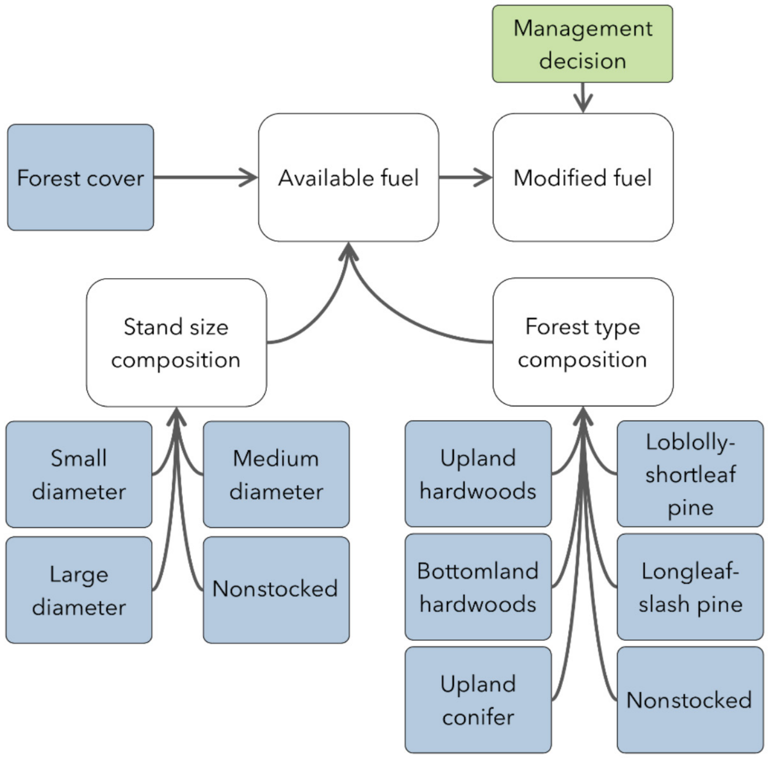

Figure 5—Flow chart showing structure of the Bayesian network model used to project fuel load, conditional on variability in forest cover, forest-type composition, and forest size-class composition. The model associated those variables with present-day fuel load values, then projected future values under the Resources Planning Act Assessment scenario-climate futures. Blue boxes are data inputs. The management decision included the same unmodified fuel load versus reduced fuel load scenarios as the main risk model.

the learned conditional probabilities in the model to project fuel load, given the projected forest data under the possible scenario-climate futures.

We also estimated potential smoke exposure for each RPA scenario-climate future. The futures altered exposure through changes in fuel loading and monthly mean maximum temperature. Figure A.1 clearly shows a degree of temperature dependence in both mixing height and ventilation index. A simple regression model was used to introduce climate change-induced variations into our mixing height and transport wind speed estimates. Though this temperature-dependent regression approach is an oversimplification of the factors influencing seasonal changes in mixing height and transport wind, the information required to calculate these values is not available as part of the statistically downscaled climate data chosen for the RPA. Note that the ventilation index is the product of mixing height and transport wind; therefore, transport wind speed can be derived from knowledge of the other two factors.

Projecting future changes in firescape distributions

To examine future changes in the spatial distribution of firescape classes, we first projected the factors generated via factor analysis, for the current and mid-century periods. To do this, we used the modeled climate, forest-type group and size class, fuel load, and smoke exposure variables under the RPA futures, with all other variables held at their static observed values. We assigned new values for each of the eight established factors, for each hexagon, by recalculating factor scores given the new data and the established factor analysis. We then reassigned all hexagons to the clusters established in cluster analysis on the basis of their new factor scores. Thus, changes in cluster memberships (i.e., firescape ID) for hexagons were driven only by changes in climate variables, forest-type and size-class compositions, fuel load, and smoke exposure variables. We used this process for the current (1992–2021) and mid-century (2041–2070) periods to assess change.

Projecting future changes in risk

For projecting risk model outputs under the RPA scenario-climate futures, we used the projected factor scores to update the BN risk model's four factor inputs from the factor analysis (table 1, fig. 2). We also updated the fuel load and smoke exposure inputs under the scenario-climate futures. Finally, we used the recent 3-year climate realizations for the Tmax and RHmin anomaly inputs, and for 3-year SPEI. Thus, for each of the 16 scenario-climate futures, the full risk model had 10 iterations that used each of the recent climate realizations. The watershed importance and forest carbon variables were not dynamic, remaining at their current values in projections. Furthermore, although we projected all four factor inputs, the data underlying the social vulnerability and structure and population density factors were mostly static, so that projections of those two factors were also essentially static. Drivers of projected future changes in risk were therefore primarily in the drivers of hazardous fire potential and hazardous smoke exposure potential.

Both fuel management scenarios, business as usual and fuel load reduction, were assessed under the futures. For each future/management combination the model had five iterations, one for each vulnerability component alone (i.e., people and structures, forest carbon, important watersheds, and smoke exposure) and one for combined vulnerability. We used this process for the current (1992–2021) and the mid-century (2041–2070) periods to assess change. The resulting 2,400 model runs were accomplished using Netica-C API software (Norsys Software Corp. 2024).

Results

In the following sections, we first summarize findings for current conditions and then report mid-century projection results. We use shorthand names throughout for the scenarios and GCMs as given in figure 3 and table 2, sometimes mentioning technical names when useful. For example, LM-least warm refers to the least warm (MRI-CGCM3) climate model coupled with the LM (lower warming, moderate growth) scenario. In general, results for the LM and HM scenarios were representative of the variability across scenarios, so we focused on reporting for these two scenarios coupled with the four climate GCMs.

Smoke Exposure

Use of the logarithmic scale makes each integer change in PPES or VPPES reflect an order-of-magnitude change in the number of people impacted. Figure 6A illustrates the potential smoke exposure for current fuel and climate conditions. Hexagons with high values of PPES tended to be either near populated areas, or had higher fuel loads whose plumes tended to have greater extent to reach populated areas.

Using the vulnerability-adjusted population to determine the potential population exposed yielded only minor differences between VPPES and PPES; however, several broad areas showed notable differences (fig. 6B). As the social vulnerability index ranges from 0 (low vulnerability) to 1 (high vulnerability), the VPPES values remain fairly unchanged when the plumes impact predominantly vulnerable populations, and values decline in areas where plumes impact less vulnerable populations. We see examples of the former case in south Georgia, eastern Oklahoma, and western Arkansas. For these areas, smoke-receiving hexagons tended to have more vulnerable populations, resulting in little change in their contribution to the PPES values. In contrast, for simulated wildfires in northern Virginia and northern Arkansas, the areas impacted by smoke plumes tended to have lower estimated social vulnerability, decreasing the contribution of those hexagons to the overall PPES values and therefore reducing VPPES.

For the climate GCMs used in this analysis, the hot (HadGEM2-ES) model produced on average the warmest projections, and the dry (IPSL-CM5A-MR) model produced one of the driest and warmest projections. These hot and dry conditions represent the greatest expansion of potential drought, which is likely to yield some of the highest fire potential. Examining the difference in VPPES for these models and current conditions revealed mostly minor differences of ±10 percent (fig. 7). There were also very localized exceptions with projected increases above 10 percent, mainly in Florida and along the lower Atlantic Coastal Plain. Though the models yielded greater fuel loads in many areas that can translate to higher smoke exposure, the warmer temperatures also link to higher mixing heights and greater ventilation, increasing the atmosphere's ability to disperse the smoke. A swath of potentially elevated future VPPES values extends from western Arkansas eastward to the southern Appalachian Mountains, and parts of the coastal plains showed similar projections. Finally, reducing fuel loads is the primary mechanism available to reduce potential smoke impacts. It is clear from our enhanced fuel reduction management scenario that fuel reduction investments could reduce the potential smoke exposure from wildland fire, even offsetting potential future climate-induced increases in many areas (fig. 8).

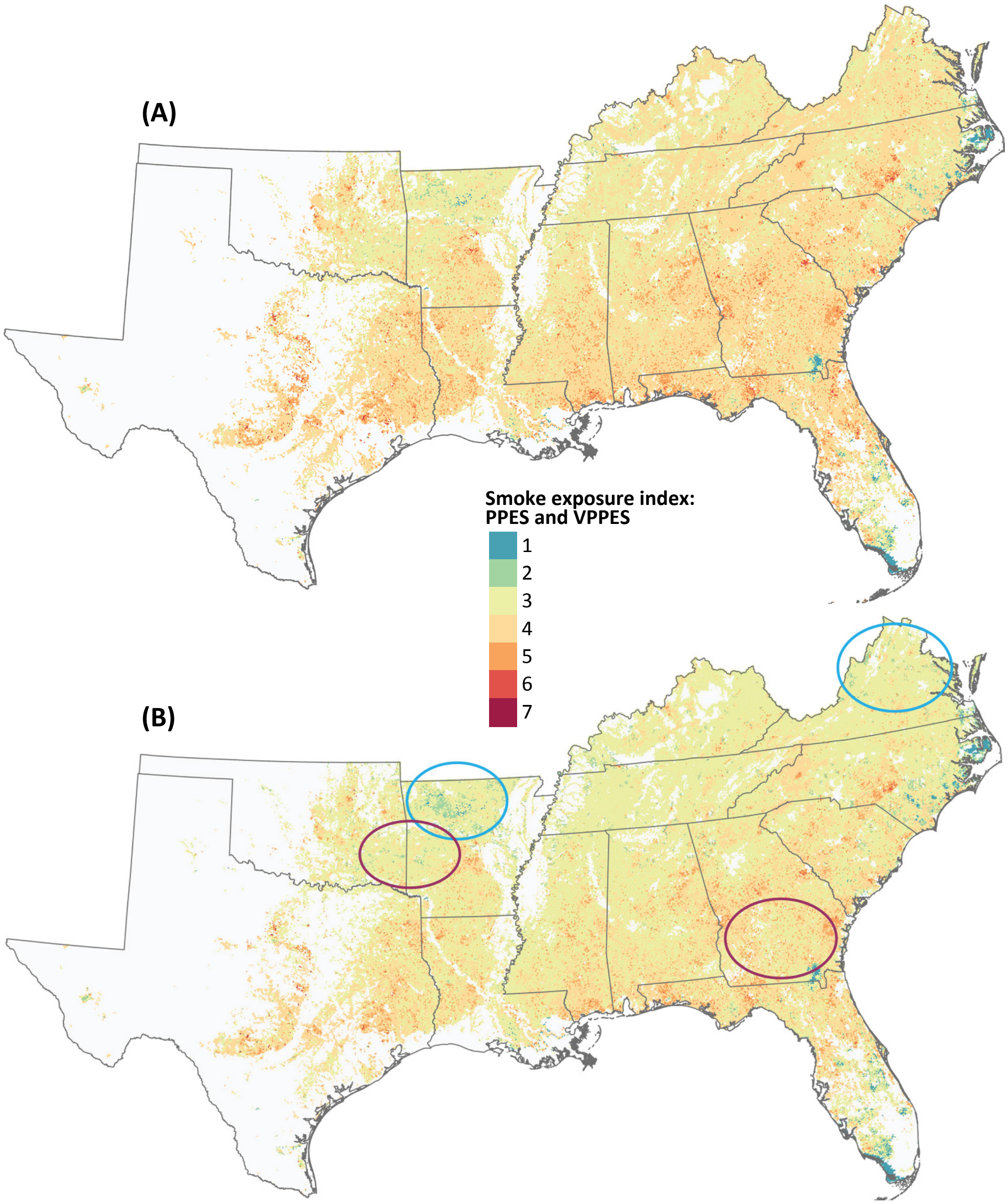

Figure 6—(A) Potential population exposed to smoke (PPES) for current conditions. (B) Vulnerability-adjusted potential population exposed to smoke (VPPES) for current conditions. Potential exposure values are for the modeled burn locations (i.e., the smoke source), not the location of the affected populations. Blue circles illustrate broad areas where low social vulnerability of the receiving populations reduced PPES, and red circles illustrate where high social vulnerability left PPES relatively unchanged. Each integer increase in PPES or VPPES reflects an order-of-magnitude increase in the number of people impacted.

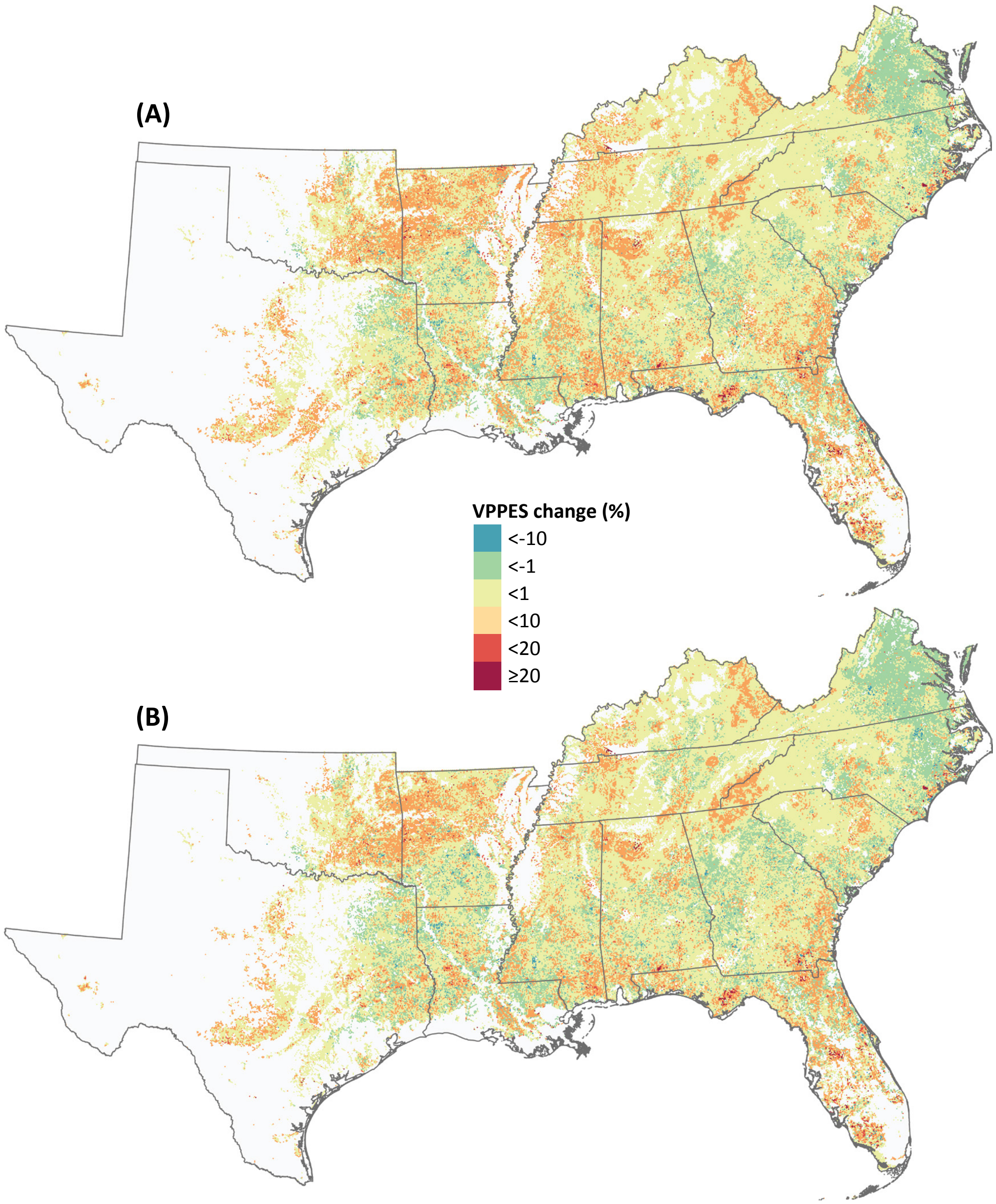

Figure 7—Difference in projected future vulnerability-weighted potential population exposed to smoke (VPPES) values compared to current. (A) HM-hot and (B) HM-dry, two of the more extreme scenario-climate futures, at mid-century (2041–2070).

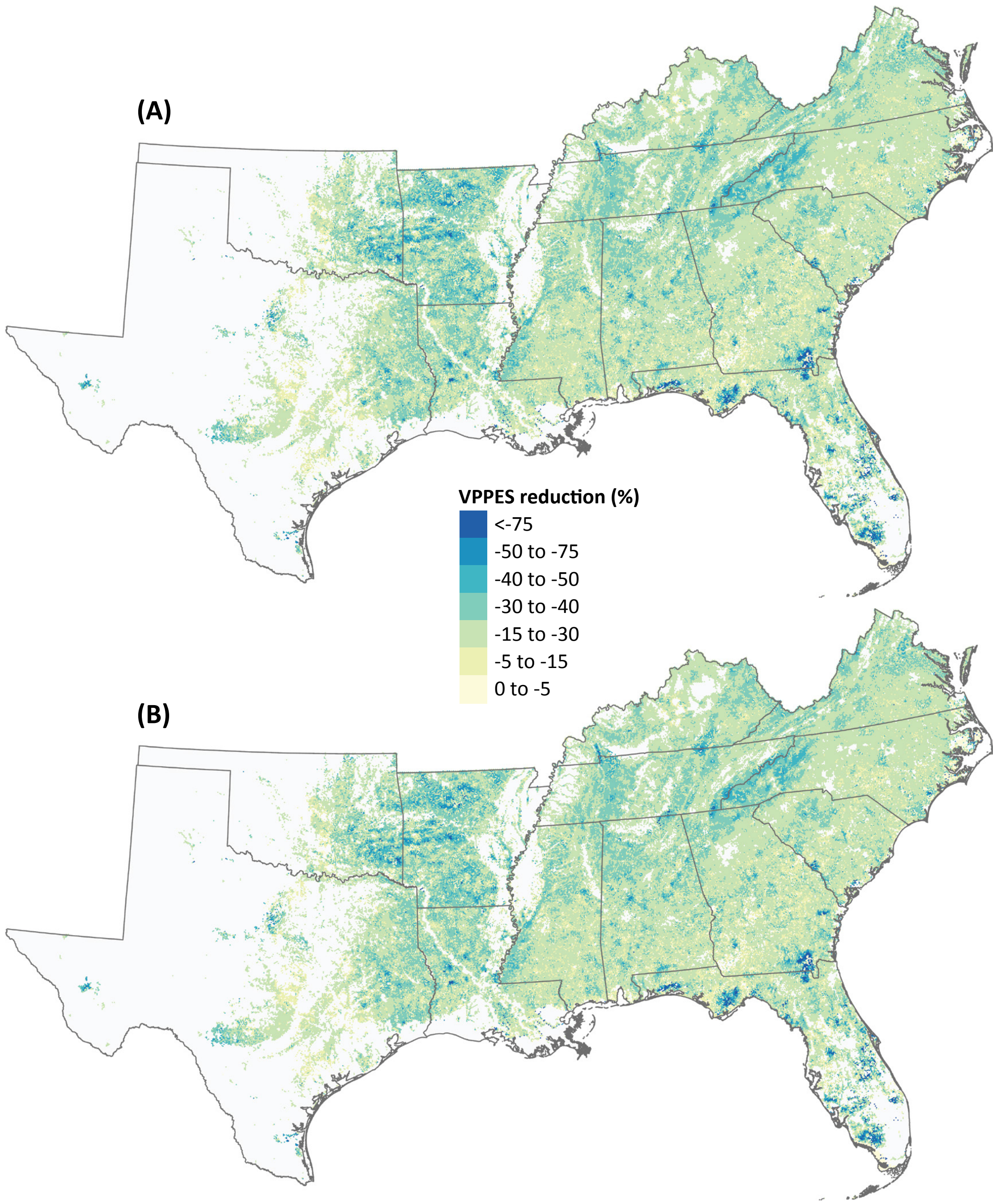

Figure 8—Modeled potential for decrease in future vulnerability-weighted potential population exposed to smoke (VPPES) at mid-century (2041–2070) obtainable by increased investment in fuel treatments, for (A) HM-hot and (B) HM-dry, two of the more extreme scenario-climate futures.

Firescapes

Current conditions

Factor analysis resulted in 8 factors, explaining 45.4 percent of the total variance in the original 73 spatial variables. Additional variance can be explained with additional factors, but they capture increasingly small fractions of the total variance, and there can be difficulty interpreting their relevance for firescape delineation or risk assessment. The decision to include the first eight factors was based on both variance explained and interpretation criteria (Gould et al. 2023). Descriptions of each factor (table 3) are based on the factor loadings for the original variables (table A.1). For full reporting of the factor loadings see Gould et al. (2023). Cluster analysis of these factors resulted in nine firescapes (table 4); plain-language descriptions of the firescapes are based on their characteristic (centroid) factor values and geography. Quantitatively, each firescape is characterized by its centroid value for each of the eight factors (fig. 9).

Mapping the current firescapes for forested lands across the South reveals clear geographic pattern in the landscape and climate characteristics underlying the firescape definitions (fig. 10), associated in part with well-known biophysical features in the region such as the coastal plain, Piedmont, and interior highland subregions. Other patterns visible in this mapping are related to more local variation in land use, socioeconomic characteristics, forest types, and fire history. Forest lands in eastern Oklahoma and central Texas are distinguished from those further east, via the (7) warm and dry, mixed woodlands firescape. Periurban, WUI-dominated lands with fragmented forests fall predominantly in the (4) urban periphery firescape. The classification resulted in an important distinction between the (5) rural agriculture, vulnerable communities, and low wildfire potential firescape and the (3) rural pine forests, intense fire, and vulnerable communities firescape, which together dominate much of the eastern and central parts of the region outside of montane subregions. Though both of those are largely rural with moderate to high social vulnerability, one is distinguished by higher pine forest cover and greater potential for high-intensity fire. Both of those are distinguished from the (9) semirural with low social vulnerability and moderate climate firescape, another common rural firescape, distributed further north with generally low social vulnerability and mild climate. That firescape tended to occur in rural areas peripheral to small and medium-sized towns and cities (Gould et al. 2023).

Table 3—Key dimensions of landscape variability relevant to wildfire dynamics, risks, and management in Southeastern U.S. forest landscapes

Factor name	Key characteristics	Variance explained	Cumulative variance explained
Climate and species at risk	Climate (multiple variables), threatened and endangered plants and animals, large-diameter forest, wildfire fuels, potential for smoke	0.076	0.076
Wildfire intensity and fire-prone forests	Potential flame length exceedance, wildfire hazard potential, longleaf and slash pine forest, small-diameter forest, hot climate	0.074	0.149
Fire history	Area burned and fire frequency	0.062	0.212
Population, infrastructure, and wildland-urban interface (WUI)	Developed land use, mixed urban-forest landscapes, WUI proportion, wildfire risk in the WUI	0.061	0.273
Forests and carbon	Forest cover, forest carbon stocks, conservation values, fuel load, and potential wildfire exposure	0.059	0.331
Wildfire potential	Burn probability, risk to potential structures, wildfire hazard potential	0.044	0.375
Social vulnerability	Multiple dimensions of socioeconomic vulnerability	0.041	0.416
Land use/cover change	Agricultural and natural land use/cover change	0.038	0.454

Generated through factor analysis of 73 spatial variables (table A.1). Variance explained = variance in the full dataset accounted for by each factor.
Source: Gould et al. (2023).

Table 4—Firescape classification of landscapes with at least 25 percent forest cover in the Southeastern United States

Firescape ID	Firescape name	Key characteristics	Area (square miles)
(1)	History of fire, potential for intense fire	Rural areas with recent history of fire, pine forest cover, moderate potential for high intensity fire, low burn probability, low risk to structures, low population density, low social vulnerability	5,876
(2)	Cool and wet broadleaf mountain forests	Mountain forest landscapes with cool, wet climate, high deciduous (nonconifer) forest cover, high conservation value, high fuel load and carbon stocks, moderate risk from wildfire smoke, low potential for intense fire	70,630
(3)	Rural pine forests, conversion to agricultural lands	Moderate pine forest cover, natural land cover conversion to agriculture, moderate potential for high-intensity fire, low population density and wildland-urban interface (WUI), moderate social vulnerability	22,734
(4)	Urban periphery landscapes	Exurban and urbanizing landscapes with high population density, development, WUI, and WUI risk	13,104
(5)	Rural agriculture, vulnerable communities, and low wildfire potential	Rural areas with low forest cover, carbon stocks, and fuel load; mild climate; low burn probability; low risk to structures and wildfire hazard potential; high social vulnerability; moderate gain of natural land cover	109,707
(6)	Rural mixed forests with hazardous fire potential	High potential for hazardous fire, history of wildfire, low/mixed forest cover with some pine and hardwoods, low population density and WUI	5,436
(7)	Warm and dry, mixed woodlands	Warm and dry climate, low to moderate forest cover with mixed hardwoods and conifers, low carbon stocks, wildfire potential, but low potential for intense fire	48,745
(8)	Rural pine forests, intense fire, and vulnerable communities	High pine forest cover, fuel load, and carbon stocks; potential for intense fire; low population density; high social vulnerability	147,757
(9)	Semirural with low social vulnerability and moderate climate	Low social vulnerability, moderate forest cover, moderate climate, low-moderate wildfire potential and fire history	87,290

Generated through analysis of 73 social and ecological spatial variables. Firescape characteristics are based on the factor score values characteristic of each class, as shown in figure 9.

Source: Gould et al. (2023).

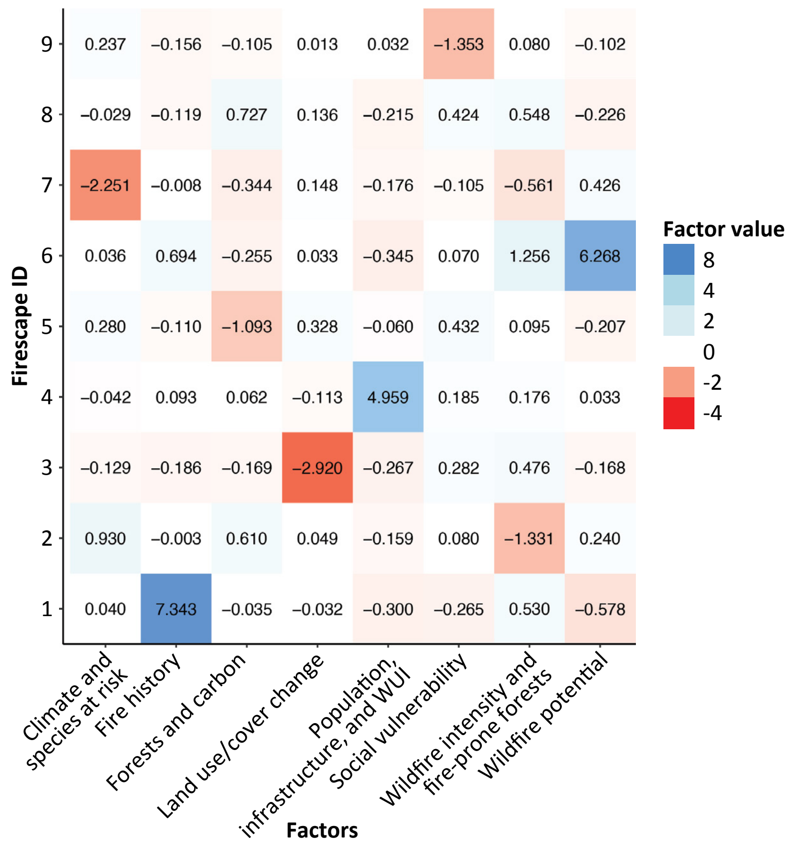

Figure 9—Firescape heat map indicating the characteristic values of eight factors (x-axis), for each of nine firescapes (y-axis) across the Southeastern United States. These values underpin the key characteristics of the firescapes (table 4). WUI = wildland-urban interface. Source: Gould et al. (2023).

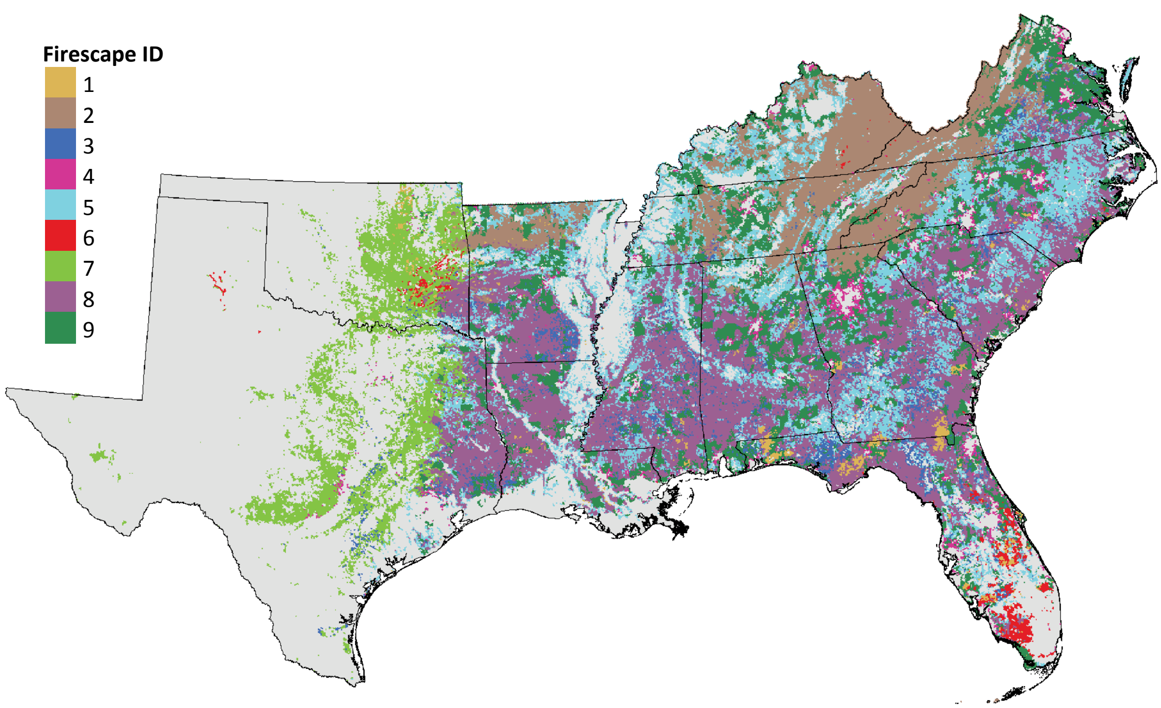

Figure 10—Firescape classification of landscapes (2,470-acre hexagons) with at least 25 percent forest cover in the Southeastern United States. Generated through analysis of 73 ecological and social variables for recent, observed landscape conditions. See table 4 for firescape information. Source: Gould et al. (2023).

Projected change, current to mid-century

Mid-century projections resulted in strong variation in firescape changes among climate GCMs and RCPs. Variability among SSPs was negligible, which was expected given the low variation among SSPs at mid-century among the dynamic variables included in our analysis, whereas some of the more dynamic components under SSPs such as population size were static in our models. The LM and HM scenarios, combined with the four GCMs, were therefore adequate to represent variation in projections. Across the different futures, on average 24 percent of the hexagon landscape units showed a change in firescape. These were strongly dominated by transitions to the (7) warm and dry, mixed woodlands firescape, and to a lesser degree the (8) rural pine forests, intense fire, and vulnerable communities firescape (table 5). In the latter case, gains in the eastern coastal plain and Piedmont were matched or, under more hot and dry models, outpaced by losses of that firescape to (7) warm and dry, mixed woodlands in the western part of the region (fig. 11). The (2) cool and wet broadleaf mountain forests firescape that dominates interior highland areas in the current distribution showed losses under all futures, with the strongest losses under the more hot and dry scenario-climate futures. In general, firescape changes resulted from changes in climate variables towards warmer and drier conditions in the 30-year, mid-century climate normals. To a lesser degree, projected forest changes towards compositions dominated by more fire-prone forest-type groups (e.g., upland conifer) and smaller forest tree size classes also contributed to the firescape changes. Other variables characterizing firescapes such as social vulnerabilities, population density, and high conservation value lands were not dynamic in our models. As a result, the modeled firescape changes did not directly imply shifts in those features.

Table 5—On average, 24 percent of forest landscapes (2,470-acre hexagonal areas) transitioned from one firescape to another when projected under the Resources Planning Act Assessment scenario-climate futures from current (1992–2020) to mid-century (2041–2070)

From firescape	To firescape	Percentage of change
(8) Rural pine forests, intense fire, and vulnerable communities	(7) Warm and dry, mixed woodlands	29.5
(5) Rural agriculture, vulnerable communities, and low wildfire potential	(7) Warm and dry, mixed woodlands	20.8
(9) Semirural with low social vulnerability and moderate climate	(7) Warm and dry, mixed woodlands	15.3
(5) Rural agriculture, vulnerable communities, and low wildfire potential	(8) Rural pine forests, intense fire, and vulnerable communities	9.1
(2) Cool and wet broadleaf mountain forests	(7) Warm and dry, mixed woodlands	8.3
(2) Cool and wet broadleaf mountain forests	(8) Rural pine forests, intense fire, and vulnerable communities	4.5
(9) Semirural with low social vulnerability and moderate climate	(8) Rural pine forests, intense fire, and vulnerable communities	4.4

Only the most frequent transitions are shown, accounting for 90 percent of all transitions. Percentages are across all Resources Planning Act Assessment scenario-climate future combinations examined.

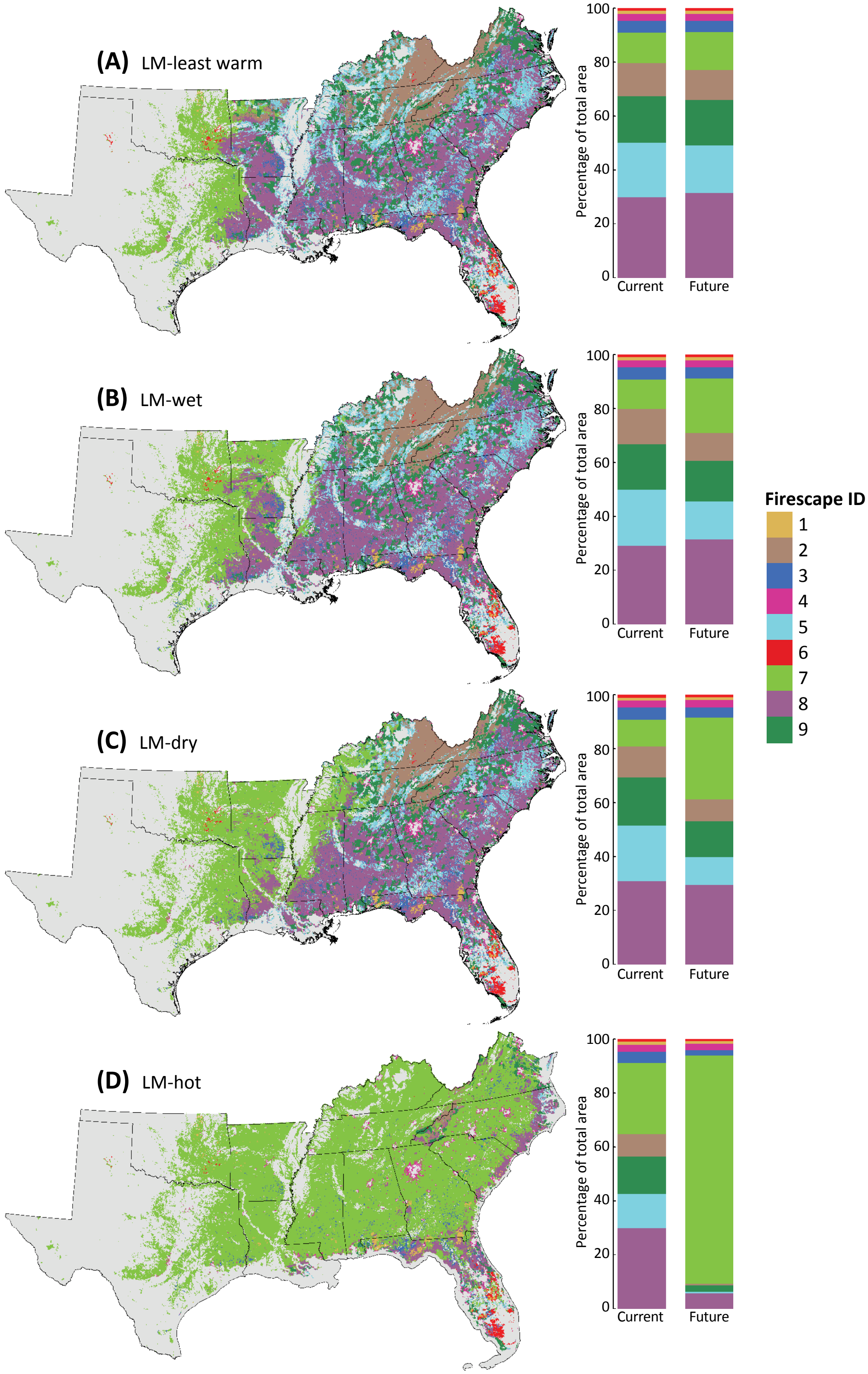

Figure 11—Projected change in the distribution of firescapes, current (1992–2020) to mid-century (2041–2070). (A–D) Scenario-climate futures represent the range of variation across the futures examined, from (top) most conservative to (bottom) most extreme change. Variation was driven mainly by general circulation climate models (GCMs) and representative concentration pathways (RCPs), rather than shared socioeconomic pathways (SSPs).

Wildfire Risk

Current conditions

Results from the BN risk model suggest that the strongest potential for exposure to hazardous fire was mainly in Florida and both coastal plains, and to a lesser extent in eastern Texas and upland subregions including the Ouachita, Ozark, and Appalachian Mountains, including much of eastern Kentucky (fig. 12A). Combined climate and fuel load conditions drove the potential for hazardous fire in the coastal plains, whereas high fuel loads were a more important driver than climate in the upland and montane subregions (Nepal et al. 2023). Geographic distributions varied considerably among the four population and ecosystem service vulnerabilities we examined (fig. 12B–E). Forest carbon vulnerability and the potential for harmful smoke emissions were spatially correlated, largely corresponding to high forest cover, forests in the large tree diameter class, and high fuel load. Local differences were driven in part by proximity to populated places and the resulting potential for smoke to reach people. Vulnerable people and structures, and vulnerable watersheds, showed more distinctive regional distributions.

Combining potential exposure to hazardous fire and all vulnerabilities, the greatest expected risks (fig. 13A) were concentrated in Florida and the coastal plain from North Carolina to east Texas, and interior highlands areas, largely following the potential for hazardous fire. However, the distribution of vulnerabilities causes subregional differences between exposure and risk. For example, heightened risk in eastern Kentucky is driven by concentrations of vulnerable ecosystem services and socially vulnerable populations (fig. 12). Viewed individually, direct risk to populations and structures, indirect risks from smoke exposure, and risks to forest carbon and important watersheds all show distinctive spatial distributions at local to regional scales (fig. 13B–E). Places with the highest combined risk (fig. 13A) are typically places with multiple overlapping vulnerabilities, as expected, but there are local exceptions. Furthermore, the degree to which particular vulnerabilities drive risk can vary considerably, with consequences for the interpretation of overall risk. For example, along the Atlantic Coastal Plain, where overall risk is consistently high, combinations of individual risk factors (fig. 13B–E) vary from State to State.

The relative utility of fuel treatment investments to reduce risk (e.g., through more aggressive prescribed fire programs) broadly follows the pattern of overall risk, but this relationship across the region is not linear (fig. 14). Instead, the utility of fuel reduction increases disproportionately with increasing risk; this arises directly from the intention to place increasingly high value on risk reduction in the landscapes with the most risk. Nonetheless, there is considerable variation in this relationship, with some high-risk landscapes showing low utility of fuel reduction—often in the coastal plains and Florida, and other high-risk landscapes showing high utility—often in the interior highlands. This broadly corresponds to the degree to which fuel load, rather than climate or other factors, drives risk, and therefore the degree to which more agressive fuel reduction beyond currently maintained efforts can further mitigate risk (Nepal et al. 2023).

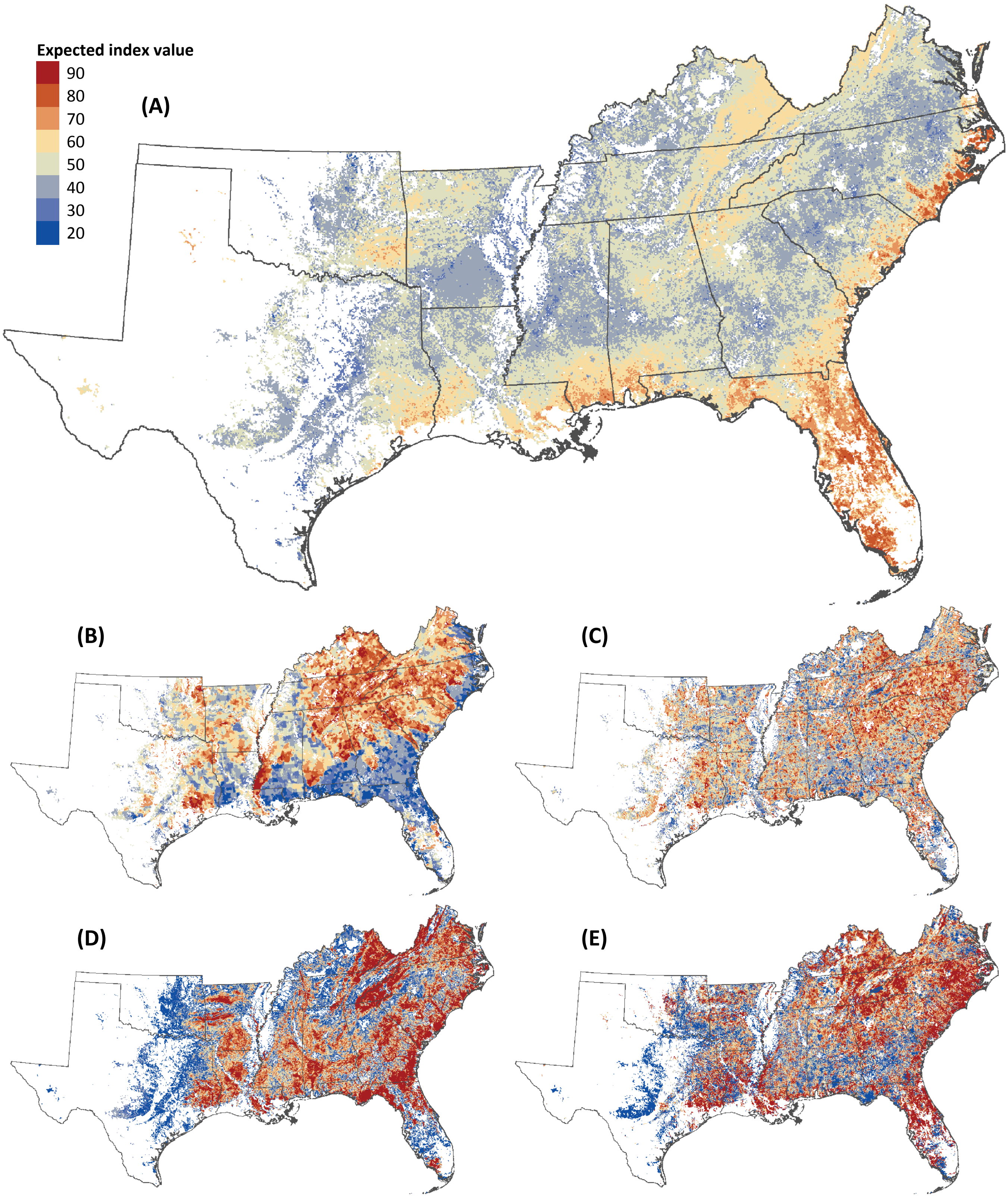

Figure 12—(A) Potential exposure to hazardous fire and (B–E) vulnerabilities estimated for recent, observed landscape conditions. (B) watershed importance weighted by social vulnerability; (C) population and structures weighted by social vulnerability; (D) forest carbon stocks; and (E) potential sources of wildfire smoke reaching human populations at unsafe levels, weighted by social vulnerability. Expected (highest probability) values are a relative index ranging from 0 to 100. Source: Nepal et al. (2023).

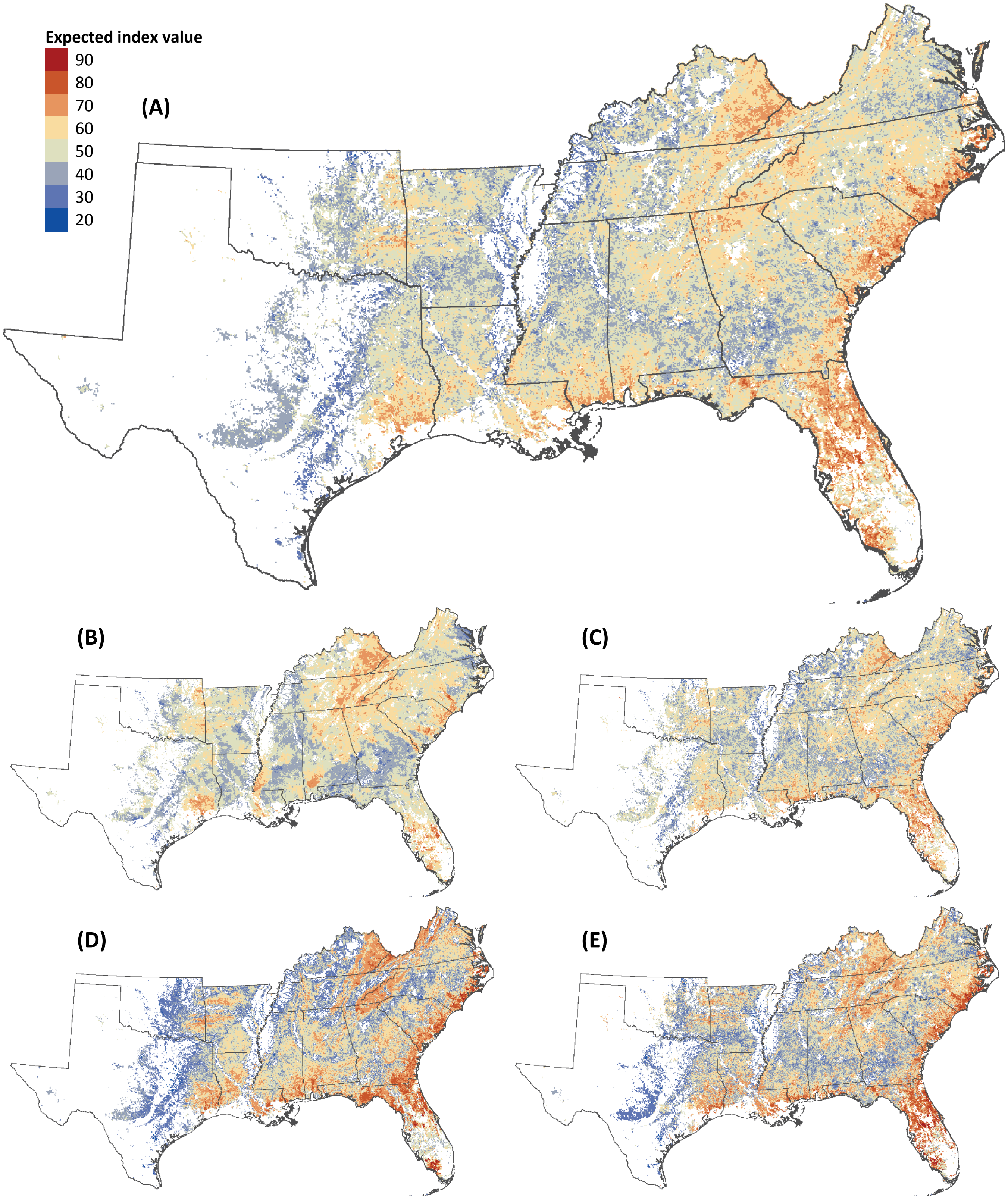

Figure 13—Risks associated with wildfire estimated for recent, observed landscape conditions. (A) Combined risk conditioned on the four following components: (B) risk to important watersheds weighted by social vulnerability; (C) risk to populations and structures weighted by social vulnerability; (D) risk to forest carbon stocks; and (E) risk from unsafe smoke emissions reaching human populations, weighted by social vulnerability. Expected (highest probability) values are a relative index ranging from 0 to 100. Source: Nepal et al. (2023).

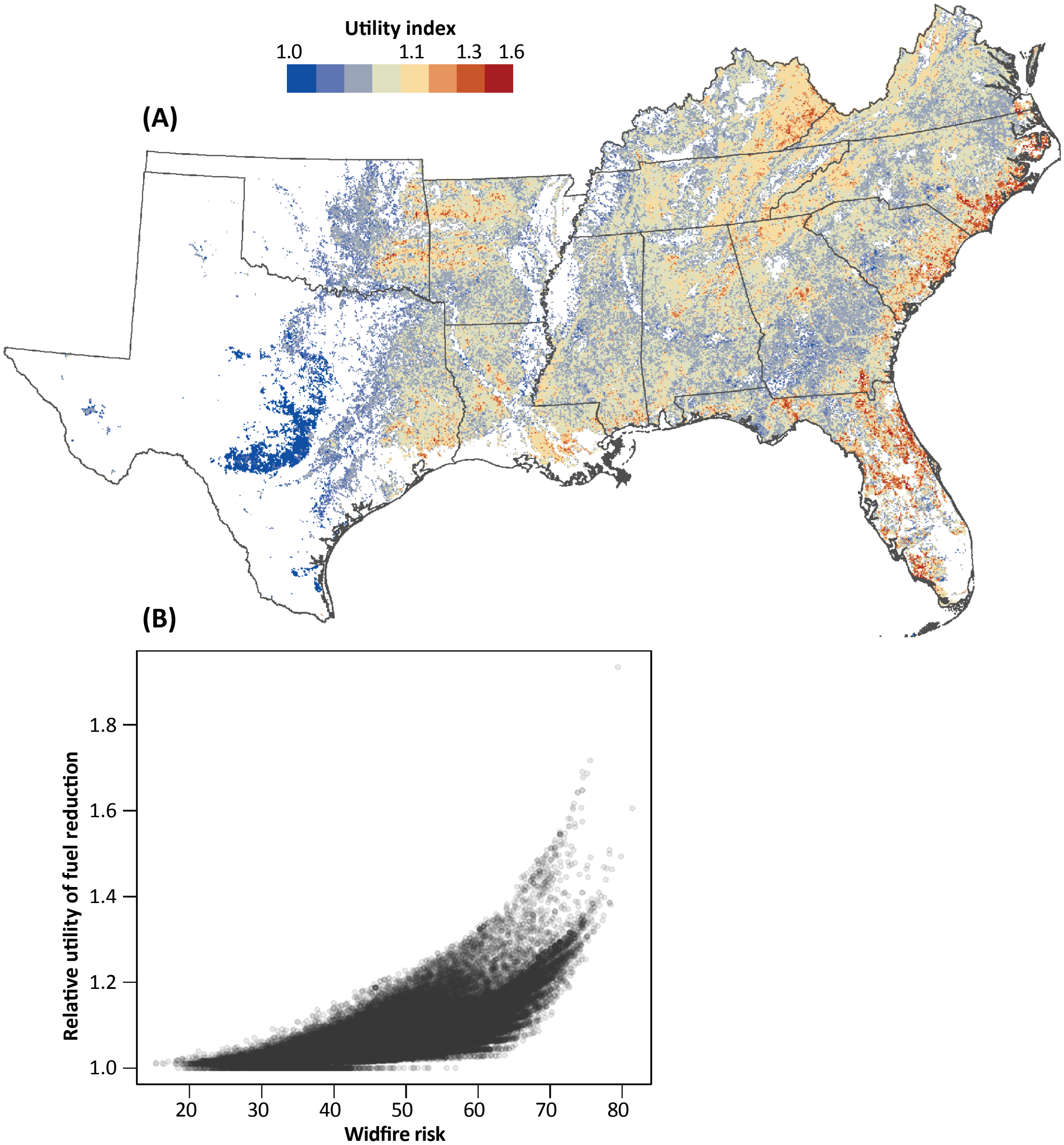

Figure 14—Relative utility of enhanced fuel reduction efforts for reducing wildfire risk, estimated for recent, observed landscape conditions. (A) Utility of fuel reduction for reducing combined risks from smoke exposure and direct fire exposure to people and structures, forest carbon, and important watersheds. (B) Utility is closely related to risk, but not equivalent. Utility values are greater than 1.0 when the utility of enhanced fuel reduction effort is greater than the utility of maintaining existing investments or efforts. Source: Nepal et al. (2023).

Projected risk change, current to mid-century

Projected change in wildfire risk between the current (1992–2020) and mid-century (2041–2070) periods, in terms of the regional median change, ranged from negligible under the LM-wet and LM-least warm scenario-climate futures to substantial increase under the HM-hot and HM-dry scenario-climate futures (fig. 15). Comparing these possible futures, projected change in risk was sensitive to both temperature and precipitation changes, and appeared highest when both were extreme, i.e., hot and dry. However, spatial variation in the degree of change within a given possible future was high relative to the median change, and was also high relative to the variation among the possible futures. Even for the futures with negligible median change, there were subregional hotspots of risk increase, and more widely dispersed landscapes showing decrease (fig. 16). The futures with greatest median risk increase showed more pervasive increase across the region, but still showed significant subregional variation.

For each change projection under a possible future, there were 10 realizations of 3-year climate anomaly and drought change, and therefore 100 comparisons by which to assess change (10 current, each compared to 10 mid-century). Agreement among these realizations in the direction of risk change (increase or decrease) also showed marked regional variation, with a pattern of generally stronger agreement on increasing risk for the more hot and dry climate futures (fig. 17). The most consistent agreement on increasing risk among realizations and possible scenario-climate futures were across the interior highlands subregions, and in Florida and southern Georgia. Agreement on decreasing risk was more variable across possible scenario-climate futures, although localized parts of east Texas and central Virginia showed some consistency.

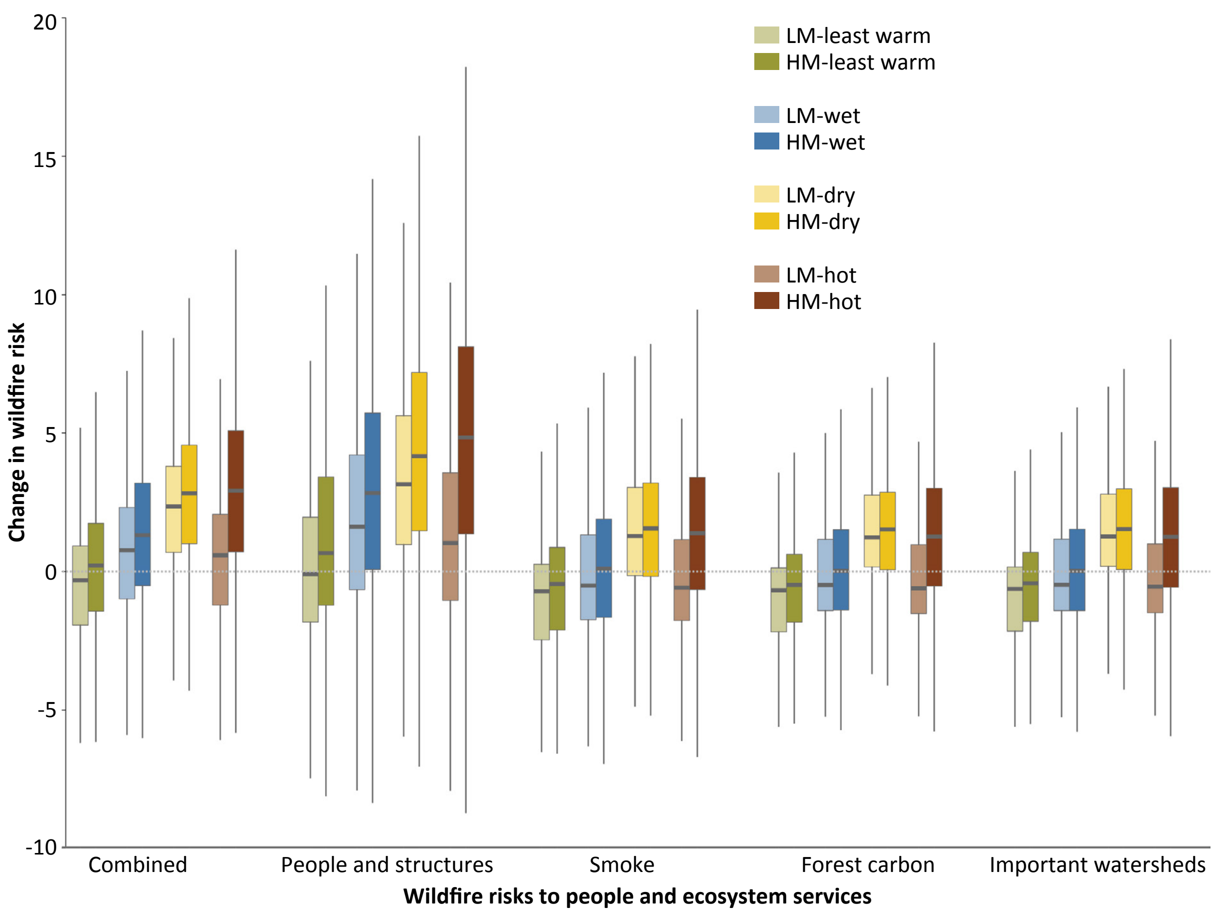

Figure 15—Projected change in wildfire risk to people and ecosystem services, from current (1992–2020) to mid-century (2041–2070). Boxplots indicate regional change, and variation across the region (boxes delineate first and third quartile values, black bars are the median, with whiskers extending to the minimum and maximum), for a given scenario-climate future. The region is characterized by strong spatial variation in expected risk change under the modeled futures, relative to the median change values. This highlights the importance of potential hotspots of change within the region (fig. 16). Relative risk can range from 0 to 100, with realized values typically between 20 and 85.

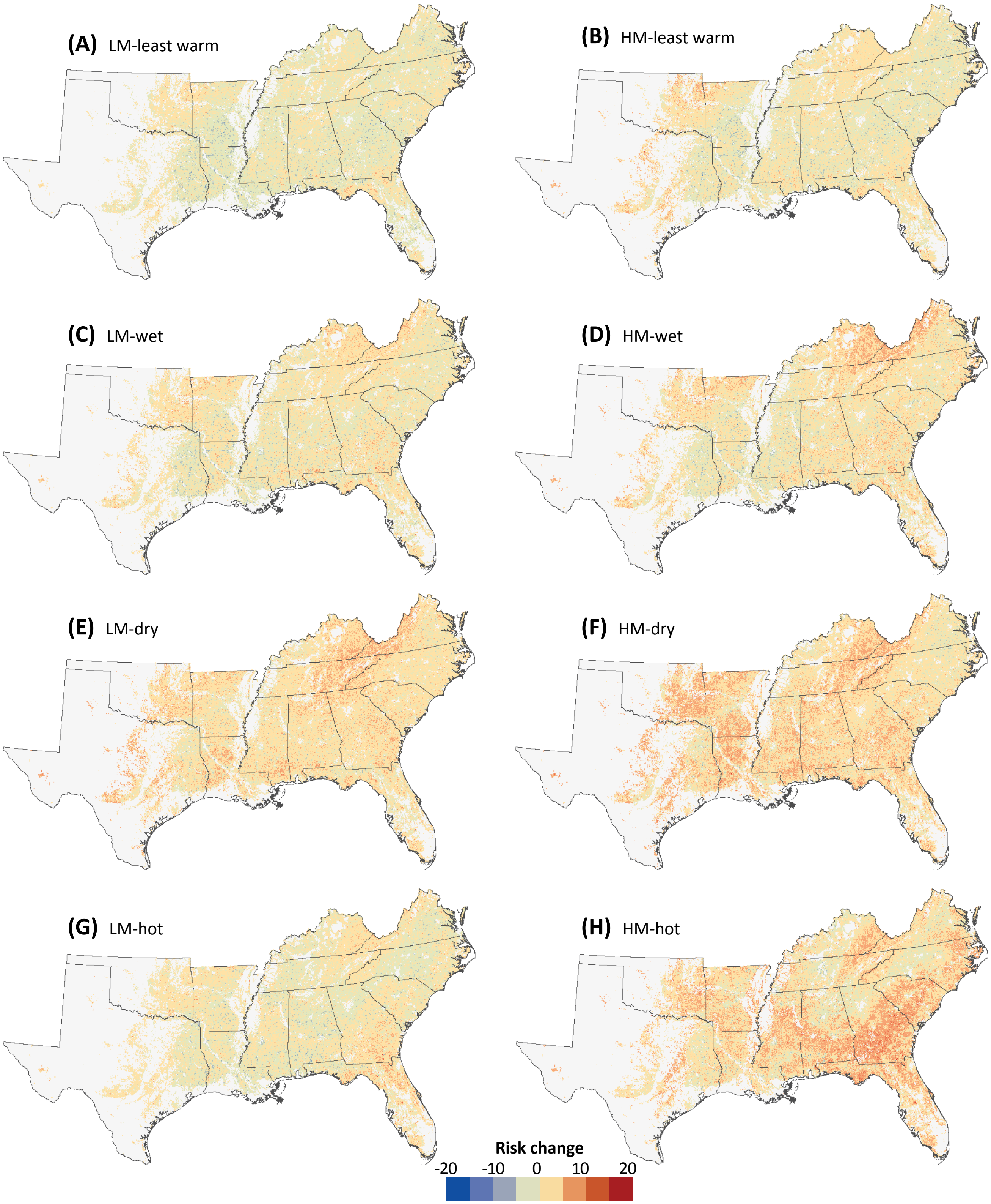

Figure 16—Projected change in wildfire risk to people and ecosystem services (all combined risks), from current to mid-century. Relative risk can range from 0 to 100. (A–H) Scenario-climate futures shown illustrate the range of variation across those evaluated.

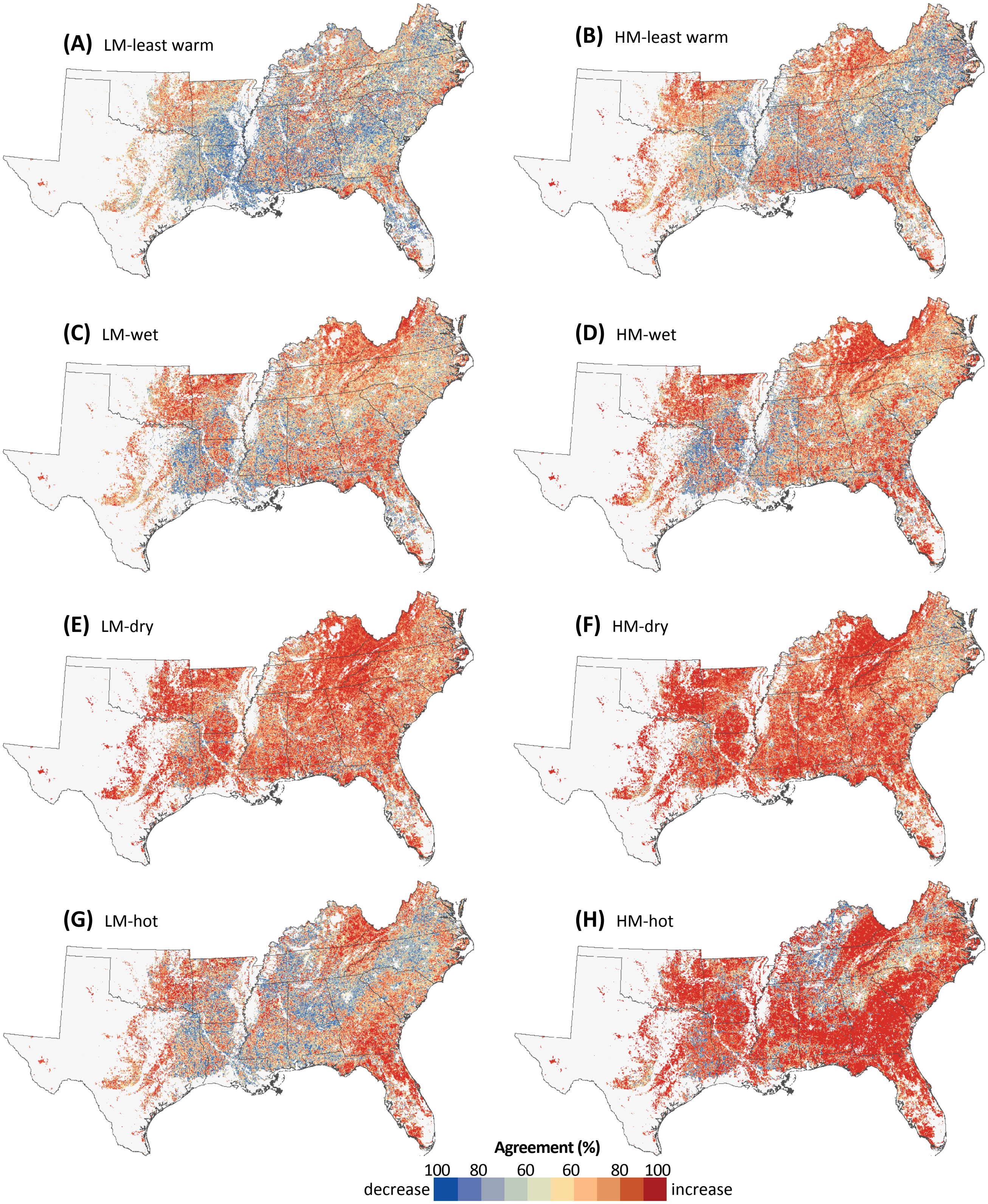

Figure 17—Agreement among 100 climate realizations in the direction of change in combined wildfire risk to people and ecosystem services, from current to mid-century. (A–H) Maps indicate the degree of agreement that risk increases (red) or decreases (blue); they do not indicate the magnitude of change. Scenario-climate futures shown illustrate the range of variation across those evaluated.

Potential impacts of fuels management

Assessing the potential utility of fuel treatments for reducing projected future risks can provide insight at broad spatial scales for anticipating possible negative future outcomes and identifying opportunities to proactively reduce the likelihood of negative outcomes. The mid-century projections of relative utility suggest substantial opportunities for avoiding or mitigating future risks. Just as the utility measure under existing conditions (fig. 14) mostly followed patterns of existing risk, utility for reducing future risks (fig. 18) mostly followed the spatial pattern of projected future risks.

Utilities for reducing current and future risks also broadly coincided at the regional scale, reinforcing, for example, the importance of risk management investments in the coastal plain from North Carolina to east Texas, and in interior montane subregions (fig. 19). The future projections also pointed to some mismatch between opportunities for reducing current and future risks, particularly under the more dry and hot climate GCMs and RCP 8.5. Compared to current utility, the utility for reducing future risks in the Ozark Mountains was broadly similar under the hot and dry climate GCMs or even slightly reduced under the least warm and dry GCMs. In contrast, future utility was higher than current utility in a broad band across the southern Piedmont and upper coastal plain (primarily under the hot and dry climate GCMs with either RCP 4.5 or 8.5), and in parts of the southern Appalachian Mountains (under all models, but moderated under the least warm climate GCM).

Finally, the relative utility measure suggested both spatial differences and similarities in opportunities for wildfire risk reduction among the different vulnerabilities we assessed (fig. 18B–E). Patterns for direct risk to people and structures, forest carbon, and important watersheds were broadly concordant, but potential opportunities to reduce risk from hazardous smoke emissions were much more pervasive across the region, at least under the hotter and drier possible futures.

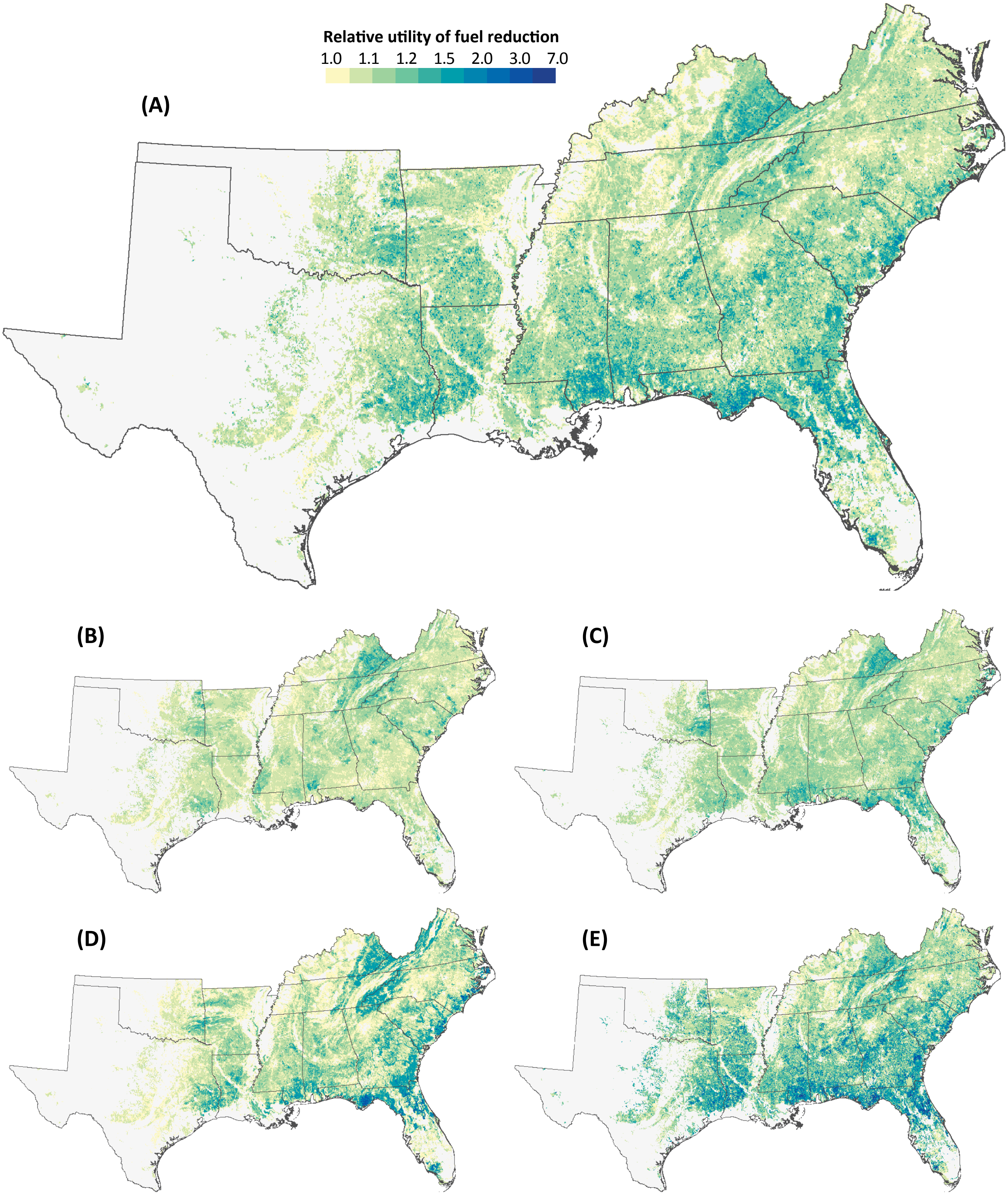

Figure 18—Relative utility of fuel reduction investments for reducing projected future wildfire risk at mid-century. (A) Combined utility, conditioned on the four following components: (B) important watersheds weighted by social vulnerability; (C) populations and structures weighted by social vulnerability; (D) forest carbon stocks; and (E) hazardous smoke emissions reaching populations, weighted by social vulnerability. Results are shown for the LM-hot scenario-climate future (HadGEM2-ES365, RCP 8.5, SSP2). Utilities under other scenario-climate futures were spatially similar, but magnitudes varied.

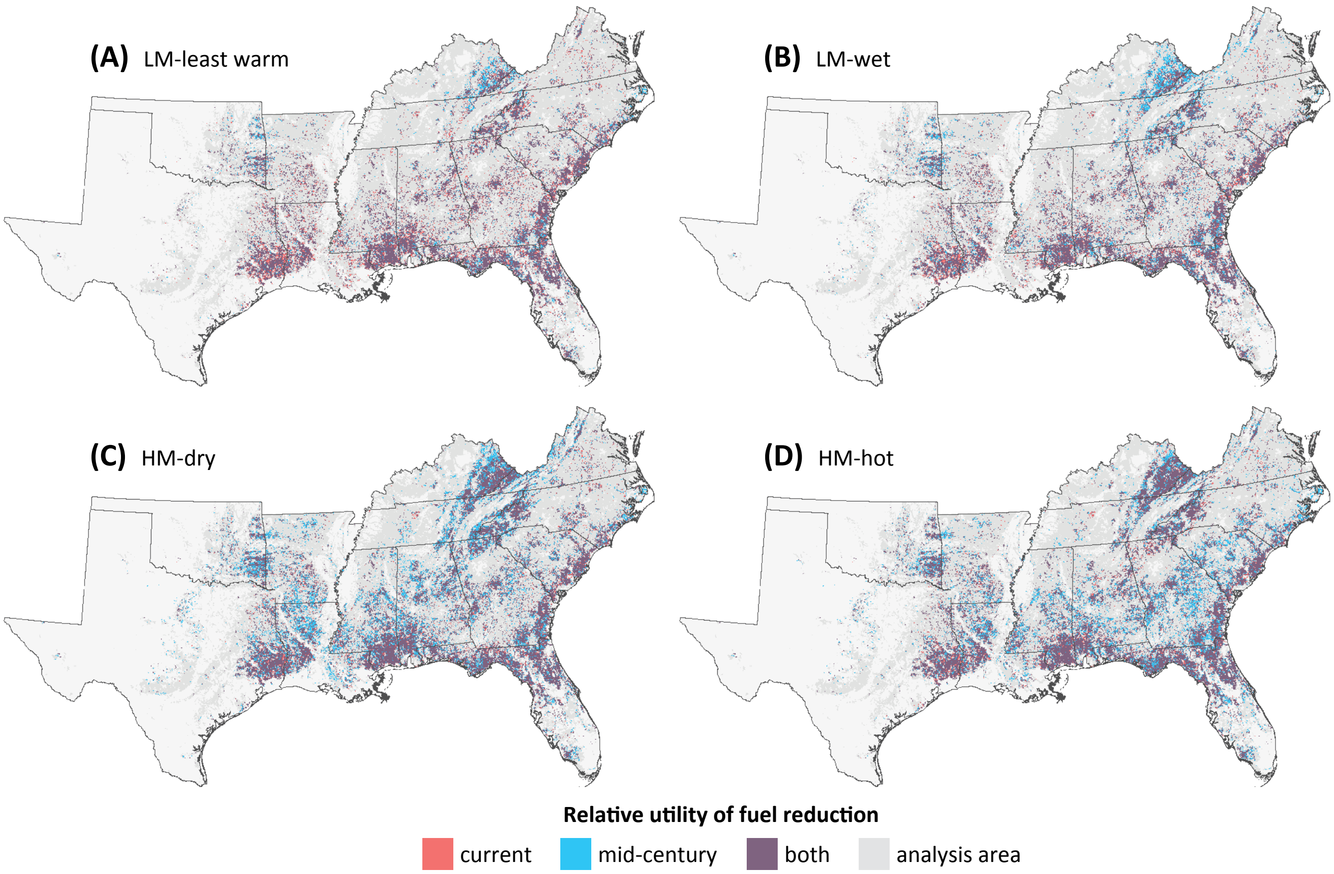

Figure 19—(A–D) Relative utility of fuel treatment investments for reducing wildfire risk at current (1992–2020) and mid-century (2041–2070) time periods. Only landscapes with utility values greater than the current 80th percentile value across models (1.135) are shown in color, to highlight landscapes with especially high expected utility. In many areas, new efforts to enhance fire management programs could address both current risks and potential future risks (purple). Other areas with currently moderate utility but showing increasing utility by mid-century (blue) could offer opportunities to proactively manage emerging risks and build resilience. The utility measure shown here is based on all population and ecosystem service risks combined, weighted towards risks to populations.

Firescapes and Wildfire Risk

We summarized the risk assessment results to the firescapes shown in figure 10 to further describe the regional geography of risk, in terms of differences among firescapes. There was wide variation in risk among the hexagon landscape units within any given firescape, but overall differences in median risk also existed among firescapes (fig. 20). The spatial correspondence of high (or low) estimated risk (fig. 13A) with high-risk (or low-risk) firescapes was clear; for example, high-risk montane areas were mostly contained in the (2) cool and wet broadleaf mountain forests firescape, and high-risk coastal plain areas fell mostly within the (8) rural pine forests, intense fire, and vulnerable communities firescape. Others were less obvious, but of equal importance. For instance, the (4) urban periphery firescape had limited regional extent and was highly discontinuous because it is comprised of WUI-dominated landscapes near urban areas. But it had the highest median risk of any firescape, under both the business as usual management scenario and the fuel reduction scenario. Potential risk reduction under the fuel reduction scenario was less for some firescapes including the (4) urban periphery; (7) warm and dry, mixed woodlands; and (5) rural agriculture, vulnerable communities, and low wildfire potential firescapes, mainly because forest cover and fuel loads were already comparatively low in these places, and risk was driven by other factors (Nepal et al. 2023).

We also examined differences among firescapes in the relative utility of fuel reductions to reduce risk, under current and future conditions (fig. 21). For consistent comparison, the hexagon landscape units were kept fixed at their current firescape identities (fig. 10). Utility varied among firescapes, and these differences remained under different possible futures (fig. 21). Utility was similar under current versus future projections for the milder scenario-climate futures (LM-least warm and LM-wet). Under more extreme warming futures (HM-dry and HM-hot) there were more evident, though still small, median increases in utility. Similar to risk, the utility values showed strong within-firescape variation, emphasizing the importance of local spatial variation and hotspots of growing or declining utility. The only firescape that showed a median decline in utility was the (4) urban periphery (and WUI-dominated) firescape. This was the primary firescape showing reduced forest fuel loads at the landscape scale, apparently due to forest loss from urbanization under the possible futures. This suggests a potentially complex mix of changes in the drivers of risk, including an expanding WUI with growing population and structure densities, declining forest cover and associated fuels, and reduced capacity to mitigate risk through fuels management in remaining forests.

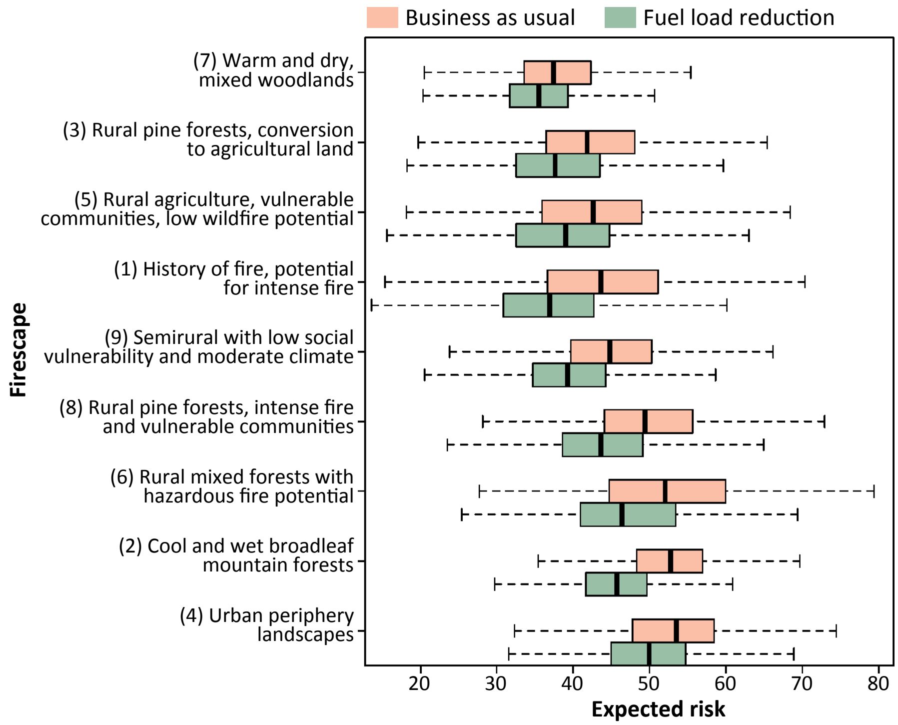

Figure 20—Estimated wildfire risk (all vulnerabilities combined) under scenarios of business as usual and enhanced investment in fuel reduction. Boxplots indicate the distribution of risk values within firescapes, under current conditions (as shown in figure 10), with firescapes ordered by median expected risk (black vertical bars). Boxes are bounded by the first and third quartiles and whiskers show minimum and maximum values. The degree of risk reduction potential in each firescape depends largely on the degree to which risk is driven by fuel load rather than wildland-urban interface expansion, climate, or other factors. Source: Nepal et al. (2023).

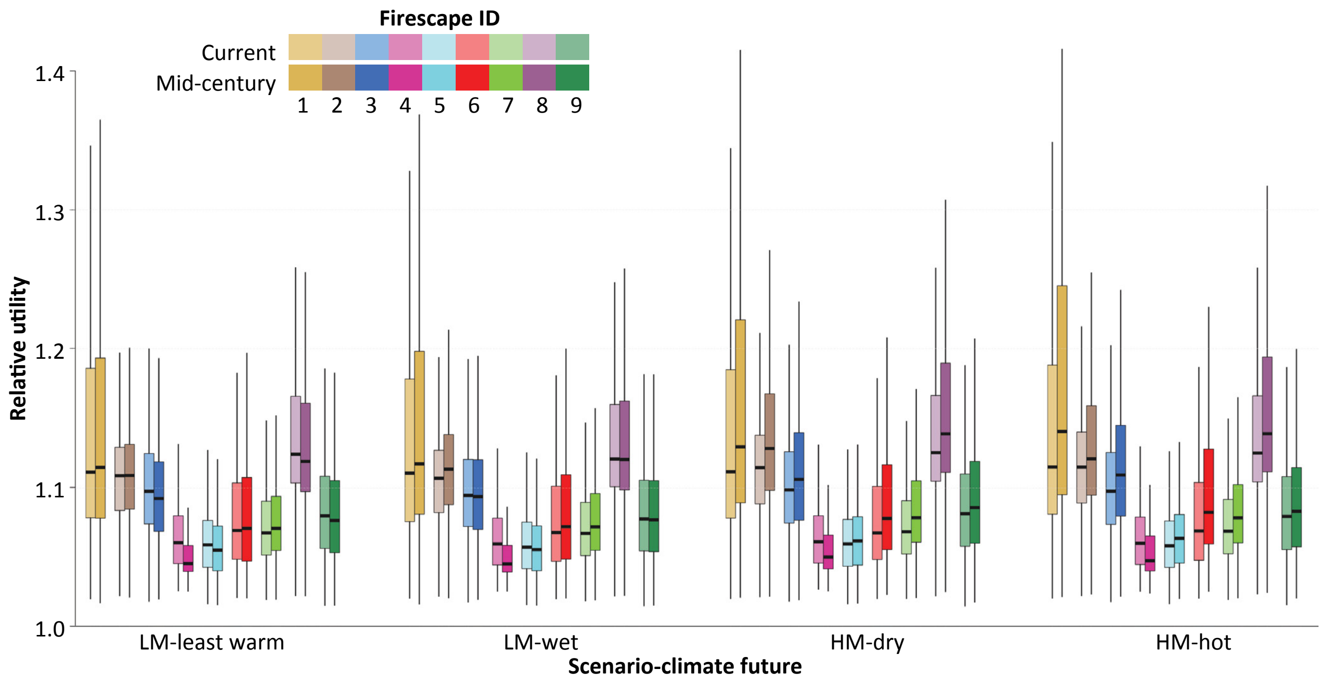

Figure 21—Relative utility of fuel treatment investments for reducing projected current risk and projected future risk at mid-century. Boxplots summarize the distribution of utility values within firescapes (figure 10; the fixed current firescapes were used for consistent comparison). Boxes are bounded by first and third quartiles, black bars are median values, and whiskers show minimum and maximum values. The combined utility shown is conditioned on all population and ecosystem service vulnerabilities. These scenario-climate futures illustrate the variation in utility across all futures examined. The utility of fuel reduction varied more among firescapes than it did between the two time periods, but in some cases small changes over time further increased the differences among firescapes (e.g., compare firescapes 1 and 2 to firescape 4).

Discussion

Our assessment results suggest complex changes in the role fire plays in southern landscapes, in response to ongoing and projected changes in climate, forests, and society. These changes have an important geographic dimension that strongly implies the need for locally varied, adaptive responses to manage risk and build resilience. There are also important shared landscape and societal characteristics that can guide risk management at broader regional and subregional scales. We first discuss the broad dimensions of change, in part through the lens of the firescapes concept, with particular attention to climate, the WUI, and fire regimes. We then discuss projected changes in wildfire risk and the implications for risk management into the future, with special emphasis on the role of prescribed fire.

Fire in a Changing South

Climate change context

Climate is a key driver of ecological and socioeconomic factors that shape both fire regimes and the impacts of fire on people and forests (Bacciu et al. 2022). Climate change trajectories are making the weather and climate conditions that are suitable for wildfire more common, enhancing fire likelihood and lengthening fire seasons (Smith et al. 2020). The IPCC has highlighted expected increases in the frequency and severity of drought conditions contributing to growing wildfire risk globally, and increasing the likelihood of larger and more frequent fires in much of the United States (Bladon et al. 2014, Hicke et al. 2023). Climate change is also expected to increase the likelihood or severity of other natural hazards such as hurricanes that can increase local fuel loads, exacerbating wildfire risks and complicating risk management options. Indirect socioeconomic consequences of climate change can also impair the capacity of communities to prepare for and respond to fire (Hicke et al. 2023).

A changing climate is likely to exacerbate complexities in forecasting, evaluating, and communicating the probabilities and consequences of wildfire, increasing uncertainties around management interventions that are required to reduce risk. Facing such changes, land managers need information on the likelihood and magnitude of altered fire regimes, forest conditions, and risks to communities and ecosystem services (Bacciu et al. 2022, Mitchell et al. 2014). Our results assessing modeled firescapes and wildfire risks under a range of projected climate futures suggest broad outlines for how risks, as well as constraints and opportunities for risk management, may be impacted at the regional level and over decadal timescales. Regional assessment of this kind does not supplant local knowledge but can help to better characterize uncertainties by illustrating plausible future changes, as a context for informed regional- to local-scale decision making.

Projected firescape results under the climate models we examined support the notion that southern landscapes increasingly exposed to warmer and drier climate conditions will be characterized by more fire-prone forests, often driven by increasing drought potential. Projected future changes in precipitation in the South are less certain than temperature projections, but some degree of increasing potential for drought exposure by mid-century is expected for most forests across the region, especially under hotter and drier model projections (Costanza et al. 2023). Agreement among scenario-climate futures was generally high in terms of this trend, especially for western and northern parts of the region, but varied in the magnitude of regional projected change. For example, all projected futures suggested varying degrees of loss of the interior highlands (2) cool and wet broadleaf mountain forests firescape, transitioning to hotter and drier firescapes. This firescape is also characterized by high fuel loads, so fuel load reduction could be particularly useful to offset climate-induced increase in hazardous fire potential. Projections of wildfire risk also provide insight into regional challenges and opportunities for accelerated risk management efforts in the context of a warming climate. For example, many areas with projected risk increase were areas that already show high risk, including significant parts of the interior highlands and coastal plains. Unlike the interior highlands, the coastal plains and Florida already have some of the most intensive and extensive prescribed fire programs in the Nation, and opportunities to increase existing levels of prescribed fire may be more limited.

The wildland-urban interface

The WUI land area in the United States grew by 33 percent from 1990 through 2010, with the South experiencing more growth than most other regions (Radeloff et al. 2018). Growth of the WUI slowed during 2010–2020, but absolute change remained positive in the South, and in particular Southern States continued to experience growth in housing density within the existing WUI (Radeloff et al. 2023). These changes and other related land-use intensifications are likely to continue, with continued construction of road networks, expansion of electrical infrastructure including transmission lines, and development of landscapes near cities and towns. Future (mid-century) projections of natural-developed interface landscapes under a range of socioeconomic and climate scenarios are sensitive to uncertainty in socioeconomic futures, but show continued increases, especially in the South (Riitters et al. 2023).

At the same time, climate-driven changes in the frequency, severity, and extent of wildfire can have a compounding effect on risk in the context of an expanding WUI. For example, most wildfire in the South has human ignition sources, and conditions favoring such ignitions are likely to increase not only with a growing WUI that puts more people and infrastructure in direct proximity to wildlands, but also with a growing prevalence of conditions favoring fire such as drought (Balch et al. 2017, Costanza et al. 2023). The combination of more fire, potentially year-round wildfire seasons, and an expanding WUI clearly places people and infrastructure in the WUI at increasing risk.

As the number of people living in the WUI increases, efforts to protect homes and communities and to prevent and suppress fire in these landscapes will receive increased attention, and their costs are likely to grow. Reducing fuels in and near the WUI will be increasingly important, but the use of prescribed fire in WUI landscapes is constrained by the potential for exposing people to smoke, risks of fire escape beyond planned burn perimeters, and negative public perceptions of fire. Mechanical treatments can be a useful complement to prescribed fire in this context. Collaborative community-based approaches to risk management that include public education and outreach to build prescribed fire tolerance, reduce human ignitions, and create defensible spaces are particularly important in WUI landscapes (Nelson et al. 2004, USDA Forest Service 2022b, U.S. Fire Administration 2022).

The firescape with the overall highest wildfire risk was the (4) urban periphery, which was the most strongly WUI-dominated firescape. Baseline risk in these landscapes was primarily driven by population and structure densities rather than inherently greater potential for hazardous fire than nearby rural areas, which often had more forest and more available fuels. Due to relatively low available fuels, urban periphery landscapes also showed less opportunity for reducing risk through fuel reduction, and those opportunities were projected to decline further by mid-century under the more extreme climate models and scenarios. This was apparently due to projected fuel load decline, as a function of forest loss in urbanizing landscapes.

We do not interpret this result as a declining importance of fuel reductions in WUI landscapes. Remaining, fragmented forests in these landscapes still contain significant fuels, and are likely to be increasingly exposed to human ignition sources. Our model did not account for patterns of population and structure density increases by mid-century (except in that attendant forest cover losses were modeled), so projected risk increases in these landscapes are conservative. The combined findings of unusually high risk and growing challenges for risk management in WUI landscapes are consistent with widely recognized needs for effective place-based and community-based strategies that employ a diversity of fire management tools in these landscapes.

Fire regimes

Fire regimes are characterized by the frequency (fire return interval), intensity, severity, seasonality, and spatial patterns of fire observed over long periods of time (Greenberg and Collins 2021, Kobziar et al. 2024, Vose et al. 2021). Fire regimes vary with vegetation type and composition, and across climatic, topographic, and other environmental gradients. In general, more frequent, lower severity fire regimes are driven by more seasonal or frequent dry periods, whereas long intervals between droughts can induce less frequent, higher severity fires where surface fuel accumulation or stand structure allow (Greenberg and Collins 2021). People also shape fire regimes in fundamental ways. Human activities that affect forests impact their fire regimes across the United States and in the South, including forest conversions to and from other land uses; land-use fragmentation; forest management practices including tree harvest and prescribed fire; fire suppression and exclusion; and wildfire ignition (Vose et al. 2021). In particular, prescribed fire can disrupt regimes characterized by less frequent, higher severity fire.

Climate change is expected to impact fire regimes in multiple ways, not only directly through changes in drought patterns but also indirectly through long-term vegetation impacts and even societal changes such as wildfire response capacities (Raymond et al. 2020, Terando et al. 2024). Under hot and dry future climate scenarios in particular, there is an expectation of more frequent and severe wildfires, with a projected 2 to 3 months longer fire season for the South on average, but changes are not likely to affect all parts of the region equally (Liu et al. 2014, Mitchell et al. 2014).

Fire regimes involve multiple fire behavior characteristics that are each driven by complex relationships among the various natural and human factors mentioned above. Uncertainties among these dynamics make it challenging to project specific fire regime properties of future forests, but the broad outlines of increasing variability, frequency, severity, and size of wildfires are well supported (Bowman et al. 2020, Hicke et al. 2023). As climate change continues to impact both biophysical and human aspects of fire regimes, changes to ecosystem services will be impacted as well, including risks for outdoor recreation, forest carbon stocks, surface water quantity and quality, and more (Greenberg and Collins 2021, Roces-Diaz et al. 2022, USDA Forest Service 2023).

Contemporary wildland and prescribed fire management are built to a degree on understandings of current and historical fire regimes. There will therefore be direct implications of altered fire regimes for how fire is managed in the future (Kobziar et al. 2024, Terando et al. 2024). Disruption to managed fire regimes may critically impact ecosystems in the South such as pine forests where fire management plays a key role (Carter et al. 2018, Glitzenstein et al. 2021, Mitchell et al. 2014, Stambaugh et al. 2011). In more passively managed systems such as upland oak forests, where there are needs and opportunities to expand prescribed fire footprints, climate-induced disruptions will exacerbate uncertainties for planning and executing active management (Kupfer et al. 2020).

In all cases, confronting increased uncertainties and building adaptive capacity at scale will require greater emphasis on collaborative partnerships for management, monitoring, and research among Federal, State, and local agencies, tribal and private landowners, nongovernmental organizations, and others (Vose et al. 2021). Changes from a warming climate without recent historical analogue, continued changes in land use including an expanding WUI, and the dominant role of human influences on fire regimes in the South make presumed historical fire regimes an increasingly unrealistic context for managing forest lands for future resiliency (Vose et al. 2018). But the established role of human fire regimes in the region may provide a significant degree of adaptive capacity to help direct changes in forest ecosystems and their fire dynamics towards resiliency and sustainability (Higuera et al. 2019, McWethy et al. 2019).

Firescape projections

Firescapes provide a perspective complementary to traditional fire regime descriptions that highlights the broader social and ecological properties of present-day landscapes influencing fire and the various impacts from and responses to fire (Smith et al. 2016, WFLC 2014). A firescape represents a particular combination of landscape properties found together, defining a landscape type that can be observed in many places across a region. Changes between firescapes—either from place to place or in one place over time—are likely to have consequences for fire regimes and appropriate management responses. Cautious interpretation of firescape change projections is recommended, because not all landscape variables were dynamic in our models. But there are nonetheless clear implications relating especially to projected climate and forest changes. An advantage of our modeling approach is that projected changes in vegetation, fuels, smoke, and climate are quantified together (Liu and Wimberly 2016).

On average, across the possible futures we examined, 24 percent of landscapes underwent a change in firescape by mid-century, indicating considerable stability. This may not be surprising given the fairly broad level of the classification (i.e., only nine possible firescape types for the region), so that a shift into a different firescape required pronounced change in the underlying variables. Projected changes nonetheless suggest shifts towards conditions more like those in the western and southern parts of the region, with warmer climate and forests more prone to hazardous fire. These findings are consistent with generalized expectations for more fire, reduced fire return intervals (Gao et al. 2021, Mitchell et al. 2014, Senande-Rivera et al. 2022), and shorter prescribed burn windows (Chiodi et al. 2018, Kupfer et al. 2020), at least within traditional burn seasons in the South. For example, Gao et al. (2021) projected potentially strong increases in annual fire probabilities in the South by mid-century.

Results also provide insight into possible long-term forest structure and composition changes shaped by changes in climate, land use, and fire regimes (Vose and Elliott 2016). Projected firescape transitions were overwhelmingly to the (7) warm and dry, mixed woodlands and (8) rural pine forests, intense fire, and vulnerable communities firescapes. The dominance of transitions to the former is driven by projected shifts towards warmer and drier conditions in mid-century climate normals under the climate futures we examined and, to a lesser degree, by projected forest changes towards compositions dominated by more fire-prone forest-type groups (e.g., upland conifer) and smaller tree size classes. A broad shift from (8) rural pine forests, intense fire, and vulnerable communities to (7) warm and dry, mixed woodlands dominated the projected transitions west of the Mississippi River. Although driven mainly by climate projections, this also suggests possible shifts away from pine-dominated forests towards more mixed forest composition in that subregion.

Transition to the (7) warm and dry, mixed woodlands firescape suggests reduced potential for high-intensity fires, but in our risk model projections, burn probability and wildfire hazard potential showed moderate increases in some western parts of the region under hot and dry climate models, suggesting overall risks would remain an important concern. Reduction in potential wildfire intensity implied by some of the projected firescape changes have also been projected for other temperate forests in conjunction with reduced fire return intervals (Erni et al. 2021). Conversely, projected shifts to the (8) rural pine forests, intense fire, and vulnerable communities firescape from other common rural firescapes in the eastern and central parts of the region broadly suggest increased potential for high-intensity fire, increased or stable forest cover and fuel loads, and possible pine forest cover gains. The (5) rural agriculture, vulnerable communities, and low wildfire potential and (3) rural pine forest conversion to agricultural lands firescapes were also characterized by high social vulnerabilities, so increases in hazardous fire could come with particularly heightened risks for communities in those areas.

Dimensions of Future Risk

Projected risk increases by mid-century under our models often occurred in subregions that already have high estimated risk, adding emphasis to the need for effective risk management in those places. This was true for all four categories of wildfire and smoke risk to people and ecosystem services that we examined. But some places with currently moderate to low estimated risk also showed potential for growing risk, e.g., much of the southern Piedmont and central Texas. Attention to both current and potential future risks will be essential for meeting existing risk management needs while building forest and community resilience to ongoing change in southern landscapes.

Risks to people and infrastructure, and the role of social vulnerability

In general, direct risk of wildfire to people and structures showed greater increases by mid-century than did estimated risks from smoke or to ecosystem services. This was in part due to its higher vulnerability to increasing hazardous fire potential in our model (Nepal et al. 2023). But projected increases in hazardous fire potential also showed broad overlap with many areas in the region with high population and structure densities when those were weighted by social vulnerability. The role of social vulnerability in broadening the overall risk was considerable, especially because it tended to expand estimated vulnerability beyond WUI-dominated landscapes near cities and towns, into more rural landscapes with fewer but more socially vulnerable people.

Projected risk to people and structures nonetheless remained concentrated in high-WUI landscapes, including many of the places within the WUI-dominated urban periphery firescape. We did not model future growth of the WUI itself; this growth can be expected to increase risks from direct fire exposure and smoke emissions, even independently from climate change. As mentioned above, this makes our risk projections conservative, especially in periurban landscapes. Under extreme future scenarios, the scale and severity of wildfires combined with WUI changes have the potential to surpass capacities to protect people and infrastructure (USDA Forest Service 2022b).

Model projections suggest substantial and regionally pervasive increases in smoke exposure risk by mid-century, even without accounting for population growth. Spatial patterns of smoke risk and increase in that risk were broadly concordant with those for direct fire exposure risk. But the capacity of smoke emissions to expose distant populations to harm resulted in more broadly distributed risk beyond the immediate vicinity of densely populated landscapes. Similar to direct fire exposure, accounting for social vulnerability also broadened smoke risk to landscapes where fire might expose more rural populations.

The most socially vulnerable populations are the most likely to lack the necessary resources for effective adaptation to fire, including capacity to invest in preparedness and economic security to recover from wildfire. These communities will be disproportionately affected by wildfire and smoke impacts (Coughlan et al. 2019, Fischer and Frazier 2018). It is increasingly clear that information about socially vulnerable communities and their unequal risk for adverse effects from wildfire or prescribed fire smoke can improve planning for risk mitigation. This can help improve overall public health and safety, and could bolster response planning and communication during wildfire and prescribed fire events (Afrin and Garcia-Menendez 2021, Rappold et al. 2017). Increasing communities' resilience to the effects of fire and smoke can partly be accomplished by addressing fundamental social vulnerabilities of communities at risk, even if direct links to fire risk are not obvious (Coughlan et al. 2019). This will be especially important under a changing climate in places where wildfire-associated hazards are most likely to increase. Ongoing research and monitoring that includes social vulnerability dimensions of risk, as well as implementation of similarly inclusive social and ecological adaptive management strategies, can help address the public health and safety risks posed by wildland fire in a changing climate (Coughlan et al. 2019, McWethy et al. 2019).

Risks to ecosystem services

Stressors on ecosystem services from wildfire are broadly expected to increase due to climate change, with impacts likely to vary geographically and among ecosystem services (Roces-Diaz et al. 2022). Our assessment of two key ecosystem services across the South bear this out, in terms of current risks and projected future risks. Risks to forest carbon stocks and to important watersheds for drinking water showed distinct distributions at local to regional scales, driven by differing distributions of the resources themselves.

Forest watershed importance for drinking water showed an idiosyncratic distribution concentrated in the northern and upland parts of the region, mainly because much of the coastal plain relies on groundwater rather than surface water sources (Mack et al. 2022). High potential for hazardous fire at present, and under plausible futures, nonetheless heightened expected risk to watersheds in some coastal plain forests, in addition to the montane landscapes where potential for hazardous fire more broadly co-occurred with watershed importance. Climate change influences on forest water quality and quantity in the South will likely be both direct and indirect, not only through precipitation variability and changing fire regimes but also through long-term changes in vegetation composition and other impacts. Impaired watershed conditions can result from severe fire, but changing future risks are also likely to be shaped by complex interactions with these additional factors (Caldwell et al. 2020, Hallema et al. 2018). Nonetheless, where and when more severe wildfires become more common, the risk of impairment is also likely to increase, with important consequences for forest ecosystems, outdoor recreation, and human health and safety (Bladon et al. 2014, Mitchell et al. 2014, Thompson et al. 2013). Moreover, growing demand for water as populations increase in the South will heighten the importance of forest watersheds in supplying clean water, raising the stakes for effective risk management in and around those places.

Our spatial projections of wildfire risk to forest carbon were closely tied to the distribution of mature forest cover, where most of the region's carbon pool is stored (Coulston et al. 2023). At the regional level, our projections suggest moderate increase in risk to stored forest carbon from extreme wildfires under the hot and dry climate futures, but not under the least warm and wet futures. Carbon dynamics in the region and their interactions with fire dynamics and climate change are complex and subject to strong uncertainty, and the consequences of increasing wildfire risk for overall forest carbon pools are likely to be strongly contingent on interactions with multiple other factors. The southern region also has a large proportion of forest in young age classes, with high rates of net primary productivity and carbon sequestration (Mitchell et al. 2014). However, with projected increases in the potential for hazardous wildfire, reduced rates of long-term postfire carbon accumulation (Harris et al. 2019) may become more common in southern forests. This may be compounded by declining sequestration rates as forests throughout the region naturally age (Coulston et al. 2015). Landscape transitions in firescape projections suggest possible increases in cover of small-diameter forest stands, as well as increases in mature, high-carbon forests, in different parts of the region. Although not assessed, such transitions could have mixed consequences for forest carbon pools and fluxes (Coulston et al. 2023). Wide geographic variation in these factors and forest carbon storage, sequestration rates, risks from wildfire, and other forest disturbance agents highlight the importance of identifying regional hotspots of climate risk to this resource.

Managing Current and Future Risks

Future of prescribed fire in the South

Prescribed fire will be crucial for managing southern forests as they respond to wildfire and climate change. Our results suggest that there are substantial opportunities for reducing risk through fuel treatments, even given projected climate change, recognizing that the intensity of management required to compensate for projected risk increase is subject to strong uncertainty, and is likely to vary widely across the region. Targeted management investments can be prioritized in landscapes where prescribed fire and other tools are likely to be particularly effective both for managing current risks and for avoiding likely future risks. Where risks are high or expected to increase, but fuel treatments alone are insufficient or impractical, building capacity for alternative or complementary risk management strategies is equally important.

Prescribed fire reduces the potential for uncontrolled fire, can protect populations from more extreme air pollution typically generated by wildfire (Afrin and Garcia-Menendez 2021), and can reduce the likelihood and severity of wildfire impacts on ecosystem services (Hurteau et al. 2019, Liu et al. 2014, Mayer et al. 2020). Prescribed fire allows land managers to maintain lower fuel loads, at the expense of releasing potentially harmful smoke into the atmosphere (Kobziar et al. 2015). But the amount of smoke produced by prescribed fire is typically lower than during a wildfire due to the weather and fuel conditions selected for the burn; wind conditions are also selected to minimize the potential impact of that smoke on nearby populations by following recommended smoke management practices (Long et al. 2017). The key factors to reducing human health and safety risks from smoke exposure are to minimize emissions and direct smoke plumes away from populated areas; prescribed fire provides the ability to address both.

Prescribed fire is already used extensively across the South, especially in managed pine-dominated forests. It is challenging to understand how future climate change will impact the planning and implementation of prescribed fire in the region, especially as land uses and populations also undergo change. Prescribed fire may be less cost-effective, more complex, and riskier as desired weather and short-term climate conditions that govern burn windows become less frequent and more erratic, and as a growing WUI increases the likelihood of exposing communities to smoke or escaped fire. Opportunities for using prescribed fire safely are likely to be more constrained by mid-century, requiring increased flexibility and enhanced monitoring systems for strategic scheduling of operations under safe conditions (Kupfer et al. 2020). Other fuel treatment methods, including forest thinning, may also grow in importance for mitigating wildfire risk either in combination with prescribed fire, or where prescribed fire is impractical (Brose and Wade 2002).

Anticipating changes in burn windows

Fuels accumulate rapidly in southern forests due to high average annual rainfall and warm year-round temperatures, which generally leads to relatively short fire return or burn intervals. The South is expected to see rising nighttime temperatures and increased drought (Carter et al. 2018, Costanza et al. 2023), limiting suitable days for implementing prescribed fire. Spring and summer prescribed burning opportunities in particular are likely to be increasingly limited due to increased risk of controlled burns escaping the target areas, with some parts of the South potentially losing all suitable burn days during summer (Kupfer et al. 2020). Overall, the result may be either less prescribed burning or shifting to fall and winter months for controlled burns (Chiodi et al. 2018, Kupfer et al. 2020). Prescribed fire windows may be further limited by projected changes in the frequency and intensity of hurricanes and extreme winter weather events associated with climate change in the South (Hoffman et al. 2023), where large amounts of downed timber may increase postevent fuel loads. Burning these heavy, wet fuels is not optimal because higher smoke emissions impact visibility, air quality, and health risks to nearby communities. Given these changes, as well as the uncertainties introduced by increasing short-term climate variability, adaptive prescribed burns with multiple burn seasons, and increased flexibility of burn schedules, will likely be needed to sustain desired burn frequencies in the South (Glitzenstein et al. 2021).

Prioritizing investments for resilience: tools for adaptive planning and decision making

Current fire management is unlikely to be sufficient to respond to accelerated changes in wildfire frequency, extent, and severity without substantial new investments and a broadened view of socioecological adaptation to fire (Bacciu et al. 2022, McWethy et al. 2019). Investments that build resilience to future change and successfully manage risk will likely include enhanced capacity for direct ecosystem management and community preparedness activities, as well as improved information resources for strategic planning, decision making, and monitoring outcomes (U.S. Fire Administration 2022, WFLC 2023, Wildland Fire Mitigation and Management Commission 2023).

Prescribed fire and other fuel treatment methods are one tool in the broader approach needed to foster fire-resilient communities and forests. Preparing communities for fire, especially those with high social vulnerabilities, is also necessary to minimize damages from inevitable, if unpredictable, wildfires. Managing forests for resilience to more frequent and intense drought and fire will also entail more than fuel treatments alone. Ecosystem management geared to create forest tree composition and structural conditions that favor low-severity over high-severity fire play an important role in maintaining forest health, restoring desired ecological conditions, and reducing risks to ecosystem services and nearby populations.

All such activities are costly, and there is a premium on applying them in a way that maximizes their effectiveness and efficiency. As new investments are made to build resilience proactively, all southern landscapes deserve attention, locally appropriate planning, and sustained investment (for example, maintaining prescribed fire applications over the long run). At the same time, some places and people experience greater risk than others, and future increases in risk are unlikely to be evenly distributed. Strategic planning can help gear risk management to these differences, at scales from national to local, from multidecadal to within-year timescales, involving public and private sector actors, and including local and indigenous knowledge and evidence-based science (Bowman et al. 2020, Raymond et al. 2020).

Careful application of collaborative decision-science principles can help identify effective wildfire risk management strategies. Scenario planning and related approaches to data-driven planning can be used together with spatial information products to design, test, and communicate ranges of options for addressing future risk, while accounting for broad uncertainties and clearly defined assumptions (Ager et al. 2021, Hiers et al. 2003, Miller and Ager 2013, Riley et al. 2018). The spatial products generated by our assessment provide one example of a broad-scale information tool. Our modeling approach assessed spatial and temporal dynamics of risk, and socioecological conditions that shape risk and risk management opportunities. Results suggest that the various components of the analysis (smoke exposure, compromised ecosystem services, likely impacts of fuel reduction, and more) do not always share the same spatial pattern or potential for future change. Planning tools can leverage this information, assessing tradeoffs and synergies among different ecological and social goals, to inform management choices that minimize tradeoffs and maximize efficiencies. In the South where forest ownership and management are fragmented and diverse, coordinated planning in a shared stewardship framework can help address the priorities and shared challenges of diverse regional and local stakeholders (USDA Forest Service 2018, 2022b).

Conclusions

Our goal was to assess likely trajectories of change over the coming decades in a broad suite of factors relevant for understanding risks associated with wildfire, and opportunities for managing that risk—in particular through fuel reduction. We sought to provide quantitative as well as literature review-based information that can support efforts to (1) significantly increase the scale and pace of prescribed fire and other fuel treatments to manage wildfire risks in the face of a changing climate; (2) do this while accounting for impacts to forest carbon stocks and water supplies, two key ecosystem services; (3) do this while accounting for the potentially disproportionate impacts of fire for socioeconomically vulnerable populations; and (4) make efficient and effective risk management and resilience-building investments. We also sought to address how the expansion of the WUI, changes in fire regimes, and changes in seasonal availability of safe prescribed burning conditions are likely to impact management efforts in the near future, including constraints on prescribed fire implementation.

Spatial results from our analysis provide broad-scale information about where in the region wildfire and smoke risks are currently likely to be greatest for people and ecosystem services, and where high return on fuel reduction investments can be achieved to efficiently reduce the greatest risks. Modeled future changes under a collection of climate models and socioeconomic scenarios broadly suggest shifts towards conditions like those in the western and southern parts of the region, with warmer climate and forests more prone to hazardous fire. These findings are consistent with generalized expectations for reduced fire return intervals and shorter prescribed burn windows, at least within traditional burn seasons in the South. The degree of shift towards increased risk varied considerably among the future scenarios considered, the particular values and resources considered to be at risk, and landscapes and subregions. Strong spatial variation in current and potential future risks, and in capacities for risk reduction through fuels management, highlight the importance of subregional risk hotspots for focusing landscape-scale management efforts.

Most areas with projected heightened wildfire risk by mid-century are where risk is already high, but parts of the southern Piedmont and forests west of the Mississippi River with moderate risk also show strong projected increase. The highest agreement among possible scenario futures that showed increased risk was in northern, interior highland subregions, and Florida. Risk of direct exposure of people and structures to wildfire showed the strongest, and most consistent, increase across the region. The southern Appalachian Mountains, Ozark Mountains, and pockets along the coastal plain consistently showed increase in risk of smoke emissions to populated areas, forest carbon loss, and potential impacts to important watersheds.

Our findings suggest that enhanced fuel treatment programs could offset climate-related increases in the potential for smoke exposure from wildfires, and most increases in other risk factors. The degree to which this is possible varies across the region, and among different plausible future projections. Finally, accounting for community differences in socioeconomic vulnerability—beyond population and structure densities alone—causes local and subregional shifts in emphasis of wildfire and smoke risks. Understanding changes in socioeconomic factors such as wealth, mobility, housing, and household composition will be important for anticipating and managing risks into the future.

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Appendix

Table A.1—Variables included in spatial data synthesis for 13 States in the Forest Service's Southern Region

FIRE DYNAMICS AND HISTORY		
Variable name	**Source**	**Description**
Burn probability	Forest Service Wildfire Risk to Communities	Annual probability of wildfire burning in a specific location
Flame length exceedance probability (4 feet)	Forest Service Wildfire Risk to Communities	Probability of flame lengths >4 feet, if fire occurs
Flame length exceedance probability (8 feet)	Forest Service Wildfire Risk to Communities	Probability of flame lengths >8 feet, if fire occurs
Fire return interval	Forest Service and U.S. Department of the Interior LandFire	Fire return interval, all fire (mean period) between fire under presumed historical regime
Forest area burned, 2001–2021	Forest Service/NASA MODIS Burned Areas	Summed area burned, 2001–2021
Forest burn frequency, 2001–2021	Forest Service/NASA MODIS Burned Areas	Times a pixel (approximately 450 m^2) burned during 2001–2021 (mean for landscape)
Forest burn frequency, 2012–2021	Forest Service/NASA MODIS Burned Areas	Times a pixel (approximately 450 m^2) burned during 2012–2021 (mean for landscape)
Human-caused fires, 2009–2018	Forest Service Research Data Archive (Short 2022)	Human-caused fires 2009–2018
Natural-caused fires, 2009–2018	Forest Service Research Data Archive (Short 2022)	Natural-caused fires 2009–2018
Fire acreage burned, 2009–2018	Forest Service Research Data Archive (Short 2022)	Total acres burned 2009–2018
Human-caused fires, 2000–2018	Forest Service Research Data Archive (Short 2022)	Human-caused fires 2000–2018
Natural-caused fires, 2000–2018	Forest Service Research Data Archive (Short 2022)	Natural-caused fires 2000–2018
Fire acreage burned, 2000–2018	Forest Service Research Data Archive (Short 2022)	Total acres burned 2000–2018
MTBS burned area, 2000–2020	Monitoring Trends in Burn Severity	Total acres burned 2000–2020, MTBS
Maximum burned area (composite)	Maximum composite, MTBS (Short 2022), MODIS burned areas	Maximum acres burned, among three data products, 2000–2021
FIRE AND COMMUNITIES		
Variable name	**Source**	**Description**
Wildland-urban interface (WUI)	SILVIS Lab, University of Wisconsin-Madison	Sum of interface (housing in vicinity of contiguous vegetation) and intermix (housing and vegetation intermingle)
Wildland-urban interface (WUI) risk	Southern Group of State Foresters	The WUI risk index is a rating of the potential impact of a wildfire on people and their homes
Risk to potential structures	Forest Service Wildfire Risk to Communities	Index measures wildfire likelihood and intensity with consequences to a home
Exposure type	Forest Service Wildfire Risk to Communities	Where homes are exposed to wildfire from adjacent wildland vegetation, exposed from indirect sources such as embers and home-to-home ignition, or not exposed due to distance from direct and indirect ignition sources
Wildfire hazard potential	Forest Service Wildfire Risk to Communities	Relative potential for uncontrolled wildfire
Potential wildfire smoke exposure	Forest Service Southern Research Station	The vulnerability-weighted population exposed to hazardous smoke (at least 40 mg per m^3) if a fire occurs
Potential wildfire smoke exposure, prescribed fire-reduced fuels	Forest Service Southern Research Station	The vulnerability-weighted population exposed, given an assumption of reduced fuels resulting from fuels management

(Continued)

Table A.1 *(continued)*—Variables included in spatial data synthesis for 13 States in the Forest Service's Southern Region

Variable name	Source	Description
SOCIAL AND CULTURAL		
Housing unit density	Forest Service Wildfire Risk to Communities	Residential housing units per km^2 generated with 2018 population and housing data from the U.S. Census Bureau, building footprint data from Microsoft, and land cover from LANDFIRE
Population density	Forest Service Wildfire Risk to Communities	Residential population density generated using 2018 population data from the U.S. Census Bureau, building footprint data from Microsoft, and land cover from LANDFIRE
Private forest ownership	Forest Service Research Data Archive	Proportion of forest land in private ownership
Federal forest ownership	Forest Service Research Data Archive	Proportion of forest land in Federal ownership
State forest ownership	Forest Service Research Data Archive	Proportion of forest land in State ownership
Local forest ownership	Forest Service Research Data Archive	Proportion of forest land in local government ownership
Vulnerability index: socioeconomic	SEDAC/CDC	Socioeconomic data based on variables: below poverty, unemployment, income, and no high school diploma
Vulnerability index: household composition and disability	SEDAC/CDC	Household data based on variables: aged 65 or older, aged 17 or younger, civilian with disability, single-parent households
Vulnerability index: minority status and language	SEDAC/CDC	Minority status and language data based on variables: minority and speaks English less than well
Vulnerability index: housing type and transportation	SEDAC/CDC	Housing type and transportation data based on variables: multiunit structures, mobile homes, crowding, no vehicle, group quarters
Vulnerability index: overall	SEDAC/CDC	Overall social vulnerability, composite
FOREST PROPERTIES		
Variable name	**Source**	**Description**
Fuel load	LANDFIRE	Total available forest fuels (tons)
Forest carbon stocks	Forest Service FIA BIGMAP	Total forest carbon (tons per acre), 2014–2018
Upland conifer	Forest-type groups, FIA BIGMAP	Includes pinyon/juniper group, fir/spruce/hemlock group
Longleaf/slash pine	FIA BIGMAP	longleaf/slash pine group
Loblolly/shortleaf pine	FIA BIGMAP	loblolly/shortleaf pine group
Bottomland/moist soil hardwoods	FIA BIGMAP	Includes oak/gum/cypress group, elm/ash/cottonwood group, tropical hardwoods group, exotic hardwoods
Upland hardwoods	FIA BIGMAP	Includes oak/pine group, oak/hickory group, maple/beech/birch group, aspen/birch group
Nonstocked forest-type group	FIA BIGMAP	Considered forest but currently nonstocked (e.g., postharvest)
Stand-size class: small	FIA BIGMAP	Forest dominated by small-diameter trees, 2014–2018
Stand-size class: medium	FIA BIGMAP	Forest dominated by medium-diameter trees, 2014–2018
Stand-size class: large	FIA BIGMAP	Forest dominated by large-diameter trees, 2014–2018
Nonstocked size class	FIA BIGMAP	Considered forest but currently nonstocked
Projected total basal area loss from all pests	Forest Service, Forest Health Protection	Projected loss to basal area from all pests by mid-century (risk)

(Continued)

Table A.1 *(continued)*—Variables included in spatial data synthesis for 13 States in the Forest Service's Southern Region

Variable name	Source	Description
LANDSCAPE PROPERTIES		
Variable name	**Source**	**Description**
Vegetation departure index	LANDFIRE	Proportion of vegetation that has departed from historical vegetation
Growing season greenness trajectory, 2001 to 2017	Forest Service LanDAT	Trajectory of change in mean growing season greenness (NDVI), 2001–2017
Growing season greenness trajectory, 2008 to 2017	Forest Service LanDAT	Trajectory of change in mean growing season greenness (NDVI), 2008–2017
Natural cover density change, 2000 to 2019	Forest Service/LCMAP	Change in cover density; natural excludes developed and agricultural
Natural cover density change, 2010 to 2019	Forest Service/LCMAP	Change in cover density; natural excludes developed and agricultural
Agriculture cover density change 2010 to 2019	Forest Service/LCMAP	Change (gain or loss) in agriculture cover
Development density change 2010 to 2019	Forest Service/LCMAP	Change (gain or loss) in developed area
Forest land cover	NLCD	Proportion forest cover
Developed land cover	NLCD	Proportion developed (all urban classes)
Agricultural land cover	NLCD	Proportion agriculture
WATERSHEDS		
Variable name	**Source**	**Description**
Watershed importance for surface drinking water	Forests to Faucets 2.0	Important HUC12 watersheds for surface-derived drinking water
Downstream drinking water population	Forests to Faucets 2.0	Sum of surface drinking water population downstream of HUC12 watershed
Proportion of watersheds with high to very high WHP	Forests to Faucets 2.0	Proportion of HUC12 watershed with high or very high wildfire hazard potential
Land-use change risk to surface drinking water, medium scenario	Forests to Faucets 2.0	Land-use change risk to important watersheds under RCP 4.5 scenario, 2010–2040
Land-use change risk to surface drinking water, high scenario	Forests to Faucets 2.0	Land-use change risk to important watersheds under RCP 8.5 scenario, 2010–2040
Proportion natural cover	Forests to Faucets 2.0	Proportion natural cover, HUC12
Proportion impervious	Forests to Faucets 2.0	Proportion impervious, HUC12
BIODIVERSITY		
Variable name	**Source**	**Description**
T & E plants	U.S. Fish and Wildlife Service current range	Total number of T & E plant species
T & E wildlife	U.S. Fish and Wildlife Service current range	Total number of T & E wildlife species
T & E plants and wildlife	U.S. Fish and Wildlife Service current range	Total number of T & E species combined
Southeast blueprint conservation priority areas	Southeast Conservation Blueprint	Combined medium and high priority areas

(Continued)

Table A.1 *(continued)*—Variables included in spatial data synthesis for 13 States in the Forest Service's Southern Region		
CLIMATE		
Variable name	**Source**	**Description**
Potential evapotranspiration (PET) (monthly)	Forest Service Research Data Archive, RPA, MACAv2/METDATA	30-year normal (1992–2021)
Minimum relative humidity (monthly)	MACAv2/METDATA	30-year normal (1992–2021) and 3-year anomaly (2019–2021); anomaly baselined to 1979–2008 normal
Minimum precipitation (monthly)	MACAv2/METDATA	30-year normal (1992–2021)
SPEI drought index	MACAv2/METDATA	30-year mean (1992–2021) and 3-year departure (2019–2021); baselined to 1979–2008
Maximum temperature (monthly)	MACAv2/METDATA	30-year normal (1992–2021) and 3-year anomaly (2019–2021); anomaly baselined to 1979–2008 normal
Maximum downward radiation (SRAD) (monthly)	MACAv2/METDATA	30-year normal (1992–2021)

MODIS = Moderate Resolution Imaging Spectroradiometer; MTBS = Monitoring Trends in Burn Severity ; SILVIS = Spatial Analysis for Conservation and Sustainability; CDC = Centers for Disease Control; SEDAC = Socioeconomic Data and Applications Center; FIA = forest inventory and analysis; NDVI = normalized difference vegetation index; LanDAT = Landscape Dynamics Assessment Tool; LCMAP = Land Change Monitoring, Assessment, and Projection; NLCD = national land cover database; WHP = wildfire hazard potential; HUC12 = 12-digit hydrologic unit code; T & E = threatened and endangered species; SPEI = standardized precipitation evapotranspiration index; RPA = Resources Planning Act.

The dataset was used to generate synthetic factor variables used in the initial firescape and risk analyses for observed conditions. Individual variables in the risk analysis (table 1) were also sourced from this dataset.

Source: Gould et al. (2023).

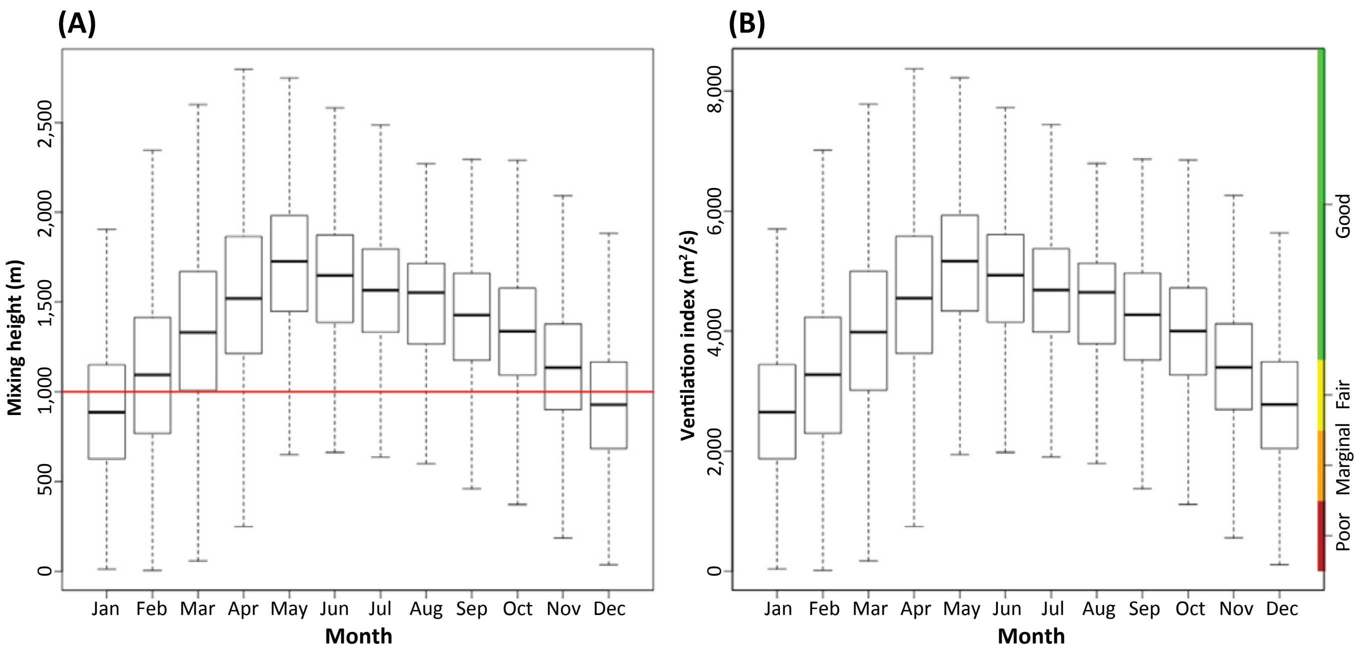

Figure A.1—Monthly (A) median afternoon mixing height and (B) median ventilation index for a location in north Florida (-82.48 E, 30.15 N). Boxplots were generated by using the Ventilation Climate Information System (Ferguson et al. 2003). The red line at a mixing height of 3,281 feet (1000 m) above ground level indicates where morning mixing heights are set in cases where interpolation problems occur at very high elevations (this rarely occurs in the Southern United States). Boxplots show the median (dark bars) and the first and third quartiles, with whiskers extending to the minimum and maximum.

Pomara, L.Y.; Gould, N.P.; Nepal, S.; Emmett, K.D.; Goodrick, S.L.; Lee, D.C. 2025. Fire: An Analysis to Support the Southern Forest Outlook. Gen. Tech. Rep. SRS-280. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 58 p. https://doi.org/10.2737/SRS-GTR-280.

This report in support of the *Southern Forest Outlook* assesses current and future risks associated with wildfire and smoke in the Southern United States, through a synthesis of literature review and new analysis. Key questions concern wildfire risk management and resilience-building efforts in the face of a changing climate, risks to forest ecosystem services, the potentially disproportionate impacts of fire and smoke on socioeconomically vulnerable populations, and how the growing wildland-urban interface, changes in fire regimes, and changes in safe prescribed burning conditions are likely to impact future management efforts. Results portray the regional geography of wildfire and smoke risks to people and ecosystem services, and where high return on fuel reduction investments can be achieved. Modeled future changes suggest shifts towards forests more prone to hazardous fire, with changes in risks to people and ecosystem services varying geographically and among different future scenarios. Results also suggest that preemptive forest management efforts including prescribed fire can offset future changes in wildfire and smoke risks. Ongoing and future changes in climate, forests, and society present complex wildfire risk challenges, but pathways exist to build forest resilience and mitigate risk.

Keywords: Wildfire risk, climate change, prescribed fire, smoke emissions, social vulnerability, risk management, ecosystem services.

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