Understanding the Onset of Impacts, Management Responses, and Utility of 30-m Evapotranspiration Data for Ecological Drought in Montana

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ECOLOGICAL DROUGHT WORKSHOPS REPORT

Understanding the Onset of Impacts, Management Responses, and Utility of 30-m Evapotranspiration Data for Ecological Drought in Montana

NOAA NIDIS Coping with Ecological Drought Grants NA22OAR4310225, NA22OAR4310224, and NA22OAR4310223

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Acronyms

ET	Evapotranspiration
FWP	Fish Wildlife and Parks (Montana)
MSU	Montana State University
NIDIS	National Integrated Drought Information System
NOAA	National Oceanic and Atmospheric Association

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Executive Summary

This report presents findings from two workshops conducted under the NOAA NIDIS Coping with Ecological Drought grant, aimed at understanding the onset of ecological drought impacts, management responses, and the utility of 30-meter evapotranspiration (ET) monitoring in Montana. The workshops—one in-person in Helena and one virtual—brought together 17 natural resource practitioners from diverse sectors and ecosystems across the state.

Key findings include:

Ecological Drought Impacts: Participants reported a wide range of impacts from the 2021–2022 flash drought, including delayed effects observed in 2023 and beyond. These included changes in aquatic connectivity, forest health, grassland pest outbreaks, and Indigenous food systems.

Management Challenges: While grassland management practices showed some adaptation, forest management remained largely unchanged. Barriers to change included regulatory constraints, limited resources, cultural inertia, and lack of coordination.

Opportunities for Change: Participants identified strategies to overcome barriers, such as improved communication, a need for small-scale pilot projects, use of water leasing, and more restoration efforts. Social engagement and trust-building were emphasized as critical to success in ecological drought management.

Monitoring Tools: The OpenET platform was introduced as a promising tool for retrospective analysis of drought impacts at fine spatial scales. While not predictive, it was seen as valuable for evaluating management effectiveness and informing future decisions, especially at small scales.

Broader Themes: Discussions highlighted the difficulty of pinpointing the onset and end of ecological drought impacts, the role of fear and short-term memory in response planning, and the need for proactive, community-driven drought resilience strategies.

This report underscores the importance of integrating scientific tools with local knowledge and collaborative governance to enhance ecological drought preparedness and response in Montana.

1. Introduction

This report summarizes the results of two workshops conducted as part of a NOAA NIDIS Coping with Ecological Drought grant titled "Connecting Ecological Drought Monitoring Tools with Natural Resource Stakeholders in Montana." The interdisciplinary research team planned and conducted two workshops: one in-person in Helena, MT, and one virtual. Workshop participants included practitioners from government agencies, conservation groups, and non-governmental organizations (NGOs) at the local, state, and federal levels who have a role in monitoring, managing, and/or researching various ecosystems across Montana. The findings we present in this report are the results of qualitative analysis of workshop transcripts. We report our findings based on ecosystem type without attributing specific comments to individuals due to the discussion-based nature of the workshops. These results offer qualitative and contextual insights from the workshops, highlighting trends and themes that emerged from the workshop activities and discussions. These results represent the perspectives of workshop participants and should not be generalized.

2. Methods

2.1. Workshop design and recruitment

The interdisciplinary NOAA Ecological Drought team planned the *NOAA NIDIS Coping with Ecological Drought* workshops to gather insights on drought impacts and management strategies in Montana. We designed the content of the workshops to build off information we learned from previously conducted surveys and interviews. Specifically, we used the workshops to further explore themes including ecological drought impacts emerging after 2022 and formal and informal management decision making processes.

We identified workshop participants in two ways: 1) survey respondents who noted they would like to participate in a focus group; and 2) additional online searches through agency websites. The potential workshop participants included natural resource practitioners from across Montana that worked on various landscape types (i.e., agriculture, rangelands, and grasslands; water, fisheries, and hydrology; and wildlife, parks, forestry, and recreation), including statewide drought issues. After reviewing the potential participant list, we determined that Helena, MT was a good central location for many participants to attend in-person. We chose the venue in Helena for its accessibility during winter weather, availability of free parking, and adequate facilities for presentations and discussions. We also hosted one virtual workshop due to travel restrictions and ease of participation from participants dispersed across the state. Both workshops included people working on all ecosystem types.

We planned the format of the workshops over several meetings with the research team during the summer and fall of 2024. Through these meetings, we designed the structure, questions, and engagement activities for the workshops. The team finalized the workshop discussion plan, incorporating survey results, management discussions, and the 30m ET data discussion. The in-person workshop included two small group breakouts and large group discussions, while we stayed in one large group for the virtual workshop. Each workshop included three sections: 1) a timeline activity where participants discussed the impacts respondents reported from the survey and added additional impacts; 2) a poll and corresponding discussion about what tools or data could help inform changes to manage for ecological drought, and what are barriers to change; and 3) a demonstration of the OpenET 30m resolution evapotranspiration platform, followed by a discussion of the tool's utility. These activities were tested by presenting the project and focus group plan to an advisory committee, followed by a discussion to refine statements and improve the overall approach.

We used publicly available information to conduct email outreach in the fall and winter of 2024 to engage practitioners. The research team contacted participants three times to register for the workshop. The team also developed detailed plans for venue reservations, facilitator guides, and materials preparation. We finalized the practitioner list, and contact information was solidified to ensure comprehensive representation.

Participant support was allocated for attendees, covering travel expenses, food, and event space rental. This financial support aimed to facilitate participation and ensure the workshops were accessible to all invited practitioners.

Despite challenges such as regulatory constraints and data access limitations, workshop participants emphasized collaboration, adaptive management strategies, and public education to improve drought resilience. We recorded and transcribed each focus group, and the research team took detailed notes throughout both days. Montana State University IRB # JM081722-EX covers this workshop research.

2.2. Data analysis

We recorded the workshops – the in-person workshop was audio only, and the virtual workshops was an audio/video recording. We used Otter.ai to transcribe the in-person workshop and MS Teams transcribed the virtual workshop. The research team first read all the transcripts and notes taken during each workshop. We then used Microsoft Co-Pilot to identify key themes in each workshop and small group discussion. Co-Pilot also generated summaries for each transcript. The research team discussed the Co-Pilot generated themes and then used these themes to come to a team understanding of key findings. We synthesized the results of both workshops into the results presented next. In the following report, we provide exemplary quotes to highlight themes and ideas brought up by the workshop participants.

2.3. Participant demographics

A total of n=17 participants attended both workshops where n=8 attended the in-person event in Helena, MT and n=9 attended virtually (Table 1). The majority of participants were specialists in watershed/wetland/stream/fisheries ecosystems, n=10, with fewer focused on forest, n=1, ranchland/agricultural land, n=2, and multiple ecosystem types, n=4 (Table 2). Most workshop attendees were regional or area specific experts (i.e., specializing in specific regions or locations within the state, rather than focusing on a particular landscape type) n=11.

TABLE 1 PARTICIPANT WORK SECTOR

Sector	Helena	Virtual	Total
State Agency/Position	5	1	6
Federal Agency	1	2	3
NGO	1	-	1
University	1	1	2
Natural Resource Manager	-	4	4
International Affiliation	-	1	1
Total	**8**	**9**	**17**

TABLE 2 PARTICIPANT ECOSYSTEM TYPE

Ecosystem Type	Helena	Virtual	Total
Watershed/wetland/streams/fisheries	5	5	10
Forests	1	-	1
Ranchlands/grasslands	-	2	2
Multiple ecosystem types	2	2	4
Total	**8**	**9**	**17**

TABLE 3 PARTICIPANT OCCUPATION BY SCALE

Scale	Helena	Virtual	Total
Unspecified	-	**2**	**2**
County	-	**1**	**1**
Statewide	**2**	-	**2**
Region/Area Specific	**6**	**5**	**11**
International	-	**1**	**1**
Total	**8**	**9**	**17**

3. Results

We present the combined results of both the in-person and virtual workshops as overall findings. We present results from each section of the workshops, to address the overarching goals of the project and to expand on findings from the survey and interview results.

3.1. Impacts of the 2021-2022 ecological drought

Survey findings revealed a comprehensive list of ecological drought impacts on various ecosystems that emerged in 2021 and 2022, during and following the severe and prolonged drought of 2021-2022. In the first portion of the workshops, participants were asked to review the list of impacts that began in 2021 and 2022, as reported in the survey (Table 4) administered in 2024, and to consider any additional ecological drought impacts and their timing of onset (see Haigh et al. 2025 for the survey methods and preliminary results).

TABLE 4 PROPORTION OF RESPONDENTS REPORTED ECOLOGICAL DROUGHT IMPACT ONSET BY ECOSYSTEM TYPE

Impact	2021	2022
Forests (n=9)		
Plant growth/health damaged, delayed	56%	22%
Trees dying	33%	11%
Tree blow downs	33%	11%
Outbreak of insect pests	33%	0%
Outbreak of disease	33%	11%
Rare or sensitive plants damaged	22%	0%
Increasing invasive or non-native plant species	22%	11%
Reduced survival of saplings	11%	11%
Changing vegetation composition post-fire	0%	11%
Grasslands (n=33)		
Decreasing grassland production	88%	3%
Plant growth/health damaged, delayed	73%	12%
Outbreak of disease	64%	0%
Erosion occurring/worsening	55%	6%
Increasing invasive or nonnative plant species	45%	9%
Outbreak of insects/pests	27%	12%
Overgrazing by livestock or wildlife	15%	3%
Rare or sensitive plants damaged	9%	0%
Riparian (n=8)		
Plant growth/health damaged, delayed	75%	0%
Rare or sensitive plants damaged	50%	0%
Animals damaging or overgrazing riparian areas	50%	0%
Erosion occurring/worsening	38%	0%
Outbreak of insect pests	38%	0%
Increasing invasive or non-native plant species	38%	13%
Outbreak of disease	38%	13%
Decline in health of amphibians	25%	13%
Decreasing ability to filter nutrient inputs from agriculture	25%	0%
Fire (n=5)		
Wildfire occurring	40%	20%
Wildfire burning more intensely than expected	40%	20%
Wildfire smoke affecting people or wildlife	40%	20%
Snow (n=4)		
Snow insufficient for needs of recreation	75%	25%
Snowpack insufficient for filling streams and reservoirs	50%	0%
Snowpack melting earlier than normal	25%	0%
Groundwater (n=7)		
Decreasing groundwater levels	71%	29%
Reducing groundwater return flows to rivers/streams	71%	29%
Insufficient groundwater for irrigation	71%	29%
Springs slowing or not running	43%	0%

Surface Water (n=9)		
Water storage levels lowering	100%	0%
Insufficient water for irrigation	89%	0%
Water temperatures elevating/increasing	78%	11%
Water quality impaired	78%	0%
Insufficient water for recreation	78%	0%
Insufficient water for wildlife	67%	11%
Increasing nutrient loads	56%	0%
Algal bloom occurring	56%	0%
Fish (n=3)		
Declining vegetation needed by fish	67%	0%
Water temperature detrimental to fish or other species	33%	33%
Streamflow insufficient for fish needs	33%	0%
Outbreak of disease	33%	0%
Reduced spawning	33%	0%
Wildlife (n=11)		
Declining health of birds	64%	18%
Declining health of desired insects	55%	27%
Human-wildlife conflict occurring	36%	18%
Wildlife territory restricted due to lack of water/habitat	27%	18%
Declining health of mammals	27%	9%
Wildlife lacking sufficient water	18%	36%
Wildlife migration changing	18%	9%
Wildlife lacking sufficient food	9%	0%
Wildlife disease outbreak	9%	0%

Note: *Percentage of survey respondents working in each ecosystem type who reported experiencing the onset of ecological drought impacts in 2021 or 2022.*

We asked participants two questions for the activity: 1) *What ecological drought impacts have emerged in the ecosystems you work in?* and 2) *Have you noticed anything that is not on this list? If so, when did it begin?* The impacts of ecological drought, as reported and discussed in workshops, included many of the impacts previously reported in the survey (e.g., insufficient snowpack and pest outbreaks). Participants provided specificity to impacts, such as grasshoppers when speaking about pest outbreaks. The workshop participants also introduced several new impacts, including changes to fisheries (habitat and population makeup), recreation patterns, logging and forest thinning efforts, and Indigenous food systems (Table 5). The additional impacts reported during workshops span a wide range from delayed groundwater impacts to forest management impacts, reflecting the breadth of expertise among workshop participants.

TABLE 5 ECOLOGICAL DROUGHT IMPACTS FROM THE 2021-2022 DROUGHT SEEN IN 2023 OR LATER BY ECOSYSTEM TYPE

Ecological Drought Impacts 2023 and Beyond by Ecosystem Type
Forests
Increased tree vulnerability without connection to groundwater
Decreased forest health due to lack of fuels management
Grasslands
Grasshopper outbreaks
Riparian
Unstable river channels due to drought and flood events
Increased channel incision with high flows due to rapid snowmelt
Fire
Regional wildfire severity
Increased smoke and diminished air quality
Snow
Insufficient snowpack
Change in timing of snow melt
Groundwater
Challenges with recharge
Loss of groundwater connectivity in alpine ecosystems
Surface Water
Declining base flows (persistent)
Loss of connectivity between channels
Change in timing (late season) of low flows
Warmer water temperatures
Fish counts reflect conditions two years before
Declining native fish populations
Increase in invasive species (e.g., pike)
Impaired migration patterns
Change in predation patterns due to low flows
Poor population recovery in the presence of invasives (e.g., Brown Trout in Crazy Mountains)
Fish counts reflect conditions two years before
Increase in carp populations (replacing unique cold-water species)

Wildlife
Increased disease and pathogens
Population declines (e.g., chronic wasting disease causing Mule Deer decline)
Increase in high-elevation habitat with late/low snow
Other
Indigenous food availability and harvest patterns impaired
Non-frozen ground (impaired timber harvest and fuels management)
Dry soil (can improve infiltration or promote runoff)
Dry conditions through the fall
Loss of wetland habitat and refugia due to decreased flood irrigation
Changing recreation patterns (moving upstream)
Changing fish populations could impact fishing, recreation, and economics in Montana

While accurately ascribing the timing of the onset of ecological drought impacts is challenging, workshop participants were able to identify the onset of a few notable ecological drought impacts. For example, the North Fork of the Blackfoot River was used as an example of where delayed impacts on surface water result from groundwater impacts, as *"groundwater lag times are three to five years, easily."* In this example, the onset of one ecological drought impact led to the onset of others. Participants described how compounding impacts exacerbate effects of ecological drought on ecosystem functions and services, which in turn makes the impacts challenging to anticipate. The "other" impacts reported in workshops are presented in the sections below based on the ecosystem or species they affect.

3.2. Aquatic impacts

Discussions surrounding ecological drought impacts on aquatic species and habitats were prevalent in both the in-person and virtual workshop. Impacts on aquatic ecosystems were the most reported in previous research on ecological drought in Montana (McEvoy et al. 2018). One participant group discussed delayed impacts on fisheries, as drought contributed to the loss of connectivity between tributaries and main stem rivers, for example:

> *"When the North Fork of the Blackfoot started to dry out, there were big concerns for Bull Trout. They had gotten out to spawn, but what happened is they were never able to get back downstream."*

The above quote highlights an impact on a particular species and geography, suggesting that familiarity and expertise with certain places and ecosystem types are important for recognizing ecological drought impacts. Another aquatic impact that workshop participants discussed was invasive aquatic species outcompeting native species during drought conditions, for example:

> *"I worry about aquatic invasives and drought. At this point, we've evaded the mussels, hopefully, but eventually, warmer waters are going to be better for the pike…"*

A participant followed up on this quote later, sharing that they'd already seen invasive species in the middle of a river system:

> *"I saw a baby pike in the 400-meter stretch below the Clear Water for the first time. I'm sure they've been in there for a while, but that's pretty scary because it's right in the middle of the system."*

In addition to impacts on aquatic species, consequences to aquatic and riparian ecosystems were discussed by workshop participants. Channel incision, floodplain disconnection, and changes in riparian vegetation and erosion were brought up as impacts that also influence habitats and, as a result, species:

> *"You're predicting an increasing amount of channel incision, most likely, and disconnection from flood plains, from more high flow events, and the existing streambanks not being able to contain the excessive water and velocities. So, channel incision then gets you down a negative feedback loop that is hard to get out of without intensive management and restoration."*

The above quote exemplifies the compounding potential of ecological drought impacts, particularly as they relate to hydrological changes. With snow melting earlier and more rapidly due to warming trends, channels experience higher flows and faster velocities than they can contain, leading to incision and erosion. The erosion resulting from higher flows, in turn leads to the loss of riparian vegetation and habitat. These compounding impacts are exacerbated by prolonged drought conditions, creating a positive feedback loop between drought conditions and ecological impacts. One example of this mentioned in the workshops was pervasively low base flow:

"We noticed that base flow is still declining so something that emerged in 2021 is still persisting."

All the impacts reported in the workshops highlight the challenge of attributing start and end dates to ecological drought and the corresponding impacts. While an impact may be observed, some noted it is often difficult to determine the precise moment it emerged within the ecosystem; for example:

"All the signs of those impacts emerge right then? Yeah, or is it a year later? Is it two years later... [it is] a little bit more difficult to quantify."

This challenge highlights the importance of understanding the ecosystem, species, or landscape to recognize differences.

3.3. Forest impacts

Another discussion during the workshops centered on changes to forest management practices due to drought. These impacts are notable because drought can undermine the effectiveness of certain human management practices – practices that might otherwise help mitigate drought effects – thereby compounding the overall negative consequences. One workshop participant explained how low snowpack and unfrozen ground can impair logging and fuels reduction activities during the winter.

> *"We didn't have frozen ground. That really affected our timber harvest this winter. We have conditions and specifications of when we can work in the winter. ... We didn't have the frozen ground, the frost, or the snow depth."*

This demonstrates how drought impacts influence management and planning options, thereby contributing to additional impacts. In the above example, an inability to log and reduce fuels can increase the vulnerability of forests to fire, pests, and other negative consequences related to drought. This quote also highlights the value of ecosystem-specific expertise in identifying the long-term impacts of ecological drought—insights that may only be evident to those familiar with practices like logging, where subtle changes can significantly affect operations and amplify drought-related stress on forest ecosystems. Another practitioner added to this discussion, acknowledging the challenge of conducting prescribed burns during prolonged drought, as the season for prescribed burns can be shortened or nonexistent:

> *"With prescribed fire, the windows in spring and fall are really affected by the moisture and fuels. We're seeing dry conditions right up until winter, so there's not a lot of [prescribed burn] conditions."*

The above quote reinforces the idea that drought conditions can impair ecosystem management and efforts to mitigate drought impacts, contributing to additional negative consequences. Increased vulnerability of forests to potential consequences such as wildfire and vegetation shifts may lead to larger and more severe fires. Workshop participants identified wildfire smoke as another delayed impact of ecological drought, recognizing that it does not only affect humans, for example:

> *"One thing that I'm not sure is covered under fire is increasing smoke. [It] certainly has an effect on us. I'm sure it has an effect on wildlife as well."*

The above quote highlights the pervasiveness of ecological drought impacts. In this example, wildfire smoke, which can be worsened by impaired forest management, has negative implications for wildlife populations in and around forests as well as public health issues. The onset of this impact is hard to determine as it depends on the occurrence of wildfire.

In addition to forest management related to wildfire, workshop participants discussed ecological drought impacts on forest health. One participant explained the variable capacity of different forests to cope with drought due to their reliance on deep groundwater:

> *"The main driver of ecosystem rooting depth is groundwater depth, so some of these systems are going down 30 meters, and trees are tapping into systems really, really, really deep. So, those ecosystems are super reliant on the groundwater. ... That changes their physiological adaptation strategy; they spend more investment on photosynthetic capacity and capacity to transmit water, and that will actually reduce their ability to cope with drought when it comes because the vegetation itself isn't adapted to store water."*

This example provided in the quotes above and below were provided in comparison with high-elevation forests that lack access to groundwater and have adapted to store water for use throughout the year, making them "much more resilient."

> *"Forest systems are responding to groundwater deficits even in places where you might not expect groundwater dependence."*

These quotes demonstrate the importance of ecological adaptation in response to variable water availability. Our workshop discussions suggest that as drought becomes more frequent and severe in Montana, it is possible that many species or entire ecosystems may adapt to become more resilient. For example, riparian tree species may adapt their physiology over time to enable them to store water and be more resilient to drought.

3.4. Grassland impacts

Workshop participants discussed how ecological drought impacts on grasslands often center on changes in vegetation and pests. One example of a delayed impact on grassland ecosystems is the presence of grasshoppers. Survey results included pest and insect outbreaks in 2021 and 2022 (see Table 1); workshop practitioners agreed with this finding and added details in discussions about grasshopper populations on grasslands; for example:

> *"I can't remember the feedback, but it has something to do with when you have drought, there's not as much predation on [grasshopper] egg sacks… and the next year, you see changes in [grasshopper] populations."*

The above quote exemplifies how the impacts of ecological drought can appear long after the onset of drought conditions, as predation patterns dictate future populations. This also represents another example of compounding impacts, as the presence of more grasshoppers often corresponds with the presence or absence of other insects and birds.

The influence of drought conditions on the management of grassland ecosystems was also discussed, as workshop participants reported the importance of irrigation patterns for wetland habitats; for example:

> *"Migration of waterfowl and other bird species and the role of agriculture and flood irrigation on creating wetlands. I can't remember the specific numbers, but it's something like 70% of the western United States wetlands are supported by agriculture. And the feedback of drought on the availability of surface water or groundwater to promote those agricultural practices have impacts on ecological systems."*

The above quote exemplifies how human actions can mitigate and exacerbate the impacts of ecological drought, particularly on grassland ecosystems, the habitats they provide, and the surface water available downstream. One participant specified the importance of agricultural irrigation for surface water timing:

> *"The Yellowstone is a great example of this, where irrigation truly supports late season flow."*

The above quote and the idea that irrigation patterns influence ecological drought impacts reinforce the challenge of identifying the onset of these impacts. For example:

> *"It's challenging to attribute to any specific year because pumping groundwater is a practice that's been going on for a long time and is maybe increased during times of drought."*

The above quote introduces the idea that drought conditions can influence practices that both mitigate and compound ecological drought impacts. The discussion of ecological drought impacts on grasslands underscored the complexity of efforts to mitigate ecological impacts of drought through management changes.

3.5. Other impacts

A variety of other ecological drought impacts not related to a specific ecosystem type were discussed in the workshops (see Table 6).

TABLE 6 BROAD ECOSYSTEM IMPACTS IDENTIFIED BY PARTICIPANTS

Impact	Example Quote
Indigenous Food Harvests	*"Certainly a big impact was their ability to harvest their native foods was diminished."*
Chronic wasting disease	*"In regard to wildlife, you see an expansion of disease, so chronic wasting disease in deer, increasing pathogens, and then a decrease in deer."*
Snowpack	*"Insufficient snowpack for filling streams and reservoirs that burdens recreation."*
Recreation	*"There's been a progression of recreation [fishing and floating] upstream, from areas of impact to new areas."*
Frozen Ground	*"Possible benefits to infiltration."*
Floods and Channel Stability	*"As we move into the future with potentially smaller snowpacks that opens the possibility for more frequent rain on snow floods like 2022 in the Upper Yellowstone, and if the flood frequency curve in the future is modified so that those events occur more frequently, then it's going to be difficult to maintain stable river channels with good riparian vegetation."*

The impacts reported in Table 6 demonstrate the systemic nature of ecological drought as snowpack impacts all ecosystem types and the effects of drought on aquatic ecosystems can influence recreation patterns and the state's economy. Some of these impacts, like Indigenous Food Harvesting and Recreation, point to the cultural and social effects of ecological drought as well.

"...historical and cultural ties between indigenous ways of living and eating and ecosystem functions and vice versa, the indigenous lifestyles are intrinsically tied to the land, culturally and physically" (see Table 6).

Adding the impacts discussed in the workshops to our survey results has increased our understanding of ecological drought impacts in Montana, which can inform future efforts to recognize and mitigate the negative consequences of ecological drought from a socioecological standpoint. These results can also inspire attention to novel impacts to not only ecosystems and species, but communities as well.

3.6. Synthesis of Impacts

An overall takeaway from the discussion of impacts in both the in-person and virtual workshops was the challenge of attributing timing to ecological drought. Workshop participants reflected on the difficulty of determining when droughts end, the specific year of onset of ecological drought impacts, and when the impacts of drought end. This complicates practitioners' abilities to understand impact timing, especially as impacts can compound upon each other; for example:

> *"I would say that we haven't actually come out of the 2020 drought. It's been shifting, but if you look at precipitation anomalies you can make the arguments that we're doing better but it's really long time dependencies that propagate through."*

The above quote demonstrates the difficulty of recognizing when a drought ends. In addition to this, workshop participants discussed the challenge of distinguishing multiple years of drought conditions from changing climate patterns.

"It's incredibly difficult to distinguish between a drought year versus what we're dealing with now...it's like year after year after year, we're dealing with similar impacts. It's hard to distinguish."

Both quotes underscore the challenge of determining the timing of onset of specific ecological drought impacts. Even more challenging is understanding when the impact of a drought ends, as explained by another workshop participant:

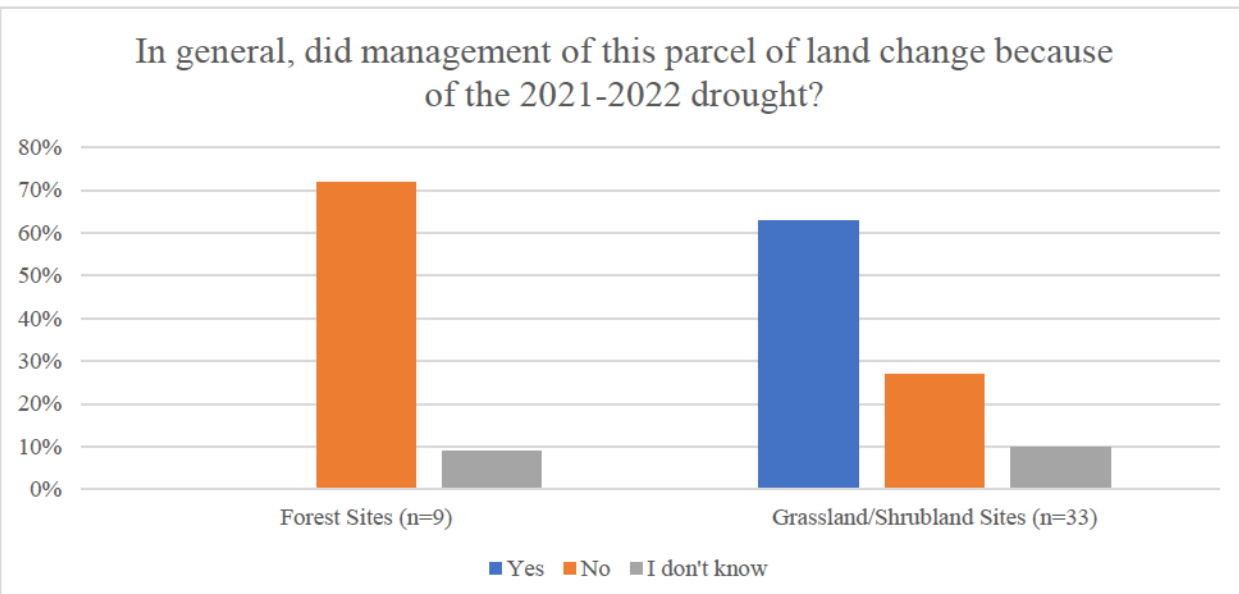
"There's a lot of recognition of the impact of compounding ecological impacts. And so, each of the things on this list influences the others. So, even if we are in some instances able to put an end point on a drought event, that doesn't necessarily end the ecological impact."

The above quote articulates the challenge of assigning timing to ecological drought impacts. While discussions about the difficulty of determining the timing of onset were common in both workshops, the idea that ecological drought impacts may never end was a novel insight. This highlights the compounding nature of ecological drought impacts, as well as the potential for ecosystem-scale transformations that can change an entire ecosystem's structure and/or function permanently.

3.7. Management response to ecological drought

In our previously conducted survey, we asked respondents, "In general, did the management of this parcel of land change because of the 2021-2022 drought?" Responses demonstrate a disparity between the management of forest and grassland ecosystems during drought, with management changes occurring in the latter and not the former (Figure 1).

FIGURE 1 PROPORTION OF FOREST AND GRASSLAND RESPONDENT REPORTED CHANGE IN MANAGEMENT PRACTICES (2021-2022 DROUGHT)



Workshop participants offered insight into the types of management changes that can occur in response to drought conditions, including efforts to increase water retention on landscapes, adapt grazing strategies, adjust irrigation timing, and restore floodplains and native vegetation. These management responses to drought do not include any changes to forest ecosystems and thus underscore the survey findings (see Figure 1).

3.8. Barriers to management change

In response to the survey findings that indicated there were no management changes in forest ecosystems during drought (see Figure 1), we wondered what barriers exist to management change in response to drought across ecosystems. When we asked workshop participants what barriers inhibit management change in response to drought, participants reported a range of barriers from social, legal, and economic to physical and cultural (Table 3). An overall theme of the discussions in response to this question highlighted a lack of adaptability due to the list of barriers presented in Table 3. One participant summed this up succinctly, proclaiming, "...we are so not nimble." Many of the barriers to changing management in response to drought reflect a reactive, rather than adaptive, approach. Participants in both workshops emphasized the need for a paradigm shift to encourage adaptation, suggesting education, knowledge sharing, financial support, and increased participation as effective strategies.

Our results suggest that barriers to management change due to policy or regulatory constraints prevent practitioners and landowners from having a choice to change management, while landscape and economic constraints impair their ability to enact management change. This highlights that changing management in response to drought is a challenge facing both agency practitioners, who may enable management change through technical assistance, information sharing, and policy making, and landowners, who implement change on the ground.

These different challenges related to people's capacity to change management inspired conversations about the importance of local coordination and trust to foster relationships between agencies and landowners to facilitate management changes. These conversations highlighted that while the capacity of practitioners is impaired by management goals and regulations, the capacity of landowners is impaired by labor, prices, and land. An important takeaway from this workshop discussion is the different barriers experienced by various actors. The challenge of changing management in response to drought requires both overcoming the breadth of barriers to enable everything from policy making to on the ground change.

The different barriers facing practitioners and landowners were exemplified by economic barriers, as practitioners often require grants or agency funding to implement management, while landowners need to generate a profit. Legal and regulatory constraints represent another discrepancy in the challenges facing different actors, as participants noted that water rights impede landowners' capacities to change management while agency mandates constrain practitioners. These examples present compounding barriers that both require top-down and bottom-up strategies to address barriers to management change (Table 7).

TABLE 7 BARRIERS TO MANAGEMENT CHANGE

Barrier	Example Quote
Buy-in	"A barrier to management is having buy-in that there needs to change to management from landowners to begin with."
Capacity	"Land management agencies that are so under capacity to achieve their objectives and have so many hurdles and logistical and regulatory roadblocks to getting any management done on the landscape."
Economic Constraints	"Economics and profit really drive management."
Landscape Constraints	"During drought situations, you're dealing with limited landscapes and don't have options for relocating cattle or changing grazing, so you end up overgrazing and causing future impacts as well."
Lease Terms	"[Land] Leases are like five years, right."
Legal Constraints	"Most of those goals that we're managing for are law, right? It's not like we have the ability to change federal or state law. What we're required to manage for is a law that takes politicians, who are generally uninformed, to change. How do you do that?"
Local Coordination and Trust	"If there isn't a group there that's driving this and bringing people to the table… who have that trust already built and engendered, there's not much that's going to happen there. Starting those collaborative efforts can be difficult."
Management Goals	"Managing for a historical ecosystem doesn't necessarily make sense. … Defining what management even means in a natural ecosystem is a challenging thing, because what is the target?"
Cultural Limitations	"If you have a legacy that you're following and the crops that you're producing may not be as viable as they were 20 years ago, that's a huge obstacle."
Policy Constraints	"Policy is a huge barrier in a lot of ways. It doesn't align with funding cycles, because pretty much every instream flow —like non-FWP in stream flow, private instream flow change is funded by grant money. Ultimately reporting requirements [are just] very, very bureaucratic grant work."
Reactive Management	"We don't have a great track record of proactive response... we operate in a paradigm of reaction."
Regulatory Constraints	"Outside parties throw a wrench into things by constantly regulating."
Resources	"Labor wise, a lack of access to labor or money to actually do the work."
Social Barriers	"The social barriers are bigger than the data. In terms of the tools working, we can do this, but the social barriers are, in lots of cases, insurmountable."
Timing of Decision Making	"Barriers to management can often just be a matter of having no availability to move livestock, or you already made a decision to grow a crop last fall that maybe you wouldn't have made this spring, but you know it's too late."
Too Much or Inaccessible Information	"It's hard for me to convince my board of directors to follow any one new tool because there are so many amazing tools. … They are too big and too amazing to comprehend sometimes, and I just don't have the time to learn something new and make it actionable."

Water Rights	"Change of use permits" and "Fear of abandonment"

3.9. Opportunities for management change

After discussing barriers to management change in response to drought, the research team asked workshop participants to think about how these barriers could be overcome. Ideas for overcoming barriers to management change ranged from specific water management strategies, like retention and cloud seeding, to more general strategies, like conversations and open-mindedness (Table 8). The technical tools reported by participants exhibit confidence in future management efforts, suggesting that practitioners and landowners have the capacity to change and improve management in response to drought if the aforementioned barriers can be overcome. Examples like aquifer recharge, water leasing, and restoration point to the potential for improved ecological management during drought (Table 8).

The results from these workshops highlight the existence of social barriers to management change (see Table 8) and offer a few strategies for addressing them. The suggestion that conversations and open-mindedness can contribute to overcoming barriers to management change in response to drought highlights the importance of bottom-up ecosystem management efforts as well as the need for increased participation in drought response.

TABLE 8 IDEAS TO OVERCOMING BARRIERS TO MANAGEMENT CHANGE

Management Action	Example Quote
Open-mindedness	"Open-mindedness within the reality of very tight commodity business with super small margins."
Conversations	"Conversations between agencies and with non-agency folks to understand and overcome barriers."
Start small	"If you can get projects off the ground that show real, meaningful value, there is availability to change laws and things. The example I just thought of is in California. The Corps of Engineers engaged with the forecast center to do tests using the weather service's long-term forecasts to manage a small portion of a reservoir. The successes in that program have led to the actual modification of Army Corps water control manuals (for a few reservoirs). ... It's these small projects that show success, and then you have small movements and laws, and big things get changed as a result."
Assessment of impacts	"Montana FWP [Fish Wildlife and Parks] is trying to understand how anglers impact fish populations. They are using research and existing datasets to see what impacts are occurring and how to revise management."
Water leasing	"There are programs for water leasing to maintain water for fisheries during times of drought."
Relief efforts	"Programs that open up restricted lands for grazing during large drought years [is happening in Canada]."
Water retention	"I would tend to default toward the same projects and actions that we know are a small step towards resilience, and that is maintaining water on the landscape as long as possible. ... How fast it leaves is the biggest thing we have under our control, and how many straws we have drinking that water is also something we have under our control. ... If you look to the Indigenous past, there were ten times more beaver on the landscape. We're never going to have that many beaver on the landscape again but, if we can make the landscape function as though it did have that many beaver that's the direction we can focus on."
Water storage & cloud seeding	"One of the shifts I'm seeing now is aquifer recharge and cloud seeding. … Any new tool or strategy that we can try that might incrementally add some snowpack. … Next step is getting political and financial support to do a pilot."

More management	"More management more often. More people doing more stuff more often on the land. … There's a fairly well-recognized body of management on the ground that leads to better ecosystem resilience, at least in SW Montana."
Restoration efforts	"Conifer encroachment, floodplain reconnection, functioning stream systems, fish passage… all these things. There aren't many people against those."

3.10. Utility of 30m ET for monitoring ecological drought

The third portion of the workshop agenda introduced OpenET, a new 30-meter resolution evapotranspiration (ET) tool supported by NASA that freely reports data from 2020-2025 via an online mapping tool. ET is the process by which water is transferred from the land surface to the atmosphere via evaporation from soil surfaces and transpiration from vegetation. It is a useful proxy for vegetative health and has been widely applied within the drought monitoring community. An important note about OpenET is that, though 30-m resolution data is available for small areas at approximately daily lag, statewide data is only available at longer lag times due to rate limiting by the data provider.

The demonstration of this tool during workshops exemplified its utility in discerning different land uses, particularly agriculture. Practitioners reflected on this use as a way to retrospectively evaluate the efficacy of management strategies by comparing ET data on a landscape or in a watershed across years with different management regimes; for example:

> "*The scale of work is very relevant. Like the field-level scale would be able to show the differences in management practices. You would know the practice, you would know what happened, and then you go here and drill down to compare*".

Using this tool to communicate the results of management could overcome the challenge of temporal resolution. Indeed, practitioners discussed having lower resolution data quickly as more important than spatial resolution (i.e., they would rather have data the next day than wait a month for higher-resolution data). For example: "*Yeah, I'd rather have data that's from yesterday that's at one kilometer than 30-meter resolution data that's a month old*". Both quotes highlight the importance of timing and scale in determining the utility of the OpenET tool.

For retrospective analyses of drought conditions across small scales (e.g., watershed or farm), practitioners reported excitement about this tool; for example:

> "*We get a lot of comments like, you know I'm 10 miles away and you're telling me that it's different than it is. And our arguments always like, well, that's not the scale of analysis that state drought assessment is really trying to accomplish.*"

The quote above is thus arguing that the OpenET tool has promise for helping with management decisions at small scales. Another potential use of the OpenET tool discussed by workshop participants was conducting retrospective assessments of management efforts to inform future planning and management practices. Thus, while this tool is not predictive, participants thought it could offer insight into the efficacy of different ecological management practices (e.g., till and fallow or conifer removal). One practitioner excitedly suggested sharing this tool with farmers to help inform decisions about their practices year-to-year; for example:

> "*I will take this back and share it with my board. They're all farmers and this is something that they'll use, or at least look into.*"

Another practitioner emphasized that the impetus for drought monitoring is to implement financial support mechanisms in response to drought events to support landowners and others economically impacted by drought:

> "*The real practical nature is based on our reactive paradigm and it's all about financial assistance. Where the money meets the road [is] why drought assessment is important for Montana"*.

Workshop participants noted that large scale drought monitoring efforts, such as statewide assessments, OpenET did not seem useful, especially due to the lag time for large-scale data availability.

> *"Yeah, yeah, like having a lower latency, like, I'd rather have data that's from yesterday, that's at one kilometer than 30-meter resolution data that's a month old, right?"*

In addition to latency challenges, participants discussed that incorporating new tools takes time, representing another barrier to use of OpenET, for example:

> "*With any of the tools we have that you work into your assessment process, sometimes it takes a little bit to look at over time and then all of a sudden it's like oh, wow, ok, this has got value.*"

However, this tool stood out to practitioners as a nice backup for existing tools (e.g., SPI, VegDri, VHI, ForDRI). This supports another participant's concern that there are so many monitoring tools and a need for communication on how to use and differentiate between them:

> "*How can we make some of these products that are developed insularly, more useful. We're always surprised that people aren't using our products."*

The above quote emphasizes the need to improve communication in order to improve engagement. In discussions about OpenET and other drought monitoring tools, participants produced novel ideas about how this tool, when used in combination with others, can contribute to decision support. For example, one practitioner asked if it would be possible to use OpenET, in conjunction with precipitation data, to model soil moisture and predict vegetation response to conditions to inform livestock decisions.

3.11. Other results

Several noteworthy takeaways emerged from a concluding discussion about the nimbleness of drought response in the in-person workshop including: the role of fear, short-term memory, drought forecasts, and outreach/education.

First, there was a discussion about the **role of fear** and how fear of making the wrong decision about drought response may influence management. In response to this idea, practitioners emphasized the importance of working collaboratively but agreed that there are challenges, including a pervasive need to improve public engagement, coordination, and trust to enhance drought responses across a watershed; for example:

> "*The state can only do so much in driving some restoration efforts... but if there isn't a group there that's driving this and that's bringing people to the table who can even open up their land for restoration opportunities, or who don't have that connection and that trust already built and engendered, there's not much going to happen there. And like starting those collaborative efforts can be, can be difficult, just as a cold start*".

Another interesting conversation centered on the challenge of **short-term memory**, as one practitioner reflected: "*You get a drought year and my phone is ringing, and people want you to come to talk about it and it's on everyone's mind and then you get a year like 2023 and the phone is dead. ... No one talks about drought or what we do about drought in a good year".* This quote exemplifies challenges in establishing drought management and response efforts as there is often little engagement before drought conditions begin.

This challenge of participation in drought response and management led to a discussion about how **forecasts** may decrease drought resilience or work against mitigation efforts. For instance: some irrigators may divert more water early, contributing to drier creeks; for example:

> *"Forecasting drought can have the opposite effect where irrigators will divert more water, they will take advantage of when they have availability and priority to prepare for drought and exacerbate those [impacts]".*

The above quote supports the need for more education and coordination of drought response to avoid more severe consequences. This led to a conversation about how to conduct drought **outreach and education**. Workshop participants disagreed with each other about whether drought is a concern for people across Montana. One practitioner argued that "*Unless they saw the impact themselves… maybe they were going to their favorite fishing holes and saw closures*" people living in urban centers are unaware of drought. This thinking was supported by a practitioner who works in forest and fire management who noted, "*We talk about the fire season of 2021, the fire season of 2017. Nobody in my circle talks about droughts. ... I would argue the general public is grossly unaware of our drought conditions*".

Finally, workshop participants discussed the idea that drought conditions are always identified **on the ground** before they appear in monitoring efforts and tools; for example: *"Have we ever identified a drought through data before people identified it on the ground? No. ... I also think that's because we take a perspective that drought is not a thing unless there's an impact.*" This quote underscores the importance of increasing landowner participation in drought monitoring and management to mitigate impacts on ecosystems.

4. Conclusions

The workshops on ecological impacts and drought in Montana underscore the significant challenges posed drought, which are exacerbated by climate change, and the necessity for adaptive strategies. Montana's climate trends include increased warming, leading to reduced snowpack, diminished water availability, and increased frequency of wildfires. These changes threaten the state's agricultural yields, wildlife habitats, and outdoor recreation economy. The introduction of tools and data sets may offer a transformative capability for water and resource management. However, effective drought management requires overcoming barriers such as regulatory constraints, funding shortages, and the need for better collaboration between agencies and landowners. There is a need for improving drought preparedness and resilience, emphasizing the importance of real-time data, adaptive management strategies, and public education. By integrating scientific data with community-driven insights, stakeholders and practitioners across Montana can develop more robust strategies to mitigate the impacts of ecological drought and climate change, ensuring the sustainability of its natural resources and the well-being of its communities.

5. Next steps

These workshops conclude the social science components of this project. Our next steps include disseminating our findings widely through appropriate platforms, conferences, and webinars, which will engage a broader audience. Developing actionable recommendations for ecological drought practitioners and policymakers will focus on overcoming barriers to management change, such as regulatory constraints and funding shortages, and highlight opportunities for adaptive management and collaboration. Enhancing public engagement and education through outreach programs, community workshops, and partnerships with local organizations is crucial. Implementing a robust monitoring and evaluation framework using tools like Open ET could support real-time decision-making and assess the effectiveness of strategies for ecological drought. Promoting collaboration and coordination between agencies, landowners, and stakeholders could also facilitate effective drought response efforts. Finally, securing funding and advocating for policy changes that provide financial support and incentives for drought resilience initiatives will ensure sustainable management practices in Montana.

6. Citations

Haigh, T. et al. (2025) Montana Ecological Drought Impacts and Management. Preliminary Survey Results.

McEvoy, J., Bathke, D. J., Burkardt, N., Cravens, A. E., Haigh, T., Hall, K. R., Hayes, M. J., Jedd, T., Poděbradská, M., & Wickham, E. (2018). Ecological Drought: Accounting for the Non-Human Impacts of Water Shortage in the Upper Missouri Headwaters Basin, Montana, USA. *Resources*, *7*(1), Article 1. https://doi.org/10.3390/resources7010014