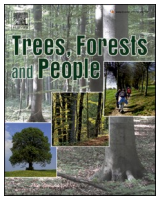
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Collaborative spatial planning for forest restoration and resilience in the southeastern United States' interior highlands

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ABSTRACT

Prioritizing restoration-focused ecosystem management across large areas is challenging when multiple goals are at stake and goals vary among forest managers. This complexity is compounded when forest restoration tools including prescribed fire and silviculture have variable efficacy across landscapes and among management goals. Collaboration between scientists and resource managers to design analyses that address these complexities can clarify contingencies and tradeoffs and provide flexible decision support. White oak and shortleaf pine forests and woodlands have shown strong declines in the eastern United States, and restoration goals are shared by a wide range of stakeholders. We used a collaborative analysis to (1) quantify spatially variable restoration potential for these two species and for wildfire risk reduction potential, and (2) prioritize landscapes for active management under a scenario planning framework. Spatial modeling and optimization relied on several interrelated engagement approaches with diverse partners and experts to generate varied planning scenarios and spatial outputs that reflect a range of prioritization options. Beginning with pre-project engagement with initial key partners, we progressively established a network of scientists, planners, and managers to provide expert input through continuous interaction in an ad-hoc advisory group, and through a series of formal scenario planning and science delivery workshops. Analytical results suggested widespread but geographically variable restoration and risk management opportunities. They also revealed geographic tradeoffs among objectives under the varying management goals and spatial constraints of the planning scenarios. We report the collaborative aspects of a process that connected expert knowledge, landscape data and models, and management support for co-produced science, arguing that collaborative planning increases the likelihood of successful ecosystem restoration.

1. Introduction

Forest lands are often managed for multiple uses including recreation, sustainable timber production and clean water, wildlife conservation, and more (Rodriguez Franco and Conje, 2022). Every forest landscape harbors diverse resources, and sustaining those resources amidst diverse and growing threats including climate change, urbanization, invasive species, and wildfire presents a complex management challenge (Littell et al., 2011; Mockrin et al., 2022). This complexity implies a role for research in advancing strategic forest management planning, and a variety of approaches have been developed to address multi-resource planning across diverse forest landscapes (Ager et al., 2017; Baskent et al., 2024; Shan et al., 2009). More recently, collaborative forest management planning has been an important component of research, actively engaging planners, decision-makers, and other stakeholders in the scientific process (Arciniegas and Janssen, 2012; Fazey et al., 2013; O'Connor et al., 2019; Sieber, 2006).

In collaborative planning, individuals and groups with diverse interests share ideas, knowledge, and resources while working together to achieve common goals (McIntyre and Schultz, 2020; USDA Forest Service, 2012). Collaborative planning for forest management is a dynamic process that needs to be constantly adapted to the interactions among diverse groups of people and landscapes, with a focus on stakeholder involvement (AlWaer and Cooper, 2020). Collaborative planning

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can be a problem-solving approach in which stakeholders are involved in an interactive process of consensus building and translating consensus into results (Long et al., 2014). In the past, collaboration in forest management mainly focused on effective communication (information sharing) but now it is more often considered an integral component of research (Arciniegas and Janssen, 2012; Fazey et al., 2013; O'Connor et al., 2019; Sieber, 2006). Involving forest management partners in the scientific process helps to ensure that research is appropriately geared to inform management that provides the expected benefits of healthy ecosystems (Campbell, 2024; Dey and Schuler, 2020). Participant expertise can influence decisions about how the research happens, with the potential to improve the research process and generate highly productive outcomes (Cheruvelil et al., 2014; Lemos and Morehouse, 2005). This coproduction model can be more efficient than traditional approaches, arriving sooner at consensus solutions (Dey and Schuler, 2020; Roitsch et al., 2024). It also brings research more fully to the awareness of resource managers and other partners, with investment in the process increasing the likelihood that decisions are informed by the best scientific evidence (Enquist et al., 2017; Ryan et al., 2018).

The United States Department of Agriculture Forest Service (FS) is an example of an organization that strives for collaboration across its own research and management mission areas to provide science-based support for resource management, facilitate strategic planning, and improve the applied value of research (Dey and Schuler, 2020). Partnerships between FS scientists and stakeholders outside the agency also emphasize cooperation to achieve forest research addressing issues such as reducing the risk of wildfire, improving forest health, and sustaining economic productivity. For example, the FS 2012 Planning Rule proposes an all-lands approach, putting National Forests (NFs) in the context of larger landscapes to better address forest management issues that cut across ownership boundaries (Long et al., 2014; USDA Forest Service, 2012). An all-lands approach implies cooperation and collaboration with diverse stakeholders to promote broad scale forest management (Golladay et al., 2016). Programmatic efforts to support such partnerships include the Collaborative Forest Landscape Restoration Program (CFLRP) and the Shared Stewardship strategy, established to encourage collaborative, science-based ecosystem restoration in priority landscapes (Beeton et al., 2022). The FS has also promoted internal and external, cross-boundary collaboration to meet national goals to develop nationwide wildfire risk reduction information and tools and implement long-term, landscape-level planning strategies to manage risk (USDA Forest Service, 2022; Wildland Fire Leadership Council, 2014). For the FS and other natural resource management organizations, collaborative approaches are needed to realize science-based decision support and to inform planning for ecosystem management investments to have the greatest impact on desired outcomes (Huayhuaca et al., 2023).

Within the USDA Forest Service Southern Region, 5-year implementation plans were recently developed for each of four subregions to advance landscape-scale decision support and planning tools, taking into consideration subregion-specific ecosystem types, management needs, and collaboration opportunities. The Interior Highlands (IH) subregion included National Forest System units in Arkansas, Kentucky, Oklahoma, and Tennessee. The IH implementation plan proposed a prioritization effort to identify high-value opportunity landscapes that promote diverse and healthy ecosystems resilient to climate change and catastrophic wildfire. The plan specifically aimed to prioritize landscapes for restoring ecological conditions for white oak (*Quercus alba*) and shortleaf pine (*Pinus echinata*) woodlands, two long-standing conservation priorities in the region (Fei et al., 2011; Guldin, 2019; Pile Knapp et al., 2024). These ecosystems provide unique wildlife habitats, ecosystem services, and economic value including timber production and outdoor recreation. Rapid loss of these forest and open woodland types in recent decades has resulted from fire exclusion and suppression, land management practices including single-species plantation silviculture, and environmental stressors including strong competition from fire-intolerant tree species (Guldin, 2019; Hanberry et al., 2012; Nowacki and Abrams, 2008). Active management including the combined use of prescribed fire and restoration-focused silviculture to favor target species and open-canopy woodland conditions is seen as crucial for restoring both white oak and shortleaf pine ecosystems (Jin et al., 2018). These restoration practices target fire-adapted, resilient forest conditions that support native biodiversity, ecosystem services, and forest health (Knapp et al., 2026; Phillips et al., 2012).

We developed a collaborative approach for a spatial prioritization analysis to identify landscapes where forest management investments can be expected to have the best chances to advance ecological restoration of white oak and shortleaf pine ecosystems, while also addressing fuels treatments to reduce wildfire risk. Our spatial analysis entailed first modeling the potential for management to advance each of the objectives and then optimizing based on those models to create a portfolio of multi-objective, spatial planning information and data products. Our research design included collaborative engagement at all stages—the project was initiated in response to partner need; spatial modeling entailed an expert-driven approach with continuous input from an advisory group; partner input was used to generate relevant management scenarios under which optimization could then occur; and science delivery was integrated in the research cycle under the project partnerships.

Here, we report on a novel approach to collaborative spatial planning that integrates several formal and informal partner engagement strategies across the full research cycle. Details of the spatial optimization analysis itself are reported elsewhere (Pomara et al., 2026). We focus here on the methods used for collaborative engagement and research co-development, as well as outcomes of the engagement in terms of how it shaped the analysis and overall project outcomes. We argue that while science coproduction of this kind faces special challenges and increases project complexity, it improves the applied relevance and uptake of science to facilitate goals such as ecological restoration.

2. Methods

We engaged collaborators through a variety of interactions, each geared to serve distinct purposes at different project stages (Fig. 1). We developed a three-tiered approach that included (1) initial engagement with the primary collaborating organization; (2) a long-term expert advisory group engaged through all project stages, and (3) workshops to engage a wider range of participants at the scenario planning and science delivery stages. In addition to the primary FS collaborators, other partners included state agencies, other federal agencies, and regional conservation consortia. In the following sections we describe how these groups were assembled and their intended roles in project development, ecological modeling, spatial prioritization, and science delivery aspects of the research.

2.1. Initial collaborative engagement—the interior highlands subregion

The science team initially coordinated with the FS Southern Region and IH subregion resource management staff to develop a framework for landscape-scale research aimed at providing science-based support for the IH 5-year implementation plan. The science team had previously established collaborative engagement with Southern Region staff and non-FS regional partners to accomplish regional wildfire risk assessment and mitigation research and science delivery (Gould et al., 2023; Nepal et al., 2023; Pomara et al., 2025). During that effort, related Southern Region and National Forest System work to develop the subregional implementation plans for a wider variety of management priorities resulted in identifying the restoration of white oak and shortleaf pine forest ecosystems as priorities in the IH subregion, while also recognizing wildfire risk management as a need. Early engagement for new research therefore had a basis in pre-existing relationships, shifting to address emerging science needs. Project development work at this stage

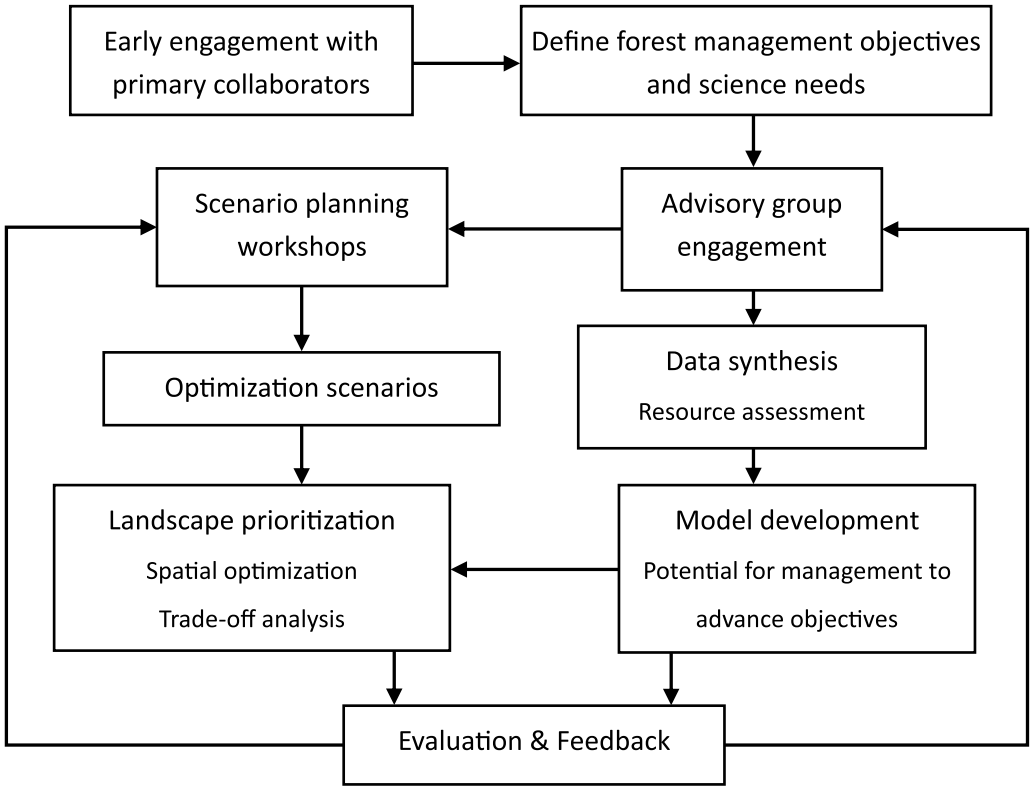


Fig. 1. Structure of the collaborative planning process for spatial prioritization of landscapes with potential to advance white oak and shortleaf pine forest restoration and wildfire risk management objectives. Research and science delivery were shaped through several structured and unstructured avenues for collaboration—initial engagement with primary forest management partners; continuous engagement with a small advisory group; and larger partner workshops.

occurred via both Southern Region programmatic meetings and science team weekly meetings.

2.2. Expert advisory group

Our prior engagement with Southern Region staff provided a platform to expand collaborative engagement, including formation of an expert advisory group. The group's intended role was to provide expert advice at every project stage from multiple resource management and scientific perspectives. Selected Southern Region staff participated in the advisory group—some of whom had participated in previous collaborative efforts with the science team, providing continuity for the prescribed fire and fuels management project components in particular (Nepal et al., 2023). These members also assisted in inviting other participants with expertise in a variety of relevant and complementary areas. The advisory group met biweekly throughout the project, providing input through unstructured discussion on ecological model development and use. The advisory group also played a key role in developing and facilitating scenario planning workshops at a later project stage. In addition to regular members, the group included ad-hoc participation from invited topical experts, including outside partners and FS scientists beyond the immediate science team.

2.2.1. Ecological modeling

The collaborative planning process reported here included developing relevant large-scale spatial data (Fig. 2). Analytical details are reported elsewhere, and the spatial assessment data are publicly available for use in landscape-scale forest management planning applications (Pomara et al., 2026; USDA Forest Service, 2026a, 2026b). We developed Bayesian belief network (BN) models to evaluate the potential for active management—the combination of prescribed fire and restoration-focused silviculture—to advance restoration goals for white oak and shortleaf pine, in separate models for each species (Barton et al., 2012; Moe et al., 2021). As graphical causal models, BNs are well-suited for making key aspects of management problems explicit during collaborative discussions and allowing participants to engage critically in the modeling process (Conroy and Peterson, 2013; McCann et al., 2006). The BNs quantified probabilistic relationships among variables in the ecological systems at hand, including the expected influence of management decisions. The expert advisory group was engaged iteratively during model development through the group's biweekly meetings, providing input on system structure (i.e., relevant variables and their relationships), spatial data sources, and the likely influence of management decisions. Finally, the science team had previously completed a wildfire risk assessment that models risk to communities and important watersheds and estimates the risk reduction that could be achieved with intensified fuels management, primarily through the use of prescribed fire (Nepal et al., 2023; USDA Forest Service, 2024). We used updated outputs from the risk model to indicate potential for risk reduction through long-term fuels reduction (Fig. 2F).

2.3. Scenario planning workshops

Results from the three spatial models then became inputs for optimization analysis to identify priority landscapes where objectives could be most efficiently and effectively advanced. To achieve this, we used a scenario planning framework in which optimization occurs under a variety of planning scenarios to address uncertainties (Peterson et al., 2003). We used structured workshops to gather information from a variety of natural resource management partners as a basis for building the planning scenarios.

A planning scenario is a plausible set of conditions and preferences under which prioritization can occur. For example, the relative importances or weights of different objectives are key conditions—white oak restoration may have greater importance than fuels management in one scenario, while in another they are equally important. When partners

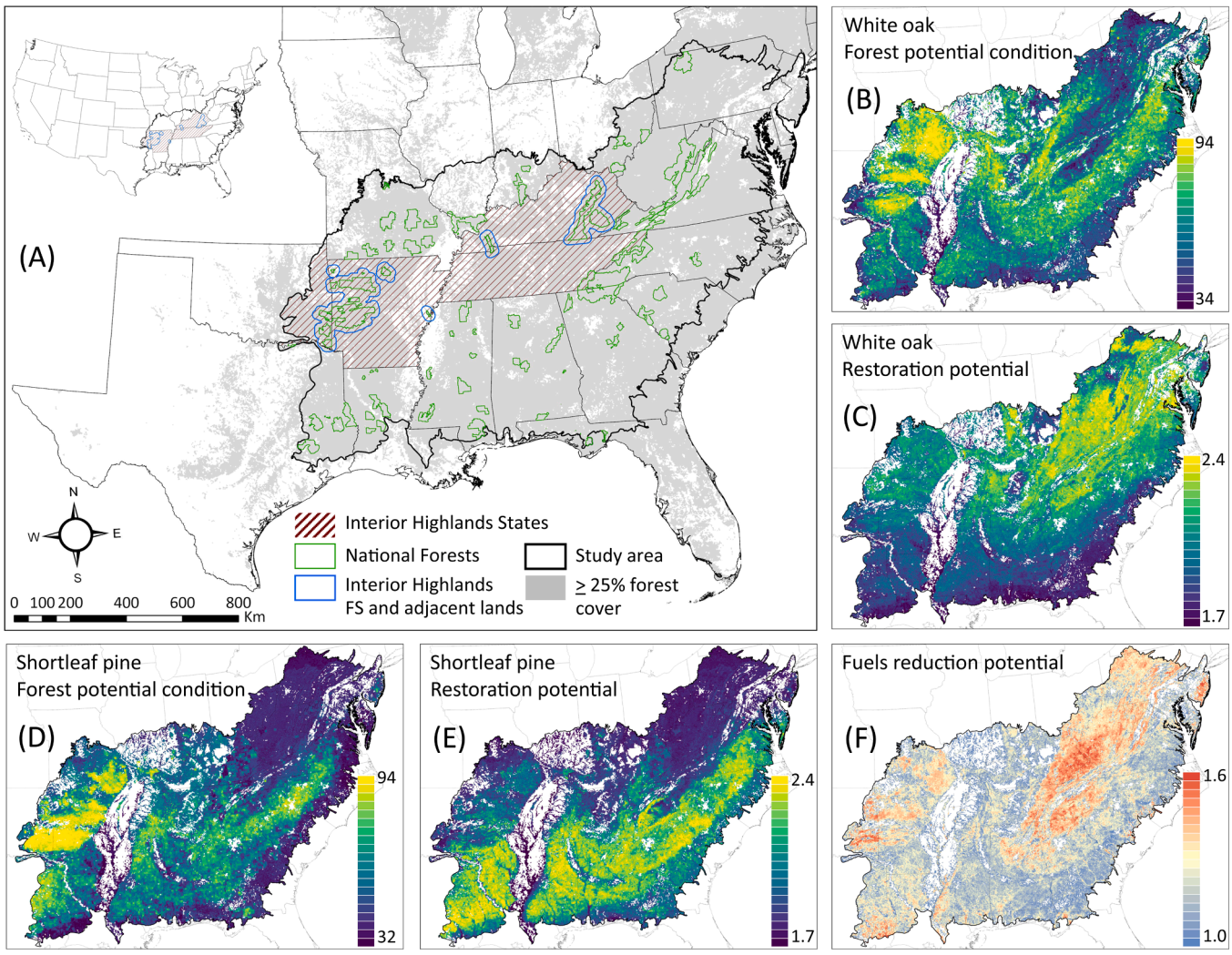


Fig. 2. Study area and input variables for spatial optimization. (A) The full ecoregion-defined study area included most of the ranges of shortleaf pine and white oak, covering parts of 23 states in the eastern United States. Landscapes with at least 25% forest cover were included in the analysis. Spatial prioritization was conducted for five nested areas of interest (AOI): (1) the entire study area; (2) the four Interior Highlands states; (3) Oklahoma and Arkansas; (4) Kentucky and Tennessee; and (5) National Forest System-managed lands in the Interior Highlands states and surrounding lands within 10 miles (16 km). (B-F) Inputs for spatial optimization included white oak and shortleaf pine potential forest condition, white oak and shortleaf pine restoration potential, and fuels reduction potential. Unitless index values are results from Bayesian network models: (B, D) high values indicate high model-predicted forest condition, assuming sustained management with site-appropriate silviculture and prescribed fire; (C, E) high values indicate high model-predicted potential to improve forest condition from current condition, through sustained management; (F) higher values indicate greater potential for fuels reductions to reduce wildfire risks.

are engaged in scenario planning, they are encouraged to envision that scenarios represent plausible plans for the future, and that actions consistent with particular scenarios would advance a particular kind of future (Oteros-Rozas et al., 2015; Peterson et al., 2003). Scenario planning is flexible as it encompasses qualitative information from stakeholders' knowledge of ecosystem management and combines that with quantitative data to formulate plausible future conditions (Miller et al., 2023).

In a spatial prioritization context, this also involves defining scenario features such as the spatial extents across which prioritization occurs (Fig. 2A, areas of interest) and spatial constraints on management efforts such as road access or preferences for contiguity of project areas. Scenarios can investigate trade-offs among objectives at different spatial extents or scales (Shavazipour et al., 2022). Spatially explicit prioritization outputs under different scenarios can be used to communicate diverse opportunities to stakeholders, providing planning flexibility under future uncertainties (Ager et al., 2021).

We conducted structured workshops to provide space for a broad group of stakeholder participants to engage in a formal scenario building process. Two virtual workshops were planned to focus on the four states within the IH subregion. The advisory group members and IH subregion coordinator used their established partner networks to develop a list of workshop invitees. The goal was to have diverse representation from NFs, state agencies, regional NGOs and other stakeholders. National Forest staff were a particular focus due to the intent of science delivery for the IH implementation plan.

Before the workshops, we sent preliminary documents to participants to establish overall goals, structure, and scope of the workshops to familiarize each participant with the nature of the project, what to expect, and how to maximize their involvement (AlWaer and Cooper, 2020). We also sent out a pre-workshop questionnaire with questions relating to how management goals are prioritized and various landscape-level constraints that could affect where forest management investments are made. Participants were asked to return the questionnaire a few days before the workshop.

Advisory group members and team scientists facilitated workshop sessions and recorded discussion notes. The science team provided a review of the analytical approach, data used in models, and model

results showing the distribution of landscapes with high potential to advance the restoration and risk reduction goals through active management (Fig. 2). The team provided strawman results illustrating how outcomes from the workshop could be used to develop scenarios, and how spatial prioritization under different scenarios could vary.

Next, participants were divided into small groups for discussion, with each group having representatives from various organizations. The responses from completed questionnaires helped to start discussions. Each group discussed the relative importance of the three management objectives and the different proposed areas of interest (Fig. 2). Constraints on active management investments under discussion included total area targeted for management on a five-year time horizon, ease of working with different partners across boundaries, and operational concerns such as smoke emissions from prescribed fire. A spatial contiguity constraint was discussed to clarify if management could occur where it is most needed even if targeted landscapes are widely dispersed, or if spatial contiguity was preferred for operational efficiency or ecological connectivity. Workshops concluded with a summary of the key ideas and planning for next steps in the collaborative engagement.

2.3.1. Implementing workshop outcomes

Planning scenarios were formulated from combined results of completed questionnaires and the workshop sessions, including clarification of questionnaire answers in light of workshop discussions. We developed a set of quantitative scenarios to represent the range of participant preferences for objective weights and constraints, then ran a spatial optimization analysis under each scenario. We used an optimization approach coded in R (R Core Team, 2023) that is computationally similar to ForSys, a spatial, multi-objective optimization platform that has been widely used for forest management planning (Ager et al., 2021; Day et al., 2023). The approach maximizes an objective function that is a weighted linear combination of the values contributed towards each of the management objectives in a given landscape, subject to constraints imposed in a given planning scenario (Ager et al., 2017). For spatial contiguity constraints we used image segmentation (Achanta et al., 2012; Mouselimis et al., 2023) to partition the area of interest into local landscape clusters based on homogeneous objective function values unique to each scenario, then clusters were ranked by their area-standardized values. We used rankings to generate prioritization maps in terms of how well forest landscapes or landscape clusters met management goals, under the parameters of each scenario. We also used results to generate trade-off curves among the objectives and suggest alternatives that could minimize trade-offs.

2.3.2. Science delivery

Two semi-structured follow-up workshops were organized by the IH subregion coordinator and the research team with the goals of (1) sharing how scenario planning inputs from the previous workshops were used in spatial prioritization analysis, (2) reporting analysis results and familiarizing participants with spatial data products, and (3) collecting additional feedback to help finalize results reporting. Participants were expected to discuss how outcomes from the analysis could be used for project planning, identify challenges in the interpretation and use of the products, and discuss ways to make the data products more widely available to potential end-users.

3. Results

3.1. Initial engagement and advisory group

Early engagement with FS partners was critical for determining broad project goals and an appropriate research framework. Weekly initial project meetings included staff from the Southern Geographic Area (SGA) Fire and Aviation Management (FAM), Southern Region Regional Information Management (RIM), and Planning program areas, with the IH subregion coordinator playing a key role in discussions. The research team also attended larger Southern Region meetings focused on better integrating landscape-level planning across program areas, including subregional implementation plans. Early consensus emerged that to be regionally relevant, assessment of restoration opportunities should include all forest lands across all or most of the distributions of shortleaf pine and white oak, and a landscape-level spatial assessment would be appropriate for broadscale planning at 5- to 10-year timeframes. To meet the IH subregion's science need to identify high-priority landscapes, a multi-objective spatial optimization emerged from discussions as an approach to rank landscapes in terms of needs and opportunities for white oak and shortleaf pine restoration as well as wildfire risk mitigation in an integrated way.

The advisory group was composed of Southern Region and SGA staff including representatives from FAM, RIM, and Planning program areas; a representative for the FS Eastern Region; and external partners including the White Oak Initiative (WOI) and the Southern Group of State Foresters. Regular bi-weekly meetings with the advisory group provided expert input on data selection for ecological restoration models, helped structure the relationships among the various model components including the likely influence of management decisions on forest conditions, and provided feedback on model outputs. A workshop-based approach for scenario planning emerged from group discussions, and advisory group members helped plan and run the workshops. This included identifying and contacting appropriate participants, facilitating the workshops, and interpreting and refining outcomes to make appropriate decisions for the subsequent spatial prioritization work. Feedback from the advisory group at each stage of the research helped to ensure management relevance and that the analyses addressed workshop participants' preferences. The advisory group also remained involved in science delivery by reviewing spatial data products, interpretive materials and reports, and distributing these through their own networks and relevant professional engagements.

3.2. Scenario planning workshops

Workshop participation from the IH NFs included district rangers, forest supervisors, ecologists, silviculturists, forest planning staff, and State, Private and Tribal forestry program representatives. State agencies with representation included Tennessee Division of Forests and Kentucky State Natural Preserves. Other participants included representatives from the Central Hardwoods Joint Venture, the White Oak Initiative, the Shortleaf Pine Initiative, and the Nature Conservancy. There were 46 participants excluding workshop facilitators - 20 for a first workshop focused on Arkansas and Oklahoma held on March 26, 2025, and 26 for a second focused on Tennessee and Kentucky held on April 29, 2025. We received 15 complete questionnaire surveys ahead of the workshop sessions. We combined the results from the two workshops and the questionnaires to provide a fuller picture for the entire IH subregion.

3.2.1. Planning area extents

Among the different spatial areas of interest, participants ranked National Forests and adjacent landscapes more highly than other, larger AOIs (Fig. 3A). This partly reflected the NF-dominated composition of participants, but also reflected acknowledgement among participants of the importance of good cross-boundary partnerships and management activities, especially near National Forests where restoration potential was high. Strong preferences were not shown across the remaining areas of interest, but based on the questionnaire responses, the 4-state IH subregion ranked slightly lower than states or the broadest ecoregion-defined AOI.

3.2.2. Objective importance

In workshop discussion and in the completed questionnaires, participants prioritized restoration objectives over wildfire risk reduction for broad scale planning, even while the importance of fuels

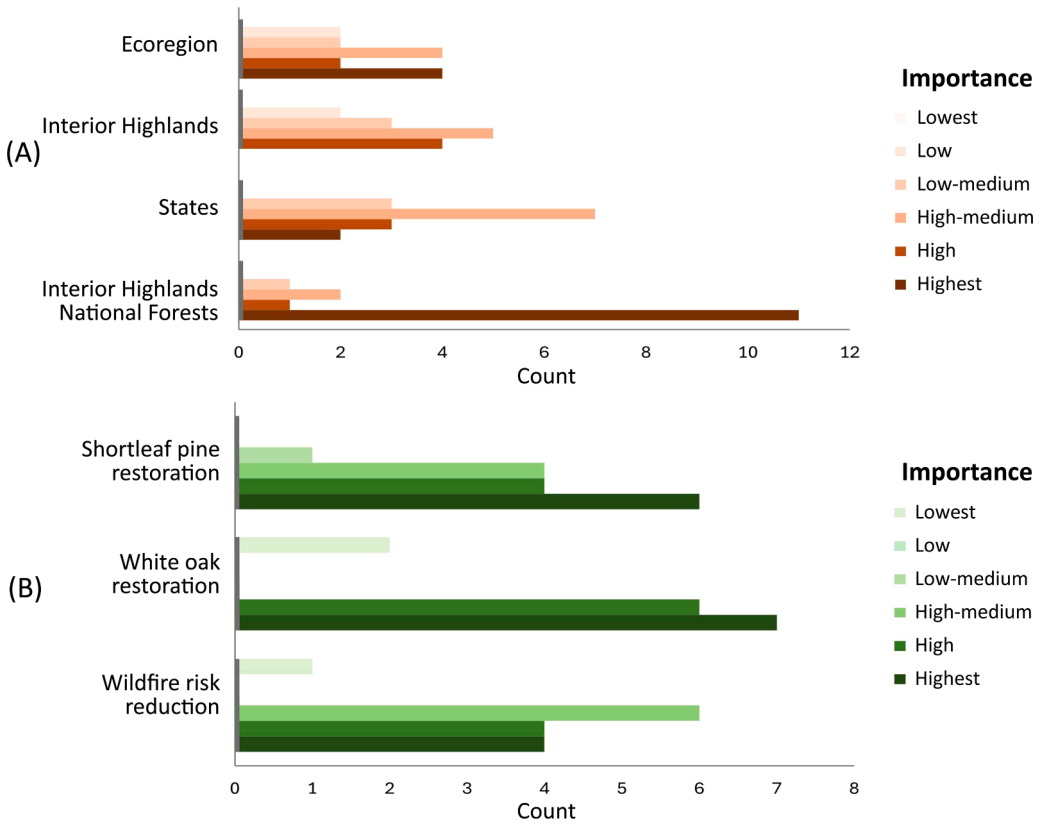


Fig. 3. Importance rankings for different (A) areas of interest and (B) management objectives based on questionnaire surveys given to workshop participants. Respondents were asked to rank the relative importance of the AOIs and objectives for broadscale planning purposes from 0 to 5, where 5 indicated greatest importance. Count (x-axis) is the number of respondents who assigned a given value. Results were combined with information gathered during workshop discussions to help build planning scenarios.

management was recognized (Fig. 3B). Participants gave white oak restoration higher priority than shortleaf pine restoration overall, particularly in Kentucky. Reasons included economic considerations around white oak production, concern that white oak has been in strong decline, perceived progress with shortleaf pine restoration in recent years making white oak a logical priority now, and a perception that private landowners may be more likely to support white oak than shortleaf pine restoration. Participants ranked direct risk to people and infrastructure as the most important wildfire risk for planning purposes, followed by risk to important watersheds, risk of smoke exposure, and finally the risk to forest carbon stocks. There was consensus on the importance of defending life and property in the wildland-urban interface.

3.2.3. *Spatial constraints*

Regarding specific target areas (i.e., the amount of forest land within a given AOI to identify as high-priority, and within which to further prioritize), participants recognized both realistic constraints on institutional capacities and strong uncertainty about the future. Participants preferred to target more area for assessment than recent prescribed fire and timber management acreage estimates (on an annual basis, extrapolated to 5-year averages), including those within the IH NFs. Reasoning followed the idea that keeping the assessment broad with larger planning areas provides more flexibility and options, and a high upper limit is useful in the event that future years provide more opportunity than expected for active management accomplishments.

Participants generally favored spatial clustering of priority landscapes to gain operational and logistical efficiency and ecological benefits of broad-scale connectivity. Discussion on landscape connectivity and clustering mainly concerned uncertainty in identifying the best landscape cluster size for different scales of analysis. Thus, there was broad agreement on the utility of clustering, but specific cluster sizes were not resolved during the workshops.

Interest was also expressed in constraining high priority landscapes to be near other landscapes with potentially good conditions for the forest type in question (white oak or shortleaf pine)—a constraint that we labeled *spatial context*. Reasons included ecological connectivity and that many such areas were likely to already have management programs in place, creating logistical efficiencies, or what one participant termed 'building on the good'. The spatial context constraint was not evaluated in the pre-workshop questionnaire or prompted by facilitators but was expressed by participants during the initial workshop. Once expressed, it was broadly supported. Finally, road access was supported as an important landscape-level operational constraint and one that could be evaluated with regionally consistent spatial data.

3.3. *Spatial optimization scenarios*

After summarizing workshop results, the final ranges of scenario parameters we included in planning scenarios were expert-driven, determined through interaction between the science team and the advisory group to be representative of participant preferences (Table 1). We generated a set of 46 plausible scenarios, to be run across the 5 AOIs, for a total of 230 scenarios (Table 2). In science delivery (project reporting, science delivery workshops, spatial data products), we further emphasized scenarios that were most representative of participant preferences and that best illustrated general results across scenarios (Table 1), given the large number of scenarios to interpret. Full results were included in products.

Objective importance was weighted towards the two restoration objectives both singly and combined (Table 2). Scenarios including the wildfire risk reduction objective with either full or half weight were also

Table 1
Value ranges for planning scenario components based on workshop participant preferences. Values given = range of values across which a component was varied in different scenarios. Reporting emphasis = emphasis placed on scenarios with particular values, in formal and informal results reporting to stakeholders.

Scenario component	Values given	Reporting emphasis
Area of interest (AOI)		
	IH NFs and surrounding lands	Yes
	Interior Highlands, all forest lands	Yes
	Full study area (ecoregion based)	Some
	AR and OK, all forest lands	No
	KY and TN, all forest lands	No
Target acreage		
	Top 5% of AOI, Top 25% of AOI	Both
Objective	**Weight**	
White oak	1, 0.5, 0	Yes
Shortleaf pine	1, 0.5, 0	Yes
Wildfire risk reduction	1, 0.5, 0	Some
Constraint		
Spatial clustering	Mean cluster size = 20,234 ha (50 K acres)	Yes / No
Spatial context	No (weight = 0), Yes (weight = 0.15)	Yes
Road access	Within 0.8 km (0.5 miles); No limit	No

evaluated, but no scenario considered risk reduction in isolation. Estimated wildfire risk was based only on direct risks to people and infrastructure and important watersheds combined. Target areas were set to 5% and 25% of total forest area in each AOI. However, rather than double the number of scenarios based on varying target areas, we chose to make all landscape rankings available in data products for comparison, while recommending that most users restrict map data to these key percentages. Similarly, a landscape cluster size of 20,234 ha (50,000 acres) was used in all scenarios, but solutions with no clustering were also made available for comparison. Scenarios were developed with and without the spatial context constraint in place, using a weight of 0.15 to favor landscapes in a spatial neighborhood of other good-condition landscapes, but not as an absolute constraint. Finally, a road access threshold was set at 0.8 km (0.5 miles) mean distance from the nearest road, and scenarios with and without the road access constraint were included.

3.4. Scenario outcomes

We present here example outputs from spatial optimization for the IH subregion under a few key scenarios to illustrate the consequences of varying scenario weights and constraints. Fig. 4(A) shows optimization results for three primary scenarios: one in which white oak restoration potential is the only objective considered (Table 2, Scenario 1), a similar scenario for shortleaf pine alone (Scenario 2), and a third in which both of those objectives are given equal weight (Scenario 3). The spatial distribution of high-priority landscapes for the two species varied considerably, and when jointly optimized with equal weights the spatial distribution was substantially different than when optimized separately. Fig. 4(B) shows a substantial spatial tradeoff between white oak and shortleaf pine restoration opportunities across all forest lands in the IH states, consistent with the differing distributions of restoration opportunity for the two species.

Workshop participants gave greater importance to ecological restoration than wildfire risk management, largely favored incorporating landscape connectivity into prioritization, and there was an interest in the landscape context constraint. Therefore, as a baseline scenario, we used equal weights for white oak and shortleaf pine, and included the landscape clustering and spatial context constraints. Fig. 5 illustrates how different scenario components altered spatial outcomes relative to the baseline scenario (Fig. 5A). Adding the wildfire risk reduction goal (Table 2, Scenario 6) caused a shift in priority to a few large-landscape areas and away from others (Fig. 5B), following clearly from the wildfire risk data (Fig. 2F).

Removing the spatial context constraint from the base scenario caused a strong eastward shift in priority in the IH states (Fig. 5C). When spatial clustering was not enforced, landscape rankings shifted locally but the broad distribution of priority landscapes was not strongly affected (Fig. 5D). This appeared to represent a local-scale tradeoff between restoration optimality and the operational and ecological benefits potentially offered by spatial clustering. The road access constraint (not shown) had a negligible effect. Road density in the IH subregion is high, so that only a few landscapes were excluded under the road access constraint. This implies that broadscale landscape analysis may not need to account for road access in the study region, but this and other similar

Table 2
Planning scenarios generated through advisory group engagement and formal scenario planning workshops. Each scenario was evaluated for five areas of interest (AOIs; Fig. 1). Target area was set to 5% and 25% in each AOI, and spatial clustering was used in each scenario. WO, SLP, and Fuels = weights assigned for white oak restoration, shortleaf pine restoration, and wildfire risk reduction potentials, respectively. Spatial context = constraint that priority landscapes be near other landscapes with good potential condition for the WO and SLP objectives included in the scenario. Road access = constraint that priority landscapes be near roads.

Scenario ID	WO	SLP	Fuels	Spatial context	Road access constraint
1	1	0	0	Yes	No
2	0	1	0	Yes	No
3	1	1	0	Yes	No
4	0	1	1	Yes	No
5	1	0	1	Yes	No
6	1	1	1	Yes	No
7	1	1	0.5	Yes	No
8	0	1	0.5	Yes	No
9	1	0	0.5	Yes	No
10	1	0.5	0	Yes	No
11	0.5	1	0	Yes	No
12	1	0	0	No	No
13	0	1	0	No	No
14	0	0	1	No	No
15	1	1	0	No	No
16	0	1	1	No	No
17	1	0	1	No	No
18	1	1	1	No	No
19	1	1	0.5	No	No
20	0	1	0.5	No	No
21	1	0	0.5	No	No
22	1	0.5	0	No	No
23	0.5	1	0	No	No
24	1	0	0	Yes	Yes
25	0	1	0	Yes	Yes
26	1	1	0	Yes	Yes
27	0	1	1	Yes	Yes
28	1	0	1	Yes	Yes
29	1	1	1	Yes	Yes
30	1	1	0.5	Yes	Yes
31	0	1	0.5	Yes	Yes
32	1	0	0.5	Yes	Yes
33	1	0.5	0	Yes	Yes
34	0.5	1	0	Yes	Yes
35	1	0	0	No	Yes
36	0	1	0	No	Yes
37	0	0	1	No	Yes
38	1	1	0	No	Yes
39	0	1	1	No	Yes
40	1	0	1	No	Yes
41	1	1	1	No	Yes
42	1	1	0.5	No	Yes
43	0	1	0.5	No	Yes
44	1	0	0.5	No	Yes
45	1	0.5	0	No	Yes
46	0.5	1	0	No	Yes

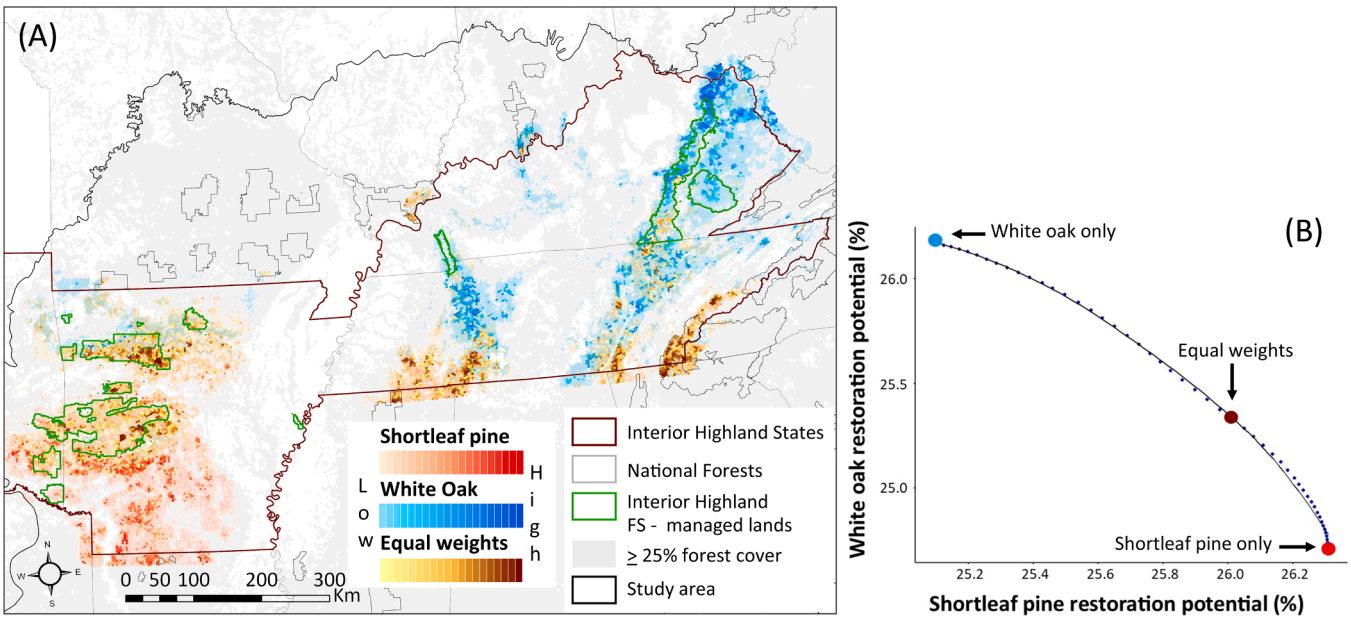


Fig. 4. High-priority landscapes for white oak and shortleaf pine restoration across the Interior Highlands subregion states, optimizing for the two species separately and combined (with equal weight). The three scenarios shown here included a landscape context constraint for proximity to other landscapes with high potential condition. (A) The top 25% priority landscapes are shown for each scenario, with darker tones showing higher priority. (B) Tradeoff curve between white oak restoration and shortleaf pine restoration shows maximum obtainable values when optimized alone, at the extreme left and right of the plot. A center point shows the outcome under the equal-weights scenario. A flatter curve suggests greater tradeoff between the objectives.

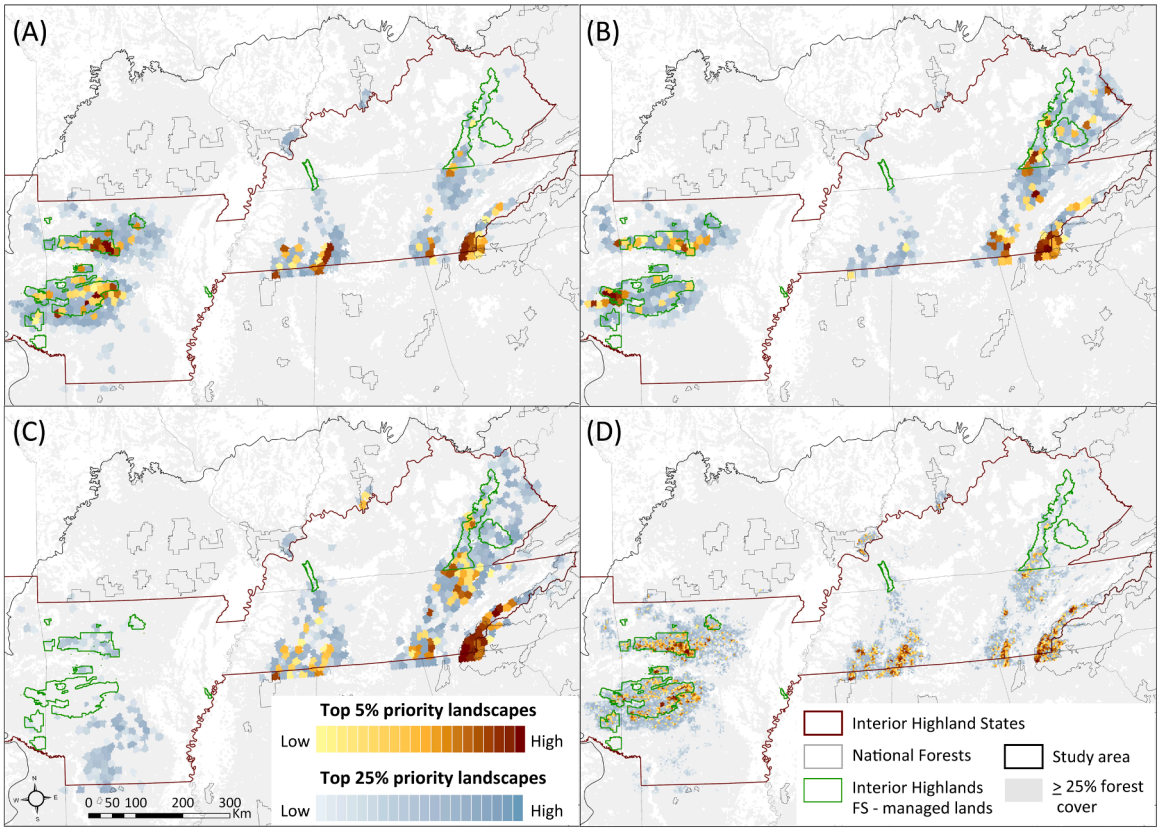


Fig. 5. High-priority landscapes for white oak and shortleaf pine restoration across the Interior Highlands subregion under different constraints. (A) Base scenario with equal weights for white oak and shortleaf pine restoration taking into consideration proximity to other landscapes with high potential condition (i.e., the landscape context constraint) and spatial clustering of landscapes; (B) adding the wildfire risk reduction objective to the base scenario; (C) removing the landscape context constraint from the base scenario; (D) removing the spatial clustering constraint from the base scenario.

operational constraints are likely to remain important at finer spatial scales.

3.5. Post-analysis science delivery

We conducted two additional workshops on February 18, 2026, and March 11, 2026, as project delivery sessions to provide an overview of the analysis and share data products. The sessions were focused on internal partners within the FS and more than 60 participants attended from all four IH NFs including forest leadership, staff officers, GIS experts, forest managers and other specialists. Spatial data products containing the results of all scenarios were made available to all participants, and visualized in a pre-workshop report and during workshops. In the first workshop, participants discussed how the outcomes of the analysis could be used for ongoing and future projects within the IH, and discussed the potential of the data products as a coordinating tool with external partners around shared restoration goals. This was followed by two office hour sessions when users were invited to discuss technical questions about interpretation and use of the data products. The final workshop followed these sessions and included both unstructured time for feedback and a participant-led sandbox session using prepared combinations of the data products with additional participant-curated planning data in selected geographic areas to examine relationships among the datasets in a group discussion setting.

4. Discussion

4.1. Effectiveness of collaborative planning

Integrating forest management stakeholders in a scientific process to provide planning-relevant information had a significant influence on all aspects of the research. Although this influence may be impossible to fully quantify, we suggest that it improved both the relevance and the quality of scientific outcomes (Long et al., 2014). Sharing data, analytical frameworks, and other project information with a diverse group of stakeholders helped them to visualize and critique the applicability of analyses and findings to resource management. Our collaborative planning was not a rigidly structured process but was made up of activities that were iterated and changed in response to a series of feedbacks. Over time, our advisory group involved different participants, each with a different contribution based on individual and institutional perspective and expertise. Through regular meetings, experts not only helped with research planning but also engaged in ongoing discussions that influenced the analysis. The advisory group also improved workshop engagements by providing expert guidance and diverse perspectives, helping achieve meaningful outcomes. The workshops would not have been successful without involvement from the IH coordinator, and participation was broadened through engagement with outside partners including the WOI who helped recruit participants we might not have otherwise engaged. Participants came together to work on a scale larger than their typical forest, management unit, or research domain to support broader landscape level forest management planning. Participants were open to collaboration across federal and state agencies and other conservation organizations, and while not quantified, this engagement worked towards a shared vision for restoration priorities and shared investment in the ensuing scientific process and its outcomes (Long et al., 2014; Smith et al., 2022; Walpole et al., 2017).

A primary goal of our research was to provide ecologically informed spatial information that can help planners identify priority areas for ecosystem management, including restoring forests with high conservation value in the study region. While it is too early to know how findings from the spatial prioritization may impact future decision-making, there is reason to believe that such impact is made more likely by the collaborative nature of the project. Beyond initial public availability of spatial products and direct delivery to NF partners, one of the most tangible results of collaborative engagement was enhanced visibility of the products to a growing community of engaged partners. This growth has led to multiple science delivery opportunities initiated by partners. For example, advisory group and workshop interactions led to subsequent science delivery opportunities with non-FS partners through both the WOI and the Shortleaf Pine Initiative, both of whose memberships comprise multiple state, federal, and non-governmental conservation and forest management entities. Both initiatives invited project members to present results at several virtual and in-person initiative-led meetings, share data products with their networks, and maintain institutional interactions to facilitate broader awareness of the project. These interactions have led to new engagement with individual organizations involved in regional forest restoration planning. Similarly, participation in the project advisory group and workshops by National Forest System resource management staff outside the IH subregion led to unanticipated engagement with NFs in the northern tier of our study region.

4.2. Scenario planning

The use of scenario planning in this study is consistent with systems thinking, data analytics, and prescriptive intervention to improve understanding of the relationships among system components likely to drive outcomes—ecological restoration and wildfire risk reduction—under realistic constraints, helping identify opportunities to make resource management more efficient and effective (Ager et al., 2021; Bowes and Krutilla, 1985). Collaborative engagement through the advisory group and workshops generated a collection of planning scenarios different from those the research team would have arrived at alone, to better address the diverse concerns of forest planners. The resulting prioritization outcomes were tailored to provide a range of spatial planning options bracketing both future uncertainties and a diversity of management goals. Uncertainties can arise from policy, budget, and staffing changes, as well as shifting forest disturbance regimes due to climate change, wildfire, forest management changes and other drivers (Price et al., 2016; Spies et al., 2010). And despite broadly shared forest management goals, specific planning priorities inevitably vary geographically. An expectation in scenario planning is that it can help navigate such uncertainties and differences, and foster adaptive strategies that are resilient to unexpected events, by exploring multiple possible futures under a clear set of assumptions (Schüll and Hoogstra-Klein, 2017). In this study, the collaborative scenario planning process led the science team to embrace a strategy wherein a wider diversity of scenarios than initially expected was generated to capture diverse participant preferences. This also required results interpretation to emphasize a smaller group of core scenarios that best reflected the most widely shared preferences and commonalities in results across scenarios—while still providing full results to end users. We argue that while the collaborative dimension of this process added considerable complexity to the project, it advanced the scenario planning goals to (a) support flexible planning under uncertainty and management goal diversity and (b) focus applied research on broadly shared natural resource management needs.

4.3. Challenges and limitations

Implementing a co-development strategy to bring stakeholders together for consensus building was not a straightforward process. Extended project timelines can be expected for research that includes meaningful co-development. Relationship-building leading to project initiation and assembling the advisory group occurred in stages across the first project year. Scenario planning workshops then occurred after several months of coordination and unexpected delays, and science delivery workshops occurred one year later, after analysis and additional coordination. Group dynamics can also present communication challenges among researchers, managers and field staff—some of which can be attributed to the pre-existing work cultures within which these groups often operate. Smaller sessions with separate groups (state agencies, NFs, NGOs) with more interactive and personalized engagement may provide better response from participants, while larger groups

can help bridge communication divides. The virtual format of our sessions could also have impacted engagement. Finally, personnel turnover occurred during the project, which can require time investment in new relationship-building and may cause priorities to shift.

This study offers a multi-scale optimization that can help decision-makers evaluate potential restoration opportunities for different areas of interest in the region. However, identifying the most appropriate scales of analysis was a challenge. Our analysis is tailored to larger landscape scales, and we ran our spatial models at a moderately broad spatial grain (1000 ha landscapes). Many workshop participants had strong interest in restoration-focused planning tools with operational relevance at finer spatial scales than the project was designed to address. This tension highlights scale mismatches in the interests and needs of different partners. Our initial key partners at the earliest project development stages were primarily FS staff with regional planning and coordination responsibilities, and we made an early decision to provide scientific support for broadscale strategic planning rather than fine-scale operational planning. In contrast, many workshop participants held more local resource management responsibilities. The adaptation of our approach to finer scales would require different parameterization based on the operative variables and causal relationships that prevail at those scales. Ideally, broadscale and fine-scale prioritization tools can be coupled in stepped processes that first assess landscape-level options then assess local or management unit-level operational options, with scale-appropriate objectives and constraints considered at each stage (Felton et al., 2020; Hof et al., 2024).

We used an all-lands approach for spatial prioritization in this study. All-lands approaches seek to transcend jurisdictional boundaries to restore and maintain forests through collaborative work. Such approaches must accommodate a wide range of landscape and institutional conditions, and the challenges to implementation are clear, but the needs are also clear (Charnley et al., 2017). Fig. 6 shows how prioritization outcomes were distributed across private and public (federal, state, local) forest ownership types under key scenarios. High-priority landscapes were mostly under private ownership, but relative to general forest ownership patterns in the IH subregion, public lands provided restoration opportunities disproportionately to their size. It is also apparent in Figs. 4 and 5 that high-priority public and private forests were frequently adjacent. This confirms the importance of considering both public and private forests for restoration activities in the region, as well as the need to promote cross-boundary restoration activities.

Generating shared scientific resources for collaborative management and planning on a large scale can be difficult when management goals vary across ownership and institutional boundaries and in different land use types such as the wildland-urban interface vs. more remote or intact conservation areas. Our scenarios were tailored towards specific ecosystem types and specific management strategies (prescribed fire and silvicultural treatments); thus, they do not represent the full range of possible future options or outcomes for all stakeholders. Further, all-lands approaches may not be economically efficient, may not account for spatial complexities within the landscape, and there may not be sufficient human resources for consistent management across different ownership types (Kelly et al., 2019). Our prioritization analysis was based on landscape ecological conditions without detailed economic or institutional constraints. Finally, our aim was to bring varied partners to establish institutional connections and work on shared goals across the broader landscape. However, participation from external partners was less than from internal FS partners, introducing potential bias in the preferences that shaped the planning scenarios. Nevertheless, the spatial data products provide planning materials that are relevant for all-lands collaboration crossing administrative and ownership boundaries, and the multi-scenario portfolio provides flexibility to partners with potentially varying priorities.

5. Conclusion

We undertook a structured collaborative process to model ecological restoration opportunities and generate realistic planning scenarios for spatial prioritization at broad landscape scales. Our aim was to use a collaborative approach in a transparent manner to improve the scientific process and management-relevant science delivery. This approach provides an example of science and management collaboration despite administrative, budget, organizational and cultural differences and challenges. Collaborative engagement is critical for bridging researcher-manager divides, providing better understanding of the needs of diverse stakeholders, and providing a platform to share scientific outcomes (Dey and Schuler, 2020). It can help bridge local and regional agencies so that results from regional scale analysis can be shared and used at local levels

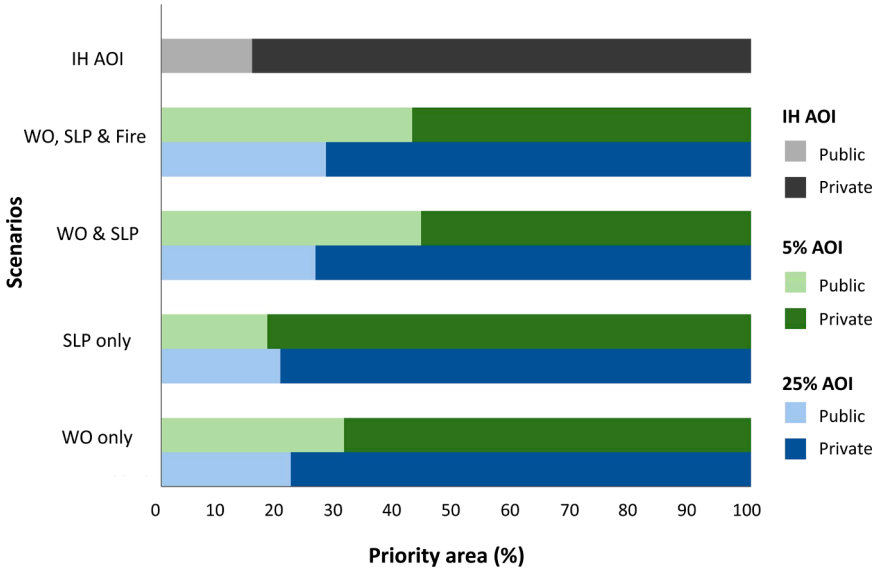


Fig. 6. High-priority landscapes on privately and publicly owned forest lands in the Interior Highlands area of interest (IH AOI) under four key scenarios. High-priority landscapes occurred disproportionately on public forest lands, relative to the scarcity of public lands in the region. The top bar shows overall forest ownership in the IH AOI. Scenarios included the white oak (WO) restoration objective only (Scenario 1 in Table 2), Shortleaf pine (SLP) restoration only (Scenario 2), equal weights on both species (Scenario 3), and adding the wildfire risk reduction objective (Scenario 6). Ownership percentages are shown for the 5% and 25% highest priority landscapes.

of management. Planning systematically at broader regional scales and implementing management activities at the most appropriate scales, informed by nested assessments and collaborative engagement at different scales, can be a key approach for managing broadly distributed resources around shared values.

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CRediT authorship contribution statement

Sandhya Nepal: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Nicholas P. Gould:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Brett W. Williams:** Writing – review & editing, Investigation, Funding acquisition. **Amy Nathanson:** Writing – review & editing, Investigation. **Lars Y. Pomara:** Writing – review & editing, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data inputs used in this study are available in ArcGIS online repository (AGOL) of USDA Forest Service. They can be found by searching for White oak forest restoration opportunity landscapes, Shortleaf pine forest restoration opportunity landscapes, and Southern Region (R8) Risk Analysis.

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