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RESEARCH ARTICLE

Qualitatively assessing trade-offs and co-benefits at local scales when considering carbon outcomes among other management goals

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Abstract

1. Natural and working lands are often touted as natural climate solutions due to their ability to take up and store carbon, and land managers are increasingly tasked with considering how management actions impact carbon outcomes alongside other management goals. As a result, there is a need to assess how management actions may drive trade-offs and co-benefits between multiple management goals. However, quantitative analysis of trade-offs is not feasible for many local-scale management projects.
2. We used a case study in an oak savanna in south-eastern Wisconsin, U.S.A. to develop and test a framework for qualitatively analysing local-scale trade-offs.
3. Our framework is built on five pillars that guide the rigorous and qualitative analysis of trade-offs between carbon and other management outcomes. This framework is intended to be flexible for use by natural resource professionals working across diverse landscapes and management goals.
4. *Practical implication*: Our work highlights how the principles of knowledge co-production, climate adaptation, and carbon stewardship can be integrated with one another into effective land management planning.

KEYWORDS
carbon management, climate adaptation, co-production, oak savanna, trade-offs

1 | INTRODUCTION

Undeniably, the effects of climate change on natural and working lands are widespread and intensifying (Calvin et al., 2023). In response, the explicit consideration of management practices for climate change adaptation has grown in recent years in the United States (Jay et al., 2023). Simultaneously, emphasis on managing lands for carbon benefits and greenhouse gas emissions mitigation has increased (Fargione et al., 2018; Seddon et al., 2020). In addition to these climate-related goals, lands are commonly managed for a suite of other benefits such as biodiversity, recreation, provisioning of timber and food, promoting healthy ecosystem functioning such as clean water, and cultural amenities, among others. As a result, land management planning today often requires integrating long-standing management goals and practices with the more recent focus on carbon and climate change mitigation.

While management goals vary across different lands, an increased attention to carbon benefits—as codified in state and federal agency guidelines and as a focus among private landowners and the general public—means natural resource professionals are facing the common challenge to understand and assess the trade-offs and co-benefits that may arise when managing for carbon benefits alongside other goals (Littlefield & D'Amato, 2022). To address this challenge, data-intensive, quantitative and coarse-scale (e.g. regional and global) spatial analyses of trade-offs are becoming more prevalent (Bayer et al., 2023; Brandt et al., 2014; Girardello et al., 2019; Lecina-Diaz et al., 2018). However, land management planning and practice commonly occur at smaller scales (e.g. stand level) and trade-offs can manifest differently at local compared to broader scales (Blumstein & Thompson, 2015; Sabatini et al., 2019). Still, there remains a lack of practical guidance for assessing the implications of multiple goal management at local scales.

Unique challenges exist for evaluating local-scale carbon trade-offs. There is often a lack of existing site-specific data to leverage for assessing the effects of specific management activities on local-scale carbon cycling. While remotely sensed data are increasingly available for diverse metrics at increasingly smaller spatial resolutions, processing such data requires a high level of specific expertise and capacity (both in time and computing power) that is rarely available to land managers (Cooper & MacFarlane, 2023). Models and tools to address the need for local scale quantification of management effects on carbon are improving but fall short in effectively assessing the impacts of complex management or restoration activities (Hanson et al., 2024). As a result, land managers are increasingly seeking guidance on how to consider local scale carbon benefits and associated trade-offs barring quantitative analysis.

In response, here we present a framework to guide managers through the process of qualitatively characterizing the trade-offs and co-benefits that emerge when managing for carbon benefits alongside other goals at local scales. This framework is intended to be integrated into a broader planning process for climate adaptation. For example, as we demonstrate below, the Adaptation Workbook (AW) is a well-developed five-step process that guides natural resource managers in how to consider climate change in management planning (Swanston et al., 2016) and can be expanded upon to examine carbon trade-offs (Ontl et al., 2020). As illustrated here, we tested our framework for assessing trade-offs with a case study in a temperate oak savanna where management goals included maintaining or increasing (1) plant biodiversity and (2) carbon uptake and storage.

Our framework emphasizes the principles of carbon stewardship and co-produced knowledge. Carbon stewardship is a way of thinking about management that encompasses the intentional assessment of carbon effects while recognizing that carbon storage is only one of many ecosystem benefits. Therefore, carbon stewardship focuses on the *optimization* rather than the *maximization* of carbon benefits. Carbon stewardship also recognizes that carbon benefits can be realized over varying timescales, from a few years to many decades and can be achieved via carbon uptake (i.e. sequestration) and/or carbon storage in one or more ecosystem carbon pools (e.g. aboveground biomass carbon, litter carbon, soil carbon). Our framework also integrates relevant scientific research with local knowledge to qualitatively assess trade-offs, which has the added benefit of enhancing dialogue between the research and practitioner communities (Nel et al., 2016). While new data collection could supplement this process, the flexible guidance we present here is intended to be used by a broad suite of practitioners on projects where additional field work and quantitative assessment of trade-offs is not feasible.

2 | CASE STUDY: THE NEWELL AND ANN MEYER PRESERVE TEMPERATE OAK SAVANNA, WISCONSIN, USA

2.1 | Study site and project team

We used The Nature Conservancy's (TNC) Newell and Ann Meyer Preserve (hereafter, Meyer Preserve) as a case study for qualitatively assessing local scale trade-offs when considering carbon outcomes among other management goals. The Meyer Preserve, a 653-acre property located in the Mukwonago River Watershed in south-eastern Wisconsin, USA (42°51′18″ N, 88°30′32″ W), encompasses oak savanna and woodlands, non-forested wetlands and mesic prairies (Wisconsin Department of Natural Resources, 2015; Figure 1). Here, we focus on the management of oak savannas and woodlands. At the study site, mean annual temperature is 8.7°C, with the warmest and coldest average daily temperatures coming in July (22.1°C) and January (−6.3°C), respectively. Mean annual precipitation is 946.4 mm, with February being the driest month on average (43.7 mm) and June being the wettest (129.5 mm) (PRISM Climate Group, 2022). Soils are loamy and the dominant overstorey species include white and bur oak (*Quercus alba* and *Quercus macrocarpa*) along with red oak (*Quercus rubra*), hickory (*Carya ovata*) and black cherry (*Prunus serotina*). Much of the savannas and woodlands on the preserve are severely degraded by historic grazing patterns and invasive species, which has altered the mid- and overstorey composition and extirpated most of the characteristic herbaceous species. In degraded areas, mesic hardwood tree species such as boxelder (*Acer negundo*) are also co-dominant. Mesophication, the shift to vegetation that prefers wetter conditions, has also occurred on some of the areas that were historically oak savanna and are now dominated by tree species such as sugar maple (*Acer saccharum*; Nowacki & Abrams, 2008). The focus of management is restoration, with an emphasis on heavy woody invasive species removal including buckthorn (*Rhamnus cathartica* and *Frangula alnus*), honeysuckle (*Lonicera maackii* and *Lonicera tatarica*) and multiflora rose (*Rosa multiflora*); frequent prescribed fire (annual to biennial); and interseeding native herbaceous species.

The Meyer Preserve case study described here spanned 2 years (Spring 2022–Spring 2024), led by a core project team intentionally composed to include diverse expertise and perspectives spanning

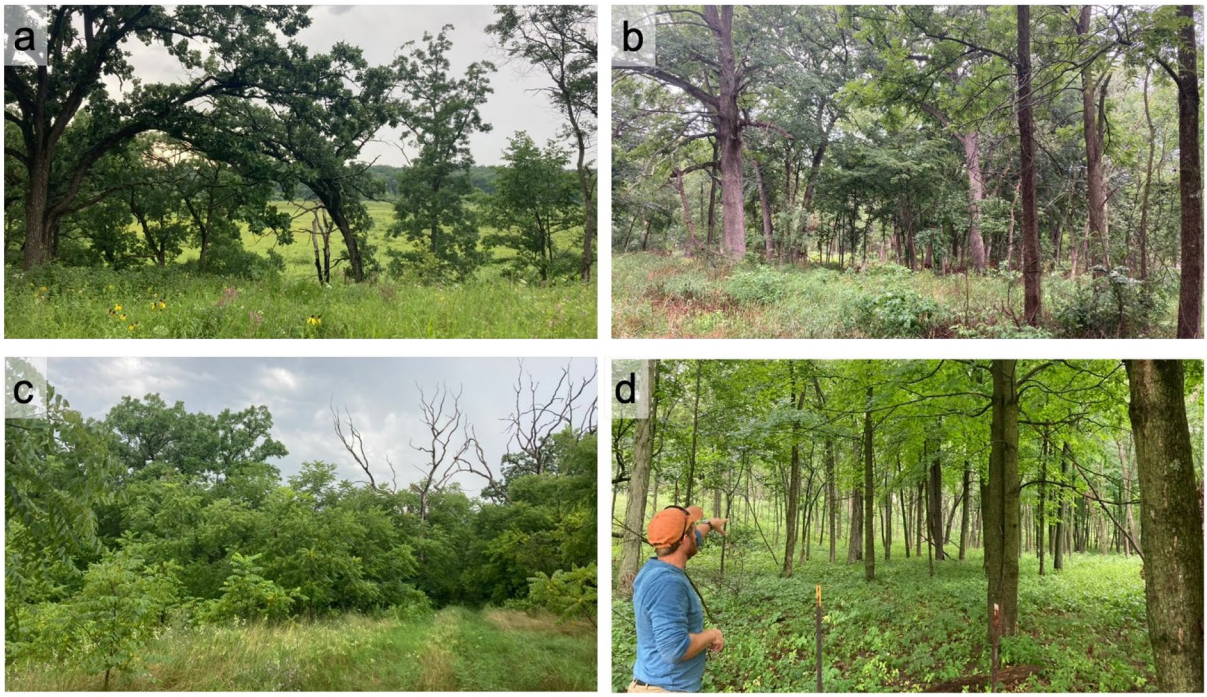

FIGURE 1 The Meyer Preserve (and adjacent managed areas) in south-eastern Wisconsin, USA is historically and presently home to oak savannas, among other ecosystem types. The Preserve hosts oak savanna with a high savanna-dependent plant biodiversity (a), oak savanna that is experiencing woody encroachment from invasives such as buckthorn (b) and is threatened by oak disease (c) and young, secondary hardwood forests that have undergone mesophication (d). The framework for assessing trade-offs presented here illuminated the property-level benefits of managing these tracts for different priorities such as maintaining and promoting a savanna-dependent herbaceous layer (a, b) versus reaping carbon benefits by allowing mesophication to progress (d).

the research-practitioner spectrum. The project team included the Meyer Preserve land manager, a regional ecosystem ecologist, a climate adaptation specialist and a research ecologist.

2.2 | Five pillars of effective local-scale, qualitative trade-offs assessment

Here, we articulate five core pillars of the process we used to assess trade-offs at the Meyer Preserve, which formed part of a larger management planning effort structured around the AW (Swanston et al., 2016). After illustrating each pillar using specifics from our case study, we highlight the key general principle of each pillar that can guide local-scale, qualitative trade-offs assessments across diverse sites and situations.

2.2.1 | Refine management goals to enable clear comparison of trade-offs

After assembling our project team, our first work together focused on articulating management goals and objectives (Step 1 of the AW). We initially drafted our management goals as 'optimize carbon on the landscape' and 'maintain and increase biodiversity', but these goals proved to be too vague to guide discussion and analysis, and we worked together to specify what we meant by 'carbon' and 'biodiversity'.

Incorporating scientists' expertise related to carbon stewardship into our initial goal-setting step was critical but insufficient. Stakeholder priorities, in this case those of TNC which owns and manages the land, were integrated with the science to guide goal setting. Globally, TNC has established its '2030 Goals' which include broad goals for the organization related to carbon and land conservation efforts, among others (The Nature Conservancy, 2025). Ecosystem restoration (i.e. promoting and maintaining biodiversity and restoring ecosystem function, without necessarily specific carbon benefits), has been explicitly identified by the TNC '2030 Goals' as the management priority for the Meyer Preserve. This consequently allows for a broad range of acceptable carbon outcomes at the study site, including reduced carbon uptake or storage if needed to achieve other conservation and restoration goals. Taking both carbon science and stakeholder priorities into account, we ultimately established that optimizing carbon benefits was an important but secondary goal to our biodiversity goals. We explicitly clarified that carbon benefits may be achieved over varying timescales and that maximizing carbon uptake and storage across the site was not a management goal.

Our initial, broadly stated goal of enhancing 'biodiversity' was also unclear because biodiversity can be evaluated in many ways (e.g. within, between or across ecosystems, also known as alpha,

beta and gamma diversity) and for different taxonomic ranks (spanning genotypes to species to kingdoms or domains). A management action to promote genotypic diversity of one rare plant species at a site may look very different compared to management aimed at increasing habitat heterogeneity to promote multi-trophic biodiversity. Therefore, we narrowed the project's biodiversity goal to focus on savanna-dependent plant community composition, an aspect of biodiversity that is relatively easy to measure and can indicate and promote biodiversity of higher trophic levels (Scherber et al., 2010). We leveraged the fact that current and planned monitoring efforts at the Meyer Preserve include coarse, plot-level estimates of plant community structure and composition (Carter et al., 2023a, 2023b). These efforts could be used to inform progress on plant biodiversity goals. Aligning management goals with metrics that will be monitored over time allows for adaptive management, as new data regarding how management actions are affecting desired outcomes can be used to modify future management actions. Thus, in the process of clearly defining management goals, it can be beneficial to conceptually jump forward in the climate adaptation planning process to consider how management outcomes will be monitored and evaluated in the future (Step 5 AW).

With these concepts of carbon stewardship and biodiversity in mind, our team refined the Meyer Preserve goals such that the primary management goal for the Meyer Preserve was to 'maintain and increase savanna-dependent plant community structural and compositional biodiversity', and the secondary goal was to 'look for opportunities to optimize (but not maximize) carbon uptake and storage' (Table 1). The process of goal setting in this case study revealed *the importance of developing well-defined and focused management goals up front in order to subsequently assess and communicate trade-offs*.

2.2.2 | Work towards competency and confidence in the fundamentals of ecosystem carbon science

We have come to recognize that the lack of training in the fundamentals of ecosystem carbon science is a barrier that natural resource professionals commonly face when assessing trade-offs between carbon benefits and other management goals. It appears that the meteoritic rise in recent years in the interest and pressure to manage land for carbon benefits has not been met with a concomitant increase in the training necessary to effectively inform such carbon-focused work. Improved literacy in understanding and communicating about carbon calls for both increased *technical competency* and enhanced *confidence in communicating about trade-offs*.

We incorporated three different elements focused on building competency and confidence in ecosystem carbon cycling into the Meyer Preserve project. First, we created new educational content focused on how, where and for how long carbon

TABLE 1 Meyer Preserve management goals, objectives and proposed actions. For additional information, visit https://forestadaptation.org/adapt/demonstration-projects/nature-conservancy-newell-g-and-ann-m-meyer-nature-preserve.

Goal	Objective	Action
Maintain and increase savanna-dependent plant community structure and composition	Reduce or maintain canopy cover to under 50% in oak openings and between 40% and 80% in oak woodlands	Mechanical thinning, herbicide treatment, mowing and prescribed fire
	Reduce % cover of invasive shrubs to under 3% in higher quality areas, with no more than 10% across the Preserve landscape	Mechanical thinning, herbicide treatment, mowing and prescribed fire
	Reduce % cover of native shrubs to under 15% in higher quality areas, with no more than 20% across the Preserve landscape	Mechanical thinning, herbicide treatment, mowing and prescribed fire
	Increase or maintain total % cover of native graminoids to 50%–65%	Prescribed fire and inter-seeding with herbaceous species mix that have diverse functional groups
	Increase the number of native plant indicator species	Prescribed fire and inter-seeding with herbaceous species mix that have diverse functional groups
	Decrease native disturbance indicators to under 30% by increasing fire frequency	Prescribed fire
Look for opportunities to optimize (but not maximize) carbon uptake and storage	Protect and promote large canopy oak trees	Prescribed fire and treat mature oak trees for disease as needed
	Promote high structural diversity by promoting diversity of plant species in mid-, understorey and ground layer	Mechanical thinning, herbicide treatment, mowing and prescribed fire
	Protect soil carbon	Minimize disturbance to soil during management activities

is stored in temperate savanna ecosystems. The 'Carbon Cycling 101 for Land Managers' presentation we developed is available for download and can be adapted and used for diverse projects considering carbon trade-offs (Supporting Information S1). The content highlights several key points of carbon stewardship including that carbon benefits can result from carbon uptake and/or storage not only in above-ground biomass but also in other ecosystem pools. Additionally, carbon benefits can be realized over different time scales as different ecosystem carbon pools vary in stability, or how long carbon persists in the pool before either transferring to a different pool or returning to the atmosphere. For example, savannas are characterized by a low density of large canopy trees where above-ground carbon storage is secondary to carbon storage in soils (Tilman et al., 2000). Soil carbon also has greater average stability than other pools, such that increasing the soil carbon pool can provide long-term carbon benefits (Jackson et al., 2017). However, significant soil carbon gains take a long time to be realized (e.g. decades to centuries). As such, management actions generally do not confer large soil carbon benefits over management project timescales, with the notable exception of highly degraded soils (e.g. revegetation of reclaimed mines; Shrestha & Lal, 2006). In sum, this basic information on carbon cycling was referred to throughout the project, from refining management goals to assessing trade-offs to considering future monitoring efforts.

Second, while the most basic principles of terrestrial ecosystem carbon cycling are relatively simple, qualitatively assessing and predicting how site factors and management actions affect carbon dynamics at local scales requires greater technical expertise. To this end, and in direct response to questions raised by regional land managers, we developed a series of technical primers that synthesize current carbon research on topics including (1) mineral wetland carbon cycling (Keller & Handler, 2024d); (2) soil carbon cycling (Keller & Handler, 2024b); (3) fire effects on carbon cycling (Keller & Handler, 2024a); and (4) earthworm effects on carbon cycling (Keller & Handler, 2024c). These primers offer more in-depth scientific knowledge about carbon cycling and how site factors and management actions may influence local carbon cycling. These primers were useful to ground discussions about carbon trade-offs in the best available science.

Third, we facilitated semi-structured discussions among project team members on how site factors and management actions may affect carbon cycling on the Meyer Preserve. Informed by the carbon presentation and primers discussed above, and guided by the team's carbon technical expert, these discussions provided an opportunity for managers to gain confidence in talking about management effects on ecosystem carbon. Climate change mitigation and carbon cycling can be difficult to discuss because they are less visible compared to other ecological metrics such as counting woody stems or estimating bird abundances, for example (Moser, 2010). We found that emphasizing the connection between carbon and plant biomass (plant biomass is ca. 50% carbon) provided a confidence-boosting handhold for managers to engage in ecosystem carbon discussions while relying on their expertise in plant biomass dynamics. Additionally, team members reported that frank acknowledgement of the limitations and potential to realize carbon benefits, along with practice communicating about carbon with peers, increased their 'carbon confidence'.

Given that managing lands for carbon benefits is a relatively new focus for many land managers, *there is a particular need to develop basic competency with respect to ecosystem carbon science. Incorporating the core principles of carbon cycling into the management planning process can also enhance the team's confidence in communication about carbon trade-offs.*

2.2.3 | Assess the vulnerability and anticipated impacts of climate change at the project site

Land management today occurs against the backdrop of intensifying climate change and associated stressors. As such, assessing the nature of and degree to which a site is vulnerable to current and projected climate change and how such vulnerabilities may impact the ecosystem and management goals and objectives in particular is critical (Glick et al., 2011). Climate change vulnerability assessments 'synthesize and integrate scientific information, quantitative analyses and expert-derived information in order to determine the degree to which specific resources, ecosystems, or other features of interest are susceptible to the effect of climate change, including climate variability and extremes' (Joyce & Janowiak, 2011). While the availability of vulnerability assessments has been increasing rapidly in recent years (EcoAdapt, 2025; United States Global Change Research Program 2025, 2025), site-specific information on climate vulnerabilities and impacts relevant to specific management goals remains a barrier to many projects. Undertaking a comprehensive new vulnerability assessment for a site is generally beyond the scope of a local-scale management project. However, combining existing vulnerability assessments with local natural resource professional expertise can provide a strong base from which to understand how climate change may affect management outcomes. For the Meyer Preserve project, we first synthesized existing national and regional vulnerability assessments to develop a broad scale understanding of vulnerabilities. Then, through an in-person workshop where we facilitated discussions with local and regional natural resource professionals, we assessed which vulnerabilities and impacts were perceived to be most relevant to the Meyer Preserve site and management goals. In this way, we effectively 'downscaled' regional climate vulnerabilities assessments using local land manager expertise without undertaking a full site-specific vulnerability assessment (see Box 1; Step 2 AW).

Considering how climate change and disturbance may influence the trajectory of carbon uptake and storage at a site over time is integral to effective carbon stewardship, which emphasizes that carbon benefits may be realized over varying timescales.

BOX 1 Summary of Meyer Project climate vulnerabilities.

Regional vulnerability of oak savannas to climate change: moderately low to moderate (Handler et al., 2020; WICCI, 2021)

Oak savannas, including oak openings and oak woodlands, are highly sensitive to fire regime. Fragmented landscapes and reduced opportunities for prescribed burns due to climate change may limit fire and result in rapid woody encroachment in savanna ecosystems. Invasive species, including common buckthorn and other woody invasives, may benefit from CO_2 enrichment and longer growing seasons. However, several factors may reduce the risk of woody encroachment including increased (a) summer droughts, (b) freeze–thaw events that can damage tree roots and (c) pests and pathogens. Overall, savanna-dependent species are generally well adapted to warmer temperatures and drought, suggesting that oak savannas may fare well in future climate conditions especially in connected landscapes that confer resilience over time and space. White and bur oak species are expected to have stable or slightly increasing populations with climate change (Peters et al., 2020). Key uncertainties include how competitive forest species will be in future climates and how the changing climate will impact prescribed burns.

Site-level considerations for oak savannas at the Meyer Preserve

Woody encroachment on oak savannas across the Meyer Preserve ranges from minimal to extensive. Invasive common buckthorn and fast-growing black walnut are two common woody species driving much of the woody encroachment. Oak regeneration is not as limited on this site as it is at other sites in this part of Wisconsin and deer browsing on site is minimal. The long-term (decadal) trajectory of these oak savannas will be driven in large part by interactions between climate change, invasive species and disease outbreaks, yet the nature of these interactions is difficult to predict. Areas where prescribed burns can consistently and effectively be carried out (e.g. due to topography, fuels, total acreage) will be more resilient over time, and current prescribed burn management practices can inform these spatial considerations.

2.2.4 | Perform a rapid scientific assessment to evaluate anticipated effects of management actions

As a part of our broader management planning, we next identified potential management actions that could be used to achieve our project objectives and evaluated how site level climate change vulnerabilities and impacts may impact the efficacy of these actions (Steps 3 and 4 AW). Thinning of woody invasives (primarily *R. cathartica* and *F. alnus*) and applying prescribed fire emerged as two appropriate primary management actions aligned with the project objectives. We acknowledged that less predictable seasonal weather patterns due to climate change present challenges, and perhaps opportunities, for implementing these actions. For example, as climate change decreases the predictability and duration of having frozen soils during the winter and increases the probability of heavy spring rains and flooding at the Meyer Preserve, the window of opportunity to perform mechanical thinning without damaging soils narrows (Marchi et al., 2018; Rittenhouse & Rissman, 2015). Similarly, given the changing climate, the windows of opportunity for applying prescribed fire on site are less predictable, making operations planning more challenging and costly (Jonko et al., 2024). However, due to shifts in seasonal precipitation and temperatures, there may also be increasing opportunities to burn across a broader range of seasons. Acknowledging such challenges and opportunities given the changing climate aids in developing a practical and effective management plan.

We performed a rapid assessment of the scientific literature to assess how these management actions may result in trade-offs between carbon benefits and plant biodiversity project goals. This literature review revealed common trends of the effects of each management action (e.g. prescribed fire) on each management goal (e.g. oak savanna carbon storage). We chose to limit our science synthesis to peer-reviewed scientific literature available in English on Google Scholar and white literature available through the USDA Forest Service's TreeSearch database (Shrestha & Lal, 2006). We found that evaluating the relevance of published literature to a specific project was challenging. We started by identifying the site factors that were most relevant to achieving each management goal. For example, for the Meyer Preserve's goals of promoting savanna-dependent plant community composition and structure and optimizing carbon benefits, we identified the following key site factors: dominant tree species (oak), ecosystem region (upper Midwest that is home to distinct native flora) and climate (moderate temperate climate that allows for savanna). We then used these factors to constrain our literature search and inform key search terms. We reviewed the relevant literature and synthesized common trends, focusing on the direction (i.e. increase, decrease and no change) and magnitude (i.e. small, moderate and large) of the effect. For example, our review of the relevant literature revealed that prescribed burning in combination with mechanical thinning (compared to either treatment alone or passive management) generally had the best outcomes for promoting oak savanna-specific biodiversity and structure in oak savannas of the Midwest with only small decreases in ecosystem carbon storage (Bassett et al., 2020; Lettow et al., 2014; Yantes et al., 2023). We integrated the outcomes of this synthesis into the visualization activity detailed below and the broader management planning process for climate adaptation.

Well-informed, local scale qualitative analysis of trade-offs relies on synthesizing existing research and relating this research to

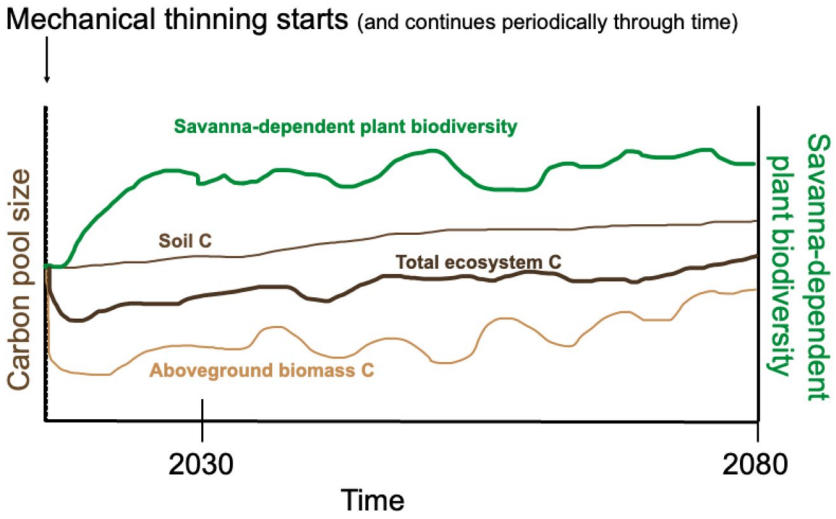

FIGURE 2 Example of visualizing trade-offs between carbon storage (i.e. pool size) and savanna-dependent plant biodiversity over time using a qualitative graphing activity. Two individual carbon pools are shown, above-ground biomass and soil, along with total ecosystem carbon storage (which includes all carbon pools, i.e. above-ground and below-ground live carbon, soil carbon, dead wood carbon and litter layer carbon) to emphasize how different carbon pools can have distinct responses to a management action such as mechanical thinning. The general direction and magnitude of each curve illustrate the projected trajectory of the given variable relative to pre-treatment conditions, while the precise shape of each curve is not important. Stochastic change and future disturbance are sketched with bumpy lines.

site-specific knowledge in order to understand how management actions may drive ecosystem outcomes and affect management goals. Iterative dialogue among researchers and managers can clarify management actions and guide the focus of a rapid scientific assessment.

2.2.5 | Visualize the direction and magnitude of trade-offs

We developed an interactive visualization activity to combine information from the rapid assessment of the scientific literature with targeted discussion among our interdisciplinary team to assess management trade-offs at the Meyer Preserve. This activity allowed our project team to collectively think through and visualize trade-offs between two or more management objectives and proved to be an effective tool for connecting the synthesized research to potential management outcomes at a specific site in a qualitative but informed way.

Details about the graphing activity are available as a facilitator's guide in Supporting Information S2. Briefly, participants can use line graphs to illustrate how potential management activities (identified earlier in the management planning process) are anticipated to affect management objectives through time. As an example, Meyer Preserve project team members started by illustrating how thinning and removal of woody invasives may affect carbon storage in the above-ground biomass and soil carbon pools and savanna-dependent plant community composition over time. The team then iterated on the activity to consider carbon storage and uptake in other individual carbon pools (not shown in Figure 2) and finally total ecosystem carbon (Figure 2). In all iterations, participants qualitatively assessed how carbon outcomes traded off with plant biodiversity outcomes.

Visualizing trade-offs graphically provides the opportunity to articulate the anticipated effects of a management action without having detailed, site-level quantitative data. A visualization activity can emphasize two factors that are often not given adequate attention when assessing management trade-offs: the relative magnitude of the management effect on a given desired outcome and how trade-offs may change over time. Such an activity can also provide structure to team conversations around uncertainty, risk and acceptable bounds of trade-offs.

2.3 | Integrating trade-offs considerations from the five pillars into broader management planning

The five pillars of our trade-offs framework can be integrated into a broader land management planning effort to develop more robust considerations for management planning. We found that understanding the effects of management on carbon stewardship and articulating the relative direction and magnitude of trade-offs between multiple goals helped the Meyer Preserve land manager incorporate and elevate strategies most likely to have benefits for both goals or to minimize trade-offs. Anticipating the effects of climate change on the feasibility and effectiveness of management strategies was also central to evaluating current strategies and selecting those more likely to be effective in the face of climate uncertainty. Finally, the Meyer Preserve management plan was able to articulate property-scale benefits that emerge from prioritizing different goals and actions in different areas of the Preserve (Figure 1).

3 | ADVANCING LOCAL SCALE ASSESSMENT OF MANAGEMENT TRADE-OFFS: OPPORTUNITIES, CHALLENGES AND NEEDS

Managing for multiple goals requires consideration of trade-offs, but precise quantification of trade-offs for a given fine-scale project is rarely feasible. However, qualitative assessment of trade-offs is not necessarily a second tier option and indeed may be preferred to quantification for many projects. In addition to typically being less time and resource intensive compared to a quantitative approach, qualitative analysis offers several benefits. First, our process described above relies on rich discussion between scientists and managers which is not prioritized in most approaches to quantitative trade-off analysis (Deng et al., 2016). We anticipate that explicit emphasis on linking scientists with practitioners may deepen relationships between these groups (Bamzai-Dodson et al., 2024; Rosemartin et al., 2023). Second, qualitatively assessing trade-offs may expand the types of management actions and desired outcomes considered in a project if outcomes that are difficult to quantify would have been dismissed in management planning were it reliant on quantitative analysis. For example, at the Meyer Preserve, our qualitative approach allowed us to consider the effects of management on soil carbon at multiple time scales. This helped us understand the overall balance of carbon benefits from actions like prescribed fire when quantitative measures of soil carbon over time were not feasible. Third, it is currently challenging and often impossible to accurately predict future climate and disturbance risks, and quantitative data of climate adaptive management practices are sparse. This may, in part, explain why climate adaptation considerations are commonly left out of quantitative trade-off analyses. In contrast, the approach outlined in this paper encourages drawing on both research and practitioner expertise to consider how vulnerability to climate change and disturbance may influence the direction and magnitude of trade-offs over time. This approach also offers space to integrate multiple ways of knowing, such as Indigenous Knowledges, which are often left out in quantitative analyses guided by a western science philosophy (Eisenberg et al., 2024).

With the Meyer Preserve project, we found that framing project goals through the lens of climate adaptation rather than a narrow focus on maximizing carbon sequestration and storage allowed for a more holistic approach to ecosystem management (Bradford & D'Amato, 2012). Similarly, using a climate adaptation planning process refined our biodiversity goal to focus on savanna-dependent plant species which are largely considered to be climate adaptive in the region. By centring climate adaptation, carbon benefits and biodiversity were assessed in the context of supporting current and future ecosystem functioning. A flexible, systems approach to natural resource management, including promoting heterogeneity from the genetic to community to landscape scale (which may be at odds with maximizing carbon benefits across the landscape), has been highlighted as critical to effective climate adaptation (Moore & Schindler, 2022) as have iterative discussions between scientists and practitioners (Clark et al., 2016).

Our work with the Meyer Preserve project illuminated several challenges and needs for effective qualitative analysis using this framework. Professional skills such as science synthesis and delivery and cross-discipline communication are called for, yet these skills are not commonly emphasized in scientific research or natural resource management career development pathways (Easterly Iii et al., 2017). Additionally, ecology is inherently context dependent and translating ecological research to management decision-making depends on the ability to assess how scientific results do (or do not) pertain to a given project or site (Clark et al., 2016). Published research can be made more useable for managers by including relevant site characteristics as well as articulating important context dependencies to consider when interpreting a study's results. Additionally, scientific research results that convey not just the direction of an effect but also the magnitude of the effect and how this effect may or may not scale to the whole system are more directly informative to management. This could look like reporting not only that prescribed burning decreased litter layer carbon but specifying that burning decreased litter layer carbon by 60% in the first year; however, given litter layer carbon is only estimated to be 5% of total carbon in these sites, the overall short-term decrease in ecosystem carbon storage due to prescribed burning was small. As the frequency and intensity of disturbance continue to increase, improving the ability to incorporate future risk into trade-off analyses is a critical need. The emerging field of ecological forecasting is likely to improve short-term predictions (Dietze et al., 2024), while advancing conceptual tools, such as the process described here, to more explicitly consider disturbance is a fruitful area of future work. Finally, the case study (and consequently, the broader process we describe here) relied heavily on western science to inform the analysis and did not explicitly incorporate Indigenous Knowledge. We highly encourage future adoption of these key considerations to expand to incorporate other ways of knowing (see Eisenberg et al., 2024 for guidance and examples of integrating Indigenous and Western Knowledges).

4 | CONCLUSION

We used our climate adaptation planning work on the Meyer Preserve in south-eastern Wisconsin, USA to demonstrate a flexible framework for natural resource professionals to rigorously and qualitatively assess trade-offs between carbon outcomes and other management goals. We offer five key pillars for implementing this framework as part of a broader management planning effort. Co-production of knowledge with research scientists and natural resource professionals is central to the process and is highlighted in the interactive visualization activity we describe, which facilitates the consideration of both the direction and magnitude of trade-offs without requiring quantification by leveraging a rapid assessment

of current knowledge alongside land manager site-level expertise. As natural and working lands are increasingly managed for multiple objectives, assessing management trade-offs is of heightened interest. The process we outline here can be used to thoughtfully consider local scale trade-offs while also strengthening relationships between research scientists and natural resource professionals.

AUTHOR CONTRIBUTIONS

Adrienne B. Keller, Stephen D. Handler, Maria K. Janowiak and Brian Miner conceived of the study. All co-authors contributed to developing the ideas, Adrienne B. Keller wrote the first draft and all co-authors contributed to revisions.

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CONFLICT OF INTEREST STATEMENT

Ann Calhoun and Brian Miner are employed by The Nature Conservancy. Caitlin Littlefield is employed by Conservation Science Partners.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.70194.

DATA AVAILABILITY STATEMENT

No new data were collected or used for this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

BRITISH ECOLOGICAL SOCIETY Ecological Solutions and Evidence

Supporting Information S1. Carbon cycling 101 for land managers.

Figure S1. Example of what the first step of the visualization activity considering four different management actions may look like.

Figure S2. Example of how management effects on carbon over time can be illustrated.

Figure S3. Example of how management effects on other management goals over time can be illustrated to visualize trade-offs and co-benefits for multiple goals.

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