ECOLOGICAL DROUGHT IN MONTANA: PRACTITIONER PERSPECTIVES, NEEDS, AND KNOWLEDGE SHARING

by

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DEDICATION

To the waters of the Pacific Northwest, where I grew up, which inspired my lasting appreciation for water as essential to the well-being of people and the planet. And to the Montana communities who know their ecosystems best, your expertise will shape our collective future.

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ABSTRACT

Ecological drought and its impacts are extensive and unpredictable, influenced by social, ecological, and interacting factors. Thus, ecological drought represents a social-ecological systems (SES) challenge characterized by dynamism, complexity, and uncertainty. SES challenges require adaptive approaches. The challenge of monitoring ecological drought is furthered by the lack of dedicated and reliable ecological drought monitoring strategies. To address this, I conducted interviews with and administered survey questions to natural resource practitioners in Montana. Practitioners were asked about the indicators they use to recognize ecological drought and the impacts they experience. Results demonstrate high levels of expertise related to individual management concerns, indicating a need for coordination among practitioners to contribute to the holistic thinking and collaboration necessary for effective adaptive approaches. Practitioners also report a need for more and better data and improved communication to improve ecological drought monitoring in Montana. These needs present practitioners' desire to reduce epistemic uncertainty and highlight strategies for operating amid irreducible uncertainty. Finally, I found that practitioners predominantly exchange knowledge about ecological drought through informal conversations, suggesting that increased valuation and incorporation of multiple types of knowledge can improve ecological drought monitoring efforts. These results underscore the importance of adaptive decision-making in response to ecological drought and highlight opportunities to foster ongoing learning, embracing uncertainty, and knowledge sharing among practitioners and other decision-makers in Montana. Overall, this dissertation contributes 1) an increased understanding of the ecological drought indicators that practitioners use and the impacts they recognize, 2) an examination of practitioners' needs for improving ecological drought monitoring amid uncertainty, and 3) a report on how ecological drought knowledge is shared by practitioners in Montana.

CHAPTER ONE

INTRODUCTION

Author Positionality

As the author of this dissertation, I approached this work with my own set of biases, informed by my identity as a well-educated, white female with a background in Western science and a lifelong concern for how water quantity and quality impact the well-being of people and the planet. Co-authors include social scientists working in water policy, stakeholder engagement, and rangeland management, and meteorologists concerned with flash drought and drought monitoring tools. Our collective biases informed the work presented in this dissertation.

Problem Overview: Ecological Drought in Montana

Drought has extensive ecological impacts that affect ecosystems, their services, and human communities dependent upon them. In Montana and much of the western United States, arid conditions are anticipated to intensify and contribute to more frequent and more severe drought events (Cook et al., 2004; Van Loon et al., 2016; Whitlock et al., 2017; Jensco et al., 2019). Recent droughts in Montana have had notable negative impacts, including intense wildfires, degraded habitats, and declines in tourism (Hoell et al., 2020). Ensuing drought conditions intensify the stress of low ecologically available water and exacerbate ecological impacts.

Ecological drought is "an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and human systems" (Crausbay et al., 2017, p. 2544). This definition acknowledges the impacts of low water availability on ecosystems and the potential for compounding stress to contribute to permanent ecosystem transformations (Crausbay et al., 2017 and 2020). Drought conditions impair ecosystem processes that can, in turn, alter ecosystem structures and services (Crausbay et al., 2020). Unexpected climate patterns, along with outcomes of human activity, can further stress ecosystems, contributing to ecological drought impacts (Crausbay et al., 2020).

In Montana, ecosystem functions and services are crucial for livelihoods. Over 62% of Montana's land is agricultural (grazing or farming), while agriculture and tourism account for more than 22% of employment and $9 billion in earnings for the state (Headwaters, 2025a and b). Ecosystems and ecosystem services are critical to both the agriculture and tourism industries, which suggests the potential significance of economic consequences of ecological drought. Recognition of the importance of ecosystem services and water availability in Montana led to the establishment of the Upper Missouri Headwaters (UMH) in southwestern Montana as a drought-priority location for a demonstration planning project by the National Drought Resilience Partnership in 2017 (Montana Drought Demonstration Partners, 2015). Raheem et al. (2019) reported a detailed catalog of ecological drought impacts that threaten Montana ecosystems and humans alike in the UMH. These include impacts on different ecosystems, recreation and tourism, agriculture, society, and public health (Raheem et al., 2019; Headwaters, 2025b). This breadth of impacts underscores the importance of understanding ecological drought in Montana and other areas where natural resources are not only important for ecology, but also closely tied to livelihoods and human wellbeing.

The research presented in this dissertation is part of a larger, interdisciplinary NOAA NIDIS Coping with Ecological Drought project that aims to inform improved decision-making support about ecological drought response. To do this, the NOAA project and this dissertation focus on practitioners representing natural resource management and policy efforts related to drought. These practitioners engage in planning, policymaking, and management guidance that can inform responses to ecological drought across ecosystems. This dissertation leverages their expertise to expose opportunities to improve monitoring of and adaptive decision-making about ecological drought in Montana, with a larger goal of fostering ecological and community resilience. Our research team included social and atmospheric scientists from Montana State University, the University of Arizona Extension, the University of Wisconsin Madison, and the University of Nebraska Lincoln. Portions of this project not included in this dissertation consider the utility of a new 30-meter resolution evapotranspiration tool for ecological drought management and the different ecological drought management responses, or lack thereof, undertaken in different ecosystem types.

The potential for increasingly frequent and intense drought in Montana requires more reliable monitoring of and response to ecological drought. A thorough understanding of ecological drought will include knowledge of the many drivers of water availability and potential impacts of ecological drought (Moss et al., 2024). Moreover, assessing how practitioners and decision-makers understand and communicate about ecological drought will be critical to developing adaptive approaches for effective anticipation of and response to ecological drought (Lemos et al., 2012; Lubell et al., 2013; Clifford et al., 2022; Smith et al., 2023; Cravens et al., 2024). Reliable monitoring strategies, knowledge exchange, and adaptive approaches to ecological drought represent knowledge gaps addressed in this dissertation. This dissertation uses a mixed-method social science research design to report on indicators and impacts of ecological drought, monitoring needs, and knowledge-sharing by natural resource practitioners.

These practitioners include scientists, educators, policymakers, planners, watershed stewards, and resource managers representing federal, state, and local agencies and organizations that engage in ecosystem management and drought preparation or response in Montana. Many of the practitioners who participated in this mixed-methods research denied being managers, distancing themselves from actions on the ground.

This dissertation leverages multidisciplinary literature on social-ecological systems, uncertainty, community resilience, adaptive approaches, and the exchange and usability of different types of knowledge. This introduction examines this literature to answer the following questions: 1) What ecological drought indicators do practitioners use and recognize? 2) What do practitioners need to improve ecological drought monitoring? 3) How is ecological drought knowledge shared by practitioners?

Literature Review

This dissertation contributes to the broad field of environmental social science, leveraging literature from multiple disciplines that informs environmental management. The theories I highlight in this section build upon each other to form the foundational thinking of this dissertation and each of the three results chapters within it. Social-ecological systems (SES) thinking draws attention to the complexity and uncertainty of dynamic and interacting social and ecological systems on ecological outcomes. This is informed by theories of uncertainty, which must be considered in approaches to SES challenges, and resilience, which is influenced by approaches to SES challenges. Adaptive approaches incorporate a range of actions that are enabled by the adaptive capacity of a group or individual and are necessary for addressing SES challenges and fostering resilience. Reference to all these bodies of literature leads to theories of knowledge sharing and scholarship about different types of knowledge that inform environmental understanding and management. This literature review concludes with discussion of the importance of incorporating different types of knowledge into adaptive approaches to address SES challenges.

Social-Ecological Systems

Ecological and natural resource management efforts to maintain steady-state ecosystems have become recognized as ineffective; this paradigm has been replaced by an appreciation for the dynamic and uncertain nature of ecosystems (Milly et al., 2008; Cote and Nightingale, 2012; Virapongse et al, 2016). This shift away from the previous command and control paradigm of conservation was motivated by increased awareness of finite resources in the 1980s and recognition of the need for holistic and adaptive approaches to managing complex ecosystems in the 1990s (Chapin et al., 2009; Westley et al., 2011; Virapongse et al., 2016; Wilmer, 2018). The complexity of ecosystems is partly due to both natural and human influences. The form and function of social-ecological systems (SESs) are influenced by social and ecological drivers, as well as their interactions (Berkes et al., 2003). Additionally, constant change and uncertainty across scales are characteristic of SESs (Berkes et al., 2003; Walker et al., 2004; Liu et al., 2007; Chapin et al., 2009).

SES frameworks hold that an individual or community action, at any scale, can act as a driver of ecosystem change, which in turn influences human systems (Folke, 2006; Walker et al., 2006; Cote and Nightingale, 2012; Wilson 2012). This idea contributes to the intricacy and nuance of SESs that create challenges for monitoring, management, and resilience. Approaching ecological drought as an SES challenge, by considering the normative, biophysical, and management forces acting upon ecosystems, is necessary to inform adaptive responses that promote ecological and community resilience amid uncertainty (Folke, 2006). The research in this dissertation considers whether practitioners' approaches to ecological drought demonstrate SES thinking.

Ecological Drought as a Social-Ecological Systems Challenge Exceptional changes in climate patterns and ecological structures and functions have generated new challenges that demand new approaches to the management of natural resources and landscapes within SESs (Benson and Stone, 2013). Ecological drought represents a complex SES challenge, influenced by and influencing social, ecological, and interacting systems (Crausbay et al., 2017). Drought impacts on ecosystems lead to ecological changes (e.g., habitat loss, vegetation change) as well as implications for human communities dependent upon those ecosystems and their services (e.g., clean water, fisheries) (Millar and Stephenson, 2015; Crausbay et al., 2017). Understanding the extent of ecological drought impacts is critical to addressing ecological drought as a complex and dynamic SES challenge that threatens communities and ecosystems alike.

Uncertainty and Unreliability in Ecological Drought Monitoring Ecological drought is characterized by both epistemic uncertainty, due to knowledge limitations, as well as irreducible uncertainty, due to inherent variability (Refsgaard et al., 2007; Wheaton et al., 2008; Yoe, 2013; Kleindl et al., 2015). The interplay of social and ecological drivers contributes to ever-changing ecological dynamics that challenge the usability of static climate information and the reliability of monitoring (Berkes et al., 2003; Chapin et al., 2009; Lemos et al., 2012; Haigh et al., 2015;

Crausbay et al., 2020). For example, over time, interacting social and ecological influences lead to unprecedented impacts that are compounded by additional social and ecological drivers.

Although our understanding of ecological drought continues to grow, shifting climate patterns and compounding social and ecological stressors contribute to irreducible uncertainty and underscore the need for the ongoing effort to account for all the impacts of ecological drought (Crausbay et al., 2020; Moss et al., 2024). While there are certainly socioeconomic impacts of ecological drought, this dissertation focuses only on ecological impacts. Pervasive variable uncertainty about the impacts of ecological drought, including their nature and timing, necessitates responses that engage adaptive decision-making informed by usable and reliable information (Lubell et al., 2013; Dilling and Lemos, 2011).

Drought monitoring efforts typically comprise a variety of hydrologic and meteoric metrics tied to hydrologic outcomes. However, changing climate patterns and drought frequencies have made these less reliable for monitoring and anticipating all types of droughts (Hoylman et al., 2022). Additionally, ecological drought impacts do not only effect hydrologic components of ecosystems. No standard monitoring strategy dedicated to ecological drought exists, making an already complex monitoring challenge more difficult (Crausbay et al., 2020). The ability of present drought monitoring tools to reliably anticipate ecological drought impacts is challenged by diverse ecosystems, compounding stressors, and human interactions that complicate responses to low ecologically available water (Crausbay et al., 2020; Cravens et al., 2024; Moss et al., 2024). The potential impacts of ecological drought are extensive, and the difficulty monitoring ecological drought, coupled with the irreducible uncertainty characteristic of SES challenges, support the need for ongoing investigation into both the indicators of ecological drought and the resulting impacts in Montana and throughout the Intermountain West. This dissertation examines how practitioners recognize uncertainty to inform their thinking and approaches to ecological drought.

Resilience

Ecological drought, like any complex SES challenge, represents ongoing disturbance to ecosystems and communities. Responses to ecological drought must therefore prioritize ecological and community resilience, encouraging adaptability and balancing social and natural forms of capital. Ecological resilience is essential for community resilience, and both are influenced by intrinsic and extrinsic factors. Embracing the complexity and uncertainty of ecological drought will underscore the need for adaptive approaches that foster resilience.

Ecological Resilience Ecological resilience was initially considered an ecosystem's ability to resist change. This concept was challenged by Holling's recognition of the gap between population dynamics in models versus actuality (1973). Ecological resilience has more recently been defined as a system's ability to absorb disturbance and return to a similar state or function (Gunderson et al., 1997; Berkes et al., 2003; Chapin et al., 2009; Wilson, 2012). This shift in thinking recognizes the importance of adaptability and transformability across scales to drive ecosystem responses to disturbance (Walker et al., 2004). Ecological adaptability and transformability are influenced by abiotic forces, such as weather and climate patterns, and human forces, such as natural resource exploitation or management (Hobbs et al., 2006). Resilience has become increasingly critical alongside the rise of transition theory, which emphasizes the basic premise that things always change (Walker and Salt, 2006). These theories all point to the potential for ecosystems to be resilient in their transformed states, which can be incompatible with management goals. Ecological resilience and appropriate management goals are needed in response to the extensive threat of drought impacts on ecosystems.

Community Resilience Community resilience importantly expands on social and ecological resilience to include both, reflecting how human systems respond to change based on social, economic, and natural forms of capital (Folke, 2006; Chapin et al., 2009; Wilson, 2012). Social resilience accounts for the inherent nonlinearity of human systems and emphasizes the need to reorganize in response to change (Folke, 2006). Social resilience represents both a process and an outcome reflecting the capacity of a human system to respond to endogenous and exogenous disturbances (Adger, 2000; Chaskin, 2008; Wilson, 2012).

In this research, I define communities as groups of people sharing a landscape and its natural resources who inevitably interact. Communities represent and operate within complex SESs, with social, economic, and natural capital influencing each other and the community's capacity to respond to change, operate under uncertainty, and continue to learn (Wilson, 2012). Community bonding, bridging, and structure drive adaptive capacity and subsequent resilience (Chaskin, 2008; Magis, 2010). To foster community resilience, promoting ecological resilience is essential. Effective monitoring of and response to ecological drought can enhance ecological resilience and the community resilience of communities impacting and impacted by ecological drought.

Adaptive Approaches

The uncertainty, dynamism, and the interrelation of social and ecological influences on ecological drought necessitate flexible, iterative, and adaptive approaches. Adaptation is recognized as the adjustment of actions in response to environmental changes to reduce negative impacts (Adger et al., 2007). Adaptation processes reflect decisions and management actions related to a specific place, ecosystem, or resource over time and increasingly include social dimensions (Adger et al., 2007; Cote and Nightingale, 2012; Wyborn et al., 2015; Murphy et al., 2017; Smith et al., 2023). The uptake of adaptation efforts depends upon the adaptive capacity of a group or individual and can be achieved through adaptive decision-making. This dissertation utilizes adaptation literature to corroborate the need for adaptive approaches to ecological drought and to assess the capacity for adaptive decision-making about ecological drought response.

Adaptive Capacity and Decision-Making Adaptive capacity represents a group or individual's ability to behave adaptively based on their individual agency, resources, information, and constraints (Chapin et al., 2009, Engle, 2011; Yohe and Tol, 2002). In addition to these aspects, adaptive capacity is determined by the potential to "respond to challenges through learning, managing risks, developing new knowledge, and devising effective approaches" (Marshall, 2015, pg. 6). Adaptive capacity is importantly not static, but variable within and across groups and can be bolstered by risk assessment, knowledge exchange, and supportive social and economic capital (Chapin et al., 2009; Marshall, 2015). Adaptive approaches to address SES challenges depend upon adaptive capacity (Yohe and Tol, 2002; Berkes et al., 2003; Adger et al., 2007; Chapin et al., 2009)

The operationalization of adaptive capacity occurs through adaptation efforts, such as adaptive decision-making. Adaptive decision-making refers to individual action in response to changing conditions (Lubell et al., 2013; Derner et al., 2022). Individual worldviews, management goals, risk tolerance, social networks, and economic circumstances drive adaptive decision-making, reflecting the theory of planned behavior and diffusion theory (Ajzen and Fishbein, 1980; Rogers, 2003; Lubell et al., 2013; Smith et al., 2023). Opportunities to encourage adaptive decision-making to address SES challenges include fostering trusted leadership and effective knowledge sharing (Lubell et al., 2013; Derner et al., 2022). In addition, ongoing monitoring to provide new information across time and scales is needed to inform decision-making in response to SES challenges (Kleindl et al., 2018). In this work, I define adaptive decision-making as a process of iterative decisions influenced by management objectives and learning that incorporate place-based knowledge to anticipate ongoing change over time and space (Payne et al., 1990, Knapp and Fernandez-Gimenez, 2009; Lubell et al., 2013).

<u>Incorporating Multiple Types of Knowledge</u> Alongside management goals and leadership, learning and information are key drivers of adaptive decision-making (Lubell et al., 2013; Smith et al., 2023). The information available to decision-makers informs both their decisions and their capacity to be adaptive (Lubell et al., 2013). Information comes in many forms, from Western science to traditional ecological knowledge, Indigenous science, and local or experiential knowledge, which includes knowledge based on relationships between people and their localities, such as social memory or cultural traditions (Olsson and Folke, 2001; Folke, 2006; Aswani et al., 2018). In this dissertation I use the term local knowledge to inclusively refer to any of these alternatives to Western science.

Sharing knowledge, especially multiple types of knowledge, can positively influence management outcomes by increasing engagement and alignment with community priorities (Fazey et al., 2006; Lemos et al., 2018; Clifford et al., 2022). Knowledge sharing is often part of the bridging and bonding that generates social capital, contributing to community resilience

(Wilson, 2012; Sherren, 2020). This is accentuated by the sharing of local knowledge, which, although not generalizable, showcases local natural resource management ideals and can illuminate discrepancies within communities (Gosnell, 2007; Metcalf et al., 2015; Epstein et al., 2019). Generation of social capital and address of potential disagreements within communities are two ways that knowledge exchange can improve our understanding of complex SES challenges and inform adaptive approaches to them (Lemos et al., 2012; Wilmer et al., 2018; Smith et al., 2023).

Research Approach

Drawing on the literature presented above, I sought to address questions about how practitioners monitor and communicate about ecological drought in Montana. In the three following chapters, I will address three distinct sets of research questions (presented in the Research Methods below) related to practitioners' monitoring of and response to ecological drought to assess whether they address ecological drought adaptively, recognizing it as an SES challenge. The results chapters in this dissertation build upon each other to assert the need to address ecological drought as an SES challenge, offering insight into how this can be achieved through holistic thinking, communication, and informal knowledge sharing to encourage adaptive decision-making.

First, this dissertation presents the indicators and impacts of ecological drought that practitioners report using and recognizing, respectively. I explore how these indicators and impacts reflect siloed or holistic thinking about ecological drought, as holistic thinking is required for an effective SES approach. Then, I report on the ways practitioners think that ecological drought monitoring can be improved. In this analysis, emphasis is placed on uncertainty, to highlight the need for adaptive approaches to ecological drought monitoring. Finally, I examine the ways the practitioners exchange knowledge about ecological drought. This highlights the importance of informal conversations to promote engagement in and incorporate multiple ways of knowing into adaptive approaches to ecological drought.

Chapters 2 and 3 emphasize ecological drought as an SES challenge, articulating the need for adaptive decision-making informed by communication across areas of expertise. These chapters also illustrate the uncertainty around ecological drought impacts and advocate for adaptive approaches to foster ecological and community resilience. Chapters 3 and 4 expand on the importance of communication both among practitioners and between practitioners and other decision-makers to facilitate learning to inform adaptive decisions. Finally, chapter 4 offers insight into how practitioners communicate about ecological drought, pointing to opportunities to encourage and increase these efforts to promote consideration of ecological drought as an SES challenge.

Research Methods

This dissertation research used a mix of social science research methods including semi-structured interviews and an online survey to address questions about how natural resource practitioners approach and respond to ecological drought in Montana. In each chapter, the significance of the threat of ecological drought is articulated, including examples of the economic, social, and ecological impacts that it poses to ecosystems in Montana. All three chapters leverage SES frameworks to apply concepts from adaptation and resilience literature to addressing ecological drought in Montana. Additional details on the methods used are reported in each results chapter in this dissertation.

This research was carried out by the social science team within a larger interdisciplinary team of social and atmospheric scientists from Montana State University, the University of Arizona, the University of Wisconsin-Madison, and the University of Nebraska-Lincoln. This collaborative team worked together over four years on a NOAA-NIDIS Coping with Ecological Drought Grant focused on new monitoring tools and decision support in response to ecological drought in Montana. The analysis and findings presented in this dissertation represent a subset of the work included in this larger project.

The results chapters in this dissertation use 25 semi-structured interviews and 79 responses to an online survey. Interviewees and survey respondents were all natural resource practitioners in Montana, from local, state, and federal agencies and organizations who represent watershed stewards, scientists, policymakers, and educators. This research focused on practitioners as users of monitoring tools that inform policies to guide ecological drought management and decision making in Montana. The role of practitioners is often to use their expertise to bring science into management through the development and implementation of plans and policies at the state level that inform decisions and enable action at local and statewide scales. Thus, practitioner perspectives were needed to understand current approaches to ecological drought that can inform future efforts to support adaptive approaches and decision-making.

<u>Interviews</u> Purposive sampling of interview participants included a comprehensive review of public data on state and federal agency personnel and practitioners already connected with the research team through previous work. We also employed snowball sampling, asking interviewees to suggest any additional practitioners we should include. This led to the

development of a sample list of 117 people, 63 of whom were contacted by the research team to ask for an interview. The remaining list that we did not contact included practitioners whose contact information we could not find, practitioners holding the same or similar roles to those already interviewed, and practitioners we learned about late in our interview process and did not have time to include. Purposively sampled interviewees were contacted by email on April 3, 2023, and up to four follow-up emails were sent in two-week intervals until June 2, 2023. Outreach to practitioners recommended by interviewees followed the same pattern, with up to four follow-up invitations sent every two weeks in accordance with the date of their initial invitation to participate. Of those contacted, we had incorrect contact information for two practitioners, did not hear back from 26 practitioners, and another 10 practitioners declined to participate, leaving us with 25 interview participants.

All 25 interviews were recorded and transcribed using TranscribeMe software and reviewed for accuracy. Myself and one other researcher completed qualitative coding of the transcripts in NVivo software as well as intercoder reliability, achieving a Cohen's Kappa score of 0.89 (where 1 is perfect agreement), which indicates a high level of consistency between researchers (Landis and Kock, 1977). Deductive qualitative coding was guided by a codebook created by the social science research team (Appendix B) to highlight predetermined themes. The codebook was generated iteratively as the research team recognized new themes and ideas while conducting interviews. I then qualitatively analyzed the data in NVivo, through queries connecting the indicators and impacts of ecological drought reported to practitioner management concerns and demographics. I also used MS Excel to categorize practitioners' management concerns and perform descriptive statistics to highlight connections between practitioners' management concerns and ecological drought monitoring strategies. The results of these interviews are reported in Chapters 2 and 3 of this dissertation.

Survey Purposive sampling was also used to determine a list of 480 individuals to invite to participate in our online survey. The survey was administered on Qualtrics and disseminated via email to Tribal, federal, state, and NGO employees in positions related to resource management in Montana (NPS, National Forests, USFS, USDA-ARS, USDA NRCS, USACE, BLM, FWS, DNRC, FWP, MTNHP, Extension, University). Similar to our interviewees, we surveyed natural resource practitioners to understand this population's perspectives on current approaches to ecological drought monitoring and management within Montana. An initial email invitation was sent on November 29, 2023 and followed by up to four reminder emails through January 8, 2024. As a final follow-up, practitioners working in forest ecosystems received phone calls during February of 2024. In total, 455 individuals were reached by phone or email (contact failed or was blocked for 25 individuals). We ended up with a total of 79 survey respondents (17% response rate) who fully or partially completed the online survey.

Survey data was downloaded from Qualtrics for cleaning and descriptive analysis in MS Excel. The data about knowledge sharing reported in this dissertation was cleaned to ensure agreement between awareness and use of knowledge sharing methods. Specifically, when a respondent indicated use of a knowledge sharing method, I made sure that they also reported being aware of it. I then used descriptive statistics to determine awareness and use of each knowledge sharing method included in the survey. I also explored the correlation of these results with respondents' ecosystem types and management goals. The results of the online survey are reported in Chapter 4 of this dissertation.

Data Collection and Analysis by Chapter Chapter 2 of this dissertation uses the 25 semi-structured interviews to catalog the indicators and impacts of ecological drought practitioners' use, as well as their experiences with ecological drought, to assess whether they approach ecological drought holistically as an SES challenge. Using a codebook generated by co-authors, one co-author and I undertook deductive interview coding and performed intercoder reliability (Cohen’s Kappa score 0.89) to ensure consistency across coding. I then analyzed the codes to understand how primary management concerns inform the ecological drought indicators and impacts practitioners reported. Chapter 2 addresses the following questions:

1. What ecological drought indicators and impacts do practitioners use and recognize?
2. Do primary management concerns influence the indicators and impacts practitioners use to recognize ecological drought?
3. Do practitioners in Montana approach ecological drought as an SES challenge?

The qualitative data from the same 25 semi-structured interviews with natural resource practitioners was analyzed further to examine what practitioners thought was needed to improve ecological drought monitoring in Chapter 3. Practitioners were asked to report things that would improve ecological drought monitoring, and their answers were coded deductively by me and a co-author using the pre-designed codebook. I then analyzed the codes to determine how these needs reflect recognition of uncertainty and synthesized the results to discuss whether addressing their needs can promote adaptive decision-making about ecological drought. The findings presented in Chapter 3 emphasize the need to operationalize SES frameworks to embrace uncertainty and complexity and promote adaptive decision-making. I present a diagram to link the adaptation envelope, an idea presented by Wyborn et al. (2015) explaining things that constrain and expand adaptive capacity, with the manager decision space presented by Clifford et al. (2022) to address of some of the needs practitioners reported and to clearly answer the following research questions:

1. What do practitioners in Montana need to improve ecological drought monitoring?
2. Do practitioners recognize uncertainty as an obstacle in ecological drought monitoring?
3. How can better ecological drought monitoring inform adaptive decision-making?

In the final results chapter of this dissertation, Chapter 4, I report the results from an online survey. A sample of 79 natural resource practitioners from local, state, and federal agencies and organizations related to land and resource management were asked to select, from various options, the methods that they are aware of, unaware of, and use to exchange knowledge about ecological drought. Using descriptive statistics, I analyzed the most and least used methods for sharing ecological drought knowledge to inform suggestions about how to encourage more knowledge sharing about ecological drought. Chapter 5 addresses the following research questions:

1. How do practitioners in Montana share knowledge about ecological drought?
2. How can sharing ecological drought knowledge promote adaptive decision-making?

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CHAPTER TWO

INDICATORS AND IMPACTS OF ECOLOGICAL DROUGHT: ADVANCING A SOCIAL-ECOLOGICAL SYSTEMS APPROACH

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Abstract

Increasing demand for water resources amidst decreasing water supply in the arid Mountain West has led to more frequent and more severe drought events. Changing climate, precipitation, and temperature patterns exacerbate this imbalance, leading to new drought concerns. Ecological drought represents the impact that drought events have on ecosystem functions and services. Ecological drought represents a social-ecological systems (SES) challenge, influenced by social, ecological, and interacting forces and exhibiting interconnected impacts on ecosystems and humans (e.g., streamflow affects aquatic habitat and water quality). However, there is no standardized monitoring strategy for ecological drought, and little is known about how it is monitored in Montana. Using qualitative data from 25 semi-structured interviews, I present the indicators and impacts of ecological drought used and seen by practitioners in Montana. Through qualitative analysis, I demonstrate the influence of primary management concerns on practitioners' approaches to ecological drought. Results emphasize the need for holistic thinking to leverage disparate expertise and facilitate a coordinated and adaptive approach to this SES challenge. This article presents a breadth of ecological drought indicators and impacts and points out the need to incorporate these into dedicated ecological drought monitoring efforts that recognize the complexity, uncertainty, and dynamism of this SES challenge.

Introduction

The twenty-first century has brought notable changes in temperature and moisture patterns to the western United States, increasing the severity and frequency of drought events in the already arid state of Montana (Cook et al., 2004; Van Loon et al., 2016; Whitlock et al., 2017). Aridity affects social and ecological systems, spanning areas from agriculture to infrastructure (McEvoy et al., 2018). Drought now poses a threat to places and people previously deemed drought-resilient, introducing escalating hazards and establishing drought management as a priority for water resource planning and management (Hammond et al., 2022). Enhancing resilience to and readiness for drought events was a key focus of the 2015 Montana State Water Plan update (Montana Department of Natural Resources and Conservation, 2015). I explored how natural resource practitioners in Montana monitor the ecological effects of drought.

Montana is renowned for its natural resources. For instance, it is part of the Greater Yellowstone Ecosystem, the largest intact ecosystem in the contiguous United States, and the Crown of the Continent, a renowned and diverse ecoregion that spans political boundaries. It is also home to the headwaters of the Missouri River, which flows through six states and boasts numerous Blue Ribbon Fisheries. The state's tourism and agricultural sectors account for more than 22% of employment and over $9 billion in earnings (Headwaters, 2025a and 2025b). However, both sectors are threatened by both short- and long-term drought impacts. Although ecologically available water is critical for Montana's economies and livelihoods, the ecological effects of drought are neither reflected in the state's drought plan nor prioritized by natural resource practitioners statewide (Montana Department of Natural Resources and Conservation, 2023; McEvoy et al., 2018). This oversight hinders ecological drought monitoring and leaves ecosystems and communities vulnerable to drought-related impacts.

Ecological drought is defined as “an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and human systems" (Crausbay et al., 2017, p. 2544). In short, I define ecological drought as the impacts of drought conditions on ecosystems and ecosystem services in both the near and long term. This broad definition implies that ecological drought may manifest in various ways depending on the ecosystems affected. In each of these definitions, ecological drought can represent a pulse (episodic) or a ramp (increasing over time) disturbance with compounding impacts emerging over time (Lake, 2000). Ecological drought, whether attributable to a pulse or ramp water deficit, can contribute to impacts well after the water deficit is resolved, leading to ramped response (Lake, 2000). The delayed onset and continued exacerbation of ecological drought impacts add to the complexity of monitoring and managing this challenge (Crausbay et al., 2020; Moss et al., 2024).

However, there is a lack of metrics and monitoring tools focused on the impacts of drought on ecosystems (González Tánago et al., 2016; Crausbay et al., 2020; Moss et al., 2024). Droughts characterized by their effects on economics and society, ranging from agricultural to meteorological, are typically assessed through hydrologic and meteorological data (Raheem et al., 2019; Hoylman et al., 2022). These data and corresponding tools represent traditional drought indicators that do not incorporate ecosystem monitoring beyond water and weather data, making them insufficient for identifying or anticipating ecological drought.

Ecological drought poses a complex social-ecological systems (SES) challenge, where humans and nature both contribute to and are affected by ecological drought (Berkes et al., 2003; Crausbay et al., 2017; McEvoy et al., 2018). Anticipating and mitigating ecosystem responses to drought is made difficult by the compounding effects of human activities and natural processes, which lead to increases demand on water supplies and shifts in climate patterns (Milly et al., 2008; Chapin et al., 2009; Kovach et al., 2019; Crausbay et al., 2020; Hoylman et al., 2022). The impacts of ecological drought on ecosystem processes include changes in vegetation and the loss of wildlife habitats, which have implications for ecosystem services through reduced air and water quality and diminished crop yields, among others (Crausbay et al., 2020). Additionally, ecological drought can lead to or exacerbate irreversible ecosystem transformations over time (Holling 1973; Walker et al., 2004; Hobbs et al., 2006; Chapin et al., 2009; Crausbay et al., 2017; Moss et al., 2024), which threatens the integrity of ecosystems and the services they provide (Crausbay et al., 2020). Ongoing research into the impacts of ecological drought suggests that the full range of possible consequences is not yet fully understood (Moss et al., 2024).

I aim to understand the indicators (signal, index, or metric) and impacts (outcomes) of ecological drought recognized by natural resource practitioners in Montana. Previous studies on practitioners' perceptions of ecological drought in Montana highlighted concern primarily for aquatic ecosystems (McEvoy et al., 2018), indicating the necessity to gain a deeper understanding of how practitioners recognize and respond to ecological drought across various ecosystems. The effects of ecological drought are experienced throughout the arid Mountain West and in other areas where water availability is inadequate to meet needs (Cook et al., 2004; Van Loon et al., 2016). Learning from practitioners working on ecosystem management related to drought preparation and response in Montana with a variety of fields of expertise will contribute to broader efforts to enhance ecological drought monitoring and response.

Effectively managing SES challenges, especially those that threaten ecosystem transformation, necessitates adaptive approaches that consider social and ecological processes (Olsson and Folke, 2001; Chapin et al., 2009; Cote and Nightingale, 2012; McEvoy et al., 2018;

Kovach et al., 2019; Crausbay et al., 2020). Adaptive strategies for natural resource challenges are marked by iteration and collaboration (Adger et al., 2007; Wyborn et al., 2015). This paper highlights the gaps in knowledge about indicators and impacts of ecological drought. These knowledge gaps can act as barriers to collaboration and adaptation, both essential for addressing ecological drought as an SES challenge (Cote and Nightingale, 2012; Virapongse et al., 2016; Crausbay et al., 2020).

In this paper, I report on the ecological drought indicators and impacts that natural resource practitioners in Montana recognize and use. Indicators represent anything that signals drought conditions or the onset of ecological drought, while impacts refer to the effects of ecological drought on ecosystems. Indicators can be independent or represent notable changes to components of an ecosystem (e.g., less surface water). Here, I examine how indicators and impacts vary based on practitioners' primary management concerns. From this, I aim to demonstrate the extent to which Montana practitioners perceive ecological drought as an SES challenge. This paper addresses the following research questions:

1. What indicators and impacts of ecological drought do practitioners use and recognize?
2. Do primary management concerns influence the indicators and impacts practitioners use to recognize ecological drought?
3. Do practitioners in Montana approach ecological drought as an SES challenge?

Literature Review

Indicators and Impacts of Ecological Drought

Drought monitoring strategies that utilize empirical hydrologic and meteoric data to predict water supplies, evaluate vegetative health, and indicate evaporative stress have become increasingly unreliable (Otkin et al., 2018; Hoylman et al., 2022). Shifting climate patterns and more frequent and severe drought events complicate monitoring efforts (Milly et al., 2008; McNeeley et al., 2016). Changing relationships between climate events and ecosystem services, accelerating ecosystem transformations, and assorted natural resource management activities add to the challenges of reliable drought monitoring (Wilhite, 2000; Crausbay et al., 2020, 2022; Hoylman et al., 2022; Sadiqi et al., 2022). These challenges have prompted studies on how specific ecosystems and species respond to drought, leading to the identification of highly specific indicators (index, metric, or other measurement) of drought conditions in some ecosystems that are not apparent in other ecosystem types (Barbour, 1999; Millar and Stephenson, 2015; Anderson et al., 2021; Moss et al., 2024). However, standardized drought indicators, as well as clear definitions of drought, remain absent in ecological research (Wilhite, 2000; Slette et al., 2019), which hinders consistency in understanding, monitoring, and responding to drought. Conventional drought indicators (e.g., precipitation, flow metrics, and temperature) and the monitoring strategies they support are insufficient for anticipating ecological drought.

Ecological drought threatens a broad set of potential impacts. Without dedicated ecological drought indicators, it is challenging to coordinate understanding, monitoring, and response efforts. The non-stationarity of ecosystems, along with compounding and long-term impacts, and the influence of humans on ecosystems and water supplies are all critical considerations for effective ecological drought monitoring (Milly et al., 2008; Crausbay et al., 2017; Kovach et al., 2019; Crausbay et al., 2020; Hoylman et al., 2022). The absence of specific indicators of ecological drought contributes to uncertainty regarding both the occurrence and severity of ecological drought impacts (Wilhite, 2000; González Tánago et al., 2016; Slette et al., 2019). This uncertainty is exacerbated by the interactions between human and natural systems, as well as compounding ecological stressors (Kovach et al., 2019; Crausbay et al., 2020; Moss et al., 2024). While research into the long-term and far-reaching impacts of ecological drought is ongoing (Moss et al., 2024), there is a clear need to identify specialized indicators that can signal the onset of ecological drought and anticipate the severity of its consequences (González Tánago et al., 2016; Crausbay et al., 2017 and 2020; Slette et al., 2019). To be effective, these indicators must include those specific to certain ecosystems, species, or services, as well as general indicators related to all ecosystem types and services (Raheem et al., 2019).

An SES Approach is an Adaptive Approach

Ecological drought poses an SES challenge that can arise, worsen, alleviate, and be influenced by natural and human factors, as well as their interactions (Crausbay et al., 2017; McEvoy et al., 2018). SESs are defined by interacting social and ecological drivers that influence the form and function of the whole, integrated system (Berkes et al., 2003). SESs challenges are characterized by continuous change, nonlinearity, and uncertainty across scales (Berkes et al., 2003; Chapin et al., 2009). Ecological drought depends on ecologically available water, which is influenced by both natural systems (e.g., precipitation patterns, temperature, and vegetation types) and human systems (e.g., water usage, infrastructure, and management actions) (Millar and Stephenson, 2015; Crausbay et al., 2017). SES thinking encompasses the ongoing interaction between human and natural systems, as well as the complexity of their mutual influences on each other and the entire system (Berkes et al., 2003; Cote and Nightingale, 2012; Wilson, 2012; Virapongse et al., 2016; Kleindl et al., 2018).

SES challenges are marked by social and natural disturbances that lead to ongoing change, whether temporary or transformative, creating inherent uncertainty (Refsgaard et al., 2007; Chapin et al., 2009; Yoe, 2013; Moss et al., 2024). The dynamic nature of SES challenges complicates monitoring and management efforts. Effectively managing SES challenges necessitates a comprehensive understanding of the interconnectedness between social and ecological systems, and flexibility to respond to shifts or disturbances and iteratively incorporate new information (Berkes et al., 2003; Folke, 2006; Chapin et al., 2009; Cumming et al., 2005; Kleindl et al., 2018; McEvoy et al., 2018). Further complicating these challenges, areas of expertise and professional responsibilities can shape practitioners' perceptions and responses to ecological drought (Kohl and Knox, 2016; McEvoy et al., 2018; Cravens et al., 2021). Addressing ecological drought as an SES challenge will require practitioners to consider indicators and impacts of ecological drought within and beyond their specific areas of expertise, moving away from reductionist thinking toward a collaborative approach that integrates various forms of knowledge (Raymond et al., 2010; Cote and Nightingale, 2012; McEvoy et al., 2018; Wilmer et al., 2018; Greene, 2021).

In addition to recognizing the various interactive drivers of ecological drought (e.g., Dunham et al., 2018), adaptive approaches are necessary to acknowledge ongoing shifts and potential transformations of ecosystems that can be both initiated and accelerated by ecological drought (Chapin et al., 2009; Wyborn et al., 2015; McNeeley et al., 2016; Crausbay et al., 2017; Crausbay et al., 2022; Moss et al., 2024). These adaptive approaches assume ongoing iteration rather than static "command and control" management (Wilmer et al., 2018). This necessitates collaboration among practitioners to develop specific, reliable, and adaptable strategies to effectively monitor ecological drought (Dunham et al., 2018; Wilmer et al., 2018). Adaptive strategies for ecological drought will enhance ecological and community resilience, as drought vulnerability is determined by exposure, sensitivity, and adaptive capacity (Adger et al., 2007; Chapin et al., 2009; Smith et al., 2023). Recognizing ecological drought as an SES challenge will require and lead to adaptive approaches to ecological drought monitoring and management.

Data Collection and Analysis

Data Collection

Semi-structured interviews were conducted as this format allowed for dynamic conversations, enabling nuanced responses and follow-up questions to provide detail and clarity (Lichtman, 2017; Deterding and Waters, 2021). The interview guide included questions related to ecological drought monitoring and response, practitioner roles, and policies and plans related to ecological drought. This methodology was approved by the Montana State University Institutional Review Board (IRB Protocol #JM081722-EX). The semi-structured interview protocol guided the conversation while allowing flexibility for rephrasing, clarification, and follow-up questions during each interview (Lichtman, 2017; Deterding & Waters, 2021). The interview protocol was collaboratively developed by the research team (comprised of co-authors) to investigate how practitioners understand and address ecological drought. The protocol included open-ended questions asking specifically about the indicators practitioners use to recognize ecological drought and the ecological drought impacts they notice or respond to. Questions about indicators were asked separately from questions about impacts. The indicators reported were not correlated with the impacts reported, though in some exemplary quotes practitioners did make connections between indicators and impacts. Indicators and impacts were reported bottom-up, imparted by practitioners rather than selected from pre-established lists.

In total, 63 individuals were contacted between April and June 2023 and 25 semi-structured interviews were conducted with environmental and natural resource practitioners throughout the state of Montana. These practitioners included scientists, planners, and managers from local organizations as well as state and federal agencies. Practitioners represent expertise in Montana natural resources as well as drought locally and nationally. Interviewees, referred to in this paper as practitioners, were identified through existing connections with the research team and by cataloging natural resource management groups and agencies across Montana. The sample encompasses natural resource practitioners engaged in drought preparation or response working at local, regional, and statewide scales across a variety of ecological interests (referred to as primary management concerns). Participants were contacted via email and invited to schedule an interview using an online scheduling platform to ensure that participation was convenient for them. During the interviews, participants were asked to recommend additional natural resource practitioners for us to include in our sample, and they were reached out to and included. In some cases, several practitioners from the same working group were suggested, and the research team included only the best-fit practitioner. Interviews were conducted virtually via MS Teams. Each interview lasted between 45 and 60 minutes and was recorded, with participant consent, and transcribed by ‘TranscribeMe’ transcription services and proofread before analysis.

Data Analysis

Interview transcripts were analyzed both deductively and inductively using NVivo software. An iteratively generated codebook by the research team was utilized to capture demographic information and interviewees' responses to questions regarding indicators and impacts of ecological drought. The codebook was developed collaboratively based on the interview guide, project proposal, and research questions to ensure that all relevant information was captured and analyzed (Table 1). Additional codes were included at the conclusion of the interviews to guide deductive coding of emergent topics and themes. The codebook encompassed numerous potential indicators and impacts of ecological drought, along with "other" codes to account for additional indicators and impacts reported by practitioners (Appendix B).

Table 1: Broad Codes from Interview Codebook (see full codebook in Appendix B)

Code	Description
Agency	What agency or organization does the interviewee work for
Impacts	Code for priority ecological drought impacts spoken about/considered major concerns by interviewees.
Indicators	Code for ecological drought indicators used or discussed by interviewees.
Primary Management Concern	Self-reported primary management concern. Responses were organized and categorized during analysis.

After a thorough discussion and clarification of the codebook and codes within the research team, two researchers qualitatively coded a selection of the interviews (n=3, >10% of the sample) to assess intercoder reliability. This reliability was established by conducting an NVivo comparison query on the three coded interviews to evaluate the consistency of the coding by the two researchers (Church et al., 2019). Through the comparison query, Cohen's Kappa score was calculated to ensure that individual biases or differences in interpretation of the codes or codebook did not affect the analysis (Kim, 2017). The resulting Cohen's Kappa score of 0.89

indicates a high level of consistency in coding between the two researchers (Cohen's Kappa scores range from -1 to 1). The remaining interview transcripts were divided equally between the two researchers for qualitative coding before further analysis.

I analyzed the coded transcripts using a series of NVivo queries to identify relationships between practitioners' main management concerns and the indicators and impacts of ecological drought they reported. I then conducted qualitative analysis in NVivo and descriptive statistics in MS Excel to find patterns among the reported primary management concerns (PMCs), indicators, and impacts of ecological drought. Specifically, I used NVivo queries to recognize the indicators and impacts reported by practitioners with different primary management concerns and then created heat maps and stacked bar charts to illustrate the differences in indicators and impacts reported by practitioners with different primary management concerns. These visualizations exposed patterns driven by primary management concerns.

I aimed to determine the indicators practitioners use to monitor and recognize ecological drought as well as the impacts they respond to and paid special attention to the differences in the ecological drought indicators and impacts reported based on PMCs. Both quantitative summaries and qualitative evidence are included in these results, while the interview protocol and codebook are provided in the supplemental material.

Results and Discussion

Demographics and Primary Management Concerns

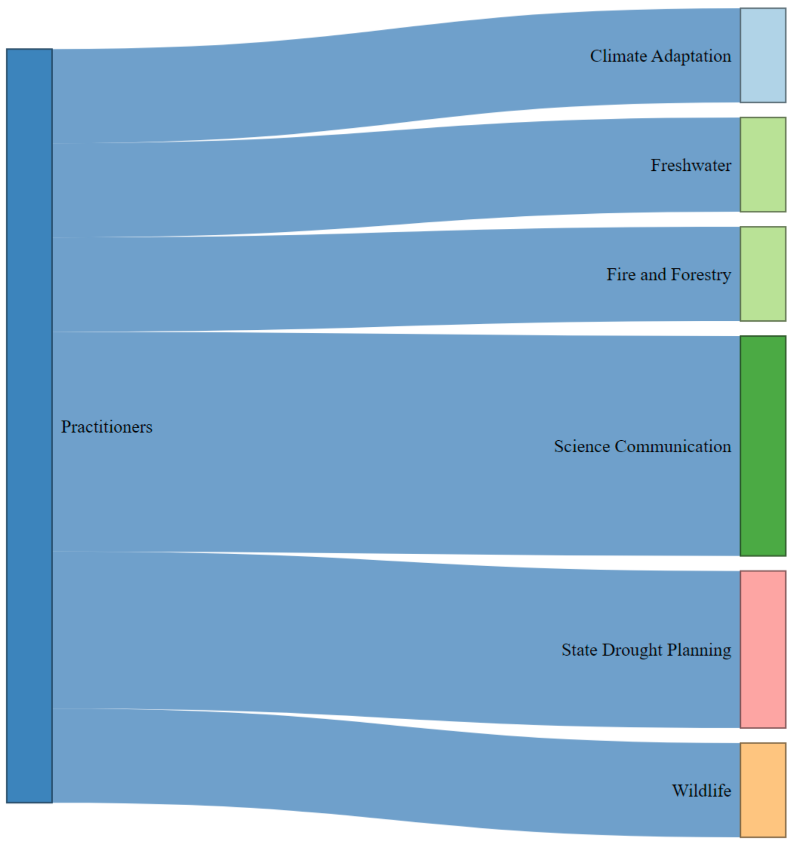
The 25 interview participants represent 13 distinct organizations, including federal, state, and local natural resource management agencies, nonprofit organizations, and universities. Our sample also encompasses a wide range of management areas and scales, from specific sites across Montana to multi-state jurisdictions (Table 2). Early in each interview, participants were asked, “In your role, what are your management goals?” Practitioners were prompted to describe their primary management concern related to ecological drought and water availability. Responses varied from managing distinct ecosystems or species types (e.g., Fire and Forestry, Freshwater Ecosystems) to drought planning and communication (Table 2). Each PMC included practitioners from different agencies, and practitioners from the same agency did not necessarily share the same PMCs.

Table 2: Practitioner Agencies Grouped by Primary Management Concern.

Agency	Area	Primary Management Concern
National Parks Service	Multi-state	Climate adaptation
U.S. Forest Service	Multi-state	Climate adaptation
U.S. Forest Service	Multi-state	Climate adaptation
Dept. Natural Resources & Conservation	Statewide	Fire and forestry management
National Parks Service	Specific site(s)	Fire and forestry management
U.S. Forest Service	Multi-state	Fire and forestry management
Bureau of Land Management	MT Region	Freshwater ecosystems and species
Local Watershed Group	Specific site(s)	Freshwater ecosystems and species
U.S. Geographical Survey	Specific site(s)	Freshwater ecosystems and species
U.S. Geographical Survey	Multi-state	Freshwater ecosystems and species
Dept. Natural Resources & Conservation	Statewide	Science communication
Dept. Natural Resources & Conservation	Specific site(s)	Science communication
Local Watershed Group	Specific site(s)	Science communication
Natural Resources Conservation Service	MT Region	Science communication
National Drought Monitor	Multi-state	Science communication
U.S. Forest Service	Multi-state	Science communication
U.S. Geographical Survey	Multi-state	Science communication
Bureau of Reclamation	MT Region	State drought planning
Dept. Natural Resources & Conservation	MT Region	State drought planning
Fish, Wildlife, and Parks	Statewide	State drought planning
MT Climate Office	Multi-state	State drought planning
National Weather Service	Eastern MT	State drought planning
Fish, Wildlife, and Parks	Statewide	Wildlife conservation
U.S. Fish & Wildlife Service	Specific site(s)	Wildlife conservation
U.S. Geographical Survey	MT Region	Wildlife conservation

The number of practitioners for each PMC ranged from three to seven (Figure 1). These results report the number of practitioners who mention each ecological drought indicator and its impact, rather than the frequency of mentions, to account for the variation in practitioners associated with each PMC. The results indicate a wide range of expertise within our sample, suggesting the potential for diverse perspectives on ecological drought. Sharing these perspectives can enhance practitioners' comprehensive understanding of ecological drought as an SES challenge (Olsson and Folke, 2001; Chapin et al., 2009; Wyborn et al., 2015; McNeeley et al., 2016; Wilmer et al 2018).

Figure 1 shows the breakdown of all 25 practitioners by primary management concern.

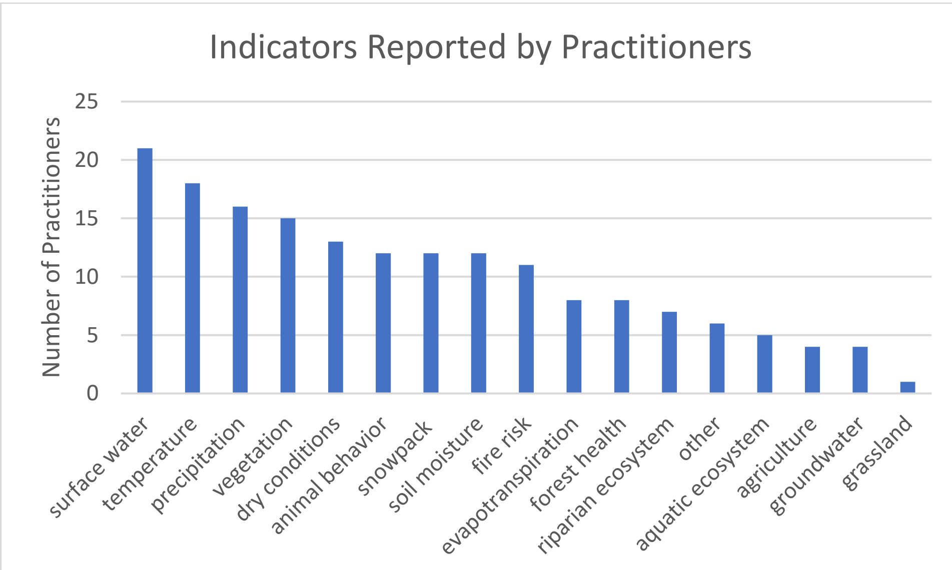


Through our analysis, six PMCs were identified based on practitioners' responses. The Science Communication category features practitioners focused on education, while the State Drought Planning category includes those focused on water rights and infrastructure. PMCs varied across different geographies, scales, and agencies, indicating that they do not dictate practitioners' scope of work related to drought.

Indicators

Common Ecological Drought Indicators Ecological drought indicators refer to any signal of the onset of drought conditions that may lead to ecological impacts. Practitioners were asked, "What information, indicators, or tools do you use to monitor the ecological impacts of drought?" They were also prompted by the research team to report as many indicators as they could think of in their responses. A common follow-up question was, "How do you know you're in a drought?" This allowed practitioners to describe the conditions they monitor. Practitioners reported a variety of indicators of ecological drought related to surface water (e.g., stream flows) and indicators of stress or change to specific ecosystems (e.g., forest health and aquatic ecosystems) (Figure 2). The indicators reported represent changes to things like surface water, aquatic ecosystems, or vegetation that demonstrate the occurrence of drought conditions, or they can be more explicit, such as high temperatures or dry conditions.

Figure 2 shows the number of practitioners who reported each ecological drought indicator (details on indicator codes are reported in Appendix B). The "other" indicator bar includes bee populations, bird surveys, informal conversations with producers and landowners, and the weather service.



The most reported indicators of ecological drought were low surface water, increased temperature, and decreased precipitation indicating the importance of water availability for drought conditions.

> "I would say you would want to look at streamflow, right, and reservoir levels… I would also think that … SPEI (Standard Precipitation Evapotranspiration Index) with a temperature component can be really useful too, to tell you how much drying you're getting, because sometimes the droughts are not just precipitation, temperature can have a huge effect on that." -Science Communication practitioner

In many cases, practitioners reported multiple indicators related to water availability. For example: "Of course, the biggest one is stream flow. … Water temperature is one of the key water quality variables that we need to manage for, so that is a secondary trigger." -Freshwater Ecosystems and Species practitioner.

Surface water, temperature, and precipitation are commonly utilized in water supply monitoring and are included in well-known drought monitoring strategies (e.g., the Standard

Precipitation Index (SPI) and flow rates at stream gages). The numerous practitioners who referenced these indicators related to water availability highlight the use of widely accepted drought indicators to assess ecological drought, given the absence of specific indicators for ecological drought (Slette et al., 2019). While reliance on water availability indicators provides a general understanding of drought conditions, it does not sufficiently anticipate the various and evolving impacts of drought on ecosystems and ecosystem services (Crausbay et al., 2020; Moss et al., 2024). This finding emphasizes the limited understanding among practitioners of how ecological drought manifests across landscapes or within specific ecosystems. The absence of reliable indicators corresponding to ecological impacts presents a challenge in monitoring all forms of drought and is further complicated by the intricate interplay of social and ecological interactions driving ecological drought (Wilhite, 2000; Raheem et al., 2019).

Other common drought and water supply metrics, including snowpack and soil moisture, were reported infrequently and groundwater was only mentioned by two practitioners (see Figure 2). This points to a potential lack of recognition of the importance of interactions between ground and surface waters among the practitioners interviewed. One practitioner expanded on the importance of groundwater for drought conditions, native species, and ecosystems.

> “We’re looking at a lot of groundwater-bounded alluvial valley bottoms. These kind of unconfined valley reaches where there’s a lot of groundwater and surface water exchange, there are a lot of hyporheic flow species like bull trout … so they’re like the cold spots on the landscape that are important for fish to complete their life cycle, but also those are the cold-water spots that they’re going to need for refuge in the future” -Freshwater Ecosystems and Species practitioner

Overall, evaporative stress monitoring tools and other advanced climate models were referenced less often than direct ecosystem measurements (see Figure 2). A previous study demonstrated agricultural stakeholders’ use of these indicators to monitor flash drought (Otkin et al., 2018). These results highlight the current reliance on ecosystem-specific ecological drought indicators and the necessity to broaden awareness of these among practitioners working in diverse ecosystems to enhance understanding of the range of ecological drought impacts. The numerous indicators reported by practitioners serve as evidence of the various drivers of ecological drought events, complicating efforts to anticipate and recognize ecological drought and manage it as an SES challenge.

<u>Indicators by Primary Management Concern</u> In this analysis, I aimed to understand how PMCs influence the ecological drought indicators reported by practitioners. Descriptive statistics were used to assess how the indicators reported differed based on practitioners' PMCs. The three most reported ecological drought indicators pertained to water availability (surface water, temperature, and precipitation; see Figure 2), followed by vegetation, dry conditions, and fire risk, which were mentioned by practitioners across all six PMCs (Table 3). These indicators were reported by practitioners regardless of their areas of expertise, indicating a shared approach to ecological drought monitoring across PMCs. This mutual understanding can foster the collaboration and holistic thinking necessary to address ecological drought as an SES challenge. (Adger et al., 2007; Wyborn et al., 2015; Virapongse et al., 2016).

Ecological drought indicators related to water availability—such as aquatic species, groundwater, surface water, soil moisture, snowpack, and precipitation—were reported by practitioners across all six PMCs. These indicators comprised the majority of those reported for four of the six PMCs (Table 3 and Figure 3). This continuity in reported indicators reflects the relevance of these indicators across PMCs and suggests cohesion among these practitioners, indicating potential for synchronization in their ecological drought monitoring. Such alignment could promote holistic thinking about ecological drought and development of comprehensive and coordinated monitoring efforts. Future initiatives to foster holistic understanding and collaboration in tackling ecological drought could lead to adaptive SES approaches (Olsson and Folke, 2001; Adger et al., 2007; Wyborn et al., 2015).

Table 3: Reported Ecological Drought Indicators by Primary Management Concern

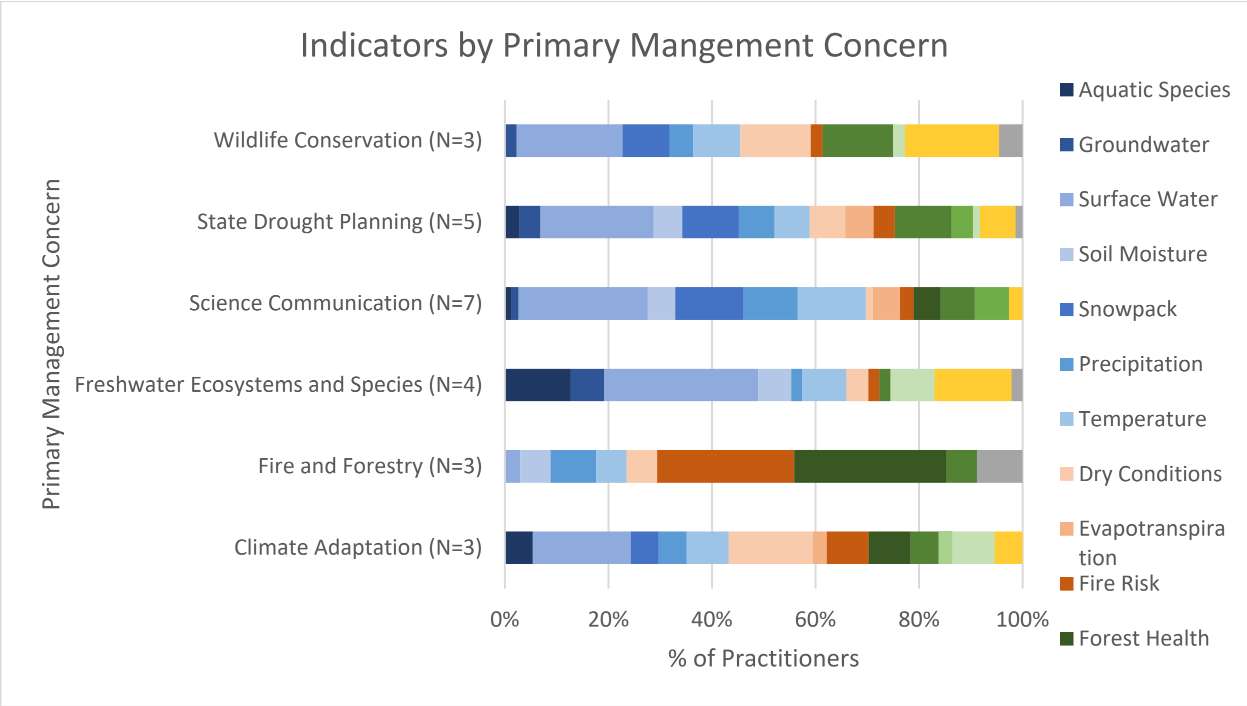
	PRIMARY MANAGEMENT CONCERN						
INDICATOR	Climate Adaptation (n=3)	Fire and Forestry (n=3)	Freshwater (n=4)	Science Communication (n=7)	State Drought Planning (n=5)	Wildlife Conservation (n=3)	Total (n=25)
Agriculture	0	0	0	4	3	0	7
Animal Behavior	2	0	3	0	2	2	9
Aquatic Species	2	0	1	1	1	0	5
Dry Conditions	2	2	2	1	4	2	13
Evapotranspiration	1	0	0	4	3	0	8
Fire Risk	2	3	1	2	2	1	11
Forest Health	3	3	0	3	0	0	9
Grasslands	1	0	0	0	0	0	1
Groundwater	0	0	1	1	1	1	4
Other	0	2	0	0	1	2	5
Precipitation	2	3	1	5	4	2	17
Riparian	1	0	3	0	1	1	6
Snowpack	2	0	0	4	5	1	12
Soil Moisture	0	2	2	4	4	0	12
Surface Water	3	1	3	7	4	3	21
Temperature	2	2	2	6	2	2	16
Vegetation	3	2	2	4	3	3	17

Note: The heat map shading shows the most reported indicators for each PMC. The "Total" column shows the number of times each indicator was reported regardless of PMCs.

While practitioners across PMCs reported the most common indicators, the variety of indicators reported by practitioners was influenced by their PMC. Those focused on Climate Adaptation, Science Communication, and State Drought Planning reported nearly all the ecological drought indicators listed in Table 3 and our codebook. In contrast, practitioners involved in Fire and Forestry, Freshwater Ecosystems, and Wildlife Conservation reported fewer overall indicators. Notably, there are also fewer practitioners with these PMCs. This confirms that the ecological drought indicators reported varied based on the practitioners' PMC and is supported by previous studies demonstrating that the types of evidence practitioners use to inform management decisions change according to the scale and type of work they do (Cook et al., 2010).

The discrepancy in the indicators reported by practitioners with varying PMCs highlights how practitioners' expertise informs their different approaches to ecological drought monitoring as they are more attuned to certain ecosystems or species types and, thus, more able to recognize changes. Practitioners' familiarity with specific locations can also contribute to their specialization and inform the indicators of ecological drought they reported. This can contribute to specialized ecological drought monitoring strategies targeted to specific locations, species, or ecosystem types, such as temperate forests (Millar and Stephenson, 2015; Anderson et al., 2021). Expertise is necessary for recognizing change; however, this also points to potential silos in practitioners' understanding and monitoring of ecological drought. Siloed thinking that considers only one PMC can hinder the holistic thinking essential for addressing ecological drought as an SES challenge. (Olsson and Folke, 2001; Berkes et al., 2003; Folke, 2006; Wyborn et al., 2015; Wilmer et al., 2018).

Figure 3 is a stacked bar chart of the indicators reported by practitioners from each primary management concern category. Results are shown as percentages of the total number of indicators (represented by color in the stacked bar chart) reported by practitioners with each primary management concern, as the number of practitioners with each primary management concern varies.



The pattern of practitioners reporting indicators relevant to their PMCs was demonstrated by unique indicators. For example, bird migration patterns were reported as an indicator by a practitioner whose PMC was wildlife conservation, who stated that bird migration patterns reflect where water is and is not. This trend was also apparent among fire and forestry practitioners who primarily reported ecological drought indicators related to heat and vegetation, including temperature, forest health, and fire risk (Figure 4). These findings confirm that there is a correlation between PMCs and the indicators that practitioners report. “To some extent, it’s resource-specific or program-specific. So, the fire folks may be using a suite of drought indicators that are different from water resource folks.” –Climate Adaptation practitioner.

In contrast to the influence of PMCs on reported indicators, some indicators were reported across all PMCs. For example, practitioners focused on Wildlife Conservation as their PMC reported more water availability indicators than indicators related to animal behavior (see Figure 3). This finding highlights the interconnected nature of water availability indicators across different PMCs and underscores the breadth of ecological drought indicators reported by each practitioner. The reporting of water availability indicators, along with indicators concerning animal behavior and habitat, demonstrates that this Wildlife Conservation practitioner recognizes signals of ecological drought both within and beyond their PMC, reflecting a broad understanding of ecological drought.

The wide variety of ecological drought indicators reported by practitioners concerned with Climate Adaptation also reflected a holistic understanding of ecological drought. These included water availability, temperature, and ecosystem-specific indicators, each accounting for nearly a third of the total reported indicators (see Figure 3). Meanwhile, State Drought Planning practitioners expressed skepticism about the reliability of any single indicator, highlighting existing challenges in reliable drought monitoring (Milly et al., 2008; Raheem et al., 2019; Hoylman et al., 2022) and emphasizing the significance of treating ecological drought as an SES challenge.

> "Are you looking at the right indicators? And are you looking at enough of them? Broadly, precipitation but also soil moisture and groundwater and whatever else you're looking at, vegetation, dryness, evapotranspiration. But then within those, are you looking at the right time scale to be able to capture the impact?" -State Drought Planning practitioner

<u>Unique Indicators</u> Most practitioners identified ecological drought indicators that were specific to their primary management concerns. Many of these indicators, including bird surveys, conifer encroachment on private lands, the presence of bees in the landscape, and discussions with

neighbors or landowners, were categorized as "other" (see Table 3 and Figure 3). These distinct indicators reflect the practitioners' primary management concern and demonstrate how it shapes their approach to monitoring drought conditions. “As soon as you say indicator, all I want to say is birds. They’re a great indicator of everything, where they go, what they do, how they’re doing indicates how the habitat or ecosystem is doing.” -Wildlife Conservation practitioner.

Unique indicators can also illustrate the differences in practitioners’ roles. While the example of birds as indicators emphasizes a practitioner’s familiarity with bird behavior, a Science Communication practitioner discussed landowner concerns about conifer encroachment as a sign of ecological drought. “I firmly believe that trees use water. … I think landowners certainly perceive conifer encroachment as a water issue.” -Science Communication practitioner.

These quotes emphasize the influence of PMCs on the ecological drought indicators that practitioners reported using to identify drought conditions. This includes indicators specific to certain ecosystems or species. These unique, context-specific indicators provide opportunities for monitoring ecological drought in particular environments. When shared, they can enhance practitioners' ability to recognize ecological drought across various ecosystems (McNelley et al., 2016; Crausbay et al., 2020). For instance, Millar and Stephenson (2015) highlight the sensitivity of temperate forests to compounded drought stress as an indicator of potential ecosystem loss or transformation. Context-specific information like this can alert other practitioners to drought conditions, enabling them to prepare for additional impacts and implement adaptive responses (Wyborn et al., 2015; McNeeley et al., 2016; Wilmer et al., 2018).

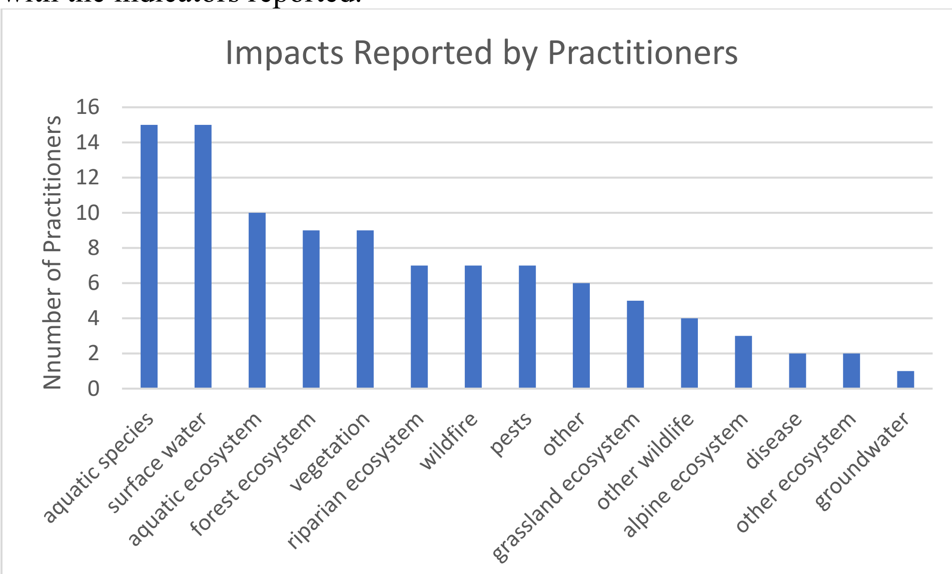
Including unique indicators in comprehensive ecological drought monitoring strategies can enhance their effectiveness (Moss et al., 2024). To establish reliable strategies for monitoring ecological drought, it is essential to incorporate indicators reported by practitioners across different management concerns, such as water supply, as well as unique indicators tailored to their specific needs. Coordinating these indicators will help practitioners gain a broader understanding of ecological drought that extends beyond their areas of expertise (Knapp et al., 2004; Slette et al., 2019). This multifaceted approach to monitoring recognizes ecological drought as an SES challenge and promotes the adaptive strategies necessary for effective drought response (Crausbay et al., 2020).

Impacts

Common Ecological Drought Impacts This research sought to understand the impacts of ecological drought that practitioners were concerned about and asked, "What ecological impacts related to drought are you seeing or most concerned about?" Practitioners were encouraged to provide multiple responses. The most frequently reported impacts of ecological drought were on surface water, aquatic species, and aquatic ecosystems, indicating a widespread concern for the effects on available ecological water among practitioners (Figure 4). "The biggest one is streamflow conditions." –Freshwater Ecosystems practitioner.

This illustrates a mutual understanding of ecological drought impacts on water availability and a lack of shared knowledge about drought impacts on other ecosystems or ecosystem services. Concern for ecologically available water may serve as a starting point for collaboration among practitioners, which is essential for tackling ecological drought as an SES challenge (Lemos et al., 2012; Virapongse et al., 2016). Furthermore, given the interconnected drivers of ecological drought impacts, coordinated efforts to alleviate constraints on ecologically available water could also lessen other ecological drought effects (Raymond et al., 2010; Crausbay et al., 2017; Crausbay et al., 2020; Moss et al., 2024).

Figure 4 shows the ecological drought impacts reported by practitioners. The "other" impacts bar includes interactions with wildlife and reduced water for irrigators. The impacts do not correlate with the indicators reported.



A few water availability indicators, including surface water flow (quantity) and temperature (quality), were also reported as impacts of ecological drought, establishing the importance of ecologically available water as a driver of impacts on ecosystems (Crausbay et al., 2017). Most practitioners reported water availability impacts, and a few connected them to ecological drought impacts on species. "We're trying to understand the pulse of the system, looking at flow, the temperature of the system, and how those changes impact ecologically important species." –Freshwater Ecosystems practitioner.

This quote demonstrates the far-reaching consequences of surface water impacts. Compounding ecological drought impacts result in challenges for species reliant on ecosystem services and habitats (Crausbay et al., 2020; Moss et al., 2024). Other compounding impacts reported by practitioners include crop limitations, due to low irrigation water, and fish die-off events, due to high in-stream temperatures. “One thing that rings a bell is from the really low water and low flow situation on the Yellowstone some years back when we had the big kill off of the mountain whitefish.” –Science Communication practitioner.

In this example, surface water acts as both an impact (outcome) and an indicator (signal) of compounding ecological drought. Practitioners demonstrate an understanding of the ecological drought impacts related to their primary management concerns, highlighting the importance of familiarity with an ecosystem or locality to observe changes over time (Raymond et al., 2010; McNeeley et al., 2016; Greene et al., 2021). For instance, surface water flows are important for recognizing ecological drought impacts on water supply when compared to flow measurements at the same site from different moments in time.

> “We have USGS stream gage stations that give us a good sense of where stream flows are at any given time and how does that compare historically to the period of record of a given gage to provide us with a sense of what we’re looking at in terms of the available water.” –State Drought Planning practitioner

Familiarity with an ecosystem or ecosystem service was reported as essential to recognizing the impacts of ecological drought beyond water supplies. One practitioner stated this clearly when discussing soil moisture and wildfires. “And you're relying on trends. Or how you bridge the data between them.” -Fire and Forestry Management practitioner.

This quote confirms that practitioners are more likely to notice the impacts of ecological drought related to their primary management concerns. By understanding ecosystem trends, practitioners can identify deviations from them that lead to ecological drought impacts. Sharing this knowledge with practitioners focused on different primary management concerns can help them recognize ecological drought, as the impacts on one ecosystem can indicate the onset of impacts in others (Raymond et al., 2010; McNeeley et al., 2016; Wilmer et al., 2018; Crausbay et al., 2020).

Besides influencing practitioners' awareness of ecological drought impacts on specific ecosystems, PMCs can also impede practitioners' recognition of ecological drought impacts outside their area of expertise. The least frequently reported impacts were on alpine ecosystems, disease, and groundwater (Figure 4). The limited number of practitioners focused on ecological drought impacts affecting alpine ecosystems and disease (in both wildlife and plants) can be attributed to their primary management concerns (Climate Adaptation and Wildlife Conservation). The scant reporting on impacts to alpine ecosystems indicates a widespread disregard for the crucial link between high-elevation moisture and water supplies (typically in the form of snowpack in Montana) (Hayes et al., 2012; Williams et al., 2020). In addition to their vital role in providing water for lower elevations, one practitioner pointed out that alpine ecosystems themselves are particularly vulnerable to low water levels. "The most sensitive locations to drought are… alpine environments above tree line. …when you do have a drought in the alpine environment, it has a pretty dramatic impact." -Climate Adaptation practitioner.

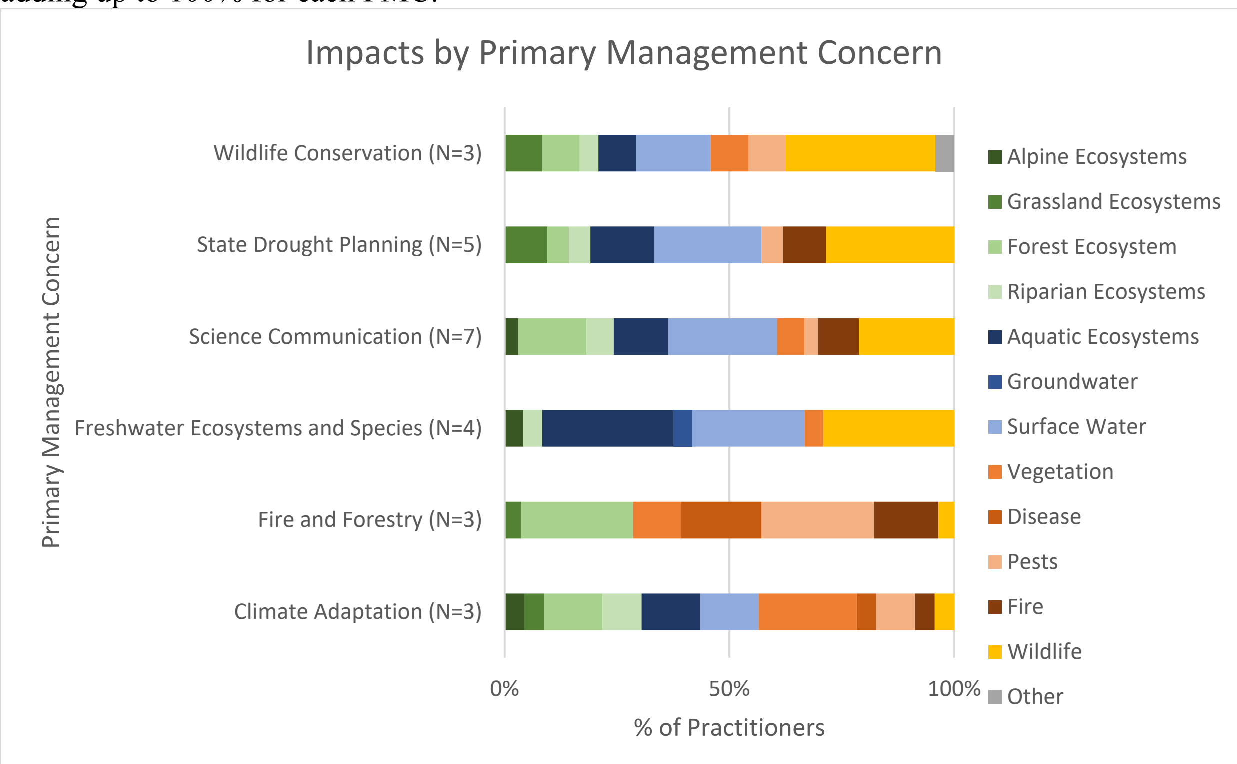
The limited recognition of potential ecological drought impacts on alpine ecosystems indicates that practitioners primarily focused on their main management concerns. Just one practitioner noted ecological drought impacts on groundwater, suggesting a lack of awareness regarding the significance of the ground and surface water interface for water supplies and drought conditions (Hayes et al., 2012; Williams et al., 2020). The sole practitioner who mentioned groundwater impacts illustrated an example of the crucial interaction between surface water (in this case, precipitation) and groundwater in riparian areas ecosystems.

> "…you can see the system just dried out, right? There's no riparian vegetation. It's not green. There's no groundwater storage. It's completely dependent on precipitation. And then just one year afterward, it induced a lot of infiltration in the groundwater. …when [riparian areas] are healthy, they have more groundwater storage, so they're less dependent on precipitation." -Freshwater Ecosystems practitioner

The result that only one practitioner commented on groundwater impacts highlights siloed thinking among practitioners. Although practitioners specifically focused on alpine ecosystems or groundwater may have been underrepresented in our sample, the limited reporting of these ecological drought impacts by practitioners with other primary management concerns is striking. Snowpack and groundwater are critical components of traditional drought monitoring strategies, informing water supply forecasts both within and across water years (Hayes et al., 2012). Standard drought monitoring strategies are insufficient for ecological drought, and dedicated monitoring approaches for ecological drought are lacking (Tanago et al., 2016; Slette et al., 2019; Crausbay et al., 2020; Hoylman et al., 2022). This has created "a giant gap between all the data and information and the practitioners sorting through it, scratching their heads trying to figure out what to do about it" - Fire and Forestry practitioner. The call for indicators specific to ecological drought is clear.

Impacts by Primary Management Concern The range of impacts reported by practitioners highlights the difficulty in identifying or responding to ecological drought. Ecological drought impacts are extensive and varied; they can influence one ecosystem or many and compound over time and space (Crausbay et al., 2020; Moss et al., 2024). A thorough understanding of ecosystems and ecosystem services is necessary to detect changes over time. As expected, PMCs inform the ecological drought impacts reported by practitioners (Figure 5).

Figure 5 is a stacked bar chart of the impacts reported by practitioners from each PMC. The number of practitioners representing each PMC varies from 3-7, as does the total number of impacts reported by practitioners with each PMC. Results are shown in percentage of the total number of reports of all impacts (represented by colors in the stacked bar chart) by practitioners, adding up to 100% for each PMC.



Many of the impacts reported by practitioners with Wildlife Conservation and Freshwater Ecosystems PMCs were related to wildlife and freshwater ecosystems (see Figure 5). "…the whole host of species that really depend on these riparian zones, everything from grizzly bears to Columbia spotted frogs and reptiles and amphibians that use these areas and the migratory birds" -Freshwater Ecosystems practitioner.

Many of the reports of ecological drought impacts on wildlife were related to fish or other aquatic species, explaining the large proportion of wildlife impacts reported by practitioners with Freshwater Ecosystems as their PMC. Climate Adaptation practitioners reported impacts on distinct ecosystem types, indicating their attention to shifts within ecosystems (see Figure 5). These practitioners also recognized ecosystem transformations in response to ecological drought.

> "…a specific example from Western Montana - kind of an open, ponderous, opine type savanna ecosystem, after we have some disturbance, like maybe a higher intensity wildfire, come through, we may be seeing a long-term shift to that being more of an open rangeland kind of setting. And so we're looking to adapt to that as appropriate." - Climate Adaptation practitioner

This quote exemplifies how PMCs can enable practitioners to more readily identify ecological changes related to their areas of expertise and anticipate potentially irreversible transformations. In this instance, a practitioner noted that an ecosystem transformation resulted from ecological drought and required adaptation. Escalating ecological drought impacts can trigger or contribute to such ecological transformations (Holling 1986; Walker et al., 2004; Crausbay et al., 2017; Harris et al., 2018; Crausbay et al., 2020). Recognizing the potential for these transformations can increase awareness of the need for adaptation in response to ecological drought, as highlighted by this practitioner (Chapin et al., 2009).

Fire and Forestry practitioners reported a variety of ecological drought impacts related to forest ecosystems and fire (Figure 4), highlighting their understanding of compounding ecological drought impacts.

> "We see with overstocked or dense forests it's kind of like being a smoker and not exercising. So, you already have a base level of unhealthiness. Then when you add a new disturbance in there, such as insects or drought-- they're just a compounding factor. And so, an overcrowded drought-stricken tree is way more susceptible to an insect outbreak or a fungal infection. And so those are so I wouldn't say like it's not

> a driver on a lot of this stuff, but it is a massive compounding factor." -Fire and Forestry Management practitioner

Pests and disease are signals of unhealthy forests as well as consequences of wildfires (Millar and Stephenson, 2015). Reports of these impacts exemplify practitioners' understanding of the compounding nature of ecological drought impacts related to their PMC. The influence of PMCs on the impacts reported by Fire and Forestry practitioners is supported by the lack of water-related impacts they reported (Figure 4). While the specificity of practitioners' understanding of ecological drought impacts can contribute to early recognition of drought (Otkin et al., 2022), a narrow focus may also impair practitioners' abilities to detect ecological drought impacts outside of their PMC.

Meanwhile, State Drought Planning and Science Communication practitioners reported diverse ecological drought impacts. Impacts on ecosystems, wildlife, and surface water accentuated their broad scope compared with practitioners focused on specific ecosystem types. These practitioners demonstrated holistic thinking about ecological drought.

> "I'm generally concerned about the effects of drought on our ecosystem as a whole. Because we're seeing huge impacts on ecosystems and other parts of the West that aren't recovering, right? ... But I'm generally concerned about where we're heading and what that looks like for Montana because so far, we haven't seen any, as far as I'm aware of, huge long-lasting ecological impacts in permanent ones." – State Drought Planning practitioner

Practitioners who report holistic and compounding ecological drought impacts across ecosystem types are more likely to view ecological drought as an SES challenge influenced by complex and interrelated factors (Olsson and Folke, 2001; Wilhite et al., 2007; Chapin et al., 2009; Wyborn et al., 2015; Wilmer et al., 2018). Most practitioners reported ecological drought impacts related to their primary management concerns, implying a tendency toward siloed thinking about ecological drought impacts. There is a need for better coordination among practitioners with different primary management concerns to foster the holistic approach necessary to tackle ecological drought as an SES challenge (Dunham et al., 2018).

Conclusions and Future Directions

All practitioners reported various indicators and impacts of ecological drought, indicating an appreciation for the broad scope of ecological drought. However, our results revealed silos in ecological drought monitoring based on PMCs. While focused expertise is critical for the effective monitoring and management of specific ecosystems or species, as demonstrated by the correspondence between reported ecological drought indicators and impacts and practitioners' PMCs, coordination is needed to foster holistic thinking among practitioners and enable adaptive approaches to ecological drought monitoring. Coordination of the indicators and impacts reported by practitioners with different PMCs is necessary to addressing ecological drought as an SES challenge (Knapp et al., 2004). This coordination can raise awareness about ecological drought indicators and impacts specific to different ecosystem types, contributing to adaptive ecological drought monitoring that appreciates expertise and promotes holistic thinking (Wilmer et al., 2018). This coordination will be useful for ecological drought monitoring in Montana and contribute to a comprehensive set of ecological drought monitoring strategies that can be put to use elsewhere.

Other factors, such as job descriptions and funding, may hinder practitioners' abilities to recognize the full range of social and natural influences on ecological drought and engage with practitioners and communities beyond their PMCs (Margerum, 1999; Folke, 2006; Lubell et al., 2013). Overcoming barriers to engagement and promoting interdisciplinary ecological drought monitoring and response by practitioners and communities will be essential for establishing ecological drought as an SES challenge and facilitating adaptive strategies to address it in Montana and beyond (Lemos et al., 2012; Dilling et al., 2015; Lemos et al., 2018). Leveraging the value of focused expertise within PMCs can translate to enhanced monitoring, anticipation, and response to ecological drought. Efforts to coordinate across areas of expertise and encourage holistic thinking are needed to address all complex social-ecological challenges. The broad range of ecological drought indicators and impacts reported by Climate Adaptation, Science Communication, and State Drought Planning practitioners exemplifies the breadth of ecological drought. Alongside appreciation of the influence of social-ecological interactions on ecological drought, a comprehensive understanding of impacts on different ecosystems, species, and services is needed (Cote and Nightingale, 2012; Ganzalez Tanago et al., 2016; Crausbay et al., 2017).

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CHAPTER THREE

NAVIGATING UNCERTAINTY: TOWARD IMPROVED ECOLOGICAL DROUGHT MONITORING

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Abstract

Much of the Western United States is experiencing patterns of increased temperatures and changes in the quantity or timing of precipitation. These conditions contribute to increasing and more consequential drought. Ecological drought, the impacts of drought on ecosystems and their services, represents a complex social-ecological systems (SES) challenge with social, ecological, and interconnected drivers. The complex and uncertain impacts of ecological drought make it hard to monitor. This article presents opportunities to enhance ecological drought monitoring through 25 semi-structured interviews with natural resource practitioners in Montana. The results indicate the desire to reduce epistemic uncertainty through the collection of more and better data, as well as the need for enhanced communication to improve monitoring amid irreducible uncertainty. Practitioners' needs reflect the complexity and uncertainty of ecological drought as an SES challenge, emphasizing the importance of adaptive decision-making to inform responses to ecological drought. A framework relating constraining and expanding influences on the capacity for adaptive decision-making is presented to guide this narrative and contextualize the need for adaptive decision-making to address the SES challenge of ecological drought.

Introduction

Changing climate patterns pose considerable challenges to monitoring and managing natural resources, as shifting patterns and responses impair the reliability of monitoring tools and strategies. Increasing changes in precipitation patterns, temperature fluctuations, and human and ecosystem resource use have increased uncertainty regarding how ecosystems will respond to disturbances (Holling 1973; Walker et al., 2003). This uncertainty complicates efforts to monitor ecosystems effectively. As drought events are likely to become more frequent and severe in the Mountain West, monitoring drought conditions is becoming increasingly critical (Van Loon et al., 2016; Whitlock et al., 2017; Sadiqi et al., 2022). Ecological drought, defined as the impacts of drought on ecosystems and their services, contributes to this uncertainty by triggering changes in ecosystem structures and functions, which can contribute to transformations of entire ecosystems (Crausbay et al., 2017). The potential impacts of ecological drought are extensive and remain a subject of ongoing study (Moss et al., 2024).

Ecosystem responses to drought are driven by compounding human and natural stressors, making anticipation of ecological drought impacts difficult (Berkes et al., 2003; Crausbay et al., 2017; McEvoy et al., 2018; Raheem et al., 2019; Crausbay et al., 2020). This challenge is amplified by a lack of dedicated and reliable ecological drought monitoring strategies (González Tánago et al., 2016; Crausbay et al., 2020; Moss et al., 2024). The breadth of ecological drought includes impacts on vegetation, weather patterns, and wildlife in forests, grasslands, and mountains as well as on humans reliant on ecosystem services (Crausbay et al., 2017 and 2020; Raymond et al., 2010; Moss et al., 2024). Relating ecological drought impacts to human systems is challenging (Wilhite, 2000), but this knowledge is critical to our ability to prepare for, identify, and respond to ecological drought (Raheem et al., 2019).

Irreducible uncertainty makes the data and tools used to monitor ecological drought unreliable, necessitating adaptive decision-making about ecological drought response and management (Lubell et al., 2013; Dilling and Lemos, 2015). Improving ecological drought monitoring to inform adaptive decision-making is necessary (Derner and Augustine, 2016); however, the pathway toward improvement remains unclear. Identifying existing ecological drought monitoring challenges is the first step in these efforts (Carter et al., 2020; Crausbay et al., 2024). Natural resource practitioners in Montana utilize a variety of data and tools to assess drought conditions. Yet, these tools are neither reliable indicators of ecological drought nor accessible to the broad range of decision-makers in Montana. In addition to practitioners, landowners, producers, landscape managers, and others make decisions about ecological drought response actions. To influence these response decisions, ecological drought monitoring strategies and the information they produce must be understood and trusted by diverse decision-makers.

In this paper, I aim to understand current barriers to effective ecological drought monitoring by asking practitioners about their needs. Here, I present the ecological drought monitoring needs reported by natural resource practitioners to answer the following questions.

1. What do practitioners in Montana need to improve ecological drought monitoring?
2. Do practitioners recognize uncertainty as a barrier to ecological drought monitoring?
3. How can better ecological drought monitoring inform adaptive decision-making?

Literature Review

The recognition of dynamism in ecosystems has led to a shift away from command-and-control management toward management approaches that appreciate complexity and uncertainty (Berkes et al., 2003; Walker et al., 2004; Liu et al., 2007). Social-ecological systems (SES) frameworks reflect the inherent complexity of systems influenced by social, ecological, and interacting drivers across multiple scales (Berkes et al., 2003; Folke, 2006; Walker et al., 2006; Chapin et al., 2009). Monitoring and management of SES challenges are complicated by the compounding influence of both human and natural stressors over time (Berkes et al., 2003; Chapin et al., 2009; Virapongse et al., 2016). Effectively addressing SES challenges requires consideration of normative, biophysical, and human forces to inform adaptive approaches (Folke, 2006).

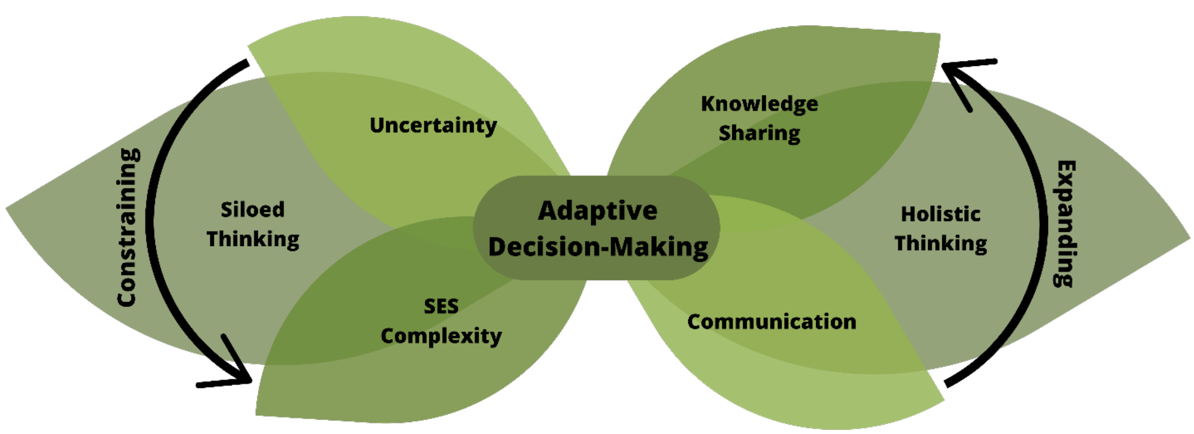
Ecological drought represents a complex SES challenge that both influences and is influenced by social, ecological, and interacting aspects of the system (Crausbay et al., 2017). A positive feedback loop exists between these drivers of change and the dynamic interactions between them. Ongoing climate shifts, such as changing precipitation patterns, combined with human influences, make ecological trajectories uncertain, impair monitoring, and necessitate adaptative approaches (Berkes et al., 2003; Folke, 2006; Milley et al., 2008; Crausbay et al., 2020). Moreover, monitoring improvements that iteratively incorporate new information across scales are needed to inform decision-making (Kleindl et al., 2018).

A Framework for Adaptive Decision-Making Capacity

I combine the ideas of an adaptation envelope, which refers to the way that constraining and enabling factors shape the capacity for adaptation (Wyborn et al., 2015), and the manager decision-making space (Clifford et al., 2022) to present the envelope of adaptive decision-making (Figure 6). I define adaptive decision-making as a process of iterative decisions influenced by management objectives (e.g., theory of planned behavior; Ajzen and Fishbein, 1980) and learning through social networks (diffusion theory; Rogers, 2003) that anticipate changes over time and space while incorporating place-based knowledge (Payne et al., 1990; Knapp and Fernandez-Gimenez, 2009; Lubell et al., 2013).

Effective monitoring and information are crucial for shaping responses to ecological drought. However, current ecological drought monitoring strategies are unreliable due to gaps in climate information, as well as epistemic uncertainty (due to a lack of knowledge) and irreducible uncertainty (due to inherent variability) (Refsgaard et al., 2007; Yoe 2013; Crausbay et al., 2020, 2024). Challenges of uncertainty and complexity can constrain an individual or community's capacity for adaptive decision-making, contributing to siloed thinking (Figure 6). Meanwhile, communication and knowledge sharing represent opportunities to overcome constraints and expand the capacity for adaptive decision-making. Each of the drivers presented in Figure 6 interact with and influence each other. Lag times between indicators and impacts of ecological drought, compounding stressors, and climate information usability gaps constrain adaptive decision-making while learning, interdisciplinary approaches, and incorporating multiple types of knowledge expand adaptive decision-making in response to ecological drought (Chapin et al., 2009; Lemos et al., 2012; Lubell et al., 2013; Meadow et al., 2015; Dilling and Lemos, 2015; Wilmer et al., 2018; Crausbay et al., 2020; Wilmer et al., 2022 Smith et al., 2023).

Figure 6 presents the envelope of adaptive decision-making, as defined by the authors. This combination of the adaptation envelope (Wyborn et al., 2015) and the manager decision space (Clifford et al., 2022) shows constraining and expanding drivers of adaptive decision-making in response to ecological drought. All of these drivers interact with and influence each other, adding complexity to an individual or community's capacity for adaptive decision-making.



Building resilience amid uncertainty is a dynamic task that demands reliable information and adaptive capacity (Camacho, 2009; Wyborn et al., 2015; Haigh et al., 2021; Church et al., 2022). Resilience refers to the ability of a system to recognize and respond to disturbance, and adaptive decision-making represents a path to building resilience (Berkes et al., 2003; Lubell et al., 2013; Smith et al., 2023).

Resilience, Uncertainty, and Adaptation

Ecological resilience refers to an ecosystem's ability to absorb disturbances while maintaining similar functions (Gunderson et al., 1997; Berkes et al., 2003; Chapin et al., 2009; Wilson, 2012). This definition has evolved from its original concept, which centered on an ecosystem's ability to resist change and maintain stability. However, even in its early form, the concept of ecological resilience acknowledged that ecological shifts can be uncertain (Holling, 1973).

The unpredictability of environmental responses to disturbances is heightened in SESs, where complex interactions between social and ecological drivers occur (Berkes et al., 2003). These interactions influence and are influenced by ecological drought, leading to ecological shifts and even transitions to entirely different types of ecosystems (Gunderson and Holling, 2002; Walker et al., 2004; Hobbs et al., 2006; Walker and Salt, 2006; Crausbay et al., 2017). While the full range of potential impacts of ecological drought is not yet fully understood (Moss et al., 2024), it is recognized that these impacts can affect social and natural capital, altering, ecological, cultural, political, financial, institutional, and built assets (Wilson, 2012; Flora et al., 2016). Moreover, the interplay among these factors poses a threat to both ecological and community resilience (Adger, 2000; Walker and Abel, 2002; Wilson, 2012; Haigh et al., 2019).

Community resilience is inherently interdisciplinary and, like ecological resilience, can be understood as either a process or an outcome (Wilson, 2012; Berkes and Ross, 2013). Community resilience pertains to the social strength of a group and examines how human systems adapt to change based on various forms of capital (Folke, 2006; Chaskin et al., 2008; Wilson, 2012). Factors such as cultural contexts, resource dependence, and institutional frameworks complicate a community's capacity to learn and adapt to change (Adger et al., 2000; Berkes et al., 2003; Chapin et al., 2009; Magis, 2010; Berkes and Ross, 2013). I define communities as groups of people who share geographic space and natural resources and who inevitably interact with one another (e.g., Bridger et al., 2002). This connection to a specific locality and its ecosystems underscores the importance of ecological resilience in fostering community resilience (Adger, 2000; Elmqvist et al., 2003; Berkes and Ross, 2013) and highlights the threat that ecological drought poses to community resilience. The uncertainty of ecological drought impacts complicates efforts to enhance resilience (Elmqvist et al., 2003; Berkes and Ross, 2013).

Uncertainty arises from either knowledge limitations (epistemic uncertainty, e.g., data gaps) or inherent variability (irreducible uncertainty) (Refsgaard et al., 2007; Wheaton et al., 2008; Yoe, 2013; Kleindl et al., 2015). Ecological drought is characterized by both epistemic and irreducible uncertainty due to the complex interplay of social and ecological factors that leads to ongoing changes in the usability of climate information and the reliability of ecological drought monitoring (see Figure 1) (Berkes et al., 2003; Chapin et al., 2009; Lemos et al., 2012; Haigh et al., 2015; Moss et al., 2024). Even as our understanding of ecological drought evolves, shifting climate patterns, compounding stressors, and human responses introduce variability and exacerbate the uncertainty problem (Crausbay et al., 2020).

The breadth of ecological drought impacts act as independent threats and compounding stressors that contribute to shifts in ecosystem services and entire ecosystem transformations (Crausbay et al., 2017; Crausbay et al., 2020; Moss et al., 2024). Acknowledging an ecosystem's potential to transform is critical to effective ecological drought monitoring, as the same indicators may signal different outcomes over space and time. The uncertainty surrounding ecological drought, due to both inadequate and unattainable knowledge about ecosystem responses to complex and ever-changing stressors, is another reason adaptive decision-making is needed to address ecological drought (see Figure 6) (Berkes et al., 2003; Folke, 2006; Wyborn et al., 2015).

Adaptation involves adjusting actions in response to environmental changes to minimize negative impacts and enhance resilience (Adger, 2000; Adger et al., 2007; Smith et al., 2023). For adaptation to be effective, it requires both individual involvement and institutional support (Benson & Stone, 2013; Church et al., 2022). Adaptation is vital when facing uncertain and dynamic social-ecological systems challenges, such as ecological drought (Berkes and Ross, 2013; Crausbay et al., 2020). Adaptation reflects an acceptance of change rather than resistance and contributes to both ecological and community resilience. (Adger, 2000; Chapin et al., 2009; Magis, 2010; Wilson, 2012).

Adaptive Capacity and Decision-Making

The ability of individuals or groups to undertake adaptation strategies is determined by their adaptive capacity, which refers to the conditions that enable or prohibit participation in adaptation (Adger et al., 2007; Benson and Stone, 2013). Adaptive capacity is determined by natural, financial, informational, policy, social, institutional, and other factors (Yohe and Tol, 2002; Adger et al., 2007), as well as resilience (see Figure 6) (Berkes et al., 2003). Additionally, risk management and knowledge generation shape a group or individual's capacity to adapt (Marshall, 2015; Wilmer et al., 2018). It is essential to recognize that adaptive capacity can fluctuate over time, vary across different locations, and differ among various communities and individuals (Adger et al., 2007; Berkes and Ross, 2013). One approach to increasing adaptive capacity is to improve the information available for addressing ecological challenges (Berkes et al., 2003; Berkes and Ross, 2013; Whitney et al., 2017; Wilmer et al., 2018). Assessing current ecological drought monitoring in Montana will help identify information gaps and opportunities to address them to strengthen the capacity for adaptive decision-making. An individual or community's adaptive capacity reflects and impacts their resilience (Berkes et al., 2003; Magis et al., 2010; Berkes and Ross, 2013) and plays a crucial role in their potential for making adaptive decisions (see Figure 6) (Lubell et al., 2013; Derner and Augustine, 2016; Smith et al., 2023).

The persistent uncertainty contributes to inadequate ecological drought monitoring that necessitates adaptive decision-making to address long-term, cross-cutting, and unpredictable impacts of ecological drought (see Figure 6) (Benson and Stone, 2013; Whitney et al., 2017; Knapp et al., 2020). Adaptive decision-making refers to the individual actions taken in response to non-stationary environmental conditions, informed by worldviews, risk tolerance, socioeconomics, and climate information (Lubell et al., 2013; Roche et al., 2016; Smith et al., 2023). Adaptive decision-making reflects the adaptive capacity of individuals and communities experiencing social and ecological change (Folke, 2006; Lubell et al., 2013; Smith et al., 2023).

Social networks, individual beliefs, trusted leadership, and effective communication to share information and understanding influence adaptive decision-making (Lubell et al., 2013; Derner et al., 2023). Unmet ecological drought monitoring needs present barriers to adaptive decision-making by perpetuating epistemic uncertainty, impairing understanding of long-term implications on different ecosystem types, and contributing to siloed thinking that does not embrace irreducible uncertainty (Wheaton et al., 2008; Lubell et al., 2013; Derner and Augustine, 2016; Derner et al., 2022; Smith et al., 2023).

Climate Information Usability Gap

The knowledge and information used in devising natural resource management strategies have historically focused on Western science (Lemos et al., 2012; Dilling et al., 2015; Knapp et al., 2020). The limitations of this approach are accentuated by the uncertainty of ecological responses to drought (Liu et al., 2007), which contributes to unreliable monitoring strategies that represent gaps in the usability of climate information (Lemos et al., 2012; Haigh et al., 2021). Epistemic and irreducible uncertainty pose challenges for ecological drought monitoring, reflecting gaps in the understanding and the availability of usable information (Refsgaard et al., 2007; Wheaton et al., 2008; Yoe, 2013). Recognizing these gaps can lead to improved ecological drought monitoring, including the development and dissemination of actionable climate information.

To be useful, knowledge must be salient, legitimate, and credible, which requires ongoing two-way communication between practitioners and other decision-makers (Innes and Booher, 1999; Cash et al., 2003; Lemos et al., 2012; Haigh et al., 2015). Effective, continuous, and transparent two-way communication can build trust and collective understanding between practitioners and decision-makers, contributing to increased participation and enhanced adaptive capacity (Cash et al., 2003; Floress et al., 2009; Sarkissian and Hurford, 2010; Floress et al., 2015; Wilmer et al., 2018; Haigh et al., 2021; Church et al., 2022). Engaging decision-makers in knowledge co-production can increase the credibility of information, close information usability gaps, and empower adaptive decision-making (Lemos et al., 2012; Meadow et al., 2015; Lemos et al., 2018; Jackson-Smith and Veisi, 2023).

Effective monitoring is crucial for informing adaptive decision-making (Derner and Augustine, 2016; Smith et al., 2023). Knowledge exchange between practitioners and other decision-makers can improve ecological drought monitoring and understanding as well as promote learning, adaptive capacity, and community and ecological resilience (Walker and Able, 2002; Berkes et al., 2003; Chapin et al., 2009; Berkes and Ross, 2013; Lubell et al., 2013; Crausbay et al., 2024). Improvements in ecological drought monitoring and knowledge sharing can address climate information usability gaps and further promote ecological drought resilience.

Methods

This paper reports on the findings of 25 semi-structured interviews with natural resource practitioners from across Montana. The practitioners interviewed represented local, state, and federal agencies and had a wide range of roles related to drought preparation and response, including scientists, policymakers, educators, and resource managers. These practitioners generate and implement policies and plans that inform and guide management decisions and actions in response to ecological drought. Practitioners in our sample were identified purposively through personal connections with the research team and comprehensive scoping of publicly available data on agencies across the state. Interview participants were contacted via email over the course of two months, with up to four outreach emails sent at two-week intervals, and interviews were conducted during May and early June of 2023.

During interviews, practitioners were asked about their primary management concerns, their roles, and the way they identify, monitor, and manage ecological drought. This led to a question about how ecological drought monitoring can be improved: *Are there tweaks to existing information, indicators, or tools – or new information, indicators, or tools – that would help you better monitor ecological drought? If so, what are those?* Researchers used phrases like "wish list" and "pie-in-the-sky" to encourage practitioners to consider ways to enhance ecological drought monitoring.

At the conclusion of each interview, practitioners were asked to suggest anyone else the research team should include in the sample, contributing to snowball sampling (Lichtman, 2017). The combination of purposive and snowball sampling generated a diverse interview sample for semi-structured interviews. Semi-structured interviews were conducted using an established interview guide developed collaboratively by the research team (Appendix A) and approved by the Montana State University Institutional Review Board (IRB Protocol #JM081722-EX). This format allowed for free-form conversation as appropriate (Lichtman, 2017). Each interview was conducted by at least two members of the research team and lasted between 40 and 60 minutes. Interviews were recorded on MS Teams (with the consent of each interviewee), transcribed using TranscribeMe software, and reviewed for quality before coding.

Interview transcripts were uploaded into NVivo software for qualitative analysis. A detailed codebook was developed by the research team to guide deductive coding for ecological drought monitoring needs reported by practitioners, generating a comprehensive list of ideas and desires (Skjott Linneberg and Korsgaard, 2019). Two members of the research team coded the interviews in NVivo, following the questions and topics outlined in the interview guide and codebook (see Appendix for both). To ensure consistency in coding, the two researchers underwent intercoder reliability testing by coding the same subset of interviews (n = 3, >10%). Intercoder reliability testing uses an NVivo query to compare the coding of each interview by both researchers and assess the agreement between the interviews coded by each researcher (Church et al., 2020). The query reports Cohen's Kappa coefficient, which represents the level of agreement; a value of 1.00 signifies perfect agreement (Kim, 2017). The two researchers achieved a Cohen's Kapp coefficient score of 0.89, demonstrating a high degree of consistency between their coding (Landis and Koch, 1997). After establishing intercoder reliability, the remaining interviews were divided between the two researchers, who independently coded the assigned interviews. Following the coding, I conducted a qualitative analysis to identify trends in the ecological drought monitoring needs reported by practitioners.

Results

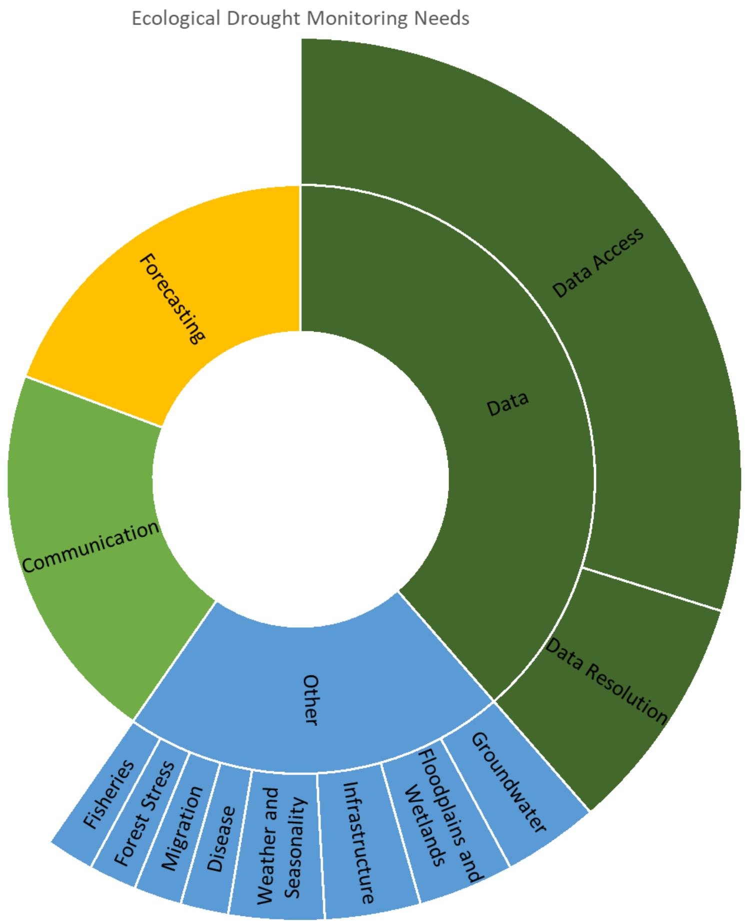
The 25 interview participants (henceforth referred to as practitioners) represented local, state, and federal agencies and organizations (Table 4). They included scientists, policymakers, educators, and researchers working on various primary management concerns, including climate adaptation, freshwater ecosystems, fire and forestry, science communication, state drought planning, and wildlife conservation. When asked to report their roles related to ecological drought monitoring and management, a few practitioners were directly concerned with the ecological impacts of drought, while most were concerned only peripherally with ecological drought impacts not related to their primary management concerns.

Table 4: Practitioners by Agency and Scale

Agency	Scale	Count
Bureau of Land Management	Regional	1
Bureau of Reclamation	Regional	1
Local Watershed Group	Local	2
Montana Climate Office	Statewide	1
Montana Department of Natural Resources	Local & Statewide	4
Montana Fish, Wildlife, & Parks	Statewide	2
National Park Service	Regional	2
Natural Resources & Conservation Service	Regional	1
National Weather Service	National	1
U.S. Fish & Wildlife Service	Local	1
U.S. Forest Service	Regional & National	4
U.S. Geological Survey	Local, Regional, & National	4
University	National	1

Practitioners were asked about their needs for improving ecological drought monitoring in Montana. Their responses encompassed a wide range of needs and ideas, from more reliable data to enhanced communication (Figure 7). These needs reflect the monitoring challenges posed by both epistemic and irreducible uncertainty and correspond with gaps in information about ecological drought. Several overarching needs were reported by numerous practitioners, including the necessity to address lag times between drought conditions and ecological impacts, the need to improve data resolution and quality, the need for more reliable forecasting, and the need for better communication regarding ecological drought monitoring (Figure 7). These needs were commonly reported irrespective of practitioners' primary management concern, scope of work, or agency.

Figure 7 shows needs for improving ecological drought monitoring reported by practitioners. The inner circle represents categories of needs, while detailed needs are displayed in the outer circle. Segment sizes reflect the number of practitioners who reported each need and practitioners may have spoken about multiple of these needs.



Following common needs, practitioners also reported ecological drought monitoring related to their primary management concerns, reflecting distinct monitoring strategies (see Figure 7, “Other”). These needs demonstrate the potential for shared and disparate ecological drought monitoring strategies among practitioners. Needs for improving ecological drought monitoring reported by practitioners are presented in depth using exemplary quotations from interviews to support findings.

Lag Times

The impacts of drought on ecosystems and ecosystem services are often only perceptible after drought occurs, which can be later in a season or even years later. Many practitioners discussed the difficulty that lag times between ecological drought, ecological drought indicators, and observable impacts presents for monitoring. For example:

> “I feel like ecological drought is sort of the way to describe that phenomenon where you may be feeling the scarcity of water and precipitation in the year that it's happening, but you really see the impacts of ecological drought in future years” – Science Communication practitioner

The lag time between measurable metrics and determining and reporting drought conditions is further compounded by the lag time between drought conditions and observable ecosystem impacts. Groundwater monitoring exemplifies lag times between drought and ecological impacts, as surface water changes may not impact groundwater until much later in a season or even seasons later. For example:

> “But one of the two of the critical pieces of information from the water balance that we don't have right now are really good groundwater information and information on how different aquifers are impacted. What's the lag time when you have a drought? … We've been paying so much attention to the surface water, but groundwater is really the big kind of thing that we need to understand better.” -State Drought Planning practitioner

Such lag times exacerbate challenges in real-time monitoring of drought conditions. These challenges exist because of the need to analyze measured drought metrics to interpret conditions and the potential for conditions to change during that lag. For example, one practitioner mentioned the need for operational information within one week of measurements to avoid obsolescence:

> “If you're using some re-analysis dataset of ET that you have a time series from 1985 to 2021, that's awesome. You can do this really cool retrospective analysis. But that doesn't help us go to the monitoring step because we need these tools to be operational for them to really help us in a monitoring framework. So, I encourage you when you're looking at potential indices to test or different datasets to use, latency, how long it takes for those datasets to be available is a really, really, really key factor. And it's something that even at the scale, if it's two weeks old or if it's three weeks old, that's much harder to use in drought assessment. A week's latency is really what we're shooting for in a lot of these cases.” – State Drought Planning practitioner

Real-time conditions reporting is further limited by uncertainty about the impacts that may result from those conditions. Ecosystem responses to low water levels differ based on ecosystem type, current conditions, compounding stressors, and shifting climate patterns, leaving few opportunities for practitioners to recognize ecological drought and anticipate impacts before they occur. One practitioner explicitly stated the need for more reliable predictive drought assessment: “We need a more proactive paradigm and drought assessment and mitigation and that's just not what I see. It's a very reaction-driven system that we're in right now.” -State Drought Planning practitioner.

This quote reflects current patterns in ecological drought monitoring, but does not recognize the organizational constraints that may be driving the reactive approach to drought assessment. While better monitoring can improve our ability to be anticipatory, institutional support and investments are also needed to enact the paradigm shift this practitioner requested.

Data Resolution, Quality, and Access

Efforts to monitor ecological drought are further impaired by inadequate data for assessing conditions and informing actions. Many practitioners reported data resolution as a limitation for localized ecological drought monitoring. Poor data resolution requires practitioners to infer conditions across landscapes and over time, thus impairing the accuracy and utility of that information. For example:

> “I'd love to see higher resolution data … when you look at a landscape, you have to make assumptions of that. Is that station more accurate, or is that one? And you're relying on trends. Or how you bridge the data between them. So I think more data.” -Fire and Forestry practitioner

While many practitioners identified and shared opportunities to improve data resolution to better corresponding monitoring strategies, one practitioner acknowledged that even with increased data the desire for more fine-scale, long-term, and operational data is insatiable:

> “My wish list, of course, would be more monitoring, which I'm sure everybody says that. But honestly, that's probably never going to meet the need that we have. We're never going to get enough monitoring stations to meet our needs. ... Other wish list items would … periods of record, but that's impossible, right? If we could get 30 years of record on all these soil moisture stations, that would be amazing because then we would be able to assess what's happening in the context of what previously happened.” -State Drought Planning practitioner

This sentiment is demonstrated by the ongoing need for more and better data related to water availability. Practitioners reported the need for both improved data collection infrastructure and increased frequency of measurements to achieve more accurate monitoring of drought conditions across spatial scales. For example: “I think that first and foremost is getting a rigorous spatially distributed monitoring network that encompasses entire drainages from the headwaters to the main stems.” -Freshwater practitioner. Alongside higher spatial resolution, practitioners reported needing data with higher temporal resolution to improve monitoring.

> “…looking beyond just the stream channel to look at upland processes and how that affects the hydrologic cycle would be really important. I think getting really fine-grained, like down to diurnal cycles and water and temperature, those are the kind of processes that would be important to incorporate at some point.” - Freshwater practitioner

While practitioners report their desire for improved data resolution, they also express concerns about data quality and accessibility. Increased amounts of data do not necessarily translate into more useful data, therefore, the need for more data is coupled with the need for increased and improved data analysis. For example: “I don't want to trade off spatial resolution for data quality. And having it available as frequently as possible, so daily would be ideal.” - Climate Adaptation practitioner.

In addition to the need for more and better data, practitioners report a need for more effective combinations of data to get a better understanding of local conditions.

> “I think we need more analysis on our existing indicators. We really need to understand better how drought actually plays out on the landscape. … I'd like a tool that could clip to your region of interest and massage all the data, and I want data from each bucket in our eco drought framework, datasets that will pull-down menu, take this one, this one, and then some analysis that puts it all together and tells me why my system is vulnerable to drought impacts.” -Climate Adaptation practitioner

Difficulties in the timing, quantity, and quality of data make monitoring for ecological drought challenging. These data needs are echoed in the need for better forecasting and predictive modeling of ecological drought.

<u>Forecasting Challenges</u> Data limitation and uncertainty hinder efforts to forecast or predict drought events (Otkin et al., 2022). Changes in climate patterns, ecological resilience, land use, and other compounding stressors contribute to both epistemic and variable uncertainty; while increased data and analysis can reduce uncertainty, the non-stationarity of drought conditions and ecosystem responses continually introduces new uncertainty (Hoylman et al., 2022). This limits

the ability to utilize data to accurately anticipate drought. Practitioners were aware of these constraints and expressed a need for improved forecasting and predictive modeling in the face of ongoing uncertainty. For example: “I'm sure you're hearing from everyone, they say, ‘Oh we'd love to have better forecasting’, and inevitably I'd have to echo that as well…” -Climate Adaptation practitioner.

Some practitioners expressed optimism about forecasting efforts that incorporate multiple types of data. One practitioner questioned whether existing data can be better used to forecast specific conditions:

> “One thing that we've struggled with quite a bit is the ability to forecast. What can we do to forecast increasing stream temperatures? What are some of those conditions? And we have a general idea of what may lead to an increase in stream temperatures. But we've kind of thought about this ourselves as to how we would do it. What data is out there that we could go ahead and say, ‘Well, utilizing this information gives us a pretty good idea that streams are starting to see an increase in temperature, fish are getting stressed.’"-State Drought Planning practitioner

Meanwhile, multiple practitioners recognized that the inclusion of multiple different indicators can improve ecological drought monitoring and increase the utility of monitoring tools:

> “…we're moving away from just looking at precipitation to what's the overall water balance? What's the whole system looking like? And I do think that is a positive thing for monitoring ecological drought as well because it's not so critically dependent on precipitation, but where's the groundwater? Where are the wetlands? Can we kind of look at the system more as a whole?” -State Drought Planning practitioner

This quote demonstrates this practitioner’s recognition of the many interacting components influencing ecological drought and the importance of considering the interplay between them. Another practitioner recognized that the predictive capacity of forecasting tools can be improved by the incorporation of more types of data was discussed indirectly in practitioners' reporting of the need for improved communication. Forecasting tools are just one need that can be at least partially addressed by more information exchange. For example, one practitioner recognized the challenge of relying on forecasts, but saw an opportunity to use them to improve communication about potential outcomes and encourage better preparation for drought impacts:

> "…our climate is changing so rapidly that we can't necessarily base our decision now on what happened in the past because everything has changed. In the context of nonstationary, how do you if a nonstationary climate, how do you assess what's happening now based on what happened 30 years ago? But if our predictive modeling gets better, maybe we do end up using forecasts more in drought assessment or at least early warning. …maybe we are able to get out and talk to folks about, look, this is something that might be coming in the future. And maybe here are some ways you can prepare." -State Drought Planning practitioner

The need for improved forecasting reiterates the need for more and better data, as well as the need for better interpretation and communication of that data. Forecasting challenges, due to dynamic ecosystems, compounding stressors, and unprecedented outcomes, perpetuate uncertainty. Predictive models are increasingly impaired by changes in ecosystem responses to disturbance that reduce the reliability of patterns between conditions and outcomes. These increasing challenges in forecasting were acknowledged by practitioners reporting the need for communication about the fallibility of current forecasting efforts and communication to raise awareness about the uncertainty of ecological drought. Communication about these challenges can encourage engagement in monitoring efforts and adaptive approaches to management responses.

Communication

Communication Among Practitioners Many of the ecological drought monitoring needs reported by practitioners are compounded by communication challenges. Whether about ecological drought metrics, how data are interpreted, or awareness of ecological drought impacts, improved communication among practitioners and between practitioners and decision-makers was a clear need discussed in all interviews. There was also agreement among practitioners about the need to improve communication about indicators and impacts of ecological drought across primary management concerns. One Science Communication practitioner reported the explicit need for “a more multidisciplinary approach to evaluating drought”. This approach includes more communication about how ecological drought is felt by different ecosystems and recognized by practitioners with different primary management concerns. For example:

> “I went to Boulder for this big NIDIS Assessing Drought in a Changing Climate Workshop. … Everybody talked about being able to quantify and objectify impacts a little bit better. And it's hard. Because every reported impact is subjective. … But oftentimes, it takes a person from the Forest Service to report an impact on a forest, or it takes a fisheries biologist to report an outbreak of whatever, like you suggested earlier, before we know that that's happening. But those don't always come in. And so then, we're left trying to kind of assess it with gridded metrics, which they're not perfect, either.” -State Drought Planning practitioner

The persistent need for better interpretation of how drought metrics correlate to actual and future ecosystem conditions exemplifies one way that increased communication among practitioners can improve ecological drought monitoring. Exchanging information with practitioners with different primary management concerns can enhance overall awareness of ecological drought monitoring strategies. For example, one practitioner reported wanting to know more about how plants and animals can reveal drought conditions:

> “I am not someone who knows hardly anything about plants or animals or anything like that. And so, for me, just having that understanding of how they're tied to [drought], and when it's important, the kind of work that you're doing would be so helpful to have that.” -Science Communication Practitioner

More communication among practitioners can lead to increased recognition of ecological drought indicators or impacts specific to certain ecosystems or species, improving monitoring for all practitioners. In addition to the need for more communication among practitioners, practitioners reported the need for more and better communication between practitioners and decision-makers, such as landowners and managers. While communication among practitioners can lead to improvements in the understanding of ecological drought and, therefore, more reliable monitoring strategies, communicating this understanding and the conditions signaled by monitoring is critical to inform effective action in response to ecological drought.

Communication for Engagement and Adaptive Decision-Making Practitioners' responses, when asked how they coordinate around ecological drought, confirmed that communication is important for action. Separately from the discussion about needs, some practitioners reported successful communication strategies, both with other practitioners and with decision-makers. For example, organized channels and meetings facilitate existing information exchange efforts among practitioners: "We had a huge email chain going with a bunch of people … I feel like it's super collaborative, and we are trying to keep people abreast of what we're seeing on the ground." – Fire and Forestry practitioner.

Other practitioners reported using informal one-on-one conversations to share information about drought conditions with decision-makers: "It's usually a conversation between a permittee and a manager." –Forest and Fire practitioner.

In some cases, formal ecological drought conditions communication channels include both practitioners and decision-makers. For example: "I'm on various different listservs. We work with a lot of rancher groups that talk about conditions, and those definitely are more focused on things like drought conditions… Definitely a lot of information exchanged." – Wildlife Conservation practitioner.

While these quotes demonstrate a variety of methods practitioners already use to communicate about ecological drought conditions, many practitioners reported disappointment with existing communication and the need for better communication to improve ecological drought monitoring. One practitioner reported the lack of agreement and clarity around what constitutes drought as an obstacle to effective communication:

> "I mean, it sounds super basic, but accurate drought assessment, making drought assessment that is applicable to people in Montana. …the deeper you go into this drought world, the more you recognize how challenging it is to actually assess drought dynamics and understand what drought even is. It's actually kind of shocking that we don't have a better definition of what drought is. …what I'm trying to say is a lot of the scientists in the drought world are splitters. And that's fine. There are benefits of splitting and lumping. But it just makes things really complicated because as you look at the drought dashboard, we have a lot of different metrics. They all show drought in different ways. And it's on us, the drought managers or assessment practitioners to try to understand how all these different datasets come together to really describe conditions on the ground." -State Drought Planning practitioner

Inconsistent definitions of drought create communication challenges that amplify difficulties in interpreting metrics to reliably anticipate ecological drought. Practitioners reported the need to not only provide more data but to more effectively explain what the data means for decision-makers as well, recognizing the need for translation of monitoring strategies. For example:

> "And maybe on that note, I think that ensuring that we have an ability to take any individual indicator that, say… climatic water deficit or ET data. Being able to not only easily access that, but also efficiently package it into something that I can then in turn message to someone who's actually making decisions on the ground, is really important. So, there's that kind of not only more data but then also, again, the packaging and delivery of it, and ensuring that it's available for decision support. I think is important too." -Climate Adaptation practitioner

Determining and communicating the implications of data related to drought conditions is critical for relying on data for monitoring and for leveraging data to inform management.

Practitioners noted that the difficulty translating ecological drought monitoring efforts into usable information negatively impacts engagement in ecological drought monitoring. For example:

> “I'm helping those managers navigate the world of information to help make better sense of the drought situation. And that's only been recently in my career just because I've recognized there's a giant gap between all the data and information and then the practitioners that are sorting through it, scratching their head trying to figure out what to do about it.” -Fire and Forestry practitioner

In discussions about the difficulty of communicating about ecological drought with decision-makers, practitioners reiterated the challenges of translating data into useful information and noted that this can generate distrust between them and decision-makers. In most cases, practitioners reported distrust as the fault of scientists, rather than decision-makers. For example:

> “The scientists suck at communicating their science, they overlook the importance of communicating early and often. Then the landowners also suffer from their degree of sucking at communicating, and then they also build up ideas of what's going on at the big bad federal government or state government agencies, and then they create all kinds of elaborate reasons why they shouldn't cooperate.” -Science Communication practitioner

In contrast, one practitioner noted finding a receptive audience can be a barrier to productive communication about ecological drought:

> “I mean, science communication is an interesting beast, really, because you can have the best science in the world, and you can communicate it as effectively as it could ever be communicated. But if you don't have a willing recipient, it just it's not-- the communication part of it is not happening. So we struggle… should we be marketing our stuff or should we be having more face time? Probably a lot more face time would help, but it's hard to schedule face time. And honestly, a lot of times managers really don't want to be bothered by the sausage making part of a project.” -Climate Adaptation practitioner

While this finding was not pervasive across practitioners, it does demonstrate the importance of two-way communication. Practitioners acknowledged the need to improve communication to build trust and engage decision-makers in monitoring. In most cases, this was referenced as a need to improve how science and knowledge about ecological drought are disseminated. A few practitioners reported the need to listen to and incorporate first-hand knowledge into their own understandings of ecological drought, again reflecting the need for ongoing, mediated two-way engagement with decision-makers. One practitioner referenced the value of first-hand knowledge of conditions on a landscape for assessing drought conditions: "We hear a lot from irrigators… if it's dry, it's dry. And if your farmers are dry, then everybody else is dry too, right?" –State Drought Planning practitioner.

This quote exemplifies how important two-way communication can be for assessing conditions. Unreliable science, whether due to the resolution or timeliness of data, can create barriers to understanding, engagement, and, eventually, trust. This points to the critical need to ensure that ecological drought information is relevant and useful to decision-makers to avoid climate information usability gaps. Communication that can effectively inform actions is an essential component of engagement, generating trust, and avoiding climate information usability gaps with decision-makers. For example:

> "But the problem is, as you well know, that information is not often conveyed very well to the general public. And so, if there're ways for us to really focus and invest in resources and tools that kind of move that along, improve that information gap, we might actually get somewhere in terms of building that better community around the whole idea of drought resilience." -State Drought Planning practitioner

This quote emphasizes the need for engagement for resilience. Adaptive decision-making fosters resilience by requiring information sharing and iteration to address change. Engaging community members in ecological drought monitoring can increase awareness about ecological drought and allow for better recognition of changes to landscapes over time, promoting adaptive approaches to ecological drought monitoring and response. Citizen science and photo documentation are examples of efforts to increase participation in ecological drought monitoring and develop more useful monitoring information. For example:

> “…what I still want is, on every monitoring station out there, a camera that allows someone to visually see what the various stages of drought look like on the landscape because that helps you communicate it to permittees. Where we had time series photos and we could say, here's when the drought was X according to these data. Look at how much plant growth was here. Here's a year where the conditions were good. Look how much forage there was. I can talk about data, and I can show numbers. It doesn't speak the same as when you actually show them. And so, if anything, I would say that that needs to complement this stuff. And it also helps calibrate everyday people. So not just agencies, but farmers and ranchers. They calibrated their eyeballs to drought. What it looks like and the onsets of it. … In some areas, there's just a massive turnover in staff at our agency. And so, they wouldn't be familiar with how landscape can look, should look. They might show up during a drought and think this is normal. This is what it looks like. And sometimes impacts can stay like that for a few years, which might be their entire career in that one place. And they make tons of erroneous decisions because of that. So, coupling metrics with something that's relatable to everyday people. Photographs, in particular, I think really would be helpful for that. There's an effort right now to expand out soil moisture and plant monitoring networks.” -Freshwater practitioner

This example reflects the context-specific nature of ecological drought and the need for localized monitoring. One practitioner emphasized the capacity for high-resolution on-the-ground knowledge of an ecosystem to contribute to more reliable assessments of conditions over time. The same practitioner simultaneously acknowledged the difficulties of obtaining this type of in-depth knowledge and the inability to generalize it across large or variable landscapes. This lack of localized understanding inhibits practitioners from sharing monitoring information and drought conditions with decision-makers. For example:

> “So unless you're doing drone imagery where you're really getting sort of centimeter-level resolution and normalizing it over a bunch of different years and precip patterns, again it's really damn hard. [laughter] I haven't cracked the nut yet. I do things like-- when I walk my project sites I'm like, ‘This used to be apple and grasses, now it's all rushes and sedges. Bingo, we did it.’ I couldn't give you a number, but if you if you had walked here eight years ago and you walk here now

> you'd see it. Here's some pictures. That's the best I can do. That is not an easy nut to crack." -Science Communication practitioner

The variability in ecological conditions and resilience across Montana, along with the variability introduced by changing climate patterns and human influence, complicate ecological drought monitoring. Engagement fostered through two-way communication can help to address this information gap by engaging decision-makers in knowledge generation, for example incorporating more local knowledge into ecological drought monitoring efforts. Additionally, decision-maker participation in monitoring can expose them to the dynamic and uncertain nature of ecological drought, revealing the need for adaptive decision-making. Adaptive decision-making that appreciates the uncertainty of ecological drought can enhance both ecological and community resilience to ecological drought.

<u>Communication to Improve Monitoring Tools</u> Better communication between practitioners and other decision-makers presents opportunities to improve the effectiveness of existing ecological drought monitoring tools. The need for improved monitoring tools was extensive and referenced by practitioners across primary management concerns. Monitoring tools include infrastructure such as stream gages and soil moisture probes, as well as remote sensing and modeling efforts like vegetative greenness indexes. These are all informed by data, further articulating the need for more robust data sets and more comprehensive data interpretations to improve ecological drought monitoring.

Practitioners suggested addressing the need for better monitoring tools through more data sharing. This practice would allow for more personalization and specification within existing tools but highlights the challenges in data accessibility. For example: "Instead of having one tool to rule them all, if everybody plays nicely and develops APIs for their data, then we can just pool data in between tools to customize what we're really looking for without creating the wheel." -Freshwater practitioner.

Additionally, obstacles in data accessibility include technological, financial, and institutional barriers, which practitioners mentioned are often insurmountable. For example:

> "…I thought that was going to be a great tool, but we can't turn those into apps and make them operational without paying that hefty subscription. ... It doesn't sound like a lot, but in order to make something operational and sustainable, we need a long-term commitment to invest in it to justify the R&D that would go into making these products and then sustaining them once the parks get used to using them. If they go away after a couple of years, then they're not that useful after all." -Climate Adaptation practitioner

Better communication can raise awareness of the potential value of incorporating more indicators and their associated data into tools. Recognizing this may lead to more accessible data and better ecological drought monitoring tools. Additionally, including more data in monitoring tools can help to bridge information gaps and enable monitoring of conditions across scales and landscapes. For example:

> "…so, can we think of multiple indicators that can help describe conditions? … If we can't have a gage network everywhere, how can you overlay to have multiple indicators to get you closer to that whether it's better soil moisture data that you could lump with some course flow data from modeling to then get closer, that would be helpful."-Science Communication practitioner

The need for better monitoring tools also reflects the need for more communication between practitioners with different primary management concerns who may have access to or rely on different data sets. Developing tools that incorporate diverse data sets can help to reduce the epistemic uncertainty created by incomplete data sets or unprecedented ecological responses. One practitioner reported the need to include more data in existing monitoring tools. Sharing data sets and understandings of landscape processes can increase the analytical efficacy of existing monitoring tools:

> “Is it cheating to say that I don't think we need any more new indicators that I think we need more analysis on our existing indicators? We really need to understand better how drought actually plays out on the landscape. And I don't think we have a good handle on that. And I think that's what we need to understand to make some effective decisions about managing for drought. I don't know. We don't really know why the trees die. We don't really know. So, I think we should learn more about our existing stuff. So I'd like a tool that could clip to your region of interest and massage all the data, and I want data from each bucket in our eco drought framework, datasets that will pull-down menu, take this one, this one, and then some analysis that puts it all together and tells me why my system is vulnerable to drought impacts.” -Climate Adaptation practitioner

This sentiment was echoed by other practitioners who, despite all the shortcomings of existing monitoring tools, emphasize that the greatest challenge in ecological drought monitoring is the limited ability to reliably interpret conditions. For example:

> “I don't think we have a problem with the tools themselves. We have a problem with translating all the noise into something actionable. And part of that is this idea of analogs. When we've been here in the past, where did we end up? Because just saying, ‘Oh, look, the drought monitor says it's brown today." That's great. But what does that mean for me here? I don't know. That's the key. Is translating all the brown and the green into something that means something a little bit in the future in my update.” -Fire and Forestry practitioner

This challenge demonstrates how uncertainty impairs forecasting and necessitates adaptive decision-making in ecological drought response.

Synthesis of Ecological Drought Monitoring Needs

In addition to the commonly reported ecological drought monitoring needs discussed above, practitioners mentioned many needs relating to their primary management concern. These range from the need for more knowledge about how specific species or habitats (e.g., forests) respond to drought to the need for more monitoring infrastructure (e.g., soil moisture probes) (Table 5). These specialized needs were often reported by just one practitioner or by a few practitioners with the same primary management concern.

Table 5: Ecological Drought Monitoring Needs and Exemplary Quotes.

Need	Example Quote	PMC(s)
Unique Ecological Drought Monitoring Needs		
Biodiversity Migration	*"I've offered up that in our new state wildlife action plan, not only should we be thinking about the rarest critters, but we should also be thinking about the ones that we're their last refuge and how do we support them? How do we maintain that and how do we take on that stewardship responsibility?"*	Wildlife
Citizen Science	*"I think, on some citizen science stuff, where you can actually take pictures of dry stream channels. And that all gets collated so that it's time and space related. And kind of that whole data, where you pull together a bunch of data. Socialization and socialization."*	Science Communication
Cold Water Fisheries	*"How can you offset warm temperatures by releasing water during drought years to allow youngsters to rear in the river before they go back to the Lake? And the thing about that is that's multiyear."*	Science Communication
Disease	*I'd say, yeah, getting a better understanding of disease and the causes and what we can do about that.*	Freshwater
Ephemeral Wet Areas	*"So yeah, if I were king for a day, to know where the damp areas were on a weekly basis in Montana throughout spring and into the summer, that would be fascinating."*	Wildlife
Floodplain Connectivity	*"Yeah, I guess what comes to mind most there is just kind of the relative activity of the floodplain, kind of how accessible floodplains are to particular stream systems, and maybe the trends that have been occurring over the years. So, I think that could be helpful in determining and prioritizing restoration opportunities if we're seeing a stream system trending towards less connectivity where it's historically had some good connectivity, and I think that could be a place to look, maybe we need to do some restoration there. Yeah, that would be kind of helpful."*	Freshwater
Forest Stress	*"Forests are one of the key kinds of ecological systems that I think about when I think about forest drought. And I think that having better tools to describe forest stress would be really useful…"*	State Drought Planning

Table 5 Continued

Groundwater	*"So, getting better at handling and mapping those [groundwater] areas out, I always hear that for managers. That's something they're really interested in. Just understanding where those cold spots are on the landscape."*	Freshwater
Infrastructure	*"...infrastructure that's not going to blow out, that will have an adequate lifespan and is going to be as resilient as possible in the landscape"*	Climate Adaptation
Seasonality	*"...if we spent more time looking at the seasonality of drought, then we could get much closer to that whole drought early warning concept. ...And got clued into when that moisture for our climatology, kind of the ecology of Montana... So, for the ecology of an area, for when that needs to get its moisture. And in southwest Montana, it's June."*	Science Communication
Soil Moisture	*"If we could get 30 years of record on all these soil moisture stations, that would be amazing because then we would be able to assess what's happening in the context of what previously happened."*	Science Communication, State Drought Planning
Weather and Climate	*"Well, one of the big efforts that I'm working towards now is helping to discriminate biophysical responses and attribute them to either weather or climate, intrinsic physiographic attributes, soils, that kind of stuff, versus some sort of management influence. So that could be conditions. So, if we're going to determine how, say, how effective the riverscape restoration project was, I need to separate out the signal of whether and climate from the signal of management."*	Freshwater
Most Reported Ecological Drought Monitoring Needs		
Better Communication	*"We have a problem with translating all the noise into something actionable. ... What does that mean for me here? That's the key."*	Fire and Forestry
Data Access, Quality, and Resolution	*"I'd love to see higher resolution data."*	Fire and Forestry
Reliable Forecasting	*"One thing that we've struggled with quite a bit is the ability to forecast."*	State Drought Planning
Understanding Lag Times	*"I feel like ecological drought is sort of the way to describe the phenomenon where you may be feeling the scarcity of water and precipitation in the year that it's happening, but you really see the impacts of ecological drought in future years."*	Science Communication

The needs reported in Table 5 demonstrate disparate understandings of and approaches to ecological drought among practitioners in Montana, further supporting the overarching need for better communication about ecological drought monitoring. The most frequently discussed monitoring needs discussed in previous sections (data, forecasting, and communication) are also reflected in Table 5.

Discussion

Addressing the needs reported by practitioners, both common and unique (see Table 5), can contribute to better ecological drought monitoring. Improved monitoring is essential to inform management of ecological drought impacts. However, continuing shifts in climate, water use, and ecosystem response patterns contribute to uncertainty around ecological drought. The ecological drought monitoring needs reported by practitioners demonstrate their recognition of uncertainty about ecological drought. Some of these needs indicate their desire to reduce epistemic uncertainty, while others demonstrate their acceptance of the need to embrace irreducible uncertainty.

Data and Forecasting to Reduce Uncertainty

The need for more and better data demonstrates practitioners' desire to reduce uncertainty about ecological drought. Increased resolution and quality of data can contribute to improved analysis and monitoring tools, reducing epistemic uncertainty (Meffe et al., 2002; Yoe, 2013). Practitioners reported a desire for more and better interpretation of data to improve monitoring tools, suggesting dissatisfaction with current science and understanding of ecological drought. These needs highlight gaps in climate information that impair ecological drought monitoring efforts. This result may also be influenced by the background, training, and experience or tenure of practitioners, which is not represented in these data but may impact their approaches to ecological drought by either encouraging or impeding holistic thinking.

Practitioners' desire for more reliable forecasting highlights the challenge of the same metrics not consistently pointing to the same outcomes as climate patterns change (Crausbay et al., 2020). This desire reflects the dynamic nature of ecological drought and the compounding stressors that drive ecosystem responses and challenge reliable monitoring efforts (Meffe et al., 2002; Liu et al., 2007; Crausbay et al., 2020; Moss et al., 2024).

Lag times between ecological drought conditions and impacts exemplify the potential for ecological drought impacts to occur over long time scales and further uncertainty. The reported need to address lag times supports practitioners' desire to reduce uncertainty and improve ecological drought monitoring through more reliable data and forecasting. However, a few practitioners acknowledged that their desire for more data is likely insatiable and that tools are unlikely to ever effectively anticipate ecological drought. This data suggests that practitioners understand that alongside efforts to improve ecological drought monitoring, efforts to consider the full scope of possible scenarios and incorporate them into ecological drought decision-making are also necessary (Meffe et al., 2002). Addressing complex SESs requires not only reliable science, but interdisciplinary approaches, too (Kleindl et al., 2018). While more reliable data and science may reduce epistemic uncertainty, practitioners need to embrace irreducible uncertainty about ecological drought impacts to realize effective monitoring and enable adaptation (Wheaton et al., 2008; Wyborn et al., 2015).

Accounting for uncertainty is critical for avoiding over-reliance on information (Refsgaard et al., 2017; Bryant et al., 2018), while accepting irreducible uncertainty is essential for expanding the capacity for adaptive decision-making (see Figure 6), representing a critical precursor to holistic SES thinking needed to address complex social-ecological systems challenges (Berkes et al., 2013; Lubell et al., 2013; Wyborn et al., 2015). Embracing uncertainty includes communicating about it with other practitioners, decision-makers, and the public to avoid over-reliance on monitoring information (Meffe et al., 2002; Refsgaard et al., 2007).

Communication and Engagement to Navigate Uncertainty

Practitioners extensively reported the need for communication to improve ecological drought monitoring. Communication among practitioners, across areas of expertise, and with a diversity of decision-makers is needed to improve ecological drought monitoring, increase awareness about uncertainty, increase engagement in ecological drought monitoring and response, and expand the capacity for adaptive decision-making (see Figure 6) (Berkes et al., 2003; Meadow et al., 2015; Roche et al., 2015; Derner and Augustine, 2016; Church et al., 2022). Currently, insufficient communication about ecological drought conditions impairs monitoring, constrains engagement, and leaves decision-makers without adequate understanding and appreciation of irreducible uncertainty related to ecological drought. This inadequate communication impedes adaptive decision-making about ecological drought response.

Practitioners reported the need for communication across areas of expertise to improve ecological drought monitoring, reflecting current silos in ecological drought monitoring. This need was reported by practitioners across all management concerns, demonstrating their own recognition of existing silos and the potential for communication to dismantle them (Roche, 2021). Considering a variety of ecologies, rather than only one primary management concern, is needed to improve holistic thinking about ecological drought as an SES challenge (Berkes et al., 2003). Communication about ecosystem or species-specific ecological drought impacts will increase the efficacy of and broaden the scope of ecological drought monitoring strategies by incorporating knowledge across fields of expertise (Berkes et al., 2003; Roche, 2021). Thus, practitioners need to communicate with each other across areas of expertise to foster holistic and improved ecological drought monitoring.

Practitioner recognition of the need for communication to improve ecological drought monitoring reflects a willingness to learn and innovate, which are critical to adaptability (Chapin et al., 2009; Smith et al., 2023). The reported need for more communication between practitioners and decision-makers acknowledges the importance of two-way communication that includes listening to increase participation and understanding of natural resource challenges (Berkes, 2009; Floress et al., 2009; Floress et al., 2015). The need for two-way communication implies that transferring information is not sufficient; for communication to inform decision-making, decision-makers need to be engaged in the generation and sharing of knowledge (Cash et al., 2003; Jackson-Smith and Veisi, 2023). Engaging decision-makers in two-way communication is notably critical to the utility of climate information and ensuring its salience, credibility, and legitimacy (Cash et al., 2003; Haigh et al., 2015). Increased communication between practitioners and decision-makers can address climate information usability gaps related to ecological drought monitoring by sharing and implementing multiple types of knowledge into monitoring strategies (Lemos et al., 2012; Lubell et al., 2013; Haigh et al., 2015).

Knowledge exchange, collaboration, and the inclusion of decision-makers in generating climate information have demonstrably contributed to adaptive ecological management in agriculture (Easterling and Mjelde, 1987; Meinke and Stone, 2005; Cabrera et al., 2007; Mase and Prokopy, 2014; Haigh et al., 2015; Virapongse et al., 2016; Wilmer et al., 2022). Additionally, exchanging different types of knowledge (e.g., local knowledge and Western science) is a strategy for increasing adaptive capacity (Berkes et al., 2003; Lemos et al., 2012; Wilmer et al., 2022). The reported need for more communication between practitioners and decision-makers recognizes the importance of engagement for learning and knowledge sharing to expand the adaptive decision-making envelope (see figure 6) and foster resilience (Bridger et al., 2002; Chapin et al., 2009; Wyborn et al., 2015; Ulrich-Schad, 2018; Clifford et al., 2022).

Engagement is the result of not only more two-way communication, but translation and mediation as well, which effectively include decision-makers in generating and sharing information and increase the credibility, salience, and legitimacy of ecological drought monitoring information (Cash et al., 2003; Meadow et al., 2015; Church et al., 2022). Specifically, two-way communication establishes alignment between experts and decision-makers to foster credibility, ongoing communication ensures that information is current and salient, and inclusive communication confirms legitimacy (Innes and Booher, 1999; Cash et al., 2003; Berkes, 2009). Practitioner reports of the need to better explain how data can inform action recognized the need for inclusive and ongoing two-way communication to build trust with and empower decision-makers (Yoe, 2013; Jackson-Smith and Veisi, 2023).

Effective two-way communication must also be transparent about epistemic and irreducible uncertainty related to ecological drought (Cash et al., 2003). Uncertainty can impair decision-making (Derner and Augustine, 2016), but ignoring uncertainty can constrain understanding, adaptation, and decision-making (Camacho, 2009). Embracing, or accepting, irreducible uncertainty by explicitly addressing it as an inherent aspect of ecological drought monitoring is critical to the credibility, salience, and legitimacy of information to decision-makers by engaging them in the dynamic and complex challenges of ecological drought monitoring (Cash et al., 2003). The need to embrace irreducible uncertainty highlights the importance of two-way communication that includes translation and mediation for encouraging holistic thinking and adaptive decision-making in response to ecological drought (Wheaton et al., 2008; Camacho, 2009; Derner and Augustine, 2016).

Spreading understanding about the dynamic and unpredictable nature of ecological drought impacts can perpetuate acceptance of uncertainty and enhance the credibility and legitimacy of information (Cash et al., 2003; Crausbay et al., 2017; 2020). Long-term and inclusive mediation can lead to increased participation in ecological drought monitoring and response and further the credibility and legitimacy of knowledge shared by experts to decision-makers, closing climate information usability gaps (Lemos et al., 2012; Dilling et al., 2015; Knapp et al., 2020). A collective appreciation of irreducible uncertainty will accentuate the need for and encourage ongoing engagement in adaptive decision-making in response to ecological drought that adjusts in response to new information (Meffe et al., 2002; Refsgaard et al., 2007; Derner and Augustine, 2016). The dynamic nature of ecological drought exacerbates the need for frequent and ongoing communication to ensure the salience of information shared and used in decision-making (Cash et al., 2003). Adaptive decision-making informed by credible, salient, and legitimate information about ecological drought can influence decisions in response to drought that support both community and ecological resilience (Walker and Abel, 2002; Berkes et al., 2003; 2009; Cash et al., 2003; Wyborn et al., 2015).

Concluding Remarks

The results presented outline a broad array of opportunities to improve ecological drought monitoring in Montana and beyond, as the needs reported by practitioners are likely felt elsewhere. Improving ecological drought monitoring data and tools will reduce epistemic uncertainty around ecological drought, lead to better forecasting, and enable adaptive decision-making (Derner and Augustine, 2016). However, the dynamic nature of ecological drought ensures lasting irreducible uncertainty (Crausbay et al., 2020). Addressing the need for better communication presents an opportunity to spread acceptance of this uncertainty, which can lead to increased participation in monitoring, lessened information usability gaps, and more adaptive decision-making about ecological drought (Meffe et al., 2002; Wheaton et al., 2008; Lemos et al., 2012; Lubell et al., 2013). Adaptive decision-making appreciates the need for communities and ecosystems to recognize, absorb, and respond to unavoidable disturbances to be resilient (Berkes et al., 2009; Lubell et al., 2013; Derner and Augustine, 2016).

Future research into how these needs can be met and which to prioritize will further support ecological and community resilience to ecological drought. Efforts to expand acceptance of irreducible uncertainty in ecological drought monitoring will underscore the need for adaptation. Coordination of a dedicated forum for communication about ecological drought monitoring and response can help to address information gaps and leverage practitioners' expertise to contribute to holistic and adaptive approaches to ecological drought in Montana. Including other decision-makers in such an effort will promote adaptive decision-making by increasing communication and knowledge sharing to address the complexity and uncertainty that can constrain adaptive decision-making (see Figure 6). Research is needed to understand how such coordination and knowledge sharing can be achieved and what barriers must be overcome. This effort will require the engagement of practitioners and other decision-makers to achieve actionable outcomes. While the sample of survey respondents is small, the need to better understand and encourage knowledge sharing, especially two-way communication that engages decision-makers, is not unique to Montana. These results can be used to support future efforts to understand knowledge sharing about other complex SES challenges.

All of the results and future directions presented underscore the lack of dedicated and standardized ecological drought monitoring. Due to the complexity of ecological drought as a social-ecological systems challenge and the need to incorporate knowledge across ecosystem types and fields of expertise, no single monitoring strategy may be adequate. However, communication and coordination of practitioners' expertise can lead to more comprehensive, dynamic, and reliable ecological drought monitoring.

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CHAPTER FOUR

THE ROLE OF CONVERSATION: PRACTITIONER PREFERENCES FOR SHARING ECOLOGICAL DROUGHT KNOWLEDGE

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Abstract

In the arid Intermountain West, precipitation and temperature patterns have shifted to create conditions that foster more frequent and severe drought events. Ecological drought refers to the impact of drought on ecosystem functions and services and, in turn, human communities. Ecological drought is a social-ecological systems (SES) challenge that is influenced by and influences social, ecological, and interacting systems. The impacts of ecological drought threaten the loss of ecological functions and lead to entire ecosystem transformations, necessitating adaptation. Effective responses to SES challenges require the incorporation of both human and ecological dimensions. However, there is little understanding of how natural resource practitioners, such as policymakers and scientists, in Montana obtain and share information about ecological drought to inform decision-making and responses. In an online survey, practitioners were asked what methods they are aware of and use to exchange knowledge about ecological drought. Paramount to this inquiry was the inclusion of local knowledge as a critical information source for effective adaptation. Results demonstrate that informal conversations are the most used method for sharing knowledge about ecological drought, while scientific publications and the U.S. Drought Monitor are used by only a small portion of respondents. This understanding of how practitioners share information can guide future efforts, investments, and tools in support of ecological drought monitoring and response in Montana and beyond.

Introduction

Natural resource availability drives economic and livelihood trends in Montana, with water resources at the heart of the state's abundant agriculture and ample recreation (Robbins, 2006; Cravens et al., 2021; Headwaters, 2025). Yet, like much of the Mountain West, Montana is characterized by ever-increasing aridity and experiencing increasingly frequent and severe drought events (Millar and Stephenson, 2015; Whitlock et al., 2017; Wilson, 2018; Jensco et al., 2019; Crausbay et al., 2020; Hoylman et al., 2022). Ecological drought, defined as low water availability that "drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedback in natural and human systems" (Crausbay et al., 2017. Pg. 2544), is an emergent concern for Montana's people and resources. Conventional drought types consider only human water needs (e.g., for agricultural use or municipal water supplies) (Crausbay et al., 2017; McEvoy et al., 2018; Kovach et al., 2019), while ecological drought recognizes the water needs of ecosystems alongside human needs and use (e.g., water for fish habitat or to reduce dry fuel for fire risk) (Crausbay et al., 2017; Kovach et al., 2019; Cui et al., 2024). Ecological drought represents a social-ecological systems (SES) challenge that is continuously influenced by both ecology and human actions and contexts (Wilhite et al., 2007; Crausbay et al., 2017; McEvoy et al., 2018; Kovach et al., 2019; Crausbay et al., 2020).

Drought monitoring is typically carried out using empirical hydrologic and meteorological data and models; however, changing climate patterns, water demands, and ecological responses have impaired the accuracy and ability of these strategies to anticipate drought events and their impacts (Milly et al., 2008; Crausbay et al., 2020; Hoylman et al., 2022). Monitoring challenges are furthered by the influence of human actions and management and the emergence of both short and long-term drought impacts (e.g., changing crop yields and ecosystem transformations) that increase uncertainty and make monitoring ecological drought and measuring its impacts very difficult (Kovach et al., 2019; Crausbay et al., 2020). Strategies that address changes in seasonal patterns, lags between drought conditions and ecological impacts, and the ongoing influence of human actions are needed to better embrace uncertainty in recognizing all types of droughts (Wheaton et al., 2008; Crausbay et al., 2020). Although efforts to monitor ecological drought exist across geographies (e.g., Cui et al., 2024), there is not yet a standardized and reliable monitoring strategy for anticipating ecological drought (Moss et al., 2024). Dedicated ecological drought monitoring is needed to better anticipate ecological drought events and inform management.

Ecological drought also presents novel environmental management challenges. As an SES concern, ecological drought impacts, and is affected by, both ecological and social contexts and actions; efforts to manage ecological drought events and impacts require an SES approach (Folke, 2006; Crausbay et al., 2017; McEvoy et al., 2018; Crausbay et al., 2020). SESs are continuously influenced by interactions between humans and nature, necessitating effective management approaches that anticipate change and iteration in both the resource management challenge itself and its management (Berkes et al., 2003; Cumming et al., 2005; Chapin et al., 2009; Virapongse et al., 2016). Thus, appropriate and effective SES management must be adaptive.

Incorporating diverse types of knowledge into environmental management efforts can lead to a deeper understanding of the social and ecological components of a system and enhance the outcomes of both overall management and adaptive management efforts (Raymond et al., 2010; Virapongse et al., 2016). Adaptive approaches to SES management necessitate the involvement of decision-makers to ensure acceptance and enhance efficacy over time (Dilling et al., 2015; Lemos et al., 2012; Wilmer et al., 2018). I use the term decision-makers to refer to individuals on a landscape who will be affected by and are in positions to respond to the impacts of ecological drought. One strategy for engaging decision-makers in adaptive approaches is to share knowledge and, specifically, incorporate their knowledge into management (Knapp and Fernandez-Gimenez, 2009; Virapongse et al., 2016). To incorporate different types of knowledge into management, existing knowledge must first be identified and shared (Raymond et al., 2010).

This study examines how current knowledge about ecological drought in Montana is shared by practitioners to inform decisions about ecological drought preparation and response. I use the phrase ecological drought knowledge to refer to observations, metrics, tools, conditions, impacts, and management or response options. This knowledge can take numerous forms, ranging from formal data sets and reports to informal anecdotes and conversations. In a survey, practitioners were asked how they share knowledge about ecological drought. Our findings indicate the importance of informal knowledge exchange in promoting effective ecological drought management. This paper reports results related to the following research questions:

1. How do practitioners in Montana share knowledge about ecological drought?
2. How can sharing knowledge about ecological drought promote adaptive decision-making?

Literature Review

Ecological Drought Monitoring

The potential impacts of drought events on ecosystems are widespread, from changes to vegetation and habitat to altered fire risk and resultant air quality (Crausbay et al., 2020). Yet, the timing, severity, and extent of occurrences of ecological drought impacts remain unpredictable (Crausbay et al., 2017; Crausbay et al., 2020). Enhanced ecological drought monitoring efforts and a deeper understanding of ecological drought impacts are necessary to more effectively anticipate and mitigate adverse consequences. Monitoring is also essential for recognizing how ecological management efforts influence ecosystem structures and functions across scales (Kleindl et al., 2018). Current metrics used to monitor drought events are limited in their ability to consider ecological water needs and ecosystem responses to low water availabilities (Crausbay et al., 2017; McEvoy et al., 2018).

An initial challenge in monitoring ecological drought is understanding vulnerability to drought, which is driven by exposure, sensitivity, and adaptive capacity. Exposure refers to conditions that dictate water availability, while sensitivity represents a lack of resilience. Exposure and sensitivity are influenced by ecological conditions (e.g., natural water storage, vegetation type, wildlife water demands, etc.) as well as human use of and influence on water resources and ecosystems (e.g., vegetation management, infrastructure to store or divert water, and consumptive water use) (Crausbay et al. 2017). There is a need to identify and utilize indicators specifically tailored to ecological drought to enhance monitoring efforts and address the complexity of this SES challenge (McEvoy et al., 2018; Cravens et al., 2021).

Ecological drought events are driven by teleconnection (patterns connecting conditions—e.g., meteorological, hydrological, or ecological—to ecological responses) and responses to human actions and management in conjunction with low ecologically available water (Crausbay et al., 2017; Kovach et al., 2019; Crausbay et al., 2020). Cravens et al. (2024) use the term "ecologically available water" (EAW) to refer to the amount of water available to ecosystems for meeting specific ecological requirements or sustaining key functions (e.g., photosynthesis) and is an important corollary to the concept of ecological drought.

An important factor of adaptive capacity is people's ability to learn, organize, and access and exchange information (Adger et al., 2007; Engle et al., 2011; Smith et al., 2023). In the case of ecological drought, both social and ecological drivers influence vulnerability and must be accounted for (McNeeley et al., 2016; Crausbay et al., 2017; Kovach et al., 2019; Crausbay et al., 2020). Current drought monitoring efforts do not account for ecological water needs, the impacts of humans, or the compounding stress of these concurrent influences (Kovach et al., 2019; Crausbay et al., 2017; McEvoy et al., 2018).

Local Knowledge for Adaptive Approaches

Addressing ecological drought as an SES challenge requires recognizing different types of existing knowledge before evaluating and integrating it into management (Berkes, 2009; Raymond et al., 2010). Historically, natural resource management has prioritized Western science over other types of knowledge (Robbins, 2006). A recent shift in environmental management has emerged, moving away from approaches strictly based on empirical biophysical data and toward approaches that integrate multiple forms of knowledge (Berkes et al., 2003; Folke, 2006; Raymond et al., 2010; Eaton et al., 2022). This transition acknowledges the importance of alternative types of knowledge to account for the interrelatedness of humans and ecology (Berkes, 2009), which is critical for developing strategies to address and adapt to unfamiliar drought challenges (McNeeley et al., 2016; Crausbay et al., 2020).

Local knowledge is increasingly important for adaptive approaches to SES challenges. I use local knowledge to refer to the knowledge held by communities using and managing natural resources on a landscape, including traditional ecological knowledge, indigenous science, and experiential knowledge, all of which are representative of relationships between people and their localities and developed through hands-on experience, cultural traditions, and social memory (Folke, 2006; Aswani et al., 2018; Olsson and Folke, 2001). Local knowledge can be defined as knowledge developed through historical interactions between people and natural landscapes (UNESCO, 2022) and is "rooted in direct experience and observation, produced over time within a socio-ecological context" (Snitker et al., 2024, p. 3; Kloppenburg, 1991; Knapp and Fernandez-Gimenez, 2009). Importantly, local knowledge is not generalizable across people or places (Lemos et al., 2018).

Incorporating different ways of knowing into ecological management has a positive impact on outcomes by ensuring alignment with local community priorities, capacities, and interests (Fazey et al., 2006; Berkes, 2009; Virapongse et al., 2016). This can be achieved through participatory co-production that combines scientific or technical knowledge with practical, experiential, or traditional knowledge (Eaton et al., 2022). Co-production processes recognize different types of knowledge, account for social contexts, promote engagement, and can improve acceptance, optimism, and outcomes of adaptive approaches to SES natural resource challenges (Knapp and Fernandez-Gimenez, 2009; Dilling and Lemos, 2011; Lemos et al., 2018; Clifford et al., 2022). Discussions about ethical, efficacy, and evaluation concerns of co-production in the environmental management space are ongoing, demanding consideration of who is involved in, and who benefits from, the co-production process (Lemos et al., 2018; Eaton et al., 2022; Church et al., 2022; Jackson-Smith and Veisi, 2023).

Literature highlights the importance of local and experiential knowledge for producer decision-making (Knapp and Fernandez-Gimenez, 2008; Cook et al., 2010; Lehebel-Peron et al., 2016; Sumane et al., 2018; Snitker et al., 2024). In contrast with climate information, which is used to refer to formal data and tools (e.g., evapotranspiration data or the U.S. Drought Monitor), local knowledge is seen as more trustworthy and risk-averse by producers (Haigh et al., 2017; Smith et al., 2021; Lemos et al., 2012, Mase and Prokopy, 2014; Knapp and Fernandez-Gimenez, 2008; Carolan 2006; Moschini and Hennessey, 2001). In fact, Pullin and Knight (2005) found that practitioners are comfortable making management decisions using experiential knowledge alone (Cook et al., 2010). This finding has supported numerous calls for integrating local and experiential knowledge into climate information in agriculture to enable adaptive and sustainable approaches (Travis and Bates, 2014; Kettle et al., 2014; Smith et al., 2021; Snitker et al., 2024). Co-production of agricultural management, including drought preparation and response, can foster mutual understanding between producers and practitioners about how local observations and on-farm trials can improve climate models and forecasts (Smith et al., 2021; Snitker et al., 2024).

Examples of local knowledge successfully anticipating drought events have been documented all around the world (Chisadza et al., 2013 and 2014; Giordano et al., 2013; McNeeley et al., 2016; Sam et al., 2020, Pauli et al., 2021; Liguori et al., 2021; Greene et al., 2022; Chanza and Musakwa, 2022). In many cases, local knowledge can anticipate drought events much sooner than empirical drought metrics (Jensco et al., 2019; Snitker et al., 2024). For example, in Zambia, drought predictions made by a local community based on indicators informed by local knowledge (e.g., the flowering time of a specific tree) proved more accurate in predicting drought events than forecasts based on meteorological data (Chisadza et al., 2014). This was due, in part, to the resolution of drought metrics, which do not always appropriately represent localities. In the Chisadza et al. (2014) study, the timing of a flowering tree was used as a localized and specific drought indicator exemplifying one of many ways that local knowledge can enhance current monitoring efforts (Giordano et al., 2013).

The Greater Yellowstone Ecosystem of southwest Montana is known for inconsistencies in water resource management priorities as producers, recreators, tourists, second homeowners, and state or federal agencies hold different views of and goals for the shared resource (Epstein et al., 2019; Metcalf et al., 2015; Gosnell et al., 2007). In this region, the value of local knowledge held by landowners, ranchers, and other local decision-makers, based on their tenure and experience on the landscape, is becoming increasingly recognized by scientists and decision-makers (Robbins, 2006; Gosnell et al., 2007; Epstein et al., 2019; Gilbertz and Hall, 2022). These examples underscore the need to integrate diverse types of knowledge, namely local and experiential knowledge, into information that influences decision making about drought preparation and response more meaningfully at and across various scales (Giordano et al., 2013; McNeeley et al., 2016).

Exchanging different types of knowledge improves understanding of complex SESs by considering social context, increasing local participation, and informing adaptive approaches necessary to manage them (Lemos et al., 2012; Wilmer et al., 2018; Smith et al., 2023). Sharing knowledge about ecological drought is crucial for enhancing understanding, preparing for, and responding to ecological drought events. The value of sharing knowledge and integrating local knowledge to better anticipate drought events abounds, encouraging co-production efforts to improve drought monitoring (Travis and Bates, 2014; Snitker et al., 2024). Yet, little attention has been paid to how practitioners share knowledge to incorporate local knowledge into management decisions (Lemos et al., 2012; Snitker et al., 2024). There is a need to understand how practitioners, scientists, managers, and policymakers exchange ecological drought knowledge and how different types of knowledge inform ecological drought preparation and response decisions.

In this paper, I present survey results about how ecological drought knowledge is currently shared among natural resource practitioners in Montana, and explore opportunities to incorporate different types of knowledge into management. Informed by prior interviews with drought practitioners in Montana, I sought to understand how current dissemination and information-sharing options are, and are not, used.

Methods

An online survey was developed to gain a deeper understanding of the tools and data used to address ecological drought in Montana. Results from previously conducted semi-structured interviews suggested that communication about ecological drought is important to improve monitoring and inform decisions about ecological drought response (Rhodes et al., 2025). Following those findings, this survey included questions about how ecological drought information is shared, asking which knowledge sharing methods practitioners are aware of or unaware of, as well as which methods they use. By asking this question, the survey aimed to determine how ecological drought knowledge is being shared among natural resource practitioners in Montana.

The online survey was developed in Qualtrics Survey Software and distributed via email during the winter of 2023-2024, with approval from the Montana State University Institutional Review Board (IRB Protocol #JM081722-EX). The survey sample was comprised of a variety of natural resource practitioners in Montana generated based on the research team's (co-authors) knowledge of agencies, NGOs, tribal, and other groups working on resource management in Montana (NPS, National Forests, USFS, USDA-ARS, USDA NRCS, USACE, BLM, FWS, DNRC, FWP, MTNHP, Extension, University) (N = 455). Natural resource practitioners were focused on because of their roles in preparing for and responding to drought conditions and impacts on ecosystems. Individuals received an email invitation to participate in the survey in November of 2023 and up to four additional email reminders through January of 2024. Follow up phone calls were provided during February of 2024 to practitioners working with forest resources. The 70 survey respondents yielded a 17% response rate, which is consistent with the finding that online surveys tend to have lower response rates (10-25%) compared to paper surveys (Sauermann and Roach, 2013). This relatively small sample size restricts these results from being widely generalizable.

Responses were downloaded from Qualtrics into .csv format for descriptive statistical analysis in MS Excel. The results presented here focus on a subset of survey questions. The results from this survey include (1) demographic information about practitioners' roles and the type of landscape they work in, and (2) how knowledge about ecological drought is currently shared by practitioners. Respondents were asked to indicate "aware", "unaware", or "use" for a list of twelve ways to share knowledge, including "other" (check all that apply) (Table 6). Participants were also invited to write in any additional ways they share knowledge about ecological drought in a follow-up question.

Table 6: Methods for Sharing Knowledge about Ecological Drought.

Knowledge Sharing Method
MT Drought Impacts Reporter*
Reporting or News
Scientific Publications
National Drought Monitor
Informal Conversations with Producers
Informal Conversations within an Agency
Informal Conversations between Agencies
Community Meetings
Watershed Meetings
Regional Meetings
Collaboration Across Agencies
Other (please state)

*The MT Drought Impacts Reporter is a public online platform maintained by the Montana Climate Office. Anyone can post and review observations, photographs, and comments about drought conditions or events around the state. All data is tied to a specific location (GIS coordinates), resulting in high-resolution and diversified drought monitoring.

While not all participants responded to every question, the response rates were consistent for each portion of this question (n=53-55). During analysis, discrepancies between respondents who indicated they are “aware” of versus “use” certain ways to share knowledge emerged. It was determined that it is essential to be aware of something to use it, and the data were cleaned up to reflect this (any selection of “use” was paired with “aware”). The results of how practitioners share ecological drought knowledge are presented and discussed below, noting the roles and landscapes with which each respondent is concerned.

Results

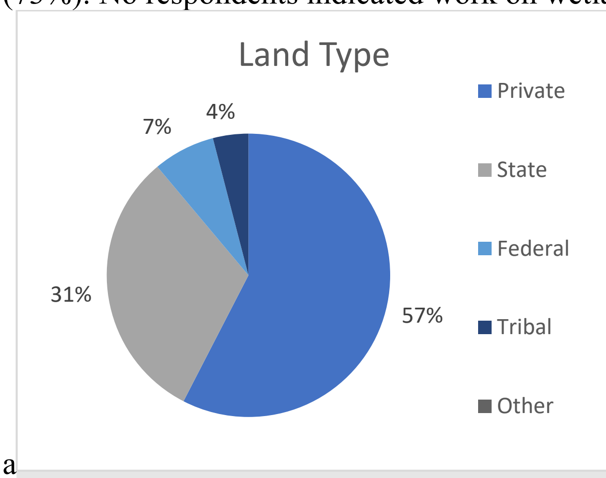
Demographics

The 79 survey respondents included agency scientists, program administrators, educators (college or extension), restoration professionals, fire mitigation professionals, consultants working with private landowners, land managers (state, working, and preserved lands), managers of field staff, conservation planners, researchers, drought mitigation professionals, and grazing consultants. These practitioners work on private, state, federal, and tribal lands, constituting grassland, forest, and shrubland ecosystems (Figure 8a). Survey respondents were asked how long they had been working on their respective ecosystem types, and most reported 1-5, 6-10, or 11-20 years (42%, 18%, and 18%, respectively), while 11% of respondents reported working in their ecosystems for less than one and another 11% reported more than twenty years.

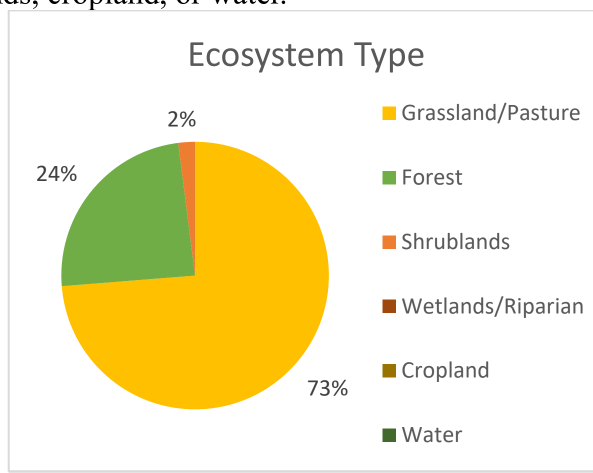
Survey respondents were overwhelmingly focused on grassland ecosystems compared to other ecosystem types (73%, Figure 8b). Practitioners working in wetlands and croplands made up small percentages of our survey respondents. In addition to the types of land and ecosystems respondents worked on, the survey asked, "How would you describe the goals of the ecological management of this land? (check all that apply)." The distribution of management goals aligns with the findings from Figure 8b, with grazing as the highest reported goal among respondents (n=38) and agricultural production as one of the lowest (n=5) (Figure 9). The result of grazing as a management goal for so many respondents points to the importance of agriculture across

Montana, which makes up about 62% of the land and accounts for a $4.6 billion industry providing 4% of the state's employment as of 2022 (Headwaters Economics' EPS; NASS, 2020).

Figures 8a and b show the types of a) land and b) ecosystems that survey respondents work in (check all that apply). The majority of respondents work on private lands (57%) and grassland ecosystems (73%). No respondents indicated work on wetlands, cropland, or water.

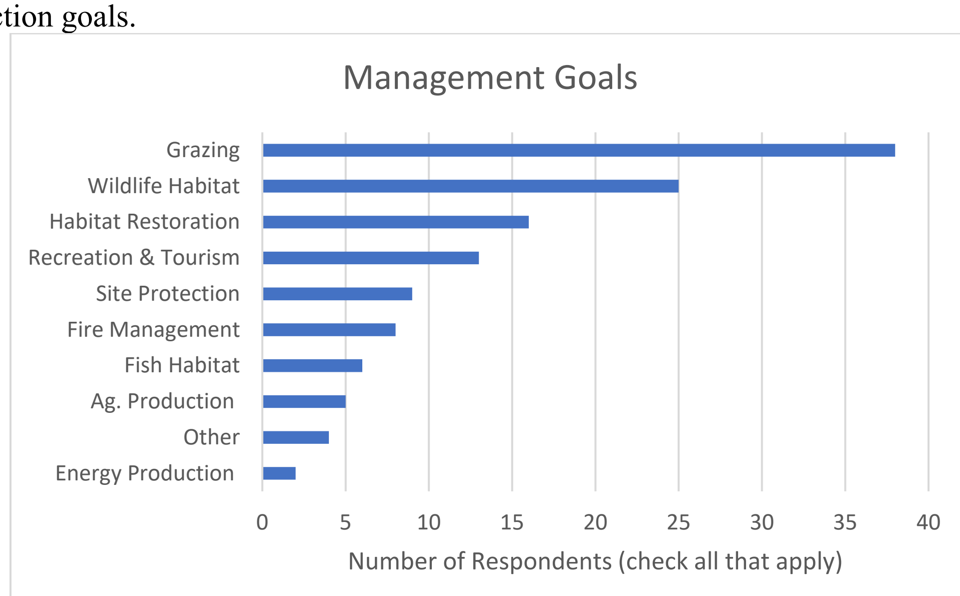


a



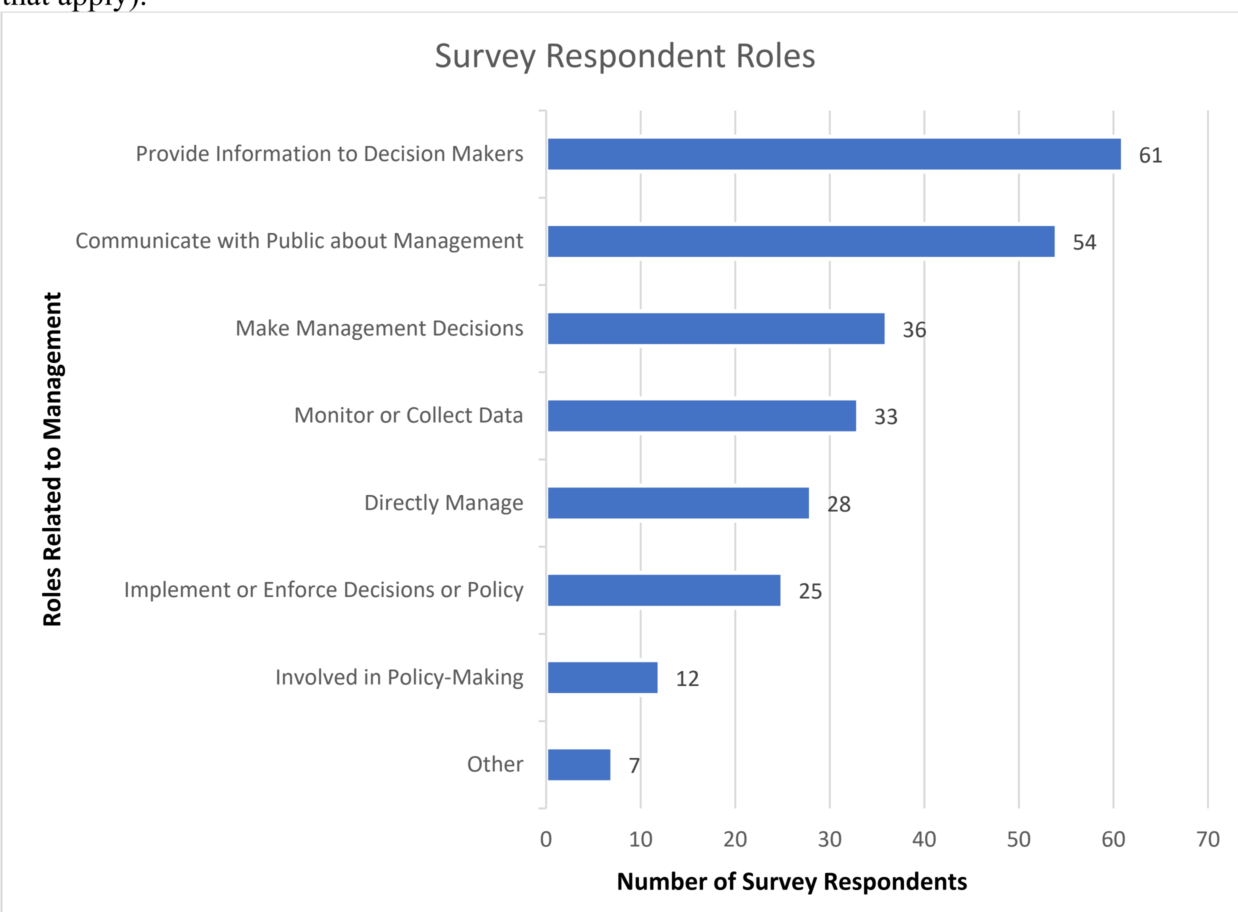
b

Figure 9 shows the distribution of management goals reported by survey respondents. Grazing was the most common goal among respondents, while few reported agricultural or energy production goals.



I was interested in how survey respondents' roles relate to management decisions and actions and found a variety of roles, including informing, communicating, and making management decisions. In response to the question, “What is your role with regard to land/water resource management? (check all that apply),” most respondents indicated that they provide information to decision-makers (n=61) and communicate with the public about management (n=54) (Figure 10). Thirty-six respondents reported that they make management decisions and 28 directly manage.

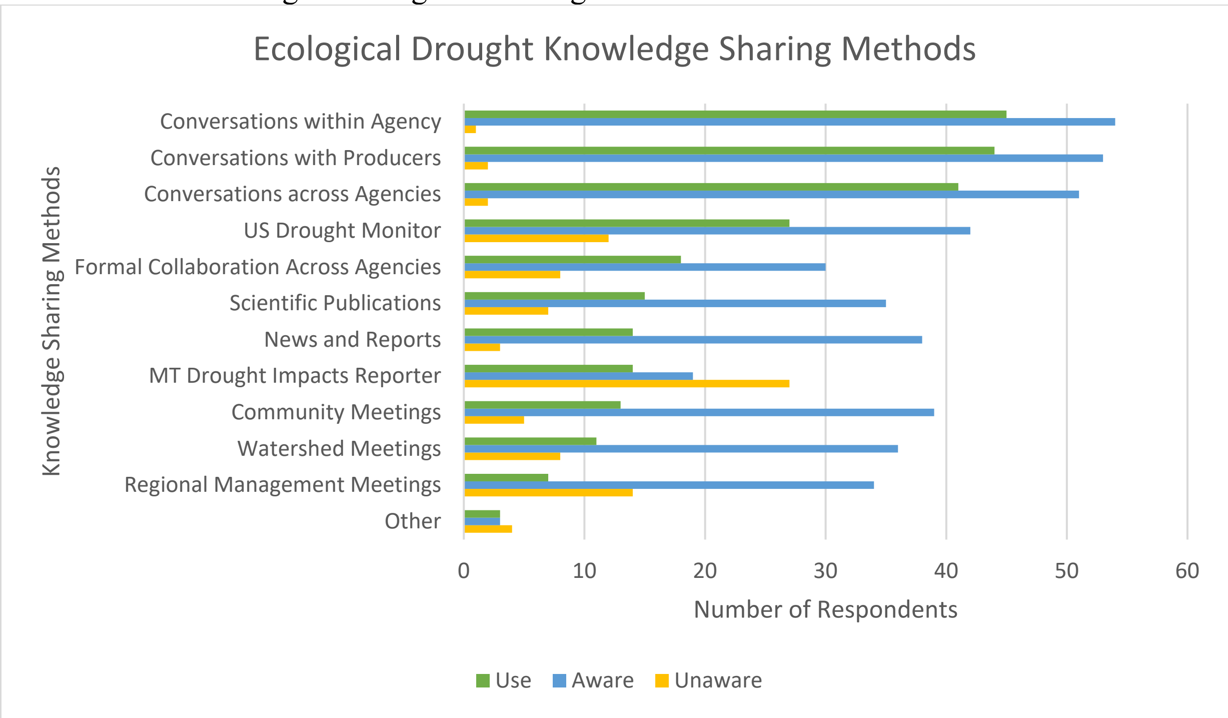
Figure 10 shows practitioners’ roles related to water resource management in Montana (select all that apply).



Knowledge Sharing

Respondents were asked to indicate which knowledge-sharing methods they are aware of and use to exchange information about ecological drought in Montana. Respondents were generally aware of most of the knowledge-sharing methods asked about, aside from only 35% of respondents indicating they were *aware* of the Montana Drought Impacts Reporter while 49% indicated they were *unaware* (Figure 11). For every other knowledge-sharing method, the percentage of respondents *aware* of each communication method was greater than both *unaware* and *use*. The methods with the highest *awareness*, conversations across agencies, with producers, and within an agency (96%, 96%, and 98%, respectively), were also reported as those with the highest *use* (77%, 80%, and 82%) (Figure 11).

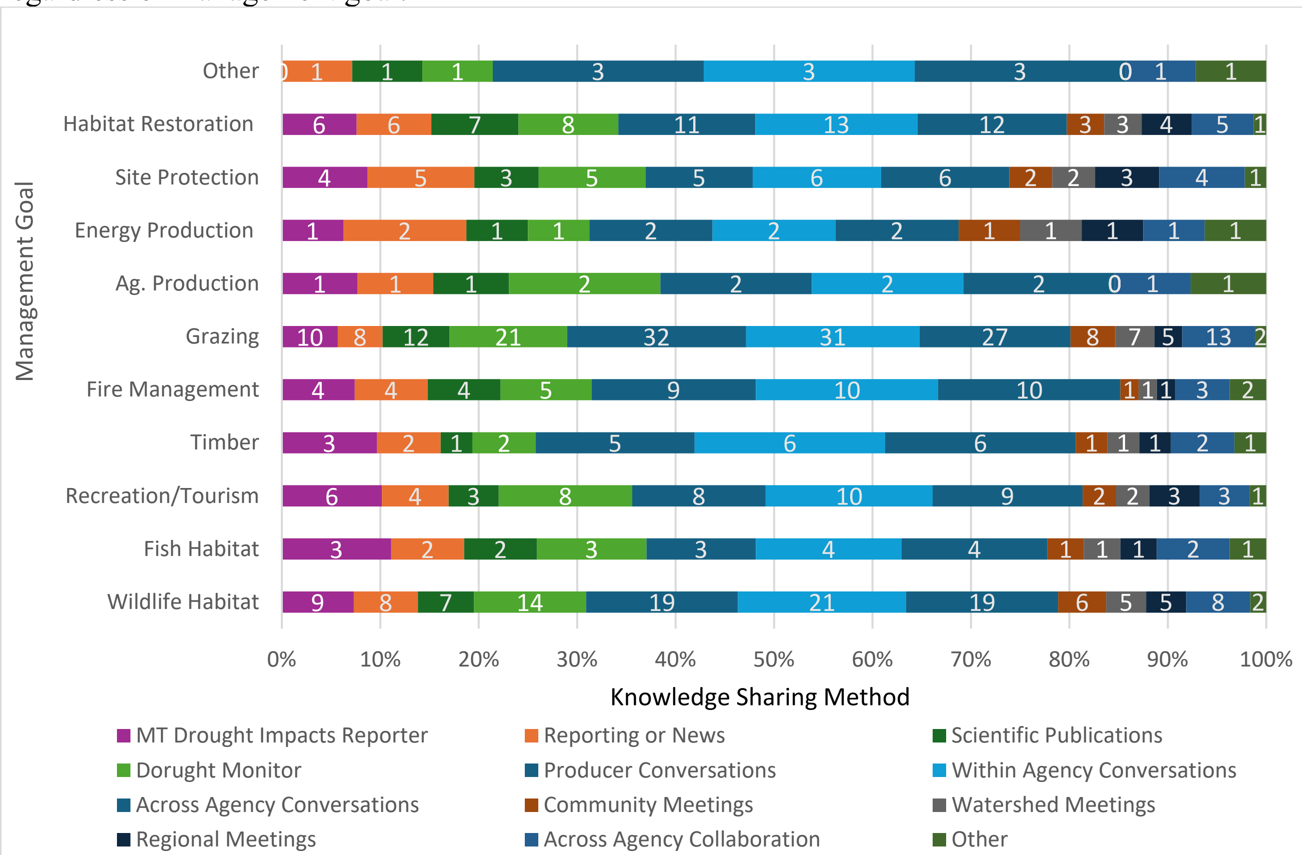
Figure 11 shows the number of respondents who were *aware of*, *unaware of*, and *used* each method to share ecological drought knowledge.



For all other methods of sharing knowledge, awareness ranged from 60-80%, while *use* was much lower. *Use* of news and reports and scientific publications is notably low (26% and 28%, respectively) compared with the numbers of respondents *aware* (70% and 65%, respectively) of these ways to share knowledge. In the case of both news and reporting and scientific publications, awareness does not reflect use (see Figure 11).

Next, I analyzed how the knowledge-sharing methods *used* relate to respondents' management goals (see Figure 9). The results of this comparison confirm that conversations with producers, conversations within an agency, and conversations between agencies are the most *used* methods for sharing knowledge about ecological drought, regardless of management goal (Figure 12). *Use* of the U.S. Drought Monitor varied by management goal, while *use* of scientific publications, news or reporting, the Montana Drought Indicators Reporter, and watershed meetings was low across all management goals. Previous studies report similar findings of practitioners not using published science but instead experiential evidence to inform management plans and decisions (Pullin and Knight, 2005; Cook et al., 2010).

Figure 12 shows the number and percentage of respondents concerned with each management goal (y-axis) who use each knowledge-sharing method. Informal conversations, colored in shades of blue (located in the middle of the figure), were the most *used* way to share knowledge regardless of management goal.



A few survey respondents reported using “other” methods to share ecological drought knowledge including Montana State University Extension, landowner organizations such as the Montana Forest Owners Association, snow course surveys and local SNOTEL sites, and private weather stations (1 respondent each) (see Figure 12). These represent a combination of educational and conversational opportunities, as well as raw data.

Discussion

Informal Ecological Drought Knowledge Sharing

Ecological drought is an emergent and complex natural resource management and SES challenge that is influenced by both ecology and humans (Crausbay et al., 2017; McEvoy et al., 2018). To date, droughts are monitored using drought metrics based on meteorological and hydrologic data, but these strategies are increasingly impaired by shifting climate patterns and human actions (Hoylman et al., 2022; Crausbay et al., 2020; Crausybay et al., 2017). There is a need to develop new drought monitoring strategies that account for human influences on and ecological impacts of drought to improve our ability to anticipate and recognize ecological drought events (Crausbay et al., 2020).

Monitoring and management of complex SESs and natural resources often require adaptive strategies that diverge from or expand upon traditional metrics and methods (Virapongse et al., 2016; Smith et al., 2023) and can be informed by different types of knowledge (Lemos et al., 2012; Meadow et al., 2015, Dilling et al., 2015). Incorporating different types of knowledge, including local knowledge, into monitoring and management has demonstrated improvement in both our understanding and management of complex SES challenges (Berkes, 2009; Raymond et al., 2010; Virapongse et al., 2016). Local knowledge is shared through social networks and informal learning (Knapp and Fernandez-Gimenez, 2009). Therefore, integrating local knowledge into ecological drought monitoring strategies will require looking beyond reports, publications, and technical tools.

I report evidence in support of this, as informal conversations emerged as the primary method by which most of our respondent practitioners reported sharing knowledge about ecological drought in Montana. This finding is true across all types of informal conversation (with producers, within agencies, and between agencies) and across all management goals (proportionally the most-used way to share knowledge). Thus, I suggest that informal conversations need to be both prioritized and encouraged by agencies, organizations, and other management entities as valuable and generative. Hall et al. (2016) suggest treating informal interactions and the resultant learning as empirical data to inform policy, planning, and decision-making. Local feedback is considered during weekly drought mapping processes. Formalizing this can emphasize the value of local knowledge, encourage additional community input, and improve the transparency and legitimacy of monitoring and management strategies and policies (Hall et al., 2016; Meadow et al., 2015; Floress et al., 2015).

While sharing knowledge about ecological drought is critical to increasing understanding, preparation, and response, informal conversations also engage and build trust with and between practitioners and local communities (Floress et al., 2015). There is also a need to emphasize that knowledge exchanged in conversations is valuable and can improve management (Knapp and Fernandez-Gimenez, 2009). Formalizing the knowledge shared informally may further participation in and foster just and generative co-production of ecological drought monitoring and management (Floress et al., 2015; Yoe, 2013; Jackson-Smith and Veisi, 2023). However, formalization of informally shared knowledge could also hinder future use of informal conversations if not done with intentional and ethical engagement (Jackson-Smith and Veisi, 2023). Formalization could also perpetuate the existing challenges with using published science, including accessibility and trust (Cook et al., 2010). Thus, valuing these informal mechanisms for sharing knowledge needs to be done carefully to avoid unintended consequences that decrease their utility.

Agricultural Vulnerability to Ecological Drought

The demographics of survey respondents show a disproportionate representation of practitioners working on privately owned land in grassland ecosystems with grazing and wildlife-related management goals. This emphasizes the importance of ecological drought for livelihoods and local economies in Montana, as agriculture is a $4.6 billion industry accounting for over 62% of land in Montana (Headwaters, 2025; NASS 2020). Furthermore, agriculture and producers in the western United States are vulnerable to drought events (Smith et al., 2021; Kuwayama et al., 2019; Mount et al., 2016). Montana producers and landowners will be disproportionately impacted by ecological drought and need to be included in future ecological drought research and management efforts (Shrum et al., 2018; Snitker et al., 2024). The high representation of practitioners concerned with grasslands, grazing, and providing information to decision-makers (see Figures 8a, 9, and 10) in our sample points to the importance of ecological drought for both agricultural landscapes. Understanding and promoting ecological drought knowledge exchange with agricultural decision-makers (producers) is needed to increase awareness of and resilience to ecological drought.

Mismatches and Opportunities

Our survey results suggest that current government investment in drought monitoring tools and knowledge sharing may not match the methods of sharing knowledge that practitioners use. This is particularly true for news reports and scientific publications (see Figures 11 and 12). These are the result of substantial effort yet are two of the least-used methods for sharing ecological drought knowledge among our respondents. The mismatch between the use of and investment in news and scientific publications is not due to a lack of awareness (see Figure 11), suggesting that these methods are either not convenient, unreliable, or inaccessible for practitioners, and points to a need for further evaluation and potential revision of investments into these strategies. Previous research suggests that inaccessibility is a key barrier to the use of published science by practitioners (Pullin and Knight, 2005; Cook et al., 2010) while Cash et al. (2003) assert that published science often lacks legitimacy, credibility, or salience for the end user. Ample research demonstrates low use of climate information and tools by producers (Snitker et al., 2024; Smith et al., 2021; Haigh et al., 2015; Lemos et al., 2012), and our results suggest low use by practitioners as well. This finding is surprising given that, in some cases, practitioners may be the authors of these reports or publications. Additional research may shed more light on the cause of this mismatch in effort and use and uncover who, if anyone, is using these products, while efforts to address and minimize climate information usability gaps, through increased engagement in monitoring or knowledge co-production, can highlight both useful information and useful ways of sharing it.

Montana Drought Impacts Reporter Reported use of the Montana Drought Impacts Reporter was very low and it is the knowledge sharing method survey respondents were the least aware of (see Figure 11). This tool, hosted by the Montana State Library and created by the Montana Climate Office, is a public online platform where anyone can share comments, photographs, or other data (qualitative or quantitative) about drought conditions across the state. The goal is to provide highly localized information about drought conditions throughout the state, encouraging engagement in drought monitoring and addressing data resolution challenges (Smith et al., 2021;

Montana Climate Office, n.d.). In contrast to the results of high awareness and low use of scientific publications and reports, the low reported use of the Montana Drought Impacts Reporter may be due to low awareness (see Figure 11). Improving awareness of this tool represents an opportunity to increase use; however, accessibility, trust, and risk often impair tool adoption and may also contribute to the lack of use (Snitker et al., 2024; Knapp and Fernandez-Gimenez, 2009).

With increased use, the Montana Drought Impacts Reporter has the potential to enhance the exchange of diverse types of knowledge, as contributions often incorporate combinations of empirical data, climate information, personal observations, photographs, and local knowledge. The public-facing platform is inclusive and accessible as practitioners, decision-makers, and others share information about drought conditions in their respective landscapes. This represents a formal platform for sharing all types of knowledge about drought conditions and may increase engagement in ecological drought monitoring and the co-production of related information in Montana. The tool is also especially useful for monitoring at local scales where data resolution may be lacking.

With more use, this tool and the diverse information it holds can contribute to improved ecological drought monitoring and response strategies informed by practitioners, producers, and other community members. Alongside increasing awareness and use, efforts to integrate the information shared on this platform into reporting, policy, and management can encourage ongoing use and lead to the generation of novel and adaptive approaches to ecological drought in Montana.

Conclusion

Our findings point to the importance of informal knowledge sharing for ecological drought monitoring in Montana. Practitioners indicate that conversations are the most used method for sharing knowledge about ecological drought, while formal scientific reporting and publications are used the least. Substantial literature demonstrates the importance of local knowledge and informal knowledge exchange for influencing producer decision-making about drought and management in the Western U.S. (Knapp and Fernandez-Gimenez, 2009; Smith et al., 2021; Snitker et al., 2024), while Cook et al. (2010) reported the use of experiential evidence in practitioner decision-making in Europe (Pullin and Knight, 2005). These results emphasize the importance of informal knowledge sharing for practitioners who provide information to decision-makers.

The incorporation of local knowledge, particularly of people familiar with and/or local to the landscape or ecosystem experiencing drought, into ecological drought monitoring needs to be prioritized so that this knowledge can inform decision-making in response to ecological drought (Aswani et al., 2018; Snitker et al., 2024). The accessibility and utility of conventional knowledge-sharing methods should be critically evaluated to better understand why practitioners report low use of scientific publications, the National Drought Monitor, and the Montana Drought Impacts Reporter. This understanding can lead to reallocation of resources to support the knowledge-sharing methods used by practitioners. Natural resource challenges of today and the future are characterized by uncertainty and change. Similar efforts can be applied to other natural resource challenges to understand how knowledge about them is shared and how resources can be allocated to support that sharing. Adaptive approaches that incorporate local knowledge, consider social contexts, and are grounded in informal knowledge sharing are needed to iteratively address ecological drought.

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CHAPTER FIVE

CONCLUSION

This dissertation sought to understand how practitioners in Montana approach ecological drought. Drawing from social-ecological systems, adaptation, and community resilience literature, I presented practitioner perspectives on monitoring and preferences on knowledge sharing related to ecological drought. This work exemplified the uncertainty and complexity of social-ecological systems challenges and called for adaptive approaches to ecological drought that incorporate multiple ways of knowing and fields of expertise. Additionally, this dissertation exposed the importance of adaptive approaches to ecological drought to protect and promote community resilience in Montana. Through a mixed-method approach, this work features analyses that can inform improved approaches to ecological drought in Montana: 1) promoting holistic thinking about ecological drought through collaboration, 2) adaptive decision-making about ecological drought amid uncertainty, and 3) prioritizing informal conversations to inform ecological drought response.

Addressing Ecological Drought as an SES Challenge

In all three of the results chapters presented above, the need to address ecological drought as a social-ecological systems (SES) challenge was clear. The breadth of ecological drought indicators and impacts pointed to the complexity of ecological drought and the need for monitoring strategies that consider ecological drought as a dynamic, unpredictable, and multi-scalar challenge (Ostrom, 2009). While expertise is critical, the results of chapter one pointed to the need for increased coordination across primary management concerns to foster the holistic thinking needed to treat ecological drought as an SES challenge. The irreducible uncertainty of SES challenges is represented by the ongoing emergence and compounding of ecological drought impacts and necessitates adaptive approaches (Berkes et al., 2003; Folke, 2006; Crausbay et al., 2020; Moss et al., 2024). Needs for improving ecological drought monitoring reflect irreducible uncertainty and the need to try to monitor better despite it. Finally, sharing knowledge through informal conversations emphasized the importance of iterative exchange of different types of knowledge to navigate the complex, uncertain, and dynamic SES challenge of ecological drought. While all of the data presented in this dissertation is specific to Montana, the themes that emerged in these results are likely present wherever ecological impacts of drought are being felt and wherever natural resource practitioners are confronting complex SES challenges.

The results presented in this dissertation offered insight into how practitioners monitor and respond to ecological drought in Montana, pointing out opportunities for improvement and informing adaptive approaches. Throughout this work, the way that human communities are impacted by the ecological impacts of drought was highlighted, from the extensive impacts of ecological drought that include changes to critical ecosystem services to the unreliability of predictive monitoring. The challenges ecological drought poses to communities suggest the ability for human actions to impact ecological drought as well. The findings presented in this dissertation highlighted opportunities for human actors (practitioners and other decision-makers) to impact ecological drought outcomes by thinking holistically about ecological drought as an SES challenge, embracing uncertainty in monitoring efforts, and sharing different types of knowledge informally. Each of these can contribute to the capacity for practitioners and decision-makers to adopt adaptive decision-making about ecological drought.

Drawing on SES frameworks, adaptive approaches comprised of holistic thinking and collaboration are needed to address SES challenges (Berkes et al., 2003; Chapin et al., 2009; Virapongse et al., 2016). The extensive and unexpected ecological drought impacts affirm the need for adaptation in response to ecological drought (Crausbay et al., 2020). Practitioners reported a breadth of ecological drought indicators and impacts, highlighting the value of their expertise and familiarity with specific ecosystems. However, if not shared, this expertise can lead to siloed understandings of ecological drought, impeding the holistic thinking needed to effectively address ecological drought as an SES challenge (Olsson and Folke, 2001; Chapin et al., 2009; Dunham et al., 2018). Siloed understandings can inhibit early recognition of drought conditions and diminish practitioners' abilities to anticipate and mitigate ecological drought impacts if indicators are apparent outside their area of expertise (Otkin et al., 2022). Thus, the findings in this dissertation support the need for holistic thinking that utilizes a variety of expertise across practitioners to inform effective adaptive decisions in response to ecological drought.

Holistic thinking can be encouraged through better communication and knowledge sharing (see Figure 6). Improved communication includes translation and mediation outlined by Cash et al. (2003) to be transparent about uncertainty and continuously engage decision-makers in knowledge generation to ensure two-way communication about credible, salient, and legitimate information for decision-makers. This type of communication, geared toward increasing engagement, can address climate information usability gaps to enhance appreciation of irreducible uncertainty and promote adaptive decision-making. However, agency mandates, role responsibilities, and training can also influence how practitioners think about ecological drought. Training practitioners to communicate across management concerns and foster engagement with decision-makers can stimulate their holistic thinking about ecological drought and promote addressing ecological drought as a complex SES challenge.

Improving Ecological Drought Monitoring Amid Uncertainty

While ecological drought monitoring needs reported by practitioners were diverse, the need for more and better data across management concerns stood out. These needs suggest that practitioners desire to reduce uncertainty. Practitioners referenced lag times, inaccessible data, or poor data resolution as challenges in ecological drought monitoring that impair early detections of ecological drought. They also reported the desire for better forecasting, to be achieved through incorporating more data into predictive tools to improve their reliability. While increasing the quality and quantity of data related to drought conditions can improve understanding of conditions on the ground, irreducible uncertainty will persist due to the complex and compounding influences driving ecological drought.

The results in this dissertation suggested the need for more and better data while acknowledging the need for collaboration and engagement to implement adaptive strategies in response to ecological drought that navigate irreducible uncertainty. Practitioners frequently reported the need for more communication to improve ecological drought monitoring among practitioners and other decision-makers. This indicated an awareness of the importance of coordinating knowledge across areas of expertise and including decision-makers in monitoring efforts to build trust, ensure that the information they receive is useful and operational, and empower them to make adaptive decisions (Cash et al., 2003; Berkes, 2009; Floress et al., 2009; Sarkissian and Hurford, 2010; Lemos et al., 2012; Yoe, 2013; Meadow et al., 2015; Jackson-Smith and Veisi, 2023). Moreover, this need for better communication reflects practitioners' awareness of the dynamism in information about ecological drought and confirms the importance of adaptive decision-making about ecological drought responses amid irreducible uncertainty.

Informal Conversations to Share Knowledge

Practitioner interviews highlighted the need for more communication about ecological drought. This led me to develop survey questions that asked practitioners how they share knowledge about ecological drought. The final set of results in this dissertation highlighted practitioners' reported use of informal conversations to exchange information about ecological drought. This result aligns with adaptation literature that emphasizes a need to include stakeholders in information generation and dissemination to ensure it is actionable and meets their needs (Lemos et al., 2012; Dilling and Lemos, 2011; Meadow et al., 2015). Informal conversations present opportunities to exchange multiple types of information to expand understanding and, in turn, inform holistic thinking for adaptive approaches to SES challenges and improve their outcomes (Fazey et al., 2006; Berkes, 2009; Knapp and Fernandez-Gimenez, 2009; Lemos et al., 2018).

The highly reported use of informal conversations also points to a mismatch in effort and use. Formal tools, like the U.S. Drought Monitor and scientific publications, were reported to be used much less than informal conversations. These results align with results from the United Kingdom about practitioners using experiential evidence to inform management decisions, suggesting that the use of informal conversations is not unique to Montana (Pullin and Knight, 2005; Cook et al., 2010). This dissertation posits that increased efforts to value information exchanged in informal conversations are needed to inform adaptive decision-making about ecological drought.

In addition, this dissertation advocated for better advertisement of the Montana Drought Impacts Reporter among practitioners and decision-makers in Montana. This tool represents an opportunity to coordinate different types of knowledge on a single platform, including local observations with hydrologic data and formal drought designations. Not only can this tool serve to honor information exchanged in informal conversations as valuable, but it can also address some of the monitoring needs reported in this dissertation (e.g., more data sharing and communication). Practitioners reported low use *and* awareness of this tool, unlike the low use and high awareness of scientific publications and the National Drought Monitor, suggesting that raising awareness may be an opportunity to increase use. Increased use of the Montana Drought Impacts Reporter can offer a mechanism for incorporating local knowledge and scientific data into comprehensive and high-resolution assessments of drought conditions.

Other opportunities to promote informal conversations include recognition in scientific literature as a legitimate and valuable method of data collection. Valuing informal conversations and the knowledge shared within them points to a need for a paradigm shift in traditional Western Science toward more inclusive, nimble, and diverse science and natural resource management (Cook et al., 2010). Local collaboration efforts between practitioners and decision-makers increase knowledge, participation, and acceptance of management challenges, representing a shift away from top-down management (Floress et al., 2015). Collaborative local efforts are needed to adaptively address ecological drought in Montana and beyond.

Future Directions

The results in this dissertation highlight the need to address ecological drought in Montana as an SES challenge. These results accentuate the need for more research into connections between indicators and impacts of ecological drought to promote early recognition and enable mitigation efforts. However, this effort must continue to accept the pervasive irreducible uncertainty of ecological drought due to the ongoing influence of social, ecological, and interacting drivers.

In addition to future research on ecosystem responses to drought, especially considering compounding human and natural stressors, the results of this dissertation explicitly identify several opportunities for improving ecological drought monitoring. These opportunities include improving data resolution, accessibility, quantity, and quality and encouraging widespread adoption of indicators specific to certain ecosystems or species that can contribute to more reliable monitoring. Again, these efforts must be undertaken with an awareness of the irreducible uncertainty characteristic of SES challenges.

Finally, the results of this dissertation show that more communication is needed among practitioners and with other decision-makers. Communication across management concerns must be incorporated into agency and organization mandates to promote holistic thinking while leveraging expertise about specific ecosystems, species, and landscapes. Communication can enhance the early detection of ecological drought, and the collaboration needed to facilitate adaptive approaches.

The predominant use of informal conversations to exchange knowledge reported by practitioners emphasized the need for future work to incorporate different types of knowledge exchanged in informal conversations in management decisions. The need for adaptive decision-making about ecological drought is made clear by the reported unreliability of current monitoring strategies and the irreducible uncertainty of ecological drought impacts. Efforts to promote communication, especially through informal conversations prioritizing multiple types of knowledge, can translate to adaptive decision-making that recognizes complexity and embraces uncertainty. Adaptive decision-making about ecological drought response in Montana represents an SES approach that is necessary to promote community and ecological resilience.

Future research geared toward activating these findings with practitioners and decision-makers in a shared community would be an excellent next step to ground truth the results presented in this dissertation and uncover additional barriers to addressing ecological drought as an SES challenge. This must be a long-term, community-based, and participatory effort including practitioners and other decision-makers. I contend that ongoing evaluation of and efforts to coordinate indicators across ecosystem types, enhance communication, and value informal conversations and multiple types of knowledge are necessary to the effectiveness of on-the-ground monitoring and response to ecological drought.

At this point, there is not a demonstrated effort to engage communities in adaptive approaches to ecological drought in Montana. Quality leadership, relationship and trust building, and ongoing communication and knowledge exchange can improve participation in efforts to address ecological drought in Montana. Fostering these pillars of stakeholder engagement can contribute to increased social capital and community resilience. However, few agencies engage in this type of work as it is challenging to fund. An implication of this dissertation is that it highlights what needs to be done without an explicit roadmap to achieve ideal outcomes. Long-term stakeholder engagement efforts must occur at local scales in collaboration with communities and agencies or organizations. Institutional, economic, and political barriers to this work exist within agencies and communities across Montana and will need to be addressed in future work.

Another area for future work is to include assessment of economic capital as a driver of community resilience. Wilson defines community resilience as reliant on the balance of social, natural, and economic capital (2012). I do not discuss economic capital throughout this dissertation and refer to social capital in a simplified way that does not examine nuances of political, cultural, financial, and built capital described in the community capitals framework (CCF) (Flora et al., 2016). Future work could situate the findings of this dissertation in the context of political, cultural, financial, and built capitals of communities in Montana would clarify obstacles and opportunities for community engagement in ecological drought monitoring and response to build resilience. A smaller geographic lens could lend itself to this type of contextual scrutiny and serve as a case study for other areas in Montana.

Limitations

In highlighting the need to address ecological drought in Montana as an SES challenge, this work calls for the engagement of practitioners and local decision-makers in future efforts to monitor, respond to, and build resilience against ecological drought in Montana. The central limitation of this work is that it only includes practitioner perspectives. While practitioners represent a variety of agencies and organizations across different spatial scales and management concerns, this work did not include representation from tribal entities, landowners, or producers. Adaptation and resilience literature emphasizes the importance of including stakeholders in ecological and natural resource management efforts. Additionally, this dissertation demonstrates the importance of local knowledge for acceptable and effective adaptation. This evidence, alongside the increasing recognition of the instrumental role of landowners, producers, recreators, and other natural resource decision-makers in ecological and natural resource management, highlights the primary limitation of this dissertation. Future work that incorporates these voices and their perspectives can address this limitation and strengthen this work, contributing to decision support that enables actionable opportunities to improve ecological drought monitoring and response in Montana.

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APPENDICES

APPENDIX A

NOAA NIDIS ECOLOGICAL DROUGHT INTERVIEW PROTOCOL

NOAA-NIDIS Ecological and Flash Drought Interview Protocol

Revised after interviews #1 & #2

Used this interview guide beginning with interview #3

Notes for email invitation:

- Our goal is to understand the ecological impacts of drought; identify useful information, indicators and tools for monitoring the ecological drought; and management of ecological drought, as well as flash drought.

Notes for interview process

- Research Assistant(s) (RAs) will participate in interviews and help code responses to Question 9 as “response” or “preparedness” and follow-up with prompts as appropriate

Goal of interviews:

- Our goal is to understand the ecological impacts of drought; identify useful information, indicators and tools for monitoring the ecological drought; and management of ecological drought, as well as flash drought.

Target Interviewees:

- Federal, state, and local resource managers in Montana, including those who manage riparian, grassland, and/or forest systems

Protocol:

Block 0: Introduction and Logistics

- Introduce myself and anyone else on the call (e.g., Research Assistants)
- Offer to describe the project
  - Our goal is to understand the ecological impacts of drought; identify useful information, indicators and tools for monitoring the ecological drought; and management of ecological drought, as well as flash drought.
- Explain confidentiality and consent to participate
- Obtain consent to audio record

Block 1: Role in Drought Management

1) What's your role?

2) In your role, what are your management goals?

3) What ecological impacts related to drought are you seeing or most concerned about?

4) How often do you think about, monitor for, or manage for the ecological impacts of drought?
   - Prompts:
     - When? During what times or conditions?
     - Are there specific seasons of concern?
     - When are your critical decision-making points?

Block 2: Ecological Drought Management: Indicators, Actions, Plans

5) What information, indicators, or tools do you use to monitor the ecological impacts of drought?
   - Prompts:
     - Is there a lag time between the indicator and biophysical response? If so, what's the lag time? What challenges, if any, does that cause?
     - Are these formal or informal information, indicators, or tools?
     - Are these direct measurements or indices?
     - Where do you get the information (if not a familiar source)

6) How do you know you're in a drought?

7) How, if at all, do the information, indicators, or tools you use to monitor the ecological impacts of drought change if a drought comes on very rapidly?

8) Are there tweaks to existing information, indicators, or tools – or new information, indicators, or tools – that would help you better monitor ecological drought? If so, what are those?

    - Prompts:
        i. Do you have a "wish list" for ecological drought monitoring?
        ii. Do you have any "pie-in-the-sky" desires for ecological drought monitoring?

9) Is there information or indicators that trigger specific actions to manage or prepare for drought? If so, what are the indicators and actions?
    - Prompt: What indicators trigger any action?
    - Prompt for RAs to track and ask: Depending on response, prompt to see if there are any preparedness actions for drought (if only responses are mentioned) or vice versa for responses to drought (if only preparedness is mentioned)

<u>Block 3: Ecological Drought Management: Process, Coordination, Collaboration</u>

Now I'd like to talk about the process of drought management.

10) How, if at all, do you manage for those ecological impacts of drought (Q3)?
    - Prompts:
        - Is there a formal process or plan?
        - Is there an informal process or plan?

11) How, if at all, does your management change if a drought comes on very rapidly?

12) Who is involved in the [formal]/[informal] [plan]/[process] you use to manage drought (Q5)?
    - Prompt: How are stakeholders' perceptions of drought management integrated into your management of drought, if at all?

13) Within your [agency's] drought plan or process, who makes decisions about:
    - About drought determinations?

- Drought response actions?
- Drought monitoring?

14) What other agencies or entities do you coordinate or cooperate with to manage the ecological impacts of drought, if any?

15) How does this coordination or cooperation occur? (e.g., meetings, emails, newsletters, phone tree, etc.)
    - Prompt: Is this coordination or cooperation formal or informal?

Block 4: Anything or Anyone Else

16) Is there anything else you would like to share related to the topics we discussed?

17) Is there anyone you would recommend that we talk to about these topics?

APPENDIX B

NOAA NIDIS ECOLOGICAL DROUGHT INTERVIEW CODE

BOOK

Table A1: Ecological Drought Interview Code Book (Select sections relevant to this dissertation)

Code	Description
Agency	What agency or organization does the interviewee work for?
BFC	Local watershed group
BHWS	Local watershed group
BLM	Bureau of Land Management
BoR	Bureau of Reclamation
DNRC	Montana Department of Natural Resources
FWP	Montana Fish, Wildlife, & Parks
MTCO	Montana Climate Offices
NWR	National Wildlife Reserve
NPS	National Parks Services
NRCS	Natural Resources and Conservation Services
NWS	National Weather Services
USDM	U.S. Drought Monitor
USFS	Forest Service
USGS	U.S. Geological Survey
Impacts	Code for priority ecological drought impacts spoken about/considered major concerns by interviewees.
Disease	Disease outbreak, severity, or occurrence as an impact of ecological drought in Montana
Ecosystem	This impact represents change, reduction, or loss of ecosystem regardless of type--aquatic, riparian, grassland, forest, etc. This code includes changes in habitat connectivity, landscape integrity, ecosystem services, etc.
Alpine	Alpine or high-elevation, mountainous ecosystems.
Aquatic	Freshwater ecosystems (e.g., rivers, streams, or ponds).
Forest	Forest ecosystems (evergreen or deciduous).
Grassland	Grass and rangeland ecosystems (grazed/managed or otherwise).
Other	
Riparian	Ecosystems along rivers, streams, and water ways.
Fire	Increased fire risk, fuel, or occurrence as an impact of drought in Montana.
Groundwater	Impacts of drought on groundwater in Montana. This could be a reduction in water storage in aquifers or wells, as well as soil moisture, or impacts to groundwater quality.
Other	This code is for any other ecological drought impact mentioned by interviewees.
Pests	Increase (or changing frequency/prevalence) of pests as an impact of ecological drought in Montana.

Table A1 Continued

Surface water	Impacts of drought on surface water such as diminished streamflow, surface water temperature, or the existence of surface water at all (wetlands, ephemeral ponds/springs). This includes surface water quantity and quality.
Vegetation	This impact of drought on vegetation could be loss of vegetation entirely, changes in proportions of species, or invasive species encroachment. Another impact may be earlier or later greening/blooming of vegetation.
Wildlife	This code is for drought impacts on wildlife, including loss or shifts in species/biodiversity, habitat patterns, competition, food or prey, predation, movement or migration, survivorship, or other behaviors. This may mean changes in habitat range, loss to disease or new predators, or being pushed out by invasives. Increasing human-animal conflict can also lead to changes in biodiversity as a result of drought and subsequent resource scarcity.
Indicators	Code for ecological drought indicators used or discussed by interviewees.
Agriculture	This code is for indicators of drought-related to agricultural systems. Examples could be productivity, growth, grazing, etc.
Animal behavior	An indicator of ecological drought may be the migration and habitat patterns of animals. Changes in feeding patterns and locations, as well as herd/group sizes and compatibility with other species, could also be behavioral indicators.
Aquatic species or ecosystem	Code for fish or fisheries (or other aquatic life) or as indicators of ecological drought.
Dry conditions	This code is for indicators of dry conditions that differ from precipitation, soil moisture, or other specific indicators.
Evapotranspiration	Code for ET as an indicator of ecological drought.
Fire Risk	Dry fuel that increases fire risk as an indicator of drought in Montana.
Forest health	Forest health as an indicator of ecological drought in Montana. This may be a discussion of canopy cover, location of forested areas, increased pest or disease outbreaks that signal drought, or other aspects of forest health.
Grassland	Code for grassland or rangeland indicators of ecological drought.
Groundwater	Monitoring wells, soil moisture, and aquifers can be used as an indicator for when groundwater is low and drought conditions may be occurring.
Other	Code for other indicators of ecological drought in Montana.

Table A1 Continued

Precipitation	This indicator refers to the amount, timing, and type of precipitation. For instance, rain or snow, early or late, can drive accelerated melting of snowpack or sustained soil moisture and groundwater recharge, which are indicators of ecological drought. This code can include SPI and other data sets related to precipitation, or those can be a separate code
Riparian or Wetland	Code for riparian or wetland ecosystems as indicators of ecological drought.
Snowpack	The established, monitored snowpack is an important indicator for areas where the majority of late-season flow comes from the mountains.
Soil Moisture	Code for references to soil moisture as an indicator of ecological drought.
Surface water	Streamflow and temperature are triggers for drought mitigation actions. These indicators can be combined or individual
Temperature	This indicator refers to ambient air temperatures as data that influence drought events and trigger ecological drought impacts.
Vegetation	This indicator code could include NDVI, VegDry, and other specific technical tools and models that use remote sensing data of vegetative greenness to assess drought conditions.
Needs or Tweaks	This code is for the needs or changes practitioners discuss to improve their monitoring of ecological drought. This is related to how monitoring and management are carried out, the tools, data, and knowledge used in drought monitoring efforts.
30m ET	This code is for references to the potential utility or desire for a 30m resolution ET tool.
Data Access	This code refers to the accessibility of data sets, sharing of data and tools, and the way that these influence action within science or management communities. This could be public access to an online tool that is only accessible by agency personnel.
Data Resolution	This code could refer to more monitoring, more localized data at a more granular scale, either through remote sensing or biophysical monitoring. Examples of this are more stream gages in tributaries, more soil moisture data, or more snowpack and precipitation measures across elevations. This could also be a desire for higher-resolution spatial imagery or remote sensing data.
Other	Code for other needs, tweaks, or wishlist items brought up by interviewees related to ecological drought.
Predictive Modelling	Need or desire for more or better predictive models related to ecological drought.

Table A1 Continued

Science communication	The need to better educate and conduct outreach about drought indicators and impacts, specifically concerning ecological drought. This includes communication of data and corresponding management decisions and activities between scientists, decision-makers, and communities.
Primary Management Concern	
Climate Adaptation	Expertise and concern related to changing climate patterns and corresponding impacts on people, ecosystems, or species.
Fire and Forestry	Expertise and concern related to forest health and fire risk.
Freshwater Ecosystem and Species	Expertise and concern related to freshwater species and ecosystems, including aquatic and riparian ecosystems.
Science Communication	Expertise and concern related to relaying science to communities, especially related to drought and ecological conditions. This includes practitioners focused on education.
State Drought Planning	Expertise and concern related to state drought planning and response (across all ecosystems and communities). This includes practitioners focused on water rights.
Wildlife Conservation	Expertise and concern related to wildlife populations, behavior, habitat, etc.