FINAL PROJECT REPORT

1. ADMINISTRATIVE:

Recipient: John Kupfer, Dept. of Geography, University of South Carolina
Project title: Understanding Prescribed Fire Management in the Context of Climate Change and Landscape Transformation
Agreement number: G21AC10709
Date of Report: January 31, 2024
Period of performance: 01/01/2022 - 12/31/2024
Actual total cost: $73,436

2. PUBLIC SUMMARY:

Projected trajectories of climate and land use change over the remainder of the twenty-first century may result in conditions and situations that require flexible approaches to conservation planning and practices. For example, prescribed burning is a widely used management tool for promoting longer-term resilience and sustainability in longleaf pine ecosystems, but regional stressors such as climatic warming, changing fire conditions, and an expanding wildland-urban interface may challenge its application. To facilitate the development of fire management strategies that account for such changes, we surveyed regional fire managers to elicit information on the criteria used for prioritizing burn sites, current burning practices and constraints, and expectations for changes in burning opportunities, including those pertaining to climate change and urban growth. Respondents noted that their most common criteria for selecting longleaf pine stands for burning were fire history, ecosystem health, and fuel reduction, with the presence of threatened and endangered species also given priority by public land managers. However, many respondents (38%) cited recent burn frequencies that fall short of historic burn intervals. Barriers to burning included legal, institutional, and managerial constraints, such as proximity to human developments, public concerns, and risk aversion, as well as environmental and resource constraints, including weather, air quality restrictions, and lack of personnel, equipment, or funding. Roughly half of all respondents expect that opportunities to burn will be further reduced over the next 30 years, particularly during the growing season. Fire manager perceptions of factors that will limit prescribed burning in the future include a similar suite of constraints, many of which will be affected by projected regional changes in land use and climate. Moving forward, additional research and continuing engagement with fire managers will be needed to investigate opportunities for introducing policy flexibility, leveraging shared management interests, and developing creative solutions to expand burning opportunities.

3. TECHNICAL SUMMARY:

Longleaf pine is an iconic Southeastern species that played an important role in America's history but which has become a prominent focus of conservation efforts following more than a century of losses to development, agriculture, and conversion to industrial forest types. The prevention and suppression of fires, which used to occur at intervals of every one to four years, has also altered forest structure and composition and led to fuel build up, radically changing the traditionally open canopy of healthy longleaf pine ecosystems. In turn, the loss and degradation of longleaf pine ecosystems has had negative impacts on important keystone species such as

the gopher tortoise and red-cockaded woodpecker, the only species of woodpecker to excavate cavities in live pine trees.

Utilizing a web-based survey that was distributed through the Southern Fire Exchange and the Southeast Regional Partnership for Planning and Sustainability, we received input from roughly 300 fire managers regarding their prescribed burning practices to answer three main research questions:

1. What are the most common criteria that practitioners use to decide where to burn to achieve management objectives in their longleaf pine ecosystems?
2. What are the primary factors that constrain the implementation of prescribed burning in their management units?
3. How do managers expect burning constraints and the availability of suitable burning conditions to change over the next 30-50 years?

Results of the study show that time since the last fire, ecosystem health, fuel reduction, and management of threatened or endangered species were the top priorities for a majority of respondents, with slight differences between respondents who managed private vs. public lands. In the open response portion of the survey, respondents highlighted the importance of reducing competing species, promoting longleaf pine growth, improving a site's fuel conditions, and the ability to conduct safe burns in the decision process.

Given these constraints, many respondents (38%) cited recent burn frequencies that fall short of historic burn intervals, with others expressing a desire to burn more frequently to achieve specific management goals. The most common legal, institutional, and managerial constraints were the nearby presence of human developments and risk aversion, while key environmental and resource constraints were seasonal fire weather characteristics, including those associated with temperature, drought, days since the last rainfall, wind speed, relative humidity, and smoke dispersion. Results from this portion of the study point to the fact that managers are currently working to optimize the resources and opportunities available to them but the myriad of challenges they face make it hard to maintain their desired burn regimes.

Looking to the future, roughly half of the survey respondents expect that the availability of suitable burning opportunities will be reduced over the next 30 years due to land use and urban change as well as climate change, particularly during the growing season. If these expectations pan out, the implementation of prescribed burning, perhaps the best tool for managing longleaf pine ecosystems across the region, will become increasingly difficult.

Funding provided for this project by SE CASC allowed us to analyze the fire manager survey data, complete an associated paper and initiate a second related manuscript, and disseminate the results at several relevant conferences and meetings, with an emphasis on practitioner outlets. The resulting paper has been published in *Fire Ecology*, the international scientific journal supported by the Association for Fire Ecology (2022 JCR Impact Factor: 5.1).

4. PURPOSE AND OBJECTIVES:

Prescribed burning is a key tool for managing and restoring longleaf pine ecosystems, but current burn frequencies often fall far below historic burn intervals. Barriers to burning identified in the scientific literature include proximity to human development, public concerns, and risk aversion, as well as challenges posed by weather, air quality restrictions, and lack of personnel, equipment, or funding. There is an expectation within the scientific community and among fire managers that opportunities to burn may be further reduced over the next 30-50 years due to a suite of evolving regional stressors. Human population density, rates of land use conversion, and extent of urban systems are all projected to increase dramatically in upcoming decades, altering the landscape

context within which longleaf pine forests are embedded. These changes will occur at a time when the region is expected to experience significant shifts in climate that will impact fire weather, alter wildfire regimes, and narrow the available window for setting prescribed fires.

To facilitate the application of prescribed fire as a means for managing and restoring longleaf pine ecosystems, more information is needed on the factors that shape burning practices and how managers have interpreted changes to the longleaf pine ecosystem and in turn their burn regimes. This study sought to address that need and quantify the relative importance of different constraints to prescribed burning based directly on input from southeastern longleaf pine fire managers. We also wanted to understand how fire managers expect factors to change in upcoming decades and how managers currently prioritize burn sites.

The survey used to explore these questions was deployed via Qualtrics from July-September 2019. The survey invitation asked for participation from fire managers specifically working with longleaf pine ecosystems and was distributed by two organizations that are trusted and known in the longleaf pine management space, offering the best opportunity to reach professionals throughout the region supporting fire management professionals. The Southern Fire Exchange (SFE), a wildland fire science communication program that represents states encompassing the historic range of longleaf pine (Fig . 1), circulated the survey in mid-July as an article with a weblink in *Fire Lines*, their bimonthly newsletter, and then as a standalone email with a weblink to the same list in early August. *Fire Lines* has

Figure 1. Historic range of longleaf pine

approximately 3000 subscribers, many of whom work with longleaf pine in some way. In early August, the Southeast Regional Partnership for Planning and Sustainability (SERPPAS) circulated the invitation to the southern prescribed fire community via the *Driptorch Digest*, their monthly e-newsletter, which has roughly 250 subscribers.

Overall, we received 296 responses that included answers to at least some questions; of those respondents, a majority (206) fully completed the survey and included their state and land ownership class, which differentiated those primarily responsible for managing fire on public lands (including federal, state, and local levels) from those managing private lands, including individual landholders, corporations, and NGOs. Our respondent group included managers from a diverse range of management and ownership types (public lands: n = 118; private lands: n = 89) and states. Respondents reported varying tenures in their current management positions (minimum = 0.5 years, maximum = 53 years), with a median of 10 years and over three-fourths (77.4%) serving five or more years in their current position.

We believe that all of the original objectives identified during project initiation were met without having to change, eliminate, add to, or modify any of them.
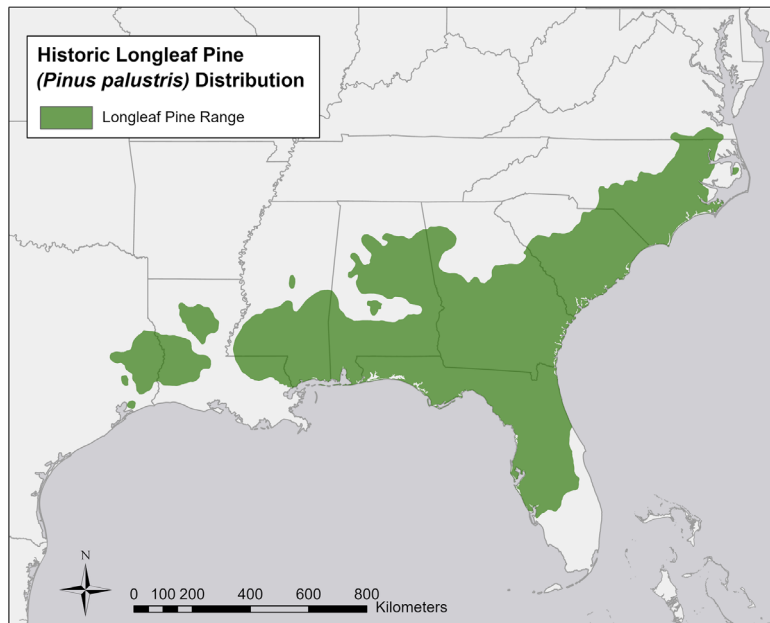
5. ORGANIZATION AND APPROACH:

We developed a Qualtrics web-based survey for fire managers working with longleaf pine ecosystems to learn more about their current burning practices, criteria for prioritizing burn sites (Table 1), factors that constrain their ability to conduct prescribed burns at desired locations and times (Table 2), and expectations of how climate change and urban growth may affect those factors in the future. We asked specifically about factors related to weather conditions, site conditions, and various legal, institutional, and managerial constraints identified in previous research. The survey consisted of 25 questions, including 6 open-ended response questions that allowed managers to provide more detailed comments. To ensure that the question phrasing, format, and survey flow were appropriate for our target audience, co-PI Hiers, who was Director of Fire Science Applications, and another fire applications specialist associated with Tall Timbers Research Station reviewed the draft survey and consulted on strategies for improvement.

Table 1. Criteria used to prioritize longleaf pine sites or stands for prescribed burning. Abbreviations in parentheses are used for corresponding variables in later figures and tables. Survey participants were asked to select their top three priorities from the specific criteria listed here.

Criterion	Examples of Significance
Overall ecosystem health of the site *(EcoHealth)*	Stand-specific conditions and fire histories affect viability and frequency of burning as a management tool.
Presence of undesired exotic or invasive plants *(ExoticInvasive)*	Managing and eradicating non-native and invasive plant species threats is a key component of ecosystem- and site restoration.
Presence of firebreaks or well-established fire lines *(Firebreaks)*	The presence of adequate firebreaks precludes the need for additional investment.
Need for fuel reduction to reduce fire risk *(FuelReduction)*	Prescribed burns can eliminate accumulations of fuel, thereby reducing risk and severity of wildfire.
Presence of threatened or endangered species (e.g., red-cockaded woodpeckers) *(TandE)*	Burn objectives are tied to the recovery and protection of species such as the red-cockaded woodpecker and gopher tortoise.
Whether a site is managed for timber *(Timber)*	Management objectives, strategies, and tools intended for timber production may differ from those associated with conservation.
Length of time since the last burn *(TimeSinceBurn)*	Frequent fire is critical for maintaining longleaf ecosystem health and restoring previously fire-suppressed areas.
Distance to developed or residential land (the wildland-urban interface) *(WUI)*	Proximity to populated areas can increase risks associated with wildfire occurrence and severity and make prescribed burning more challenging due to public health and safety issues.
Other, please specify *(OtherCrit)*	Additional (often site-specific) criteria used when making burn-related decisions.

Table 2. Potential constraints to prescribed burning in longleaf pine ecosystems. Abbreviations in parentheses are used for corresponding variables in later figures and tables. Survey participants were asked how the specific factors listed here constrained prescribed burning in their management unit.

Constraint	Examples of Significance
Legal, institutional, and managerial constraints	
Limited incentives to burn and/or institutional history focused on fire suppression (*Incentives*)	Private landowners may not be able to finance frequent burning or may have other incentives for longleaf pine stands that don't align with conservation efforts. Corporations may have limited access to publicly funded incentive programs and face higher costs to participate in conservation actions for at-risk species.
Legal constraints (e.g., navigating the NEPA process) (*Legal*)	Burning takes place within the context of environmental laws, and the required analyses and review processes may be challenging to navigate or lead to management conflicts.
Challenges posed by agreements and partnerships (*Partner*)	Collaborative management efforts may face challenges in addressing conflicting interests, developing mutual trust and shared objectives among participants, and building flexible and adaptable approaches to changing conditions.
Avoiding public objections or concerns over the use of burning (*PublicConcern*)	Lack of public understanding of fire benefits and public concerns about fire impacts and risks are impediments to burning that require effective communication with nearby communities.
Risk aversion (e.g., concern over liability, career, or political repercussions) (*Risk*)	Concerns about liability, career status, or other repercussions for escaped fires and smoke impacts may limit use of prescribed fire as a management tool.
Residential or other development in or near burn areas (*WUI*)	An expanding wildland-urban interface (WUI) increases fire risks, burning costs, and planning complexity due to a greater number of people and value of resources to be protected.
Environmental and resource constraints	
Air quality (e.g., smoke management) (*AirQuality*)	While conducting prescribed fires, burn managers must apply appropriate techniques and adhere to air quality regulations regarding particulate matter and pollutants emerging from prescribed fires.
High fuel loads (*FuelLoad*)	Higher fuel loads alter fire behavior, increasing the complexity of a burn under some conditions and posing a greater risk of harm to human health, property, and the ecosystem.
Shortage of personnel, money, or equipment (*Resources*)	Costs and lack of adequate personnel or necessary equipment may impede burning implementation.
Inappropriate weather conditions (*Weather*)	Specific weather conditions (i.e., temperature, atmospheric moisture, wind, atmospheric stability and dispersion, precipitation, drought) are needed to ensure the safe and effective implementation of fire.

Quantitative analysis of the data was conducted by PI Kupfer and Dr. John Grego, former chair of the Department of Statistics at the University of South Carolina (USC) and long-time director of USC's Stat Lab. Dr. Grego had also previously collaborated with co-PI Hiers on related work with the Jones Ecological Research Center in southwest Georgia. Co-PI Lackstrom performed analysis of the open-ended questions using NVivo 12, a qualitative data analysis software program, to analyze the text responses and provide context to managers' prescribed burning decisions. Initial coding categories aligned with the prescribed burning criteria and constraints posed in the survey and evaluated in the statistical analyses. Sub-categories were added when the text provided new details about burning criteria and constraints or when respondents discussed additional factors that affect their decisions. Individual responses could be coded at multiple categories, depending on the response content. After coding was completed, a series of queries were conducted to compare differences between management types and explore intersections between the different survey questions and codes. Of the fully or partially completed surveys, 162 contained responses to one or more open-ended questions and were reviewed during the qualitative coding. Of those 162, 148 contained demographic data (83 public land managers, 65 private land managers).

Following data collection and analysis, the entire project team worked on the associated manuscript for publication.

6. PROJECT RESULTS

Results of the survey showed that time since the last fire, ecosystem health, fuel reduction, and management of threatened or endangered species were top priorities for a majority of respondents, with slight differences between respondents who managed private vs. public lands (Table 3). In the open response portion of the survey, respondents highlighted the importance of reducing competing species, promoting longleaf pine growth, improving a site's fuel conditions, and the ability to conduct safe burns in the decision process.

The most common legal, institutional, and managerial constraints to burning were the nearby presence of human developments and risk aversion (Fig. 2), while key environmental and resource constraints were seasonal fire weather characteristics, including those associated with temperature, drought, days since the last rainfall, wind speed, relative humidity, and smoke dispersion (Fig. 3). Given these constraints, many respondents (38%) cited recent burn frequencies that fall short of historic burn intervals, with others expressing a desire to burn more frequently to achieve specific management goals. Collectively, the quantitative and qualitative results point to the fact that managers are currently working to optimize the resources and opportunities available to them, but the myriad of challenges they face can make it hard to maintain desired burn regimes.

Looking to the future, roughly half of the respondents expected that the availability of suitable burning opportunities will be reduced (either greatly or somewhat) over the next 30 years, with the greatest percentages noted for longleaf pine growing (53.5%) and candling (53.8%) seasons (Table 4). In contrast, few managers foresee increased prescribed burning opportunities in any season. While varied, the most cited future constraints to burning included a diverse mix of legal, institutional, managerial, and environmental constraints, most (if not all) of which would likely be affected by projected changes in land use, urbanization, and climate.

When managers were asked to rate how they think future changes in land use and urbanization patterns will affect prescribed burning decisions, the percentage who responded "A Great Deal" rose from 25.7% over the next 5–10 years to 62.5% for 30–50 years into the future (Fig. 4A). In contrast, the percentage

Table 3. Criteria used by fire managers to prioritize longleaf pine sites for prescribed burning.

Criterion[1]	All Responses[2]	Least Squares Means[3]		Responses, by Management Type	
	Overall (n = 206)	Estimate	Grouping	Public (n = 118)	Private (n = 88)
TimeSinceBurn	76.4%	1.141	A	81.2%	70.0%
EcoHealth	67.5%	0.715	A	70.1%	64.0%
FuelReduction	48.5%	-0.051	B	47.9%	49.4%
TandE	39.9%	-0.556	B	53.9%	21.4%
Firebreaks	17.0%	-1.568	C	17.1%	16.9%
WUI	15.5%	-1.665	C	14.5%	16.9%
ExoticInvasive	14.0%	-1.874	C, D	6.8%	23.6%
OtherCrit	8.3%	-2.419	C, D	5.2%	12.4%
Timber	4.9%	-3.030	D	2.6%	7.9%

[1] See Table 1 for criteria abbreviations.
[2] Percentage of respondents who identified the stated criterion as one of their top three criteria for determining whether a site (e.g., stand, burn unit) has a high priority for burning.
[3] Least Squares Mean estimate and Tukey-Kramer grouping for individual constraints. Least Squares Means with the same letter are not significantly different ($\alpha = 0.05$).

Table 4. Fire managers' expectations of the changing availability of suitable burning opportunities in longleaf pine ecosystems over a 30-year planning horizon compared to present conditions (N = 206).

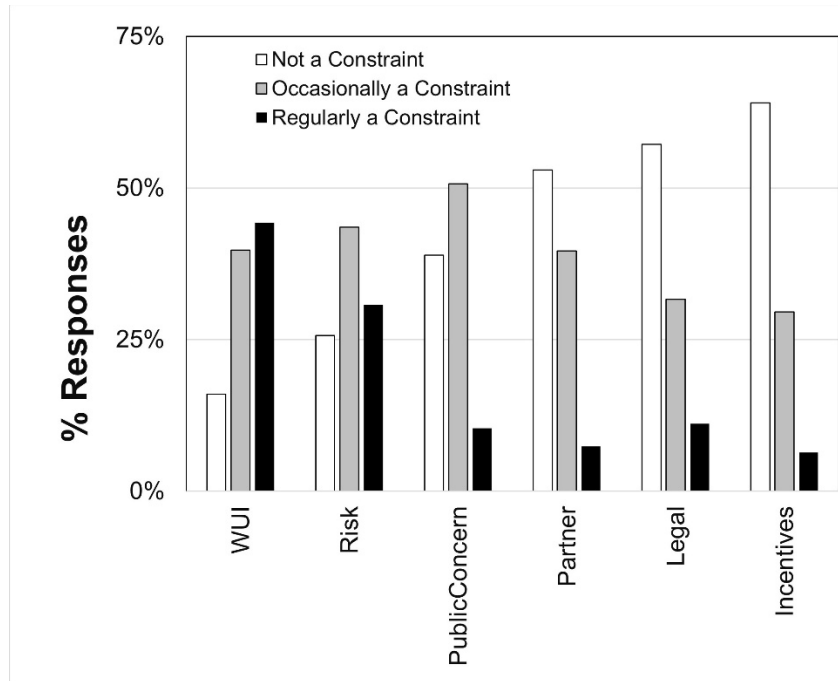|	Greatly Reduced	Somewhat Reduced	No Change	Somewhat Increased	Greatly Increased
Dormant Season	13 (6.3%)	77 (37.6%)	100 (48.8%)	11 (5.4%)	4 (1.9%)
Candling Season	18 (9.0%)	90 (44.8%)	75 (37.3%)	13 (6.5%)	5 (2.5%)
Growing Season	26 (12.8%)	83 (40.7%)	53 (26.0%)	32 (15.7%)	10 (4.9%)
Senescing Season	15 (7.7%)	71 (36.2%)	87 (44.4%)	21 (10.7%)	2 (1.0%)

Figure 2. Frequency with which legal, institutional, and managerial factors constrain burning activities in longleaf pine ecosystems. Constraints, including abbreviations, are explained in Table 2.
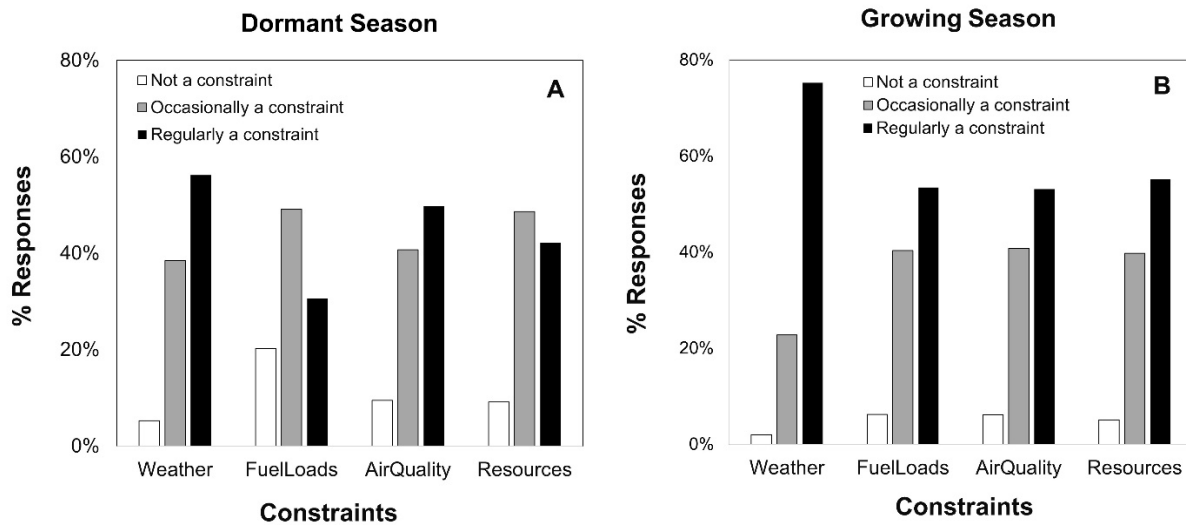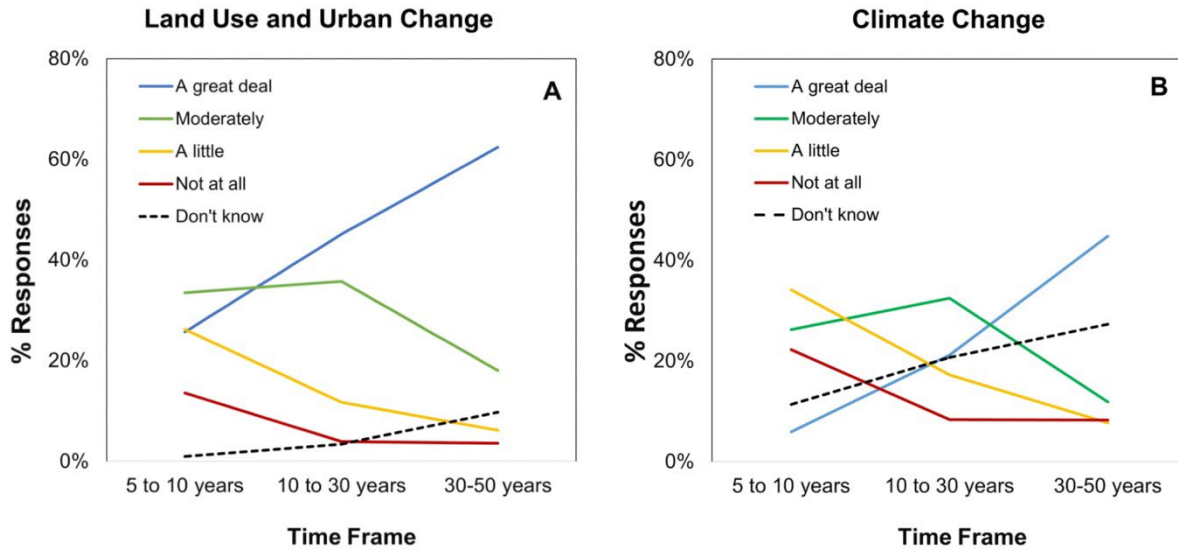

Figure 3. Frequency with which environmental and resource factors constrain burning activities in longleaf pine ecosystems for the A) dormant season and B) growing season. Constraints, including abbreviations, are explained in Table 2.

Figure 4. Fire manager perceptions regarding how prescribed burning decisions will be affected by potential future changes in: (A) land use and urban change, and (B) climate change.

of managers who responded "Not at all" or "A little" dropped from 39.8 to 9.8% for the same periods. These responses signal a clear expectation among fire managers that changes in human land uses, for example growth of the wildland-urban interface, will increasingly affect prescribed fire programs in upcoming decades.

A similar pattern emerged when respondents were asked to rate the degree to which they expect future climate change to affect prescribed burn opportunities (Fig. 4B). In this case, the percentage who responded "A Great Deal" increased from 5.9% over the next 5–10 years to 44.8% for 30–50 years into the future, while the percentage who responded "Not at all" or "A little" dropped from 56.5 to 15.9%. However, more than twice as many respondents were uncertain about the impacts of climate change on prescribed burning in the next 30–50 years (27.5%), when compared with changes in land use and urbanization (9.8%).

Finally, narrative responses provided helpful context by highlighting key factors that influence prescribed burning decisions as well as the interactions among factors that contribute to the insufficient burn frequencies reported by many respondents. With respect to current constraints, 153 respondents (81 public; 59 private; 13 not specified) submitted additional comments. After weather and resource-related factors (cited by 52.9% and 49.7% of the 153 respondents, respectively), urban growth emerged as an additional, but less-commonly cited, challenge, with 19% of respondents stating that development affected when and where they can burn and 18.3% mentioning smoke management in developed areas as a common constraint. Although fewer respondents elaborated on future burning opportunities and constraints (24 total: 9 public; 14 private; 1 not specified), factors related to land use change and urbanization patterns were the most prevalent among the coded responses. Fourteen respondents cited development in the wildland-urban interface and changing landowner incentives and objectives as future burning constraints. In contrast, only three respondents specifically mentioned climate change-related issues. We've provided a summary of some responses from survey respondents that particularly underscore the complicated nature of factors that affect prescribed burning decision in Table 5.

Table 5. Representative quotes from survey respondents illustrating the interacting factors affecting prescribed burning decisions.

Factors	Quote
Current constraints	
· Agency decisions · Fire breaks · Resources · Weather · Wildland-urban interface	"Some years we haven't accomplished burning goals due to weather, agency decisions, staffing, or any number of reasons so that we are little behind in burning. Fire breaks, WUI, and control issues bring the average fire return interval across my area down some even though many blocks are in good shape."
· Air quality/Legal · Resources · Weather · Wildland-urban interface	"Staff turnover, burn restrictions, weather extremes, and proximity to urban interface have all factored into longer than preferred burn frequencies on many units."
· Fuel and unit conditions · Management practices · Resources · Risk	"Everything. Logistical and budget constraints, smoke management concerns, difficulty of getting flatwoods (and the flatwoods duff layer) into a short season rotation and getting folks to apply growing season fire."
· Fuel and unit conditions · Risk · Smoke management · Wildland-urban interface	"(There are) not enough burning days to get all needs met within a 2-year rotation. There are too many units with narrow burn windows due to smoke direction and heavy fuels in the WUI to be able to get to them all under restriction. We use triage based on multiple variable[s] to prioritize some units over others."
Future challenges and opportunities	
· Ecosystem health · Fuel reduction · Public concern	"Living in a state where hundreds of thousands of new residents and visitors need to be educated about prescribed fire annually is extremely challenging. It is the fuel reduction mantra that people hear and not the ecosystem benefits that allows them to accept the role of fire in our landscape."
· Liability · Public Concern · Risk	"If there is not some sort of liability reform and a greater understanding of the actual economic benefit to the insurance industry of prescribed burning, well, that is a big deal…. The math needs to be done to show they lose less by supporting prescribed fire, which saves wildfire losses, even though there will be individual prescribed fire losses."
· Management practices	"Instead of talking about burning, managers need to go out and do it. Expand beyond the traditional 'season' of burning and burn year-round."

7. ANALYSIS AND FINDINGS:

Longleaf pine ecosystems illustrate many of the design and implementation challenges associated with the development of longer-term management strategies in the context of anthropogenic threats and stressors. Prescribed burning is widely considered to be one of the most important and effective tools for achieving range wide conservation goals in these ecosystems, but supporting restoration through prescribed fire may require new approaches to burning as well as additional resources and policy changes to achieve desired goals. Our findings support the idea that factors occurring on a variety of spatial and temporal scales may interact to affect a manager's ability to take advantage of burning opportunities. For instance, suitable weather conditions are needed for a manager to safely burn, but these conditions must align with organizational capacity (e.g., staffing, funding, costs, equipment availability). Similarly, the ability to adhere to air quality and smoke management requirements that were identified in the qualitative coding intersects with available weather conditions and organizational capacity.

Uncovering the existence of such interactions requires, in part, an examination of seasonal patterns in burn constraints, especially if longer-term strategies seek to utilize shifts in the seasonal timing of burns to meet conservation objectives. For example, drought and days since rain were important considerations regardless of season, but other variables, particularly those associated with temperature, differed between seasons. Several respondents even noted how extreme weather events and seasonal or annual weather variability (e.g., changes associated with ENSO, the El Niño-Southern Oscillation), can disrupt plans for prescribed burning and force managers to adapt to either expanding or contracting burning opportunities on a seasonal basis.

Understanding the intersection between legal, institutional, and managerial constraints that frame fire management with operational factors such as weather and organizational capacity that dictate day-to-day decisions is important not only for understanding current fire management practices, however. In this respect, our survey extends work from previous studies by explicitly asking managers to consider prospective constraints to their burn programs and how they may be affected by climate change and landscape transformation. Survey results articulate manager concerns about the future of prescribed burning in longleaf pine ecosystems, with roughly half of all respondents expecting reduced seasonal availability of suitable burning opportunities over the next 30 years due to issues associated with air quality, development in or near burn areas, risk aversion, and inappropriate weather conditions. These factors themselves have direct links to climate change and human land use and development.

In short, burn window availability and resource limitations constrain prescribed burning practices on an organizational level. More broadly, policy and legal frameworks coupled with trends in urbanization and climate change are expected to interact with operational constraints to challenge managers' abilities to implement landscape-scale burning strategies and achieve restoration goals.

8. CONCLUSIONS AND RECOMMENDATIONS:

Fire managers represent a valuable, yet largely untapped, source of perspective on the potential effects of evolving regional stressors on prescribed burning in longleaf pine ecosystems. Our survey results suggest that the design and implementation of future burning strategies for the long-term restoration of longleaf pine ecosystems should consider three key (but interrelated) issues to be successful:

1. While prescribed burning in these systems often focuses on achieving broader restoration objectives, other goals and objectives are also at play, including burning to reduce wildfire risks or to achieve objectives related to private uses, such as hunting, esthetics, and timber. Successful approaches and planning will need to consider

interactions between an array of conservation goals and objectives that may, or may not, be compatible.

2. Because land ownership and management in the southeastern United States is fragmented, there is a need for shared visions and fire management strategies that cross jurisdictions and ownership types. The degree to which conservation goals, objectives, and priorities in individual units are aligned will be important, as that affects how complex climate and land use stressors can be addressed on a regional or landscape level. Our results identified some differences in responses between managers working on public versus private lands, yet fire managers across the region used broadly similar criteria for site prioritization and identified many of the same constraints to their burn programs. Points of concurrence could serve as a means for increasing collaboration among interested parties and for finding creative solutions to maintaining, or even expanding, prescribed fire within the region.

3. Fire management strategies need to account for the time scales of multiple constraints. This would include identifying and articulating relationships between operational constraints and capacities (e.g., staffing, weather, logistics), slower-moving institutions (e.g., best practices, policy, and legal frameworks), and long-term environmental trends (e.g., land use and climate change). A key question is whether decisions made in current environments reinforce longleaf pine risks and vulnerabilities by limiting future flexibility, choices, and ability to adapt or achieve restoration goals.

In the context of those issues, we make the following recommendations for the design and implementation of future burning strategies that target the long-term restoration of longleaf pine ecosystems:

1. Evolving fire management plans need to account for the intersection between legal, institutional, and managerial constraints that frame fire management with operational factors such as weather and organizational capacity that dictate day-to-day decisions.

2. Fire management strategies should be aligned in objectives and priorities across boundaries (e.g. ownership types).

3. Strategies need to account for time scales of multiple constraints (operational constraints and capacities, policy and legal frameworks, and long-term environmental trends).

9. MANAGEMENT APPLICATIONS AND PRODUCTS:

Our results hold several implications for the design and implementation of fire management strategies that consider current and evolving threats to longleaf pine ecosystems. First, inadequate resources and organizational capacity to implement burning even under current conditions imply that achieving existing goals and objectives in the future will be increasingly challenging. The qualitative analysis suggests that most managers currently work to optimize the resources and opportunities that they have, yet many sites are still falling behind prescribed burning needs. The quantitative analyses, in turn, provide manager-contributed data regarding the perceived importance of various constraints. Collectively, these results suggest that managers consider evolving interactions between burn priorities and constraints, such as changes involving agency policies or burning practices, as they seek to navigate shrinking burn window opportunities.

We also posit that the (re)evaluation of longleaf pine restoration actions and goals should consider the interactive effects of urbanization and climate change on a manager's ability to meet prescribed burning objectives. Even under current conditions, many fire managers find it

difficult to maintain desired burn regimes due to a mix of environmental, resource, legal, institutional, and managerial constraints. If climate change further narrows the availability of suitable burning conditions, managers may need to consider alternative burning approaches (e.g., burning at different times or in different seasons) or the increased use of more expensive mechanical or chemical options to meet future management goals. Projected patterns of urbanization would impose an additional challenge to longleaf pine fire management as more stands are brought into an expanding wildland-urban interface. Effectively addressing these intertwined challenges will be critical because any reduction in prescribed burning is likely to result in decreased biological diversity and could contribute to increased wildfires and, with that, the potential to threaten human developments and negatively influence regional air quality.

Finally, our findings suggest that a broader re-evaluation of longleaf pine conservation goals and approaches may be needed in light of ongoing, and likely increasing, prescribed burning constraints. Increasing the use of prescribed burning underpins the larger suite of strategies intended to support long-term goals of increasing longleaf pine acreage and advancing the ecosystem's restoration. Effectively doing so may require building on existing or forging new collaborative strategies to create fire-adapted communities and landscapes that place fuels and forest health treatments in the right places and at the pace and scale needed to change the trajectory of wildfire risk to people, communities, and natural resources and to restore forest health and resilience. The need to engage with private landholders may be particularly acute given that: a) privately owned and managed lands account for over 60% of all longleaf pine acreage but only 24.3% of the acreage burned in 2020, and b) decisions for private land objectives may seek to minimize short-term risks, such as avoiding areas in which fire would be more difficult to manage, which has implications for burning. In short, it is important to consider and reevaluate whether existing conservation goals, objectives, and approaches are still adequate or appropriate given the expected trajectories of climate and land use change.

This study provides a first-hand account of the constraints and challenges faced by fire managers in the southeastern U.S. which has important implications for longleaf pine managers on both public and private lands. As John Kupfer, lead author of the study, noted in an interview: "Our work suggests that proactive and flexible management approaches that consider future environmental challenges will be needed to successfully conserve and rehabilitate the historic longleaf pine ecosystem."

10. OUTREACH AND COMMUNICATION:

Listed below are various outputs associated with this research as of the time of that this report was submitted.

<u>Publications:</u>

Kupfer, J.A., Lackstrom, K., Grego, J.M., Dow, K., Terando, A.J., and Hiers, J.K. 2022. Perspectives on prescribed fire management in longleaf pine ecosystems: Current constraints and future prospects. *Fire Ecology* 18, 27.

Hutchens, L., Kupfer, J.A.[1], Gao, P., Sanchez, G.M., Meentemeyer, R.K., Terando, A.J., and Hiers, J.K. Long-term, large-scale human influences on the spatial and functional persistence of a threatened pine savanna ecosystem. Revised for *Conservation Science and Practice*. ([1] corresponding author)

Presentations:

Changing climates, changing fires: How climate change could affect prescribed fire management in southern forests. (J.A. Kupfer, presenter) Southeastern Association of Fish and Wildlife Agencies Wildlife Diversity Committee, August 2023.

Managing fire in changing Southeastern landscapes (J.A. Kupfer, presenter). Texas A&M Univ., Dept. of Geography Colloquium, October 2022.

Prescribed fire in longleaf pine ecosystems: Fire managers' perspectives on priorities, constraints, and future prospects. (K. Lackstrom, presenter). Southeast Climate Adaptation Science Symposium. September 2022.

Implications of 21st century climate change for prescribed burning in the Southeast. Georgia Prescribed Fire Council Meeting. (J.A. Kupfer, presenter) Sep. 2021.

Perspectives on prescribed fire management in longleaf pine ecosystems. Third Thursday Web Forum: South Atlantic Landscape Conservation Cooperative / Southeast Climate Adaptation Science Center (J.A. Kupfer, presenter). July 2020.

Published Dataset:

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