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Seventy questions of importance to the conservation of the North Central grasslands of the United States in a changing climate

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Abstract

Successful conservation of ecosystems in a changing climate requires actionable research that directly supports the rethinking and revising of management approaches to address changing risks and opportunities. As an important first step toward actionable research, we reviewed and synthesized grassland management-related documents to identify broadly shared questions that, if answered, would help to support collective conservation of the grasslands in the northern Great Plains of the United States in a changing climate. A Management Priorities Working Group reviewed 183 grassland-relevant management documents and identified 70 questions. Feedback was iteratively provided by a Climate and Ecology Working Group, an Advisory Committee, and representatives from grassland management agencies and organizations. The identified questions generally fall under 15 topics: land conversion; restoration; disturbance regimes; woody encroachment; herbaceous invasives; grazing; water quality, quantity, and availability; animal species; private land;

public understanding; legal and policy changes; economic incentives; coordination across management entities; accessibility of science and tools; and novel ways of thinking. These questions can inform a research agenda for researchers looking to conduct actionable science in the Great Plains grassland ecosystems. Both the approach and the questions presented here can also be adapted and applied in other regions and ecosystems.

KEYWORDS

actionable science, adaptation, climate change, conservation, ecosystem, grasslands, Great Plains, invasive species, management, wildlife

1 | INTRODUCTION

Successful conservation of ecosystems in a changing climate requires not only foundational research—which helps us to understand how climate change is affecting ecosystem components and processes—but also actionable research—which generates information that can directly support the adaptation of conservation strategies and resource management practices (Beier et al., 2017; Meadow et al., 2015). An important step in developing actionable research is to identify the questions that are of greatest importance to practitioners (Sutherland et al., 2009). Previous studies have identified questions of greatest relevance to conservation practitioners and environmental policymakers for various geographies (e.g., Ahlering et al., 2020; Braunisch et al., 2012; Sutherland et al., 2009, 2006), species (e.g., Parsons et al., 2015), and topics (e.g., Crausbay et al., 2020, 2022); however, to date no such effort has been undertaken that focuses on grassland ecosystems in the northern Great Plains of the United States. Therefore, this study seeks to identify the key research questions and information needs for grassland managers in Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, and Kansas (hereafter, "the North Central region").

Grasslands are both highly important and greatly endangered worldwide (Bardgett et al., 2021; Knopf & Samson, 1997; Noss, 2013; Samson et al., 2004; Twidwell et al., 2021). Characterized by the dominance of grasses and other herbaceous species (see Allen et al., 2011), grasslands provide habitat for species endemic to grassland systems (Benedict et al., 1996; Mengel, 1970; White et al., 2000), are crucial to global food security (O'Mara, 2012), and support the economies of ranching communities and pastoralists around the globe (Herrero et al., 2013). Grasslands also provide many other ecosystem services including stormwater management (Flynn et al., 2017), aquifer recharge, soil water conservation during drought, improved soil properties, and soil conservation (Gibson & Newman, 2019, pp. 3–4). In addition, grasslands can store vast amounts of carbon in their underground root systems, which may make grasslands more secure carbon sinks than forests, especially in the context of increasing wildfire (Dass et al., 2018). While grasslands occur on about 31%–43% of land globally (Gibson & Newman, 2019, pp. 3–4), less than 5% of the world's grasslands have legal protection (Hoekstra et al., 2005; The Nature Conservancy, 2006) and just 1.2% of the historical extent of grasslands is found within protected areas in the Great Plains and Chihuahuan Desert regions of North America (Comer et al., 2018). Of the different types of grasslands, native temperate grasslands—including those in the North Central region of the United States—are particularly vulnerable to conversion to alternate land uses. These temperate grasslands formerly occupied about 8% of land globally (Henwood, 2010; White et al., 2000); however, conversion of temperate grasslands is outpacing their protection by a ratio of 8:1 (Doherty et al., 2013; Hoekstra et al., 2005).

Grasslands in the North Central United States are of particular importance because they support regional biodiversity (Augustine et al., 2021), local economies (Pieper, 2005), and cultural identity (Black Elk, 2016; Blackfeet Nation, 2018; Shamon et al., 2022); yet they have been severely diminished in size and quality since European colonization and settlement of the area began in earnest in the 1850s (Mann, 2005, 2011). As of 2020, only 60% of the land in the North Central grassland ecoregions is intact grassland (i.e., grassland that has not been converted to cropland since at least 2014) (WWF, 2022; see also Gage et al., 2016; Olimb & Lendrum, 2021; see Figure 1); the amount of remaining high-quality native grassland is likely lower. The North Central grasslands continue to face numerous threats, including conversion to cropland (Lark, 2020; WWF, 2020, 2021); residential, commercial, and energy development (Abrams et al., 2012; Ott et al., 2021; Reeves et al., 2018); degradation resulting from the encroachment of invasive species

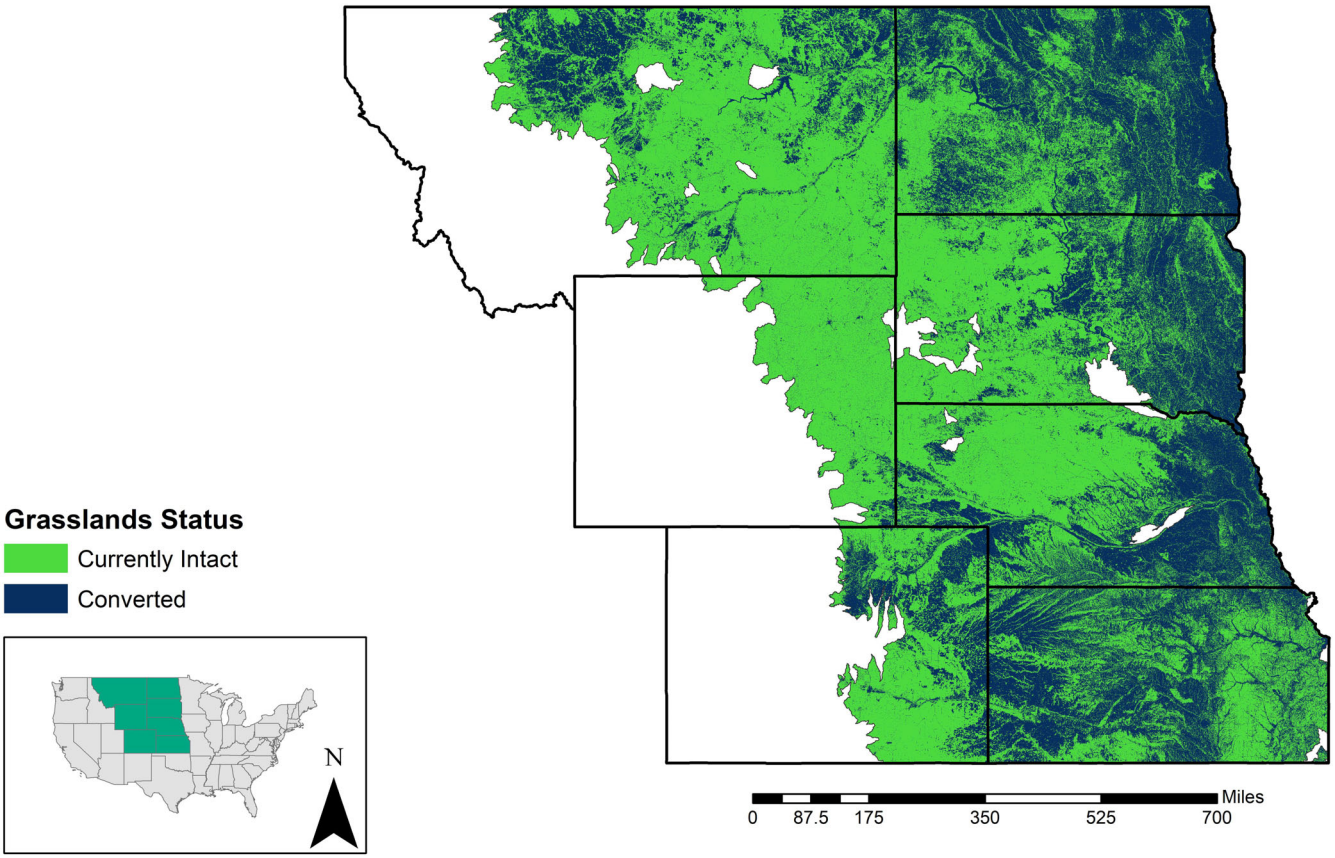

FIGURE 1 Intact grassland remaining in the North Central grassland ecoregions. "Currently intact" grassland is from the World Wildlife Fund (WWF) Plowprint 2020 dataset (WWF, 2022; see also Gage et al., 2016; Olimb & Lendrum, 2021) and includes all grassland that has not been cropland since at least 2014. White areas on the map are ecoregions other than grasslands, such as mountains and forest.

(Baldwin et al., 2019; Ratajczak et al., 2012; Stevens et al., 2017; Twidwell et al., 2021); overgrazing (CPW, 2015; Dyke et al., 2015; MFWP, 2015; Rohweder, 2015; WGFD, 2017); and disruption of the historical disturbance regime (Donovan et al., 2020; Twidwell et al., 2019). Climate change presents new threats and opportunities for the North Central grasslands in the form of increasing temperatures, shifting precipitation, and extreme events, among others (Briggs et al., 2005; Conant et al., 2018; Easterling et al., 2017; Garbrecht et al., 2004; Kloesel et al., 2018; Mufson et al., 2019; Seneviratne et al., 2021; Vose et al., 2017; Zhang et al., 2021). Climate change is also interacting with and exacerbating other existing stressors and threats (Conant et al., 2018).

Addressing these threats is further complicated by the complexity of the management landscape, which can perhaps best be described as a patchwork of federal, state, county, and municipal governments, tribal nations, and nongovernmental organizations (NGOs) managing dispersed and often isolated fragments of grassland within an area that is dominated by private land ownership and management. These grassland-managing entities have various goals (e.g., environmental conservation, cultural preservation, livelihood sustainability) and experience different constraints (e.g., geophysical, structural, financial, legal, capacity, local community support) that pose challenges for cohesive, collaborative, and complementary grassland management planning and practice.

The North Central Climate Adaptation Science Center (NC CASC) is part of a network of regional CASCs that together serve as "a partnership-driven program that teams scientists with natural and cultural resource managers and local communities to help fish, wildlife, water, land, and people adapt to a changing climate" (USGS, 2022). The NC CASC serves a region that includes large amounts of grassland; yet it was not known what the broadly shared information needs were among grassland managers in the North Central region. To address this need, a team of researchers from the NC CASC led a project to compile a list of questions broadly shared by grassland managers in the North Central region that, if answered, would help to support collective conservation of the North Central grasslands in a changing climate. In our synthesis and throughout this paper, we define the term "grassland" broadly to refer to any grass-dominated land, whether native or reclaimed prairie, or "improved" grassland (i.e., seeded to

provide improved forage to livestock). We define grassland managers as any individual, agency, or organization involved in developing grassland management plans and/or implementing those plans on the ground. We organized a working group of individuals with knowledge of grassland management in federal, state, and tribal agencies, and NGOs across the region to review existing grassland management documents to synthesize broadly shared information needs. The resulting list of 70 broadly shared questions should be useful to not only the NC CASC, but to all researchers seeking to conduct actionable science in support of grassland ecosystems.

2 | METHODS

2.1 | Document-based analysis

Coproduction and consultation to produce actionable science is a time-consuming process that places additional burdens on natural resource managers and other stakeholders. Document-based analysis can provide an important foundation for structuring future engagement while adhering to best practices for producing actionable science information and limiting stakeholder fatigue (c.f., Bamzai-Dodson et al., 2021; Dilling & Berggren, 2015). Therefore, the research team conducted a review of available plans, reports, and academic literature to determine what was already known about the information needs of grassland managers in the North Central region.

2.2 | Working groups and advisory committee

To collect, review, and synthesize these documents, the research team recruited individuals knowledgeable in grassland management and research from federal, state, and tribal resource management agencies and NGOs to serve on one of three project groups. The Management Priorities Working Group (MPWG) was comprised of 11 individuals tasked with identifying and reviewing the management-related documents in order to: (1) synthesize grassland management goals and challenges; and (2) identify questions and information needed to allow grassland managers to meet their goals within the context of climate change. The MPWG was supported in their work by the Climate & Ecology Working Group (CEWG), which included 24 scientists with various specialties relevant to climate change and grassland management, and an Advisory Committee (AC), which consisted of 22 individuals, including grassland resource managers, scientists, decision-makers, and members of relevant NGOs and boundary organizations.

2.3 | Collecting documents and identifying questions

In January 2021, the MPWG began collecting plans, reports, summaries, and peer-reviewed literature authored by or relevant to identified grassland management organizations and agencies across the North Central region. The MPWG particularly sought to collect and review documents relevant to the grassland management of the Bureau of Land Management; U.S. Fish and Wildlife Service; National Park Service; U.S. Forest Service; Natural Resources Conservation Service; Farm Service Agency; Bureau of Indian Affairs; Colorado Parks and Wildlife; Kansas Department of Wildlife and Parks; Montana Fish, Wildlife, and Parks; Nebraska Game and Parks Commission; North Dakota Game and Fish; South Dakota Game, Fish, and Parks; Wyoming Game and Fish Department; The Nature Conservancy; and Migratory Bird Joint Ventures. The region also includes 32 federally recognized tribal nations, and although special effort was made to collect tribal management plans, the MPWG was unable to identify any that were publicly available (see Section 4). The MPWG also sought to ensure that the collected documents represented the diversity of grassland ecosystem types within the North Central region, including tallgrass prairie, northern mixed grass prairie, central mixed grass prairie, shortgrass prairie, and sagebrush-grassland ecotone. Documents were collected via snowball sampling from key reports, suggestions by working group and advisory committee members, from agency and organization websites, and by searching for key phrases such as "grassland management" and "Great Plains" on Google Search and Google Scholar. Collected documents included those that directly addressed grassland management (e.g., State Wildlife Action Plans) as well as documents that related to grassland management more broadly (e.g., fire management plans). An initial compilation of documents was shared with the AC and CEWG in February 2021 to solicit their recommendations for additional documents that should be included in the review. In total, 300 grassland-relevant management documents were collected.

During February and March 2021, members of the MPWG reviewed this collection of grassland management-relevant documents by: (1) noting aspects of scale, methodology, jurisdiction, geographic location (i.e., relevant U.S. states), ecoregion, primary use or goal, stressors and threats, management methods, climate change, and science needs (see Figure S1); and (2) using a template to write annotated summaries of each document (see Box S1). One or more members of the MPWG were assigned to lead the review of documents pertaining to each major grassland management entity in the North Central region

(i.e., Bureau of Land Management, U.S. Fish and Wildlife Service, National Parks Service, U.S. Forest Service, Natural Resources Conservation Service, state fish and wildlife agencies, The Nature Conservancy, and Migratory Bird Joint Ventures) to ensure that our review and synthesis of information needs would represent the breadth of management concerns across these agencies and organizations. The MPWG met via video conference every 2 weeks to refine the review process and discuss the themes present in the management documents. By the end of March 2021, the MPWG had reviewed 183 grassland-relevant management documents (see Figure S2) and had reached inductive thematic saturation (i.e., no new grassland management goals and challenges were emerging from the continued review of new management documents; see Guest et al., 2020). The MPWG then outlined topics of importance that were broadly shared (i.e., pertaining to many or all) across grassland management entities in the North Central region using an iterative process. This was presented to the AC and CEWG for feedback and responses were used to revise and refine the outline, resulting in a list of broadly shared questions. This list of questions was then shared with the AC and CEWG for review before they were finalized. We organized the questions into two levels: highly general questions (i.e., 15 topical questions) with one or more specific or supporting questions listed under each. The organized list of questions was then shared with a representative from each grassland management entity (listed above) to ensure that they broadly reflected the information needs of each agency and organization.

3 | RESULTS

An overall finding of our review and synthesis of grassland management-related documents was that conservation is a widely shared goal across all grassland management groups. The 70 broadly shared thematic and supporting questions identified by our synthesis of grassland management-related documents span the natural and social sciences (Table 1). Addressing these questions will help further conservation of North Central grasslands in a changing climate. We provide a brief description for each of the 15 thematic questions.

3.1 | Where are grasslands most likely to be lost to other land uses?

Grassland loss (i.e., conversion to another land use) is the single greatest threat to grassland species in the United States and around the globe (Bardgett et al., 2021; Bond et al., 2005; Lark, 2020; Lark et al., 2020; Olimb & Lendrum, 2021; Stevens et al., 2017; WWF, 2020, 2021). Today, about half of all grasslands in the Great Plains (of which the North Central region is a part) have been converted to agriculture or other uses (Lark, 2020; Samson & Knopf, 1996), with grassland continuing to be converted to cropland at an annual rate of about 2% per year (WWF, 2020, 2021). Preventing the further loss and fragmentation of grasslands is important not only for conservation of at-risk grassland species, but also for addressing climate change. For example, Ahlering et al. (2016) found that protecting grassland from conversion to cropping in North Dakota and South Dakota would avoid approximately 51.6 tons of carbon dioxide equivalent emissions per hectare over 20 years. Grassland loss is driven by complex interactions between the availability of biophysical resources and socioeconomic factors and processes, both of which will be impacted by climate change (Intergovernmental Panel on Climate Change, 2019, p. 23; National Academies of Sciences, Engineering, and Medicine, 2021). Multiple types of land use (including conservation, recreation, cropping, grazing, energy development, transportation, urban development, etc.) are needed to support flourishing human communities in the North Central region. The development of criteria to help land managers to designate the best use of public lands and to guide voluntary actions on private lands would help to support both thriving grassland ecosystems and human communities in the midst of climate change.

3.2 | What are best practices for grassland restoration in a changing climate?

Restoration (i.e., reconstruction and enhancement) of previously converted or degraded grassland can help to establish more resilient habitat and address fragmentation or create corridors to facilitate species movement as an adaptation to climate change. Grassland restoration can involve re-seeding, re-introductions of grassland wildlife, and prescribed burning and grazing. While generally more expensive and less effective than protecting and maintaining existing grassland (Dodds et al., 2008; Isbell et al., 2019), interest and support for grassland restoration is increasing in part due to the potential for grasslands to store large amounts of carbon belowground where it will not be released by wildfire (Dass et al., 2018; Lal, 2004).

3.3 | How will climate change affect disturbance regimes?

The grasslands in the North Central region evolved under spatially and temporally varying regimes of disturbance

TABLE 1 Broadly shared questions that, if answered, would help grassland managers in the North Central region better meet their goals in a changing climate and the relevant fields of study needed to address them.

	Natural science		Social science			
Information needed	**Physical sciences (climatology, hydrology)**	**Life sciences (biology, ecology)**	**Sociocultural studies (anthropology, geography, sociology)**	**Political science & legal studies**	**Economics**	**Communication studies (communication, education, psychology)**
1. Where are grasslands most likely to be lost to other land uses?	**x**	**x**	**x**	**x**	**x**	
1.1 Where is cropland likely to expand and contract as the climate changes?	x	x	x		x	
1.2 Where is ranchland likely to be sold and subdivided as the climate changes?	x	x	x	x	x	
1.3 Where is urban and suburban development likely to occur as the climate changes?	x		x	x	x	
1.4 Where and how can energy be developed to minimize the extent and impact of grassland conversion?		x	x	x	x	
1.5 What criteria can be used to designate land use (including conservation, recreation, cropping, grazing, energy development, transportation, urban development, etc.) that will support both thriving grassland ecosystems and flourishing human communities in the midst of climate change?	x	x	x	x	x	
1.6 Where can conservation funds be used most efficiently to prevent grassland conversion?		x	x		x	
2. What are best practices for grassland restoration in a changing climate?	**x**	**x**	**x**		**x**	
2.1 Where will climate change diminish the suitability of land for agriculture and present opportunities for reconstruction?	x	x				
2.2 What areas could best be reconstructed to provide key habitat or connectivity for migration of grassland-dependent species in light of climate change?	x	x			x	

TABLE 1 (Continued)

Information needed	Natural science		Social science			
	Physical sciences (climatology, hydrology)	Life sciences (biology, ecology)	Sociocultural studies (anthropology, geography, sociology)	Political science & legal studies	Economics	Communication studies (communication, education, psychology)
2.3 What are the best sources for seeds for re-seeding grasslands?	x	x			x	
2.4 Where can grassland animals be successfully reintroduced?	x	x	x			
2.5 How can prescribed disturbances be used to promote grassland restoration in a changing climate?	x	x	x			
3. How will climate change affect disturbance regimes?	**x**	**x**	**x**			
3.1 How will climate change affect the severity and frequency of wildfire?	x	x	x			
3.2 How will the effectiveness of current prescribed burn practices be affected by a changing climate, and how will those practices need to be altered to be more effective in a changing climate?	x	x				
3.3 How will the effectiveness of current prescribed grazing practices be affected by a changing climate, and how will those practices need to be altered to be more effective in a changing climate?	x	x	x			
3.4 How will changing drought patterns under climate change interact with fire, grazing, and increased levels of carbon dioxide to impact the resilience, biodiversity, and functioning of grasslands?	x	x				
4. How will climate change impact woody encroachment?	**x**	**x**	**x**			
4.1 Where has climate change facilitated movement of woody species into areas that were historically grassland?	x	x				

(Continues)

TABLE 1 (Continued)

Information needed	Natural science		Social science			
	Physical sciences (climatology, hydrology)	**Life sciences (biology, ecology)**	**Sociocultural studies (anthropology, geography, sociology)**	**Political science & legal studies**	**Economics**	**Communication studies (communication, education, psychology)**
4.2 Where will woody species become more competitive and encroach on grasslands at a higher rate in the future?	x	x	x			
4.3 How will the effectiveness of current efforts to manage woody encroachment change?	x	x	x			
5. How will climate change impact herbaceous invasives?	**x**	**x**	**x**	**x**	**x**	
5.1 Where has climate change facilitated the movement of herbaceous invasives into native grasslands?	x	x				
5.2 Where will herbaceous invasives become more competitive and encroach on native grassland species at a higher rate in the future?	x	x				
5.3 How will the effectiveness of current efforts to manage herbaceous invasives change?	x	x	x			
5.4 How will management for invasives (for example, spraying), biodiversity (for example, pollinators), and water quality (for example, non-point source pollution) impact each other in a changing climate?	x	x		x	x	
6. How will climate change impact grazing?	**x**	**x**	**x**		**x**	
6.1 How will climate change impact the quantity and quality of forage?	x	x				
6.2 How will climate change impact the variability of forage temporally and spatially?	x	x				
6.3 How will climate change affect the viability of *Bos taurus* (cattle) and *Bison bison* (bison) herds, as well as other native herbivores?	x	x			x	

TABLE 1 (Continued)

Information needed	Natural science		Social science			
	Physical sciences (climatology, hydrology)	**Life sciences (biology, ecology)**	**Sociocultural studies (anthropology, geography, sociology)**	**Political science & legal studies**	**Economics**	**Communication studies (communication, education, psychology)**
6.4 What grazing management practices can help ranchers successfully adapt to climate change while also supporting healthy grassland ecosystems?	x	x	x		x	
7. How will climate change impact water quality, quantity, and availability?	**x**	**x**	**x**	**x**	**x**	
7.1 How will climate change impact the hydrological cycle of the North Central grasslands?	x	x				
7.2 How will climate change impact the health of grassland rivers, streams, prairie potholes, and playa lakes?	x	x	x			
7.3 How will climate change impact human water use and groundwater recharge?	x	x	x	x	x	
7.4 How will water quality be directly and indirectly impacted by climate change?	x	x	x	x	x	
7.5 How will climate change affect the frequency and intensity of drought and floods?	x	x	x			
8. How will climate change affect animal species of conservation concern?	**x**	**x**				
8.1 How will climate change shift and fragment habitat ranges?	x	x				
8.2 How will climate change affect the timing of species' lifecycles?	x	x				
8.3 How will climate change affect the prevalence of disease?	x	x				
9. How can conservation on private grasslands be achieved?	**x**	**x**	**x**	**x**	**x**	**x**
9.1 What technical assistance will private landowners need to promote resilient and biodiverse grasslands in a changing climate?	x	x	x	x	x	x

(Continues)

TABLE 1 (Continued)

Information needed	Natural science		Social science			
	Physical sciences (climatology, hydrology)	**Life sciences (biology, ecology)**	**Sociocultural studies (anthropology, geography, sociology)**	**Political science & legal studies**	**Economics**	**Communication studies (communication, education, psychology)**
10. How can public understanding of grasslands and their importance increase?	**x**	**x**	**x**	**x**	**x**	**x**
10.1 What are the main characteristics of grasslands and what ecosystem services do they provide?		x	x		x	
10.2 How can grasslands help support community resilience to climate change?	x	x	x	x	x	
11. What legal and policy changes can support grassland resilience to climate change?	**x**	**x**	**x**	**x**		
11.1 What legal constraints need to be addressed to promote grassland resilience to climate change?				x		
11.2 How can the Farm Bill promote conservation of private grasslands?	x	x	x	x	x	
12. How can grassland protection, enhancement, maintenance, and reconstruction be economically incentivized?		**x**		**x**	**x**	
12.1 How might landowners receive payments for ecosystem services?				x	x	
12.2 Are there opportunities for payments for carbon sequestration in grasslands?		x		x	x	
13. How can grassland management be strategically coordinated across agencies, organizations, jurisdictions, and borders?	**x**	**x**	**x**	**x**	**x**	
13.1 What are the structural barriers to cooperation and how can they be overcome?			x	x		
13.2 What are the benefits and costs of a coordinated approach to grassland management in a changing climate?	x	x	x	x	x	

TABLE 1 (Continued)

Information needed	Natural science		Social science			
	Physical sciences (climatology, hydrology)	**Life sciences (biology, ecology)**	**Sociocultural studies (anthropology, geography, sociology)**	**Political science & legal studies**	**Economics**	**Communication studies (communication, education, psychology)**
14. How can the accessibility of relevant science and tools be improved?			**x**	**x**		**x**
14.1 What information and tools are currently available to help grassland managers respond to climate change and what tools need to be developed?			x			x
14.2 How could relevant grassland science and tools best be shared and communicated with interested users?			x			x
14.3 What kinds of technical training programs and/or informational workshops would increase the capacity of resource managers to utilize scientific information and tools?			x			x
14.4 How can new technologies be employed to increase creation and sharing of relevant data for decision-making?			x	x		x
15. What novel ways of thinking are needed to successfully manage grasslands amidst climate change?	**x**	**x**	**x**	**x**	**x**	**x**
15.1 How can approaches and frameworks such as Resist-Accept-Direct (RAD), adaptive management, social-ecological systems, scenario planning, proactive management, landscape-level planning, drought planning, trade-off evaluation, state-transition models, traditional ecological knowledge, local ecological knowledge, and participatory decision-making and science help contribute to the	x	x	x	x	x	x

(Continues)

TABLE 1 (Continued)

Information needed	Natural science		Social science			
	Physical sciences (climatology, hydrology)	**Life sciences (biology, ecology)**	**Sociocultural studies (anthropology, geography, sociology)**	**Political science & legal studies**	**Economics**	**Communication studies (communication, education, psychology)**
successful management of grasslands amidst climate change?						
15.2 What strategies can be used to promote both grassland health and human community flourishing in the face of climate change?	x	x	x	x	x	x
15.3 How can trade-offs in climate mitigation (e.g., carbon sequestration) and biodiversity be carefully considered?	x	x	x	x	x	
15.4 How will human responses to climate change impact grasslands?	x	x	x	x	x	
15.5 What are the feedback loops between human actions, climate change, and ecological processes?	x	x	x	x	x	
15.6 What cascading or amplifying effects might be caused by the complex and interconnected reactions of various systems to climate change?	x	x	x	x	x	
15.7 How can we manage for shifts in the frequency and intensity of extreme events?	x	x	x	x	x	
15.8 Where will the impacts of climate change make it impossible for grasslands to continue to exist?	x	x	x		x	

Note: Questions in bold font are highly general and together represent 15 topics, each of which has one or more supporting questions. The listed fields of study are not exhaustive and the indicated relevance of each field is not the product of a structured analysis; as such, this table is not intended to be prescriptive but rather is meant to serve as a starting point for developing interdisciplinary teams.

from wildfire, intentional fires lit by Indigenous peoples, grazing by bison and other native herbivores, and ground disturbance by burrowing mammals. These disturbances were crucial for creating and maintaining a landscape with a heterogeneous vegetation structure and composition (Ceballos et al., 1999; Fuhlendorf et al., 2017; Pickett & White, 1985) that provided habitat to a wide variety of species (Davidson et al., 2012; Fuhlendorf et al., 2006; Ricketts & Sandercock, 2016; Warui et al., 2005). Extensive and intensive human use of the landscape has largely disrupted these disturbance regimes (Carbutt et al., 2017); however, grassland managers employ prescribed fire and grazing to promote heterogeneous and biodiverse grasslands and would benefit from greater understanding of how climate change will interact with these processes.

3.4 | How will climate change impact woody encroachment?

Woody encroachment is the spread of trees and shrubs into grassland ecosystems and leads to significant declines in species richness, threatens endemic grassland species, changes above- and below-ground biota, and alters plant productivity and carbon storage (Archer et al., 2017; Briggs et al., 2005; Ratajczak et al., 2012; Sepp et al., 2021). Woody encroachment is caused by numerous interacting factors, including changes in magnitude and seasonality of precipitation; fire and grazing frequency and intensity; concentrations of atmospheric carbon dioxide; and land use (Archer et al., 2017, p. 31; Barger et al., 2011, p. 1; Briggs et al., 2005, p. 243; Stevens et al., 2017). To maintain functional grasslands, managers must understand how climate change affects both woody plants and actions employed for their management.

3.5 | How will climate change impact herbaceous invasives?

Herbaceous invasives are non-woody plant species that lack biological and environmental controls on their establishment, growth, and reproduction, and are therefore able to spread and dominate in ecosystems (Rohweder, 2015). They often become established in areas that have been altered and tend to spread in areas that lack grazing and fire (Cosby, 1975; Porensky et al., 2017, 2020). Herbaceous invasives can impact habitat structure and function by displacing native grass and forb species, reducing the availability of forage required by native animals, and impacting biotic and abiotic processes belowground (Poland et al., 2021). Grassland managers across the North Central region need to understand how climate change impacts herbaceous invasives and their management.

3.6 | How will climate change impact grazing?

The grasslands in the North Central region evolved under a regime of grazing by highly mobile bison and other native ungulates. Grazing continues to be important for supporting healthy grassland ecosystems and economies, with approximately 49% of remaining grasslands in the North Central region used for grazing domestic animals like cattle (ERS, 2021). However, unsustainable grazing can occur when the stocking rate, timing, intensity, or duration of grazing has a lasting negative impact on the growth, condition, ecological functioning, or biodiversity of the grazed grasslands (DiTomaso et al., 2010; Dyke et al., 2015; Forrest et al., 2004; Helzer, 2010; Rohweder, 2015; WGFD, 2017). Understanding how climate change impacts grasslands and grazers is crucial for sustainable grazing management.

3.7 | How will climate change impact water quality, quantity, and availability?

The proper functioning of grassland systems depends on the availability and quality of water, yet many aquatic systems in the grasslands are already degraded (Barnes et al., 2017; Dahl, 2011; Schneider et al., 2011; Tiner, 1984). Climate change is expected to amplify the degradation of grassland wetlands, waterways, and water resources (Earman & Dettinger, 2011; Green et al., 2011; Huntington & Niswonger, 2012; Poff et al., 2002; Taylor et al., 2013). Information concerning climate change impacts on water quality, quantity, and availability is greatly needed by grassland managers across the North Central region.

3.8 | How will climate change affect animal species of conservation concern?

As the grassland habitats in the North Central region have been lost, fragmented, and degraded, associated wildlife populations have declined in all grassland ecoregions and are at high risk of declining further if extensive management for their conservation is not implemented (Hoogland, 2006; Horncastle et al., 2005; Rosenberg et al., 2019). Managing grasslands for animal species of greatest conservation and cultural importance is a major activity for many of the grassland management entities in the North Central region (Miller Hesed & Yocum, 2023; see also Yocum et al., 2023 for a table of all the of species of greatest conservation need listed in the North Central states' [MT, WY, CO, ND, SD, NE, and KS] State Wildlife Action Plans as of summer 2020). To ensure their efforts are effective, managers need to understand how climate change will impact habitat, species' life histories, and disease prevalence.

3.9 | How can conservation on private grasslands be achieved?

The conservation actions of private landowners are crucial for grassland conservation since approximately 83% of land across the North Central grassland ecoregions is privately owned and managed, including 1% that is under permanent conservation or ranchland easements (Figure 2). Many of the grassland management entities in

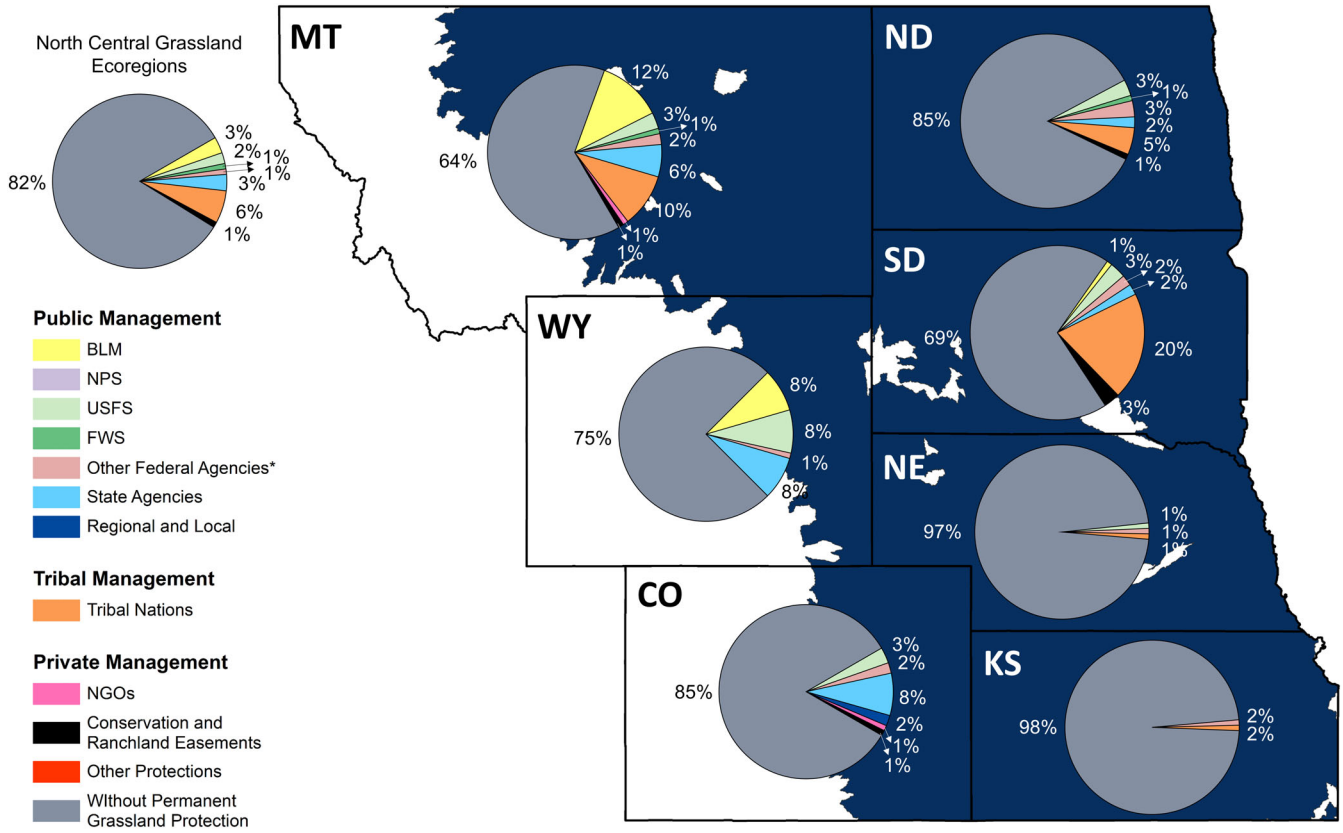

FIGURE 2 Proportion of North Central grassland ecoregions (shown in navy) managed by government agencies, tribal nations, and private landowners within each state and across the region. Data from PAD-US (USGS, 2020). Non-federal entities managing less than 0.5% of land in the grassland ecoregions are not included here. Percentages do not add to 100 due to rounding. Abbreviations in the legend are for Bureau of Land Management (BLM), National Park Service (NPS), U.S. Forest Service (USFS), Fish and Wildlife Service (FWS), and nongovernmental organizations (NGOs). *"Other Federal Agencies" includes federal agencies not discussed in this paper, as well as BLM, NPS, USFS, and/or FWS when the proportion managed by the agency is less than 0.5% in a given state. In Montana and Wyoming, "Other Federal Agencies" includes, from most to least land managed, federal agencies not discussed in this paper and NPS. In Colorado, it includes federal agencies not discussed in this paper, BLM, FWS, and NPS. In North Dakota, it includes federal agencies not discussed in this paper, NPS, and BLM. In South Dakota, it includes federal agencies not discussed in this paper, FWS, and NPS. In Nebraska, it includes FWS, federal agencies not discussed in this paper, NPS, and BLM. In Kansas, it includes federal agencies not discussed in this paper, USFS, FWS, NPS, and BLM.

the North Central region work with willing private landowners to promote conservation on privately owned grasslands (see, for example, CPW, 2020, 2021; FWS, 2021). To continue supporting conservation on private lands, grassland managers need to know what technical assistance will be needed by private landowners in a changing climate.

3.10 | How can public understanding of grasslands and their importance increase?

The longstanding perception that grasslands are a wasteland has negatively influenced policy and public support for grassland conservation efforts (Baltensperger, 1992; Dove, 2019; Hoover et al., 2020). This challenge is exacerbated by the fact that the public is generally unaware of what has already been lost in the historical U.S. range of grassland ecosystems. Because many grassland species are small, modestly colored, and/or often hidden from view, the public often does not perceive or appreciate the magnitude of this loss. Grassland management entities could use additional information to bolster their public outreach and education on grasslands.

3.11 | What legal and policy changes can support grassland resilience to climate change?

Policies and laws can create incentives or disincentives for protecting and maintaining healthy grasslands and therefore present important opportunities for promoting grassland conservation (Lark, 2020). For example,

because conversion of grasslands to agricultural cropland is one of the biggest threats to grasslands in the North Central region, policies laid out in the U.S. Farm Bill have a direct impact on the future existence and health of grasslands. Understanding the legal and policy changes that can support grassland resilience to climate change is most relevant to NGOs, partnerships, and state and tribal agencies since federal agencies are not able to advocate for policy changes.

3.12 | How can grassland protection, enhancement, maintenance, and reconstruction be economically incentivized?

Economic incentives for landowners to protect, improve, and maintain their grasslands represent an important opportunity for sustaining and increasing grassland conservation in the North Central region. For example, enhanced livestock insurance and other mechanisms to economically incentivize ranching over crop production would help reduce conversion of grassland to cropland (Brunson & Huntsinger, 2008; Davidson, 2017; Hendrickson et al., 2018). Grassland managers are also considering whether there are additional opportunities to financially incentivize grassland conservation in ways that align with climate adaptation and mitigation.

3.13 | How can grassland management be strategically coordinated across agencies, organizations, jurisdictions, and borders?

To be most effective at conserving and maintaining healthy grassland ecosystems in a changing climate, grassland management needs to be coordinated at the landscape level (Epstein et al., 2021). Yet the grasslands of the North Central region are managed by many different grassland management entities who sometimes have conflicting goals. Information needed to facilitate the strategic coordination of actions across agencies, organizations, jurisdictions, and borders includes addressing structural barriers and identifying both costs and benefits of a coordinated approach.

3.14 | How can the accessibility of relevant science and tools be improved?

While there is a growing body of scientific literature on the impact climate change has on grasslands, this research is unlikely to support grassland management unless it is accessible, usable, and relevant (Dilling & Lemos, 2011). The theory, methods, and practice of how to intentionally develop useful and usable research products is a developing field, and one common approach is to engage managers and other stakeholders in the research process (Bamzai-Dodson et al., 2021). Consideration of the availability, relevance, and usability of tools and information can guide the development of needed trainings in the use of existing data and the development of additional tools to better address manager needs.

3.15 | What novel ways of thinking are needed to successfully manage grasslands amidst climate change?

Managing grasslands within the context of climate change is complicated because of the novelty, complexity, and uncertainty inherent in projected climate change impacts. Climate change affects the intensity, duration, spatial scale, timing, and/or the relationships between many of the biotic, abiotic, and social factors and processes which together comprise grassland ecosystems. Therefore, grassland managers broadly share questions about how existing frameworks can be applied and new frameworks developed to conceptualize problems and solutions in relation to climate change and successful management of grasslands.

4 | DISCUSSION

We have identified 70 broadly shared questions that can serve as a foundation for actionable research to support grassland management in the North Central region. As others have highlighted (see Sutherland et al., 2006, 2009), synthesizing questions to support conservation over a large geographic area poses a challenge in that the questions should be both sufficiently specific to be addressed while also generic enough to encompass the diversity of issues that arise across ecosystems and management entities. In this discussion, we explore both the opportunities for developing greater specificity and the value of generality. Specifically, we outline next steps for collaborative work between researchers and conservation practitioners to further refine these questions to support actionable science and conservation on the ground in the North Central region. We then discuss the utility of broad themes that emerged from the 70 questions for informing actionable science to support conservation beyond the North Central region. We also discuss the advantages and limitations of the methodological approach used to identify the 70 questions.

4.1 | Next steps for supporting actionable science in the North Central grasslands

The identification of the 70 broadly shared questions presented above represents an important first step toward the development of actionable science to support grassland management in the North Central region within the context of climate change. Collaboration and engagement between the research and management communities is key to crafting science information that will support decision-making and adaptation planning (c.f., Bamzai-Dodson et al., 2021; Bamzai-Dodson & McPherson, 2022). Though our 70 questions provide a foundation for this engagement, additional steps are needed to build collaborative relationships and further refine these questions to address site- and management-specific challenges on the ground.

First, additional work should be done with tribal nations and private landowners to gain a better understanding of their management contexts and information needs and to understand the extent to which these questions reflect their priorities. Notably, we were unable to access and review any documents related to grassland management by tribal nations, in part because many tribal nations have not yet developed formal resource plans, or those plans were not publicly available. Contacting tribal offices was also complicated due to the disruptions of the COVID-19 pandemic. Engagement and partnership with tribal resource managers is particularly needed because tribal nations have often been underserved by research investment and excluded from regional and landscape-scale planning and decision-making. Collaborating with tribal resource managers to identify where tribal grassland information needs overlap with those articulated in this paper and where there may be additional needs will help to ensure that tribal grassland management goals are supported. Similarly, documents specific to private grassland management are often nonexistent, unavailable, or otherwise difficult to obtain. Most grasslands in the North Central region are managed by private landowners who have diverse land management practices and goals. In some cases private landowner perspectives were at least partially represented in NGO and Migratory Bird Joint Venture documents (e.g., D. J. Case & Associates, 2014; Neely et al., 2006; The Nature Conservancy, 2016). However, additional engagement is needed to ensure that tribal resource managers' and private landowners' interests are represented in future research efforts.

Second, a review and synthesis of the existing scientific literature is needed to determine where future research should be directed. Importantly, the 70 broadly shared questions do not necessarily indicate an absence of information about a particular topic. While some questions may indeed reflect insufficient information or a lack of information for the North Central region, some reflect the need for synthesis, translation, or communication of existing information to grassland managers. Therefore, an important next step is to review and synthesize the existing scientific literature. Already these questions have served as the basis for a second working group to synthesize available science to begin to address some of these questions (see Miller Hesed, Yocum, Rangwala, et al., 2023).

Third, this list of questions can serve as a framework around which to develop communities of practice that include scientists, resource managers, and conservation practitioners across multiple organizations and agencies in the region. While specifics vary from agency to agency and site to site, overall our review and synthesis of grassland management-related documents highlighted the great extent to which goals and missions are shared and/or complementary across grassland management entities in the North Central region. Initial efforts to identify the relative importance of these 70 questions across various grassland management agencies and organizations in the region suggest that there are opportunities for collaboration across these entities in pursuit of shared or complementary conservation and management goals (Miller Hesed & Yocum, 2023; Miller Hesed, Yocum, Beckmann, et al., 2023).

4.2 | Broad themes to inform conservation beyond the North Central region

Taken together, the 70 broadly shared questions we identified suggest that grassland managers have three overarching questions in regard to climate change: (1) How will climate change interact with current grassland threats and stressors?; (2) How will climate change impact the efficacy of present grassland management actions?; and (3) How and where should grassland conservation and management actions be prioritized given the projected impacts of climate change? These very broad questions could easily be adapted and applied to begin to develop an actionable research agenda for other ecosystems or geographies.

Many of the broadly shared grassland management questions require insights and input from multiple fields of study that span the natural and social sciences. As reflected by our list of 70 broadly shared questions (Table 1), conservation in a changing climate not only requires knowledge of climate and ecological processes, but also requires knowledge of human systems and processes. While this call for interdisciplinary work is not

new (see National Academies of Sciences, Engineering, and Medicine, 2021; Stone-Jovicich et al., 2018), our table of research questions explicitly identifies some of the fields of expertise that will be needed to address grassland manager information needs. Importantly, the fields of study indicated as relevant for addressing each question in Table 1 are not intended as an exhaustive list, but rather as a starting point for developing interdisciplinary research teams. In addition, traditional ecological knowledge may also provide key insights for many of the questions in Table 1.

Finally, our review of grassland management-related documents and identification of broadly shared questions highlights three overarching reasons why grasslands tend to be overlooked for conservation. First, degradation of a grassland can be quite gradual and subtle and therefore easy to miss, as pointed to by questions about herbaceous invasives, woody encroachment, and disruption of the historical disturbance regime. For example, while the die-off of trees or deforestation in a forest often occurs rapidly and is immediately and visually obvious, the slow encroachment of invasive species or trees into native grassland and its effect on ecosystem functions is more nuanced and not as readily observed (Twidwell et al., 2021). Second, grasslands have relatively fewer charismatic species around which to rally conservation funding, as illustrated by questions about public understanding of grasslands and conservation of wildlife. Grasses simply do not evoke the same sentiments as trees, and in the North Central region—as in many other parts of the world—the grassland megafauna has been largely displaced and the small species that remain are often unseen in their grassland habitat. Third, conservation is challenging in a landscape where a high proportion of the land is privately owned, as demonstrated by questions about promoting conservation on private land, economic incentives, and legal and policy changes. Coordinating conservation across a patchwork of private lands is more difficult than implementing conservation on public land as it is subject to land-use changes associated with shifting agricultural policy, fluctuating commodity markets, and variable funding for conservation programs on private land.

4.3 | Benefits and limitations of methodology

Our approach differs somewhat from other efforts to identify conservation questions and information needs (c.f., Ahlering et al., 2020; Sutherland et al., 2009, 2006) in that we first focused on analyzing existing reports, management plans, and peer-reviewed literature rather than soliciting information directly from resource managers. We employed this alternative approach to avoid overtaxing resource managers (Dilling & Berggren, 2015), and this is important when balancing considerations for when, how, and to what extent to involve stakeholders in the scientific process (Ferguson et al., 2022; Wilmer et al., 2021). However, as we found with tribal nations, underserved and overburdened communities may have fewer reports and less documentation available for this type of analysis, and so this approach should be used in addition to, and not a stand-in for, ethical consultation and collaboration. Even with well-represented groups, such as federal and state agencies, strategically focused consultation with managers helped to ensure that the questions were broadly relevant. This was especially important since our review was limited to publicly available documents that may not include emerging issues since it can take time for a new idea (e.g., climate change) to be incorporated into formal planning documents or reports. Strategically focused consultation with grassland management entities to provide feedback on these questions helped to ensure that draft questions were broadly relevant; however, this should not preclude additional future engagement to refine questions and identify priority research needs for various management entities and use cases (as we discussed above).

5 | CONCLUSIONS

We reviewed and synthesized grassland management-related documents to identify 70 broadly shared questions that, if answered, could support conservation of North Central grasslands in a changing climate. These questions can serve as a research agenda for the NC CASC and for other researchers looking to conduct actionable science for grassland ecosystems in the North Central region. Already these questions have been used to inform the call for proposals for NC CASC fiscal year 2022 research funding and to guide the agenda for a workshop on climate change and grasslands being developed for U.S. Fish and Wildlife Service grassland managers in 2023 (South Central Climate Adaptation Science Center, 2022). In addition, both the approach and the questions presented here can be adapted and applied in other regions and ecosystems. Identifying the questions that are broadly shared across resource managers—as we have done for North Central grassland managers—is an important first step in developing actionable science to support conservation practitioners' work amid a changing climate.

AUTHOR CONTRIBUTIONS

Heather M. Yocum, Molly Cross, and Aparna Bamzai-Dodson conceived the project. Christine D. Miller Hesed and Heather M. Yocum led the design of the data

synthesis and collection of data with contributions from all other authors. Christine D. Miller Hesed led the analysis and interpretation of data with contributions from all other authors. Christine D. Miller Hesed drafted and revised the manuscript with review and contributions from all other authors. Sarah Jaffe created the figures for the manuscript. Christine D. Miller Hesed prepared the Supporting Information.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data for this synthesis were collected from grassland management-related documents; for a complete list of documents reviewed and synthesized for this manuscript, please see Supporting Information.

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SUPPORTING INFORMATION

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

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