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Prescribed fire in longleaf pine ecosystems: fire managers' perspectives on priorities, constraints, and future prospects

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Abstract

Background: 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 of the southeastern United States, 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 nearly 300 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.

Results: 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. 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 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.

Conclusions: On an organizational level, burn window availability and resource limitations constrain prescribed burning practices. 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. Additional research and engagement with fire managers are needed to investigate opportunities for introducing policy flexibility, leveraging shared management interests, and developing creative solutions to expand burning opportunities.

Keywords: Longleaf pine, Prescribed fire, Compound stressors, Burn windows, Conservation goals, Climate change

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Resumen

Antecedentes: Las trayectorias proyectadas de cambio climático y cambios en el uso de la tierra sobre lo que resta del Siglo XXI puede resultar en condiciones y situaciones que requieren de aproximaciones flexibles para el planeamiento y prácticas de conservación. Por ejemplo, las quemas prescriptas son una práctica ampliamente usada como herramienta de manejo para promover la resiliencia y sostenibilidad a largo plazo en ecosistemas de pino de hoja larga (*Pinus palustris*) en el sudeste de los EEUU., aunque algunos estreses regionales como el calentamiento global, el cambio en las condiciones de los fuegos, y la expansión de la interfaz urbano-rural pueden dificultar su aplicación. Para facilitar el desarrollo de estrategias de manejo que tengan en cuenta esos cambios, relevamos la opinión de cerca de 300 gestores de fuegos para obtener información sobre los criterios usados para priorizar sitios de quema, las prácticas corrientes de quema y sus condicionantes, y las expectativas de cambio en las oportunidades de quema, incluyendo aquellas concernientes al cambio climático y al crecimiento urbano.

Resultados: Los respondientes notaron que el criterio más común usado para seleccionar rodales de pino de hoja larga para efectuar quemas prescriptas fueron la historia de fuego, la salud del ecosistema y la reducción del combustible, a lo que se agregó la presencia de especies amenazadas y en peligro, a las que le dieron prioridad los agentes manejadores de tierras públicas. Muchos de los respondientes (38%) citaron a la frecuencia de quemas recientes que estaban por debajo de los intervalos históricos de quemas. Las barreras para las quemas incluyeron aspectos legales, institucionales, y condicionantes del manejo, como la proximidad a desarrollos urbanos, las preocupaciones del público en general, y la aversión al riesgo; también lo fueron condicionantes ambientales y de los recursos, incluyendo el tiempo meteorológico en el momento de la quema, las restricciones en cuanto a calidad del aire, y la falta de personal, de equipamiento, o de financiamiento. Alrededor de la mitad de todos los respondientes creen que la oportunidad de hacer estas quemas se reducirá en los próximos 30 años, especialmente durante la estación de crecimiento. Las percepciones de los gestores de fuegos sobre los factores que limitarán las quemas prescriptas en el futuro incluyen un conjunto similar de condicionantes, muchos de los cuales serán afectados por cambios regionales en el uso de la tierra y en el clima.

Conclusiones: A nivel organizacional, la disponibilidad de ventanas de quemas y limitaciones en los recursos van a condicionar las prácticas de quema. De manera más amplia, las políticas y el marco legal acoplados a la tendencia a la urbanización y el cambio climático pareciera que interactuarán como condicionantes operacionales que desafiaran las habilidades de los gestores para implementar estrategias de quema a escala de paisaje para alcanzar objetivos de restauración. Investigaciones adicionales y el involucramiento con los gestores del fuego será necesario para investigar oportunidades de introducir flexibilidad en las políticas e influir sobre la posibilidad de compartir los intereses de manejo, y desarrollar soluciones creativas para expandir las oportunidades de quemas prescriptas.

Background

Longleaf pine (*Pinus palustris* Mill.) ecosystems are a prominent focus of conservation efforts in the southeastern United States following more than a century of losses to development, agriculture, conversion to industrial forest types, and altered disturbance regimes (Kirkman and Mitchell 2006; Oswalt et al. 2012). Even in extant stands, years of fire prevention and suppression have resulted in an increased abundance of midstory hardwoods (Provencher et al. 2001) and shrubs (Gilliam and Platt 1999; Freeman and Jose 2009), significantly altering the characteristic open-canopy structure that was maintained by frequent fires and supported high levels of vascular plant species richness. Reduced fire frequencies have also led to fuel buildup, increasing the potential for higher intensity fires (Varner et al. 2005). Collectively, the loss and alteration of these ecosystems have significant implications not only for longleaf pine, but also for associated endemic flora and fauna, including species of interest such as the red-cockaded woodpecker and gopher tortoise (Weiss et al. 2019; Hunter and Rostal 2021).

Prescribed burning, used in conjunction with mechanical thinning and fuel reduction, herbicides, and planting, is a key management tool for restoring and managing longleaf pine ecosystems (Mitchell et al. 2006; Wolcott et al. 2007). America's Longleaf Restoration Initiative (ALRI), for example, called for burning 600,000 ha of longleaf ecosystems annually as part of its Range-Wide Conservation Plan (ALRI 2009). However, the widespread application of prescribed fire may be challenged by a suite of evolving regional stressors (Mitchell et al. 2014; Costanza et al. 2016). Human population density, rates of land use conversion, and extent of urban systems are all projected to increase dramatically in upcoming decades (Wear and Greis 2013; Terando et al. 2014), expanding

the wildland-urban interface and altering the landscape context within which longleaf pine forests are embedded (Costanza et al. 2015; Radeloff et al. 2018). These ongoing threats will occur at a time when the region is expected to experience significant climatic changes that will affect species and ecosystems in complex ways (Carter et al. 2018). Changes in climate will also impact fire weather, altering wildfire regimes (Gao et al. 2021) and narrowing the available window for setting prescribed fires (Kupfer et al. 2020) in a region where more than 3 million ha are burned annually to reduce wildfire risks and achieve a range of ecological and economic objectives (Melvin 2020).

Broadly speaking, it is recognized that flexible approaches that consider how conservation planning, practices, and policies can be adapted to incorporate future environmental changes are needed to address many of the most pressing future challenges in species and ecosystem management (Golladay et al. 2016; Rissman et al. 2018; Lynch et al. 2021; Simpson et al. 2021). With respect to prescribed fire in longleaf pine ecosystems, there is a need for more information on the factors that shape current burning decisions and how fire managers expect those factors to change in the upcoming decades. Costanza and Moody (2011), for example, argued that more knowledge about how managers prioritize sites for burning and the factors that constrain prescribed burning is particularly needed to understand the potential longer-term consequences of fire management and facilitate effective management practices.

Past research has identified a suite of criteria that may influence practitioner decisions concerning which stands to prioritize for burning; these criteria include both ecological (e.g., ecosystem health of a site; the presence of threatened or endangered species) and non-ecological (e.g., presence of existing firebreaks; management objectives for timber or game) factors (Table 1). Similarly, researchers have identified potential impediments to prescribed burning that range from factors associated with legal, institutional, and managerial constraints to those associated with environmental conditions and resource availability (Table 2). While these criteria and constraints are intuitive and have been cited in longleaf pine management guides, few studies have specifically sought to quantify their relative importance via direct input from fire managers, especially across the full historic range of longleaf pine. Furthermore, efforts to adapt fire management programs to address projected changes in climate, fire weather, and land use over the remainder of the century will likely require managers to consider creative (and even novel) actions and strategies to maintain current levels of prescribed fire, let alone expand it. There is, however, relatively little information on how fire managers perceive the implications of such changes for conservation goals and actions.

Table 1 Criteria used to prioritize longleaf pine sites or stands for prescribed burning. Abbreviations in parentheses are used for corresponding variables in this paper. 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 the viability and frequency of burning as a management tool (Costanza and Moody 2011; Kirkman and Mitchell 2006; Varner et al. 2005).
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 (ALRI 2009; Wear and Greis 2013).
Presence of firebreaks or well-established fire lines *(Firebreaks)*	The presence of adequate firebreaks precludes the need for additional investment (Costanza and Moody 2011; Waldrop and Goodrick 2012).
Need for fuel reduction to reduce fire risk *(FuelReduction)*	Prescribed burns can eliminate accumulations of fuel, thereby reducing the risk and severity of wildfire (Wear and Greis 2013; Waldrop and Goodrick 2012; Kobziar et al. 2015; Shrestha et al. 2021).
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 (Hunter and Rostal 2021; Van Lear et al. 2005; Weiss et al. 2019).
Whether a site is managed for timber *(Timber)*	Management objectives, strategies, and tools intended for timber production may differ from those associated with conservation (Mitchell et al. 2006; Susaeta and Gong 2019).
Length of time since the last burn *(TimeSinceBurn)*	Frequent fire is critical for maintaining longleaf ecosystem health and restoring previously fire-suppressed areas (Brockway et al. 2005; Oswalt et al. 2012).
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 (Wear and Greis 2013; Costanza et al. 2015; Wade and Mobley 2007).
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 this paper. 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 (ALRI 2009; Van Lear et al. 2005). Corporations may have limited access to publicly funded incentive programs and face higher costs to participate in conservation actions for at-risk species (ALRI 2009; McIntyre et al. 2018).
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 (Ryan et al. 2013).
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 (Bodin 2017; Schultz et al. 2018; Costanza and Moody 2011).
Avoiding public objections or concerns over the use of burning *(Public-Concern)*	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 (ALRI 2009; Ryan et al. 2013; Wear and Greis 2013; Haines et al. 2001).
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 the use of prescribed fire as a management tool (ALRI 2009; Ryan et al. 2013; Kobziar et al. 2015; Melvin 2018; Yoder et al. 2004).
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 (Wear and Greis 2013; Waldrop and Goodrick 2012).
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 (Costanza and Moody 2011; Wear and Greis 2013; Haines et al. 2001; Melvin 2018; Cleaves et al. 2000; Blades et al. 2014; Wade and Mobley 2007).
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 (Ryan et al. 2013; Outcalt and Sheffield 1996; Varner et al. 2005; Quinn-Davidson and Varner 2012).
Shortage of resources (personnel, money, equipment) *(Resources)*	Costs and lack of adequate personnel or necessary equipment may impede burning implementation (Haines et al. 2001; Kobziar et al. 2015; Cleaves et al. 2000; Chiodi et al. 2018).
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 (Melvin 2018; Waldrop and Goodrick 2012; Chiodi et al. 2018).

Given this context, we surveyed nearly 300 fire managers across the Southeast to elicit baseline information on the goals, practices, and challenges associated with their longleaf pine prescribed burning programs. We then used a mixed-methods approach involving quantitative and qualitative analyses of survey responses to address three 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? For the first two questions, we tested for differences in criteria and constraints, whether responses differed between managers responsible for burning on public vs. private lands, and whether responses differed between the states across the historic range of longleaf pine. For the third question, we analyzed responses regarding the factors that managers believe will be most constraining in upcoming decades and explored their perceptions about the potential effects of projected regional changes in land use and climate. In doing so, this study contributes a first look at

how fire managers themselves believe changing conditions could challenge their ability to fully achieve existing conservation goals and objectives in longleaf pine ecosystems. We conclude by discussing this study's implications for the design and implementation of burning strategies that consider important evolving regional stressors.

Methods

Fire manager surveys

We developed a Qualtrics web-based survey for fire managers working with longleaf pine ecosystems to learn more about their criteria for prioritizing burn sites, current burning practices, factors that constrain their ability to conduct prescribed burns at desired locations and times, 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, as noted in Tables 1 and 2. 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-author Hiers, 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.

The survey was deployed in July 2019 and remained open through September. The survey invitation asked for participation from fire managers specifically working with longleaf pine ecosystems and was distributed by two organizations supporting fire management professionals. The Southern Fire Exchange, a wildland fire science communication program that represents

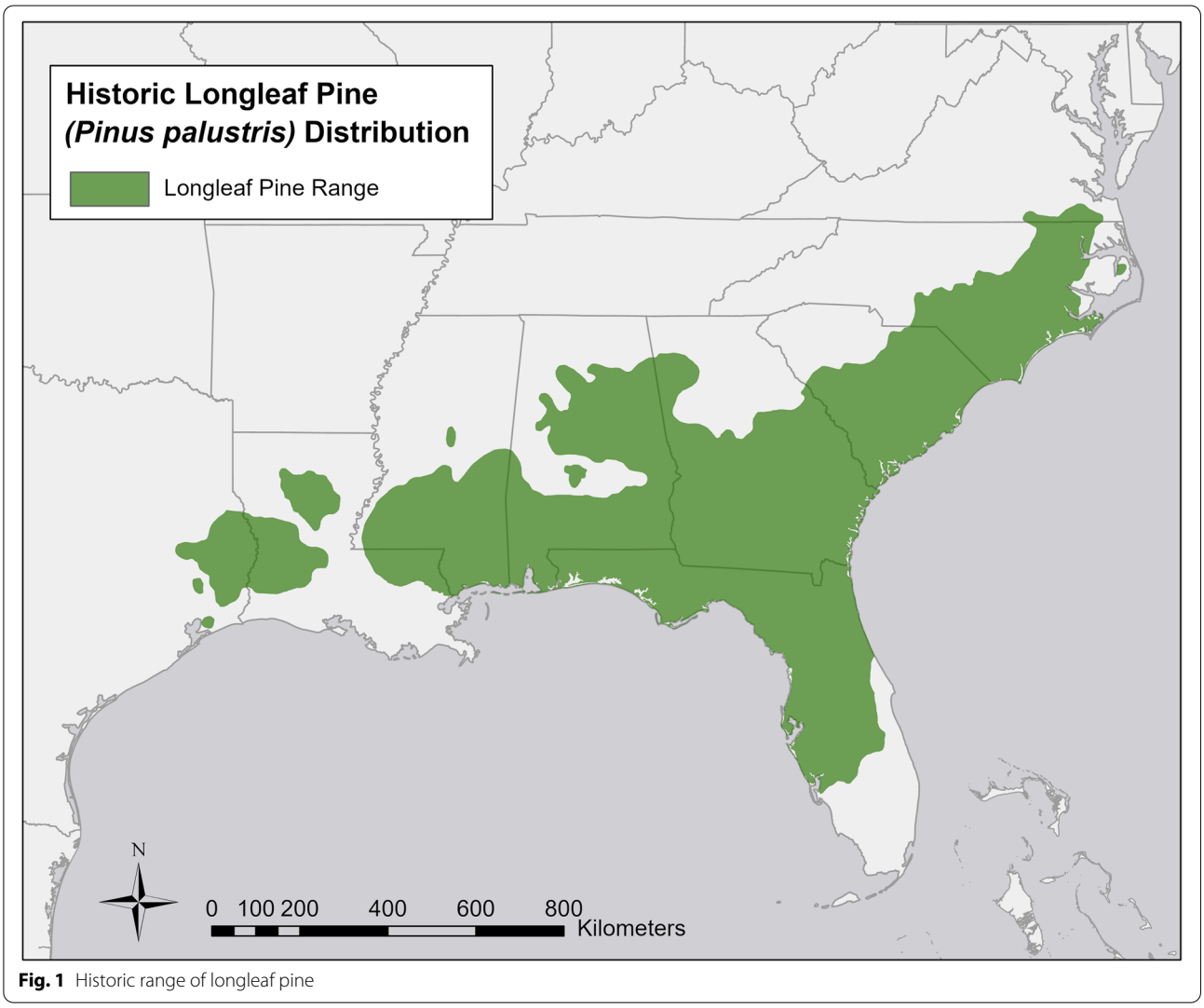

Fig. 1 Historic range of longleaf pine

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 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. If we consider the entire distribution lists for *Fire Lines* and *Driptorch Digest* ($n = 3250$), the corresponding response rates would be 9.1% for partially completed surveys and 6.3% for those providing their state and land ownership class. Calculating exact response rates is difficult, however, because the outlet memberships include fire managers who do not manage longleaf pine stands and thus would not be part of the potential survey pool. Our respondent group included managers from a diverse range of management and ownership types (public lands: $n = 118$; private lands: $n = 89$) and states, albeit with fewer responses from Louisiana ($n = 8$), Texas ($n = 9$), and Virginia ($n = 4$) (see Additional file 1: Table A1, for more detailed respondent demographics). 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 disseminated the survey through the Southern Fire Exchange and SERPPAS newsletters because both organizations are trusted and known in the longleaf pine management space and offered the best opportunity to reach professionals throughout the region. However, we acknowledge several limitations with using this convenience sampling approach and advise that while our results offer additional insight into constraints on prescribed burning practices and emerging concerns for achieving longleaf pine restoration goals, further research throughout the region is needed to elaborate and verify these findings and to investigate the causes and potential solutions to these constraints. First, while these distribution lists include a broad constituency, we cannot know for certain whether those lists were representative of all regional fire managers, defined here as individuals who plan and implement prescribed burns and have responsibility for specific management units. Second, the list likely includes individuals who do not serve in a fire manager role. Although we indicated the survey was intended for individuals who "manage prescribed burns on longleaf pine units," for those respondents who did not provide information about their state, management unit, and other demographic information, their role as fire managers cannot be certain. For the statistical analyses, we addressed this limitation by including only those respondents who provided state and management information. For other analyses, we assumed that respondents were involved in fire or longleaf pine management in a professional capacity due to their membership in the Southern Fire Exchange or SERPPAS lists and decided to use their responses. Some respondents may have experiences in fire suppression or other management activities that might contribute to variability in professional judgment, but these possibilities were accepted as part of the diversity within the population and not pursued in the survey design. In terms of survey participation, the timing unfortunately corresponded to the summer fire season, a period when some fire managers serve on fire details supporting other units and regions, which may have decreased the response rate. Additionally, the detailed nature of some questions may also have affected the response and completion rates by requiring too much time of, or information not readily available to, the respondents.

Data analysis

Criteria for prioritizing burn sites within a management unit

Managers were first asked to indicate their top three criteria for determining whether a site (e.g., stand, burn unit) within their management unit (e.g., National Forest, private land holding) had a high priority for burning given a list of factors associated with site conditions, fire history, proximity to developed areas, and potential management goals (see Table 1). Responses were coded as a binary variable for analysis (1 = selected; 0 = not selected) and analyzed using a generalized linear mixed model (GLMM: Agresti 2012). *Criteria* served as a repeated measures factor to distinguish individual criteria, while the management class (public vs. private: *PubPriv*) and state (*State*) were observational factors. Here, and elsewhere, all analyses that included *PubPriv* and *State* were based on responses only from managers who provided that information ($n = 206$). The response was modeled as a binomial random variable with a logistic link function assuming the conditional form of the GLMM. Simultaneous pairwise comparisons of

least square means (LSMEANS) were computed using a Tukey-Kramer procedure to explore significant results, and criteria with values that were not significantly different were placed into groups to facilitate the interpretation of the pairwise comparisons. All models were analyzed using PROC GLIMMIX in SAS Studio 9.4, unless otherwise noted.

Constraints to prescribed burning

We next asked managers to rate how often a set of factors served as constraints to prescribed burning at their units using three possible responses: "Not a Constraint," "Occasionally a Constraint," or "Regularly a Constraint." For both the survey and analysis, we placed constraints into one of two categories to reflect the different ways and time frames at which they affect decisions: (1) legal, institutional, and managerial constraints, including those associated with risk, liability, legal requirements, and partnerships, and (2) environmental and resource constraints, including aspects of weather, atmospheric conditions, and the availability of personnel and equipment (Table 2). The legal, institutional, and managerial constraints capture factors that bound a fire manager's decision context, for example, constraints that are rooted in long-term management objectives or settings, or that involve legal mandates or agreements with other stakeholders. Environmental and resource constraints, on the other hand, primarily relate to conditions associated with operational (i.e., near real-time) decisions on whether to burn or not.

Unlike the legal, institutional, and managerial constraints, the environmental and resource constraints have distinctly seasonal components in that factors may be constraints during some seasons but not others. For example, weather variables that define prescription burn windows in the Southeast vary seasonally (e.g., Chiodi et al. 2018), as does the availability of personnel and equipment to conduct prescribed fires. Therefore, we asked managers to provide ratings for each of the environmental and resource constraints for four seasons defined by longleaf pine phenology: (a) the dormant season, the period of slowest growth before longleaf pine growth increases to spring and summer levels; (b) the candling season, the early spring growth period before protective needles have developed around the growing buds; (c) the growing season, the primary period of late spring and summer growth; and (d) the senescing season, the autumnal period during which tree growth slows. Because calendar dates for longleaf pine phenology vary over its range in the Southeast, managers were asked to provide approximate start dates for each of these four seasonal periods and to respond to all questions using those seasons to guide their responses.

For the statistical analyses, we converted responses into a binary variable that distinguished those in which the factor is not a constraint (value = 0) from those in which it is occasionally or regularly a constraint (value = 1). For the legal, institutional, and managerial constraints, we used a GLMM with a binary logistic link, with *Constraint* serving as a repeated measures factor for the criteria and *PubPriv* and *State* as observational factors. For the environmental and resource constraints, *Season* served as an additional repeated measures factor to distinguish the two phenological seasons in which most prescribed burning of longleaf pine stands occurs, the dormant and growing seasons. We chose not to include the candling and senescing seasons in these analyses because prescribed burning is less commonly conducted during these two seasons.

Beyond quantifying the overall importance of weather as an environmental constraint, we wanted to identify which weather variables served as the greatest operational constraints to burning during the dormant and growing seasons to better understand current burning practices and because previous work has projected that changes in the number of suitable burning days will be more closely linked to some weather variables than others (Kupfer et al. 2020). We asked managers to indicate whether each variable was a common constraint to implementation of prescribed burns during each season (coded as 1 = constraint during that season and 0 = not a constraint). Provided constraints included high and low temperatures, high and low relative humidity, high and low wind speeds, days since the last measurable rainfall, drought conditions, low atmospheric dispersion index values, and the presence of strong transport winds. The result was a set of binary variables indicating whether the weather variable of interest was a common constraint in that season (value = 1) or not (value = 0). Analyses used a comparable approach to that used to evaluate environmental and resource constraints.

Future changes in burning opportunities

The final set of quantitative analyses focused on managers' perceptions of future changes in constraints to, and opportunities for, prescribed burning of longleaf pine stands. We first asked managers how they expect the availability of suitable burning opportunities to change in each burn season given a 30-year planning horizon. The response scale was ordinal: 1 = greatly reduced, 2 = somewhat reduced, 3 = no significant change, 4 = somewhat increased, and 5 = greatly increased. We then asked them to identify the most important constraints that they believe will limit their use of prescribed burning for the same time period. Respondents could select up to five

constraints from the list used previously (Table 2) or add their own. We recorded individual responses for each constraint using a simple binary scale (0 = not selected; 1 = selected). As with earlier analyses, we used a mixed binomial model with *Manager* as a random effect and *PubPriv*, *State*, and an 11-level variable (*FutConstr*) distinguishing the various constraints as a repeated measures factor.

Finally, we asked managers to rate how they think changes in future urbanization patterns (e.g., changes in the wildland-urban interface, loss of habitat to restore longleaf pine ecosystems) and climate (e.g., increasing temperature, more intense rainstorms and extreme weather events) will affect their prescribed burning decisions. Possible responses were again ordinal (1 = not at all; 2 = a little; 3 = moderately; 4 = a great deal), with an additional option of "Don't Know." Because responses would likely vary with the time frame, managers were asked to provide ratings for three future time horizons: the next 5–10 years, 10–30 years, and 30–50 years.

Qualitative analyses

For the open-ended questions, we used a qualitative data analysis software program, NVivo 12, to analyze the text responses and provide context to managers' prescribed burning decisions. Initial coding categories aligned with the prescribed burning criteria (Table 1) and constraints (Table 2) 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 burning decisions. Individual responses could be coded at multiple categories, depending on the response content. Once the data were coded, we conducted a series of queries to compare differences between management types and explore intersections between the different survey questions and codes. Of the fully or partially completed surveys (n = 296), 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).

Results

When asked how often longleaf pine stands in their management units should be burned, nearly all respondents (98.8%) cited a frequency of 1–4 years, a value that corresponds to the historic fire regime in longleaf pine ecosystems (cf. Glitzenstein et al. 2003; Rother et al. 2020). However, when asked how frequently longleaf pine stands in their units have been burned over the last decade (on average), many respondents (38.5%) gave values ranging from 4 years to never within that time span. Even managers who cited recent burn frequencies of 4 years or less noted that they are not burning as often as they would like to meet management goals. These responses underscore the importance of understanding the factors that shape prescribed burning decisions.

Criteria for prioritizing burn sites within management units

Based only on data from respondents who provided both their management class and state (n=206), the GLMM of burn criteria indicated significant differences in how often individual criteria were cited (*Criteria*: DF = 8; Den DF = 1632; F = 48.53; $p \leq 0.0001$), but no differences for *PubPriv* (p = 0.38) or *State* (p = 1.00). There was, however, a highly significant interaction between *Criteria* and *PubPriv* (DF = 8; Den DF = 1632; F = 5.11; $p \leq 0.0001$). While analysis of a main effect in the presence of significant interactions should be undertaken with caution, pairwise comparisons of LSMEANS for *Criteria* identified several discrete groups of burn criteria. These groups, listed in descending order of importance, were formed by *TimeSinceBurn* and *EcoHealth* (group A) and *FuelReduction* and *TandE* (group B), with two overlapping groups formed by *Firebreaks*, *WUI*, *ExoticInvasive*, *OtherCrit* (group C) and *ExoticInvasive*, *OtherCrit*, and *Timber* (group D) (Table 3). A majority of respondents cited time since the last burn (76.4%) and ecosystem health (67.5%) as top priorities, followed by fuel reduction (48.5%) and management for threatened and endangered species (39.9%). Other priorities were selected by fewer than 20% of respondents.

The significant interaction indicates that the *Criteria* groupings were affected by whether a respondent managed private or public lands. For private lands, two distinct, non-overlapping groups of criteria emerged. The first group of more cited criteria included *TimeSinceBurn*, *EcoHealth*, and *FuelReduction*; the second group contained *ExoticInvasive*, *TandE*, *WUI*, *Firebreaks*, *OtherCrit*, and *Timber*. For public lands, five groups with often overlapping variables were identified; these included *TimeSinceBurn* and *EcoHealth* in the group of most cited criteria, followed (in descending order) by groups consisting of *EcoHealth* and *TandE*; *TandE* and *FuelReduction*; *FireBreaks*, *WUI*, *ExoticInvasive*, and *OtherCrit*; and *WUI*, *ExoticInvasive*, *OtherCrit*, and *Timber*. The presence of threatened and endangered species was thus given higher priority on public lands compared to private lands (53.9% vs. 21.4% of respondents; Table 3) while fuel reduction appeared in the highest grouping for private, but not public, lands. There were no statistically significant differences among states, suggesting

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

Criterion[a]	All responses[b]	Least squares means[c]		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%

[a] See Table 1 for criteria abbreviations

[b] 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

[c] Least squares mean estimate and Tukey-Kramer grouping for individual constraints. Least squares means with the same letter are not significantly different ($\alpha = 0.05$)

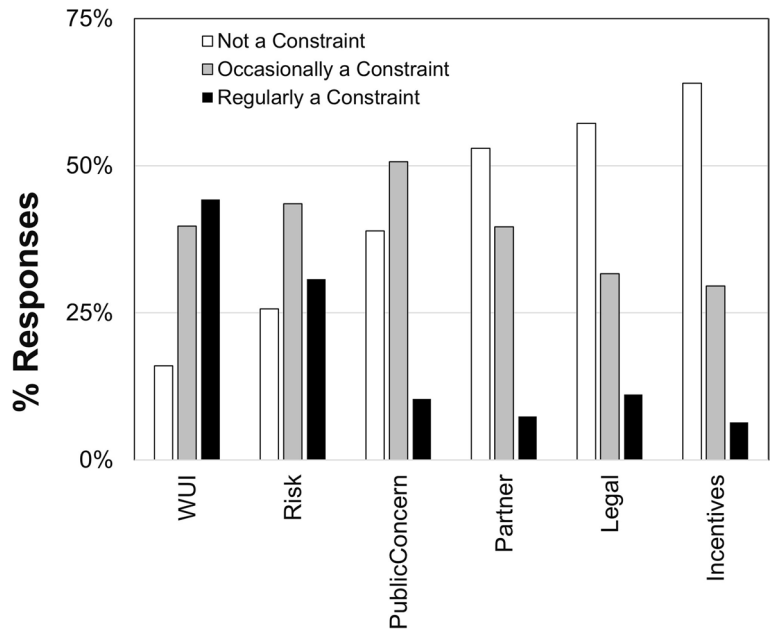

Fig. 2 Frequency with which legal, institutional, and managerial factors constrain burning activities in longleaf pine ecosystems. Constraints, including abbreviations, are explained in Table 2

that respondents across the region use similar criteria for site prioritization.

Legal, institutional, and managerial constraints

The most common legal, institutional, and managerial constraints to burning were the presence of human developments (*WUI*) and risk aversion (*Risk*), with over 70% of respondents citing those factors as regular or occasional constraints (Fig. 2). Avoiding public concerns over burning (*PublicConcern*), legal constraints (*Legal*), challenges posed by partnerships and agreements (*Partner*), and limited incentives to burn (*Incentives*) served as occasional constraints but were each cited as regular constraints by fewer than 15% of respondents.

Quantitatively, the GLMM found significant differences based on the individual constraints (*Constraint*: DF = 5; Den DF = 971; $F = 31.21$; $p \leq 0.0001$) and state (*State:* DF = 8; Den DF = 971; $F = 2.18$; $p \leq 0.027$), as well as a weakly significant interaction between *Constraint* and

PubPriv (DF = 5; Den DF = 971; $F = 2.17$; $p = 0.055$). The significant *State*-level effect was due to differences between Virginia, on the one hand, and North Carolina and Mississippi, on the other; however, this result is likely trivial because of the small sample size from Virginia ($n = 4$). For private land managers, follow-up tests of the interaction effect identified a distinct group containing *WUI* and *Risk* as the most common legal, institutional, and managerial constraints to burning, with overlapping secondary groups formed by *PublicConcern*, *Legal*, and *Partner* in one group and *Partner* and *Incentives* in another. For public land managers, *WUI* and *Risk* again formed a group of the most cited constraints, with an overlapping second group containing *Risk* and *PublicConcern* followed by a distinct secondary group containing *Partner*, *Incentives*, and *Legal.* Collectively, these results indicate that the most common constraints (nearby development, risk aversion, and liability) were the same for all managers, but public land managers more often cited avoiding public concerns over the use of burning as a constraint, while legal constraints were more often cited by private land managers.

Environmental and resource constraints

All four environmental and resource constraints were commonly cited as regular or occasional constraints to burning, but there were statistically significant differences between the constraints (DF = 3; Den DF = 1211; $F = 6.27$; $p = 0.0003$) and the two seasons (DF = 1; Den DF = 1211; $F = 14.85$; $p = <0.0001$) (Fig. 3). Tests of pairwise differences identified three overlapping groups (in descending order of importance) formed by *Weather* and *Resources*, *Resources* and *AirQuality*, and *AirQuality* and *FuelLoad* and indicated that constraints were more common during the growing season than the dormant season. There were no differences for *PubPriv* ($p = 0.80$) or *State* ($p = 0.31$) and no significant interaction effects.

For the individual weather constraints, the results indicated significant fixed effects related to the different constraints (*WxConstr*: DF = 9; Den DF = 3885; $F = 22.06$; $p < 0.0001$) and a significant interaction between *WxConstr* and *Season* (DF = 9; Den DF = 3885; $F = 28.85$; $p < 0.0001$), meaning that that some meteorological variables were more commonly cited as being constraints and that the importance of constraints varied seasonally. The frequency of respondents citing specific meteorological variables as regular constraints also provided perspective on available burn windows in the dormant versus growing seasons (Fig. 4). During the growing season, high temperatures, drought, and days since the last rainfall were the most frequently cited weather limitations, followed by high relative humidity and low wind speeds (Fig. 5: *note that vertical bars connect constraints with statistically equivalent values*). Variables associated with heat and fuel moisture were thus central in restricting burn opportunities during the hottest time of the year. Two of the main growing season constraints were also in the top group of dormant season constraints (drought, days since the last rainfall), but the other dormant season constraints in the highest group were low relative humidity, high wind speeds, and atmospheric dispersal. Growing season constraints thus reflected a greater emphasis on

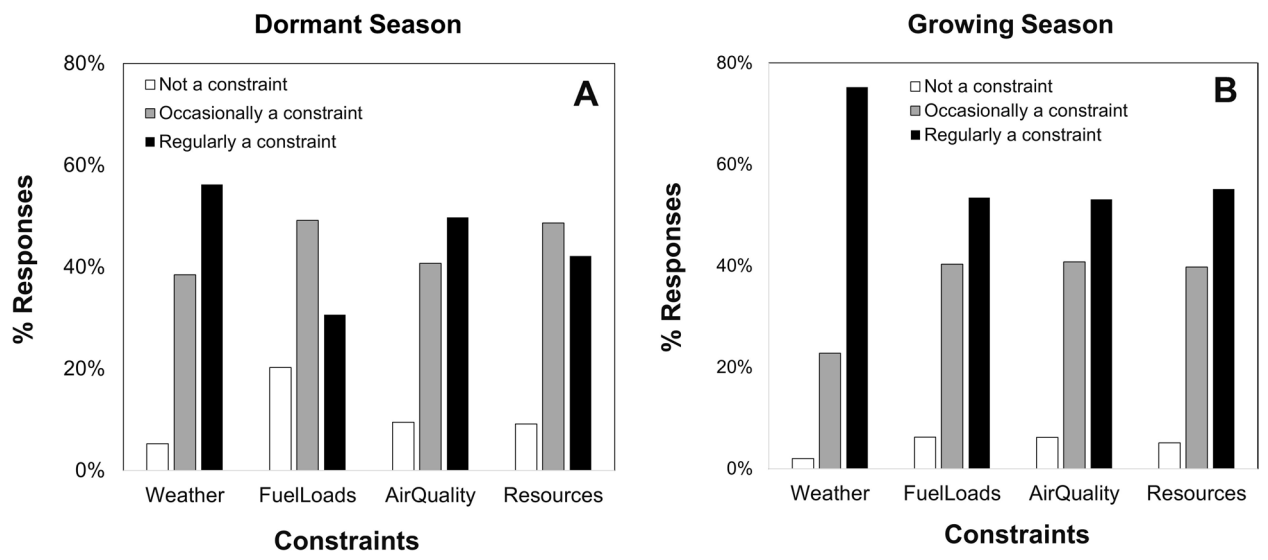

Fig. 3 Frequency with which environmental and resource factors constrain burning activities in longleaf pine ecosystems for the **A** dormant season and **B** growing season. Constraints, including abbreviations, are explained in Table 2

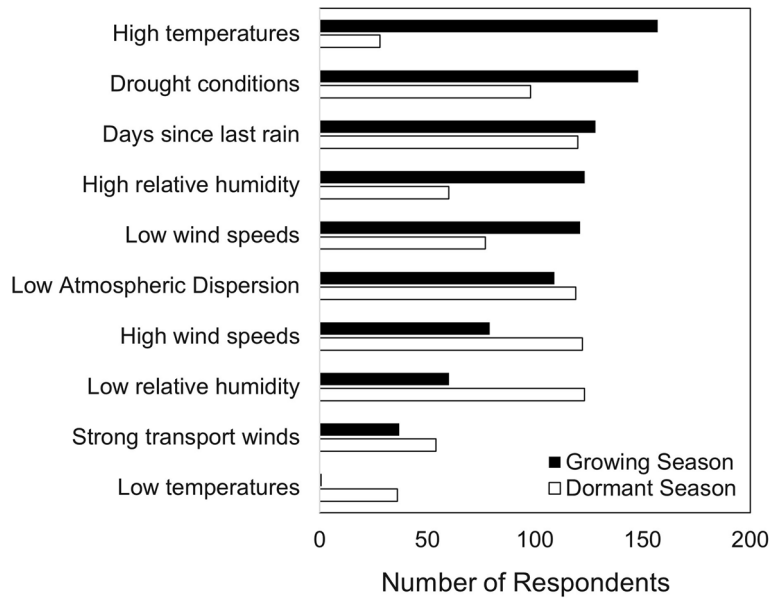

Fig. 4 Most commonly cited meteorological variables that constrain prescribed burning in longleaf pine ecosystems during the growing and dormant seasons

hotter stagnant conditions and their influence on fire control, crew safety, and smoke transport than dormant season constraints.

Future changes in burning opportunities and constraints

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 the growing (53.5%) and candling (53.8%) seasons (Table 4). In contrast, few foresee increased prescribed burning opportunities in any season.

In terms of potential future constraints, there was a significant difference in the number of managers citing specific factors (*FutConstr*: DF = 10; Den DF = 2050; $F = 39.39$; $p < 0.0001$), but no differences between those managing public vs. private lands ($p = 0.42$) or those in different states ($p = 0.34$). Pairwise comparisons illustrated the differences in how respondents view such constraints, with resulting groups (in descending order of importance) formed by *AirQuality* and *WUI* (group A); *Risk*, *PublicConcern*, and *Weather* (group B); *PublicConcern*, *Weather*, and *Resources* (group C); *Resources* and *Legal* (group D), *Legal* and *FuelLoad* (group E), and *Incentives* and *Partners* (group F) (Table 5). The most cited future constraints thus 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. 6A). In contrast, the percentage 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. 6B). In this case, the percentage who responded "A Great Deal" increased from 5.9% over the next 5–10 years

(See figure on next page.)

Fig. 5 Tukey-Kramer simultaneous pairwise comparisons of least squares means for weather constraints to prescribed burning in longleaf pine ecosystems, computed separately for the **A** growing season and **B** dormant season. Vertical bars connect constraints with statistically equivalent values ($a = 0.05$). Constraint abbreviations: HiT and LowT, high and low temperatures; HiRH and LowRH, high and low relative humidity; HiWind and LowWind, high and low wind speeds; DaysRain, days since the last measurable rainfall; Drought, drought conditions; AtmoDisp, low atmospheric dispersion; Transwind, presence of strong transport winds

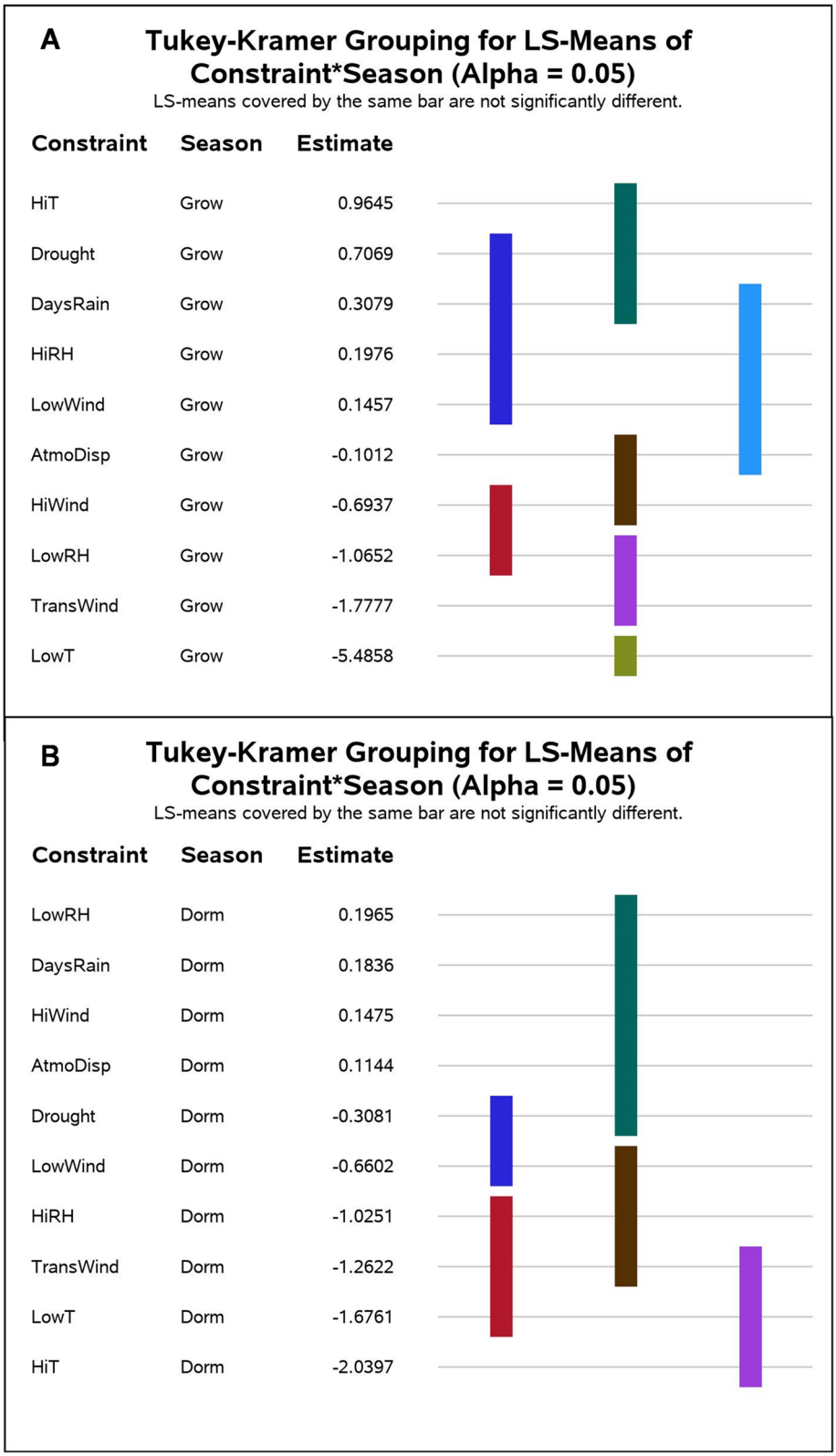

Fig. 5 (See legend on previous page.)

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%)

Table 5 Fire managers' perceptions of future constraints to prescribed burning in longleaf pine ecosystems, grouped in order of importance

Constraint[a]	Tukey-Kramer grouping for constraint least squares means ($a = 0.05$)			
	Responses[b]	Estimate	Grouping	
AirQuality	81.2%	1.4057		A
WUI	78.3%	1.2252		A
Risk	58.0%	0.2586		B
PublicConcern	46.9%	−0.1935	C	B
Weather	44.9%	−0.2525	C	B
Resources	40.1%	−0.4523	C	D
Legal	26.1%	−1.0974	E	D
FuelLoad	25.6%	−1.1485	E	
Incentives	11.6%	−2.0922		F
Partners	2.4%	−3.7626		F

[a] See Table 2 for constraint abbreviations

[b] Percentage of fire managers who selected the stated constraint as one of the top five constraints on the availability of prescribed burning opportunities over the next 30 years (N=206)

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%).

Qualitative results: interactions among stressors and constraints

Narrative responses reinforced the quantitative results 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. Regarding the prioritization of burn sites, twenty-eight respondents (8 public; 17 private; 3 not specified) provided narrative comments. Their responses were mostly associated with the *Eco-Health*, *FuelReduction*, and *Firebreaks* survey criteria. Respondents particularly noted the importance of

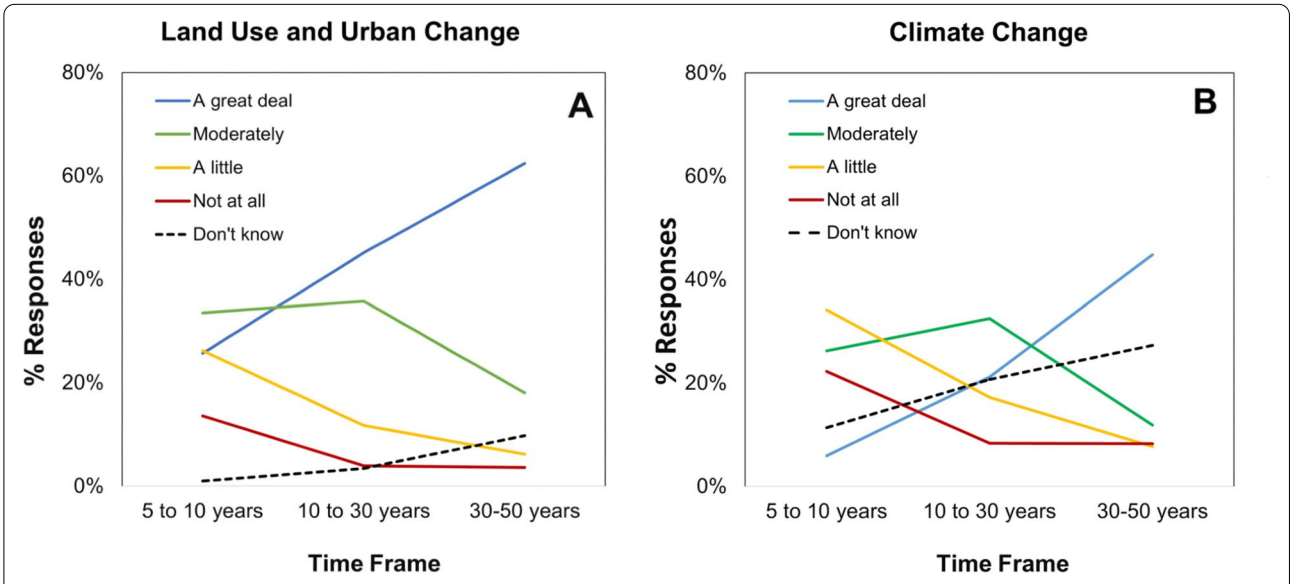

Fig. 6 Fire manager perceptions regarding how prescribed burning decisions will be affected by potential future changes in **A** land use and urban change and **B** climate change

Table 6 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."

reducing competing species and promoting longleaf pine growth, especially to support restoration objectives, and considering both a site's fuel conditions and the ability to conduct safe burns in the decision process. For other criteria (*OtherCrit*), respondents listed client interests, contractual obligations, and management objectives related to hunting and quail habitat.

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.

There was also a high percentage of narrative content coded under multiple categories (150, or 92.6%, of the 162 surveys available for qualitative analysis), illuminating the complex nature of prescribed burning decisions (Table 6). For example, 46 reports (28.4% of the total) referenced both weather and resources as affecting burn decisions, and 31 of the 36 surveys referencing human development and presence of the wildland-urban interface were jointly coded with the smoke and smoke management, weather, resources, political and policy issues, and risk aversion categories. The ability to meet air quality requirements, avoid public concerns, and hence meet management objectives is subject to myriad, interacting stressors, as illustrated by the example quotes.

As a whole, the qualitative results suggested that most managers currently work to optimize the resources and opportunities they have, yet the multi-layered set of challenges they face appear to make it difficult to maintain desired burn regimes. To address expectations that these challenges will continue, and likely increase, into the future, several respondents suggested actions or mitigation opportunities to pursue. These recommendations pertain to public education, insurance reform, and improving understanding of the economic benefits of prescribed burning. Other comments focused on altering

fire management practices, such as by expanding burn windows, taking advantage of burning opportunities in non-traditional seasons, and considering strategies such as mechanical thinning or herbicides to supplement burning.

Discussion

Priorities and constraints to prescribed burning in longleaf pine ecosystems

High rates of population growth, urbanization, and land use change coupled with projected changes in climate pose a significant threat to regional biodiversity in the southeastern United States (Carter et al. 2018). These drivers of change are common in many terrestrial ecosystems across the globe, but in landscapes with pyrophilic systems, they compound the complexity of managing beneficial prescribed fires (Vose et al. 2021). 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 rangewide conservation goals in these ecosystems (ALRI 2009), but supporting restoration through prescribed fire may require new approaches to burning as well as additional resources and policy changes to achieve desired goals (McIntyre et al. 2018). Drawing on results from a survey of longleaf pine fire managers, the purpose of this research was to provide information on the key criteria considered by practitioners when planning prescribed fires, the perceived constraints to the active use of manager-ignited fire, and beliefs about how such constraints are likely to change in the future.

Resources for conducting prescribed burns are frequently insufficient to manage lands for all conservation and resource management objectives, creating the need to prioritize the application of fire across a landscape within any given year (Hiers et al. 2003). Our results indicate that the most common criteria for selecting specific longleaf pine stands for burning were fire history, ecosystem health, and fuel reduction, with slight differences in secondary factors between public vs. private land managers (Table 3). The effective use of prescribed fire in longleaf pine ecosystems also requires understanding the constraints that factor into burning decisions. Here, fire managers cited the proximity of human development near burn units, weather, risk aversion, the availability of personnel and equipment, and issues associated with air quality as the most common constraints affecting prescribed burning. These results generally align with those from previous surveys in the southeastern United States and elsewhere that have examined prescribed burning objectives, priorities, and practices (Cleaves et al. 2000; Haines et al. 2001; Costanza and Moody 2011; Quinn-Davidson and Varner 2012; Kobziar et al. 2015; Melvin 2018).

Beyond these individual constraints, though, 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 (Table 6). 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 (Figs. 4 and 5). 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 (Table 4) due to issues associated with air quality, development in or near burn areas, risk aversion, and inappropriate weather conditions (Table 5). These factors themselves have direct linkages to climate change and human land use and development.

Design and implementation of future-looking burning strategies

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 (e.g., Quinn-Davidson and Varner 2012; Kupfer et al. 2020).

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 (Provencher et al. 2001). 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 (Costanza et al. 2015). 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 (Mitchell et al. 2014).

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 (US Forest Service 2022). The need to engage with private landholders may be particularly acute given that (1) privately owned and managed lands account for over 60% of all longleaf pine acreage but only 24.3% of the acreage burned in 2020 (ALRI 2021) and (2) 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 (Costanza et al. 2013). 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 (Stein and Shaw 2013).

Recommendations and conclusions

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. First, 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.

Second, 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 (e.g., Foster et al. 2019). 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.

Third, 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 conclusion, this study identified multiple layers of constraints to prescribed burning in longleaf pine ecosystems that occur at intersecting temporal, spatial, and decision scales (see also Becknell et al. 2015; Gillson et al. 2019). Managers' expectations that land use change and climate will pose even greater limitations with an increase in future uncertainty poses practical challenges to regional landscape restoration efforts. Given the importance of prescribed burning as a tool for longleaf pine restoration, additional research and policy flexibility may help managers and organizations optimize the (changing) windows of burning opportunities, explore other management strategies, and/or reconsider the attainability of existing restoration goals.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-022-00151-6.

Additional file 1: Table A1. Survey respondent demographics compared to longleaf pine area by ownership type, size of management area, and state. The "Private" category includes fire contractors and consultants, individual and corporate landowners, and managers of jointly managed lands (e.g., non-profits, private owners). Estimates of existing longleaf pine area are circa 2009 (America's Longleaf Restoration Initiative 2009).

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Authors' contributions
JAK, KD, KL, and JKH conceptualized the study and designed the survey methodology, with input from AJT. Analyses were selected and performed by JMG and KL. Funding for the project came from grants to JAK, KD, KL, KH, and AJT. JAK oversaw the writing of the manuscript, with contributions from KL, JKH, KD, JMG, and AJT. All authors read, edited, and approved the final submission.

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Availability of data and materials
The dataset analyzed in the current study, excluding information that could be used to identify individual respondents, is available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The research protocol and survey analyzed and presented in this article were reviewed by the University of South Carolina Office of Research Compliance (ORC) in accordance with the University's Institutional Review Board's (IRB) requirements and procedures. The study (Pro00089397) received an exemption from the Human Research Subject Regulations on June 3, 2019, based on policies outlined in the 2018 Common Rule [45 CFR 46.104(d)(2)]. Because the survey received an exemption, the informed consent process was not required.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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