Contents lists available at ScienceDirect

Weather and Climate Extremes

journal homepage: www.elsevier.com/locate/wace

A typology of drought decision making: Synthesizing across cases to understand drought preparedness and response actions

Amanda E. Cravens [a,*], Jen Henderson [b,2], Jack Friedman [c], Nina Burkardt [a], Ashley E. Cooper [a], Tonya Haigh [d], Michael Hayes [e], Jamie McEvoy [f], Stephanie Paladino [g], Adam K. Wilke [a,1], Hailey Wilmer [h]

[a] U.S. Geological Survey, Fort Collins Science Center, 2150 Centre Avenue Building C, Fort Collins, CO, 80526, USA
[b] CIRES, University of Colorado, Boulder, 216 UCB, Boulder, CO, 80309, USA
[c] University of Oklahoma, Center for Applied Social Research, 5 Partners Place Suite 4100, Norman, OK, 73019, USA
[d] National Drought Mitigation Center, University of Nebraska, Lincoln, 3310 Holdrege Street, Lincoln, NE, 68583, USA
[e] University of Nebraska-Lincoln, School of Natural Resources, 101 Hardin Hall, Lincoln, NE, 68583, USA
[f] Montana State University, Department of Earth Sciences, 226 Traphagen Hall, Bozeman, MT, 59715, USA
[g] MeroLek Research, USA
[h] USDA-Forest Service, Pacific Northwest Research Station, 11175 Auke Lake Way, Juneau, AK, 99801, USA

ARTICLE INFO

Keywords:
Drought management
Drought planning
Mental models
Social science
Human dimensions
Western United States

ABSTRACT

Drought is an inescapable reality in many regions, including much of the western United States. With climate change, droughts are predicted to intensify and occur more frequently, making the imperative for drought management even greater. Many diverse actors – including private landowners, business owners, scientists, non-governmental organizations (NGOs), and managers and policymakers within tribal, local, state, and federal government agencies – play multiple, often overlapping roles in preparing for and responding to drought. Managing water is, of course, one of the most important roles that humans play in both mitigating and responding to droughts; but, focusing only on "water managers" or "water management" fails to capture key elements related to the broader category of drought management. The respective roles played by those managing drought (as distinct from water managers), the interactions among them, and the consequences in particular contexts, are not well understood. Our team synthesized insights from 10 in-depth case studies to understand key facets of decision making about drought preparedness and response. We present a typology with four elements that collectively describe how decisions about drought preparedness and response are made (context and objective for a decision; actors responsible; choice being made or action taken; and how decisions interact with and influence other decisions). The typology provides a framework for system-level understanding of how and by whom complex decisions about drought management are made. Greater system-level understanding helps decision makers, program and research funders, and scientists to identify constraints to and opportunities for action, to learn from the past, and to integrate ecological impacts, thereby facilitating social learning among diverse participants in drought preparedness and response.

* Corresponding author.
E-mail addresses: aecravens@usgs.gov (A.E. Cravens), jen.henderson@ttu.edu (J. Henderson), jack.r.friedman@ou.edu (J. Friedman), burkardtn@usgs.gov (N. Burkardt), cooperashley45@gmail.com (A.E. Cooper), thaigh2@unl.edu (T. Haigh), mhayes2@unl.edu (M. Hayes), jamie.mcevoy@montana.edu (J. McEvoy), macypal@gmail.com (S. Paladino), awilke@umn.edu (A.K. Wilke), hailey.wilmer@usda.gov (H. Wilmer).
[1] University of Minnesota Water Resources Center, 173 McNeal Hall, St. Paul, MN 55108, (present address).
[2] Texas Tech University, Department of Geosciences, Science Building, 1200, 125 Memorial Circle, Lubbock, TX 79409, (present address).

https://doi.org/10.1016/j.wace.2021.100362
Received 19 December 2020; Received in revised form 1 July 2021; Accepted 29 July 2021
Available online 31 July 2021

1. Introduction

1.1. *Beyond water management: drought as a complex, multi-actor challenge*

Drought — defined most simply as insufficient water relative to needs (Redmond, 2002) — is an inescapable reality in many regions, including the western United States. Droughts are predicted to intensify and occur more frequently with climate change (Cook et al., 2016; Trenberth et al., 2014). Drought also interacts with other social and ecological disturbances, which themselves may cause greater damage in a changing climate. For instance, drought substantially increases wildfire risk (Wall and Brown, 2015); wildfires impact ecosystems, communities, and public health (de la Barrera et al., 2018) and are becoming increasingly frequent and larger (Dennison et al., 2014). Furthermore, hot, dry conditions stress vegetation and wildlife; if drought persists long enough, changes in vegetation composition or species ranges result (Allen et al., 2010).

Drought causes significant stress to human communities around the world and the resources upon which they rely (Kallis, 2008). Drought directly impacts diverse sectors, from agriculture to forestry to water supply to energy production (Wilhite and Vanyarkho, 2000). Pandey et al. (2007) calculate that drought-driven crop losses in China between 1978 and 2003 cost the nation 0.5–3.3 % of its agricultural GDP. In the United States, in response to a 2017 flash drought, the Department of Agriculture issued USD$206.3 million in Livestock Forage Disaster Program payouts to livestock producers in Montana, South Dakota, and North Dakota (Jencso et al., 2019). Adverse agricultural impacts will likely be amplified in the future as droughts worsen (Li et al., 2009), though farmer adaptation and learning can counteract this to some degree (Rey et al., 2017). Non-agricultural impacts of drought are often dispersed across larger regions and populations, making it more difficult to accurately assess the damages suffered (e.g., van Dijk et al., 2013). By one estimate, Australia's Millennium Drought cost nearly AU$810 million to mitigate ecological losses and replace vital ecosystem services (Banerjee et al., 2013). In the United States, 28 drought disasters between 1980 and 2020 had costs at or exceeding USD$1 billion, totaling an estimated USD$254.3 billion worth of damages (NOAA National Centers for Environmental Information, 2020).

While drought has traditionally been defined by abnormal meteorological conditions, many river basins have been so modified by human engineering that droughts today reflect both meteorological conditions and human water use (Haddeland et al., 2014; Van Loon et al., 2016). In the western United States, aridity is one of the defining characteristics of the regional socio-ecological system (Jones et al., 2019). Significant interannual variability in temperatures and precipitation, as well as spatial variability in conditions, have been observed since the first European settlements (Pederson et al., 2006). Partially in response to this variability, humans have heavily modified the hydrological environment over the past two centuries, thus facilitating the decoupling of human water demands from local meteorological and ecological conditions (Dettinger et al., 2015; Dunham et al., 2018; Nilsson et al., 2005). Such decoupling, as well as the movement of water across basin boundaries, means that drought conditions in one location can cause impacts hundreds of miles away.

Preparing for drought before it happens and responding to drought when it occurs is thus a complex task. Nevertheless, it is vital: taking action in response to drought can mitigate its impact, as can building resilience and/or adapting to environmental conditions (Wilhite, 1997; Wilhite et al., 2014). Thus, accurately characterizing drought decision makers and their intersecting decisions is critically important to understanding the effectiveness of drought preparedness or response activities and to developing models, drafting policies, building cooperative teams, and/or setting scientific agendas to address drought.

Many diverse actors – including private landowners, business owners, non-governmental organizations (NGOs), scientists, and managers and policymakers within tribal, local, state, and federal government agencies– play a range of often overlapping roles related to drought preparedness and response. Following Ostrom's notion of polycentric governance (2010), which is characterized by multiple, independent centers of decision making, it is critical to understand how various individuals' decisions interact and aggregate to determine the tradeoffs that are collectively made about how to allocate water between multiple uses in times of drought. We emphasize that these decisions and actions go beyond the management of water to include a host of other human-environment interactions, such as natural resource management decisions, agricultural activities, business directions, recreational choices, and land management policies. Managing water is, of course, one of the most important roles that humans play in both mitigating and contributing to droughts; but, focusing only on "water managers" or "water management" fails to capture key elements related to *drought management*. The respective roles played by those managing drought (as distinct from water managers), the interactions among them, and the consequences in particular contexts, are not well understood. This is the gap we address with our study.

Drought social science is a growing area of inquiry. Globally, cross-case comparisons have examined the human dimensions of drought at different administrative scales in Brazil (Gutiérrez et al., 2014), across China's provinces (Simelton et al., 2009), Ghana's regions (Antwi-Agyei et al., 2012), South Korea's administrative districts (Kim et al., 2015), the Mediterranean basin (Iglesias et al., 2009), and South Africa's regions and agencies (Vogel and Olivier, 2019). However, most U.S. studies of the human dimensions of drought focus on particular locations (e.g., Becker and Sparks, 2020 (California); Kachergis et al., 2014 (Wyoming); Kohl and Knox, 2016 (Georgia); and McLeman et al., 2008 (Oklahoma)). A place-based approach results in a deep understanding of how drought affects particular communities and highlights the interconnections among different actors in a given location. But single case studies do not reveal similarities and differences across cases, nor do they reveal the wider institutional dynamics that influence how drought unfolds at broader scales (Pulver et al., 2018).

In this paper, we address these challenges by developing a typology for understanding decision making about drought preparedness and response by synthesizing insights from 10 place-based research studies in the Western United States (Fig. 1; also see Supplemental Material, Table S1). We generate a typology with four elements that collectively describe how decisions about drought preparedness and response are made. It is a framework that we believe will be useful to decision makers who navigate the complex decision spaces of drought and desire to do so in ways that reflect the multiple scales, interactions, and dynamics of their choices. It likewise provides a useful heuristic for program managers and scientists who fund, study and/or collaborate with drought decision makers to enable more robust discussions and planning for drought preparedness and response. To this end, our typology highlights how decision makers frame their management objectives, the institutions they sit within, the decisions they make, and the ways their choices interact with or constrain those of other decision makers.

1.2. *Value and purpose of typologies*

Generating typologies is a common analytic tool in the social sciences for sorting cases, classifying dimensions of a problem, and measuring phenomena (Ayres and Knafl, 2008; Collier et al., 2012). Descriptive typologies map out observations in an area of inquiry, identifying important aspects of a concept, process, activity, or network. They are similar to, but more detailed than, a framework, which contains a "general set of variables" (Ostrom, 2010, p. 646) and is less concerned with causality than an explanatory typology (Collier et al., 2008). We present a descriptive typology with four elements that characterize how drought management decisions are made.

While there are existing frameworks and typologies for analyzing climate change vulnerability (e.g., Adger, 2006), climate change

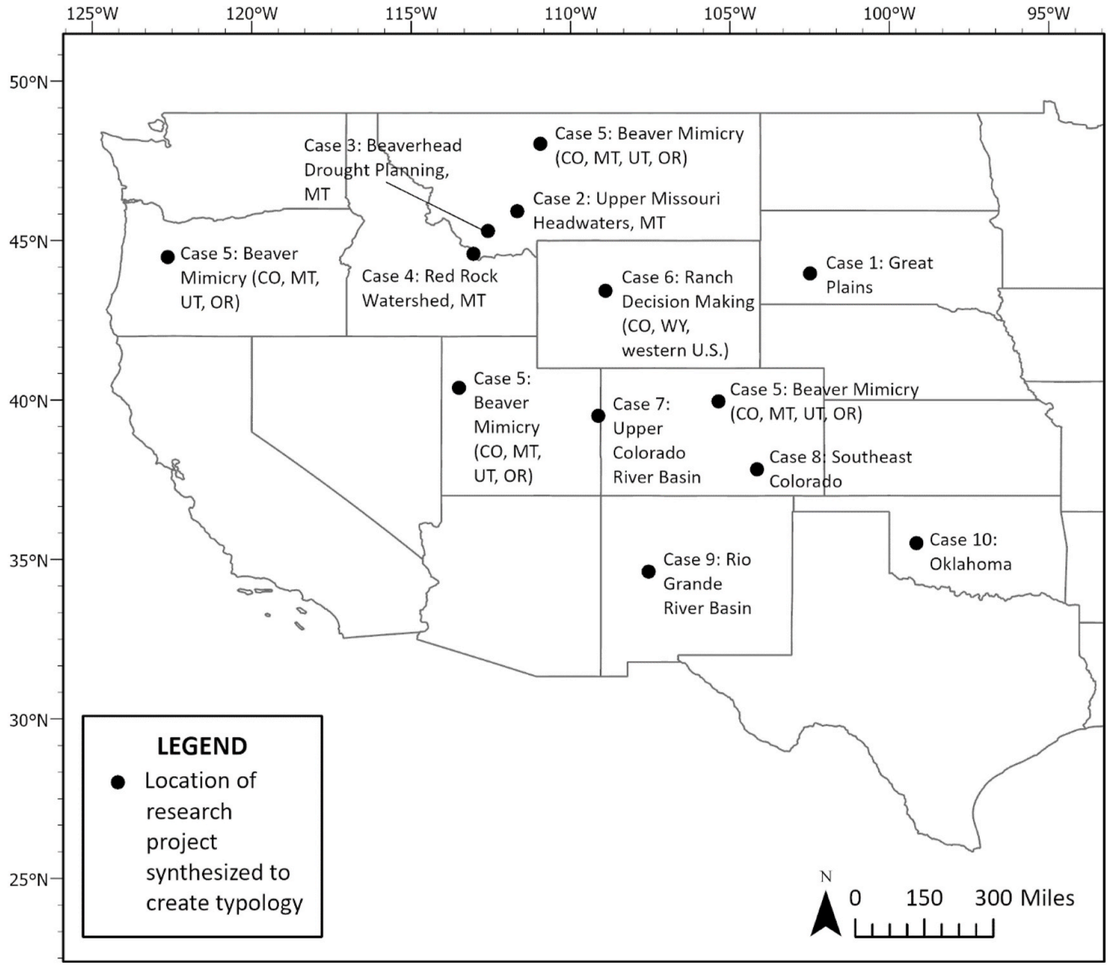

Fig. 1. Geographical distribution across the western United States of research cases synthesized to create the typology. See Table S1 in Supplemental Material for additional information about these research projects.

adaptation (e.g., Eisenack and Stecker, 2012; Moser and Ekstrom, 2010; Smit et al., 2000), water governance (e.g., Pahl-Wostl, 2015), and complex socio-ecological systems (e.g., Ostrom, 2007), these frameworks do not focus specifically on drought. For example, water governance approaches may over-emphasize "water managers" in traditional water management sectors and fail to recognize the broader range of important roles and types of actors involved in drought management. The socio-ecological systems framework has been criticized for not capturing interdependencies between multiple actors and activities (Hinkel et al., 2015). This paper fills these gaps by proposing a typology of drought decision making that highlights interdependencies and interactions between various decisions and actors.

We deliberately define drought decisions broadly, including both the actors and decisions generally considered in drought planning practice (Wilhite et al., 2005), as well as natural resource management actors whose choices affect and are affected by water shortages (Crausbay et al., 2017). In our conception, drought decision makers include those with formal decision-making authority (including water, land, and fire managers at multiple governmental scales as well as private landowners and businesses who own, use, or control water) and those they collaborate or interact with (such as watershed groups, non-governmental organizations, or recreationalists). The range of decisions these actors make is similarly broad: from the cropping choices of an individual farmer, to water releases for hydropower by a utility, to grazing plans and permits approved by a rangeland manager, to fishing restrictions implemented by a wildlife agency, to the declaration of a drought emergency by a state governor's committee.

The typology intentionally integrates multiple theoretical perspectives. It sheds particular light on the intersection between drought management and ecological management since, despite theoretical recognition of the linkages, too often research, monitoring, and management focuses more attention on either human or ecological systems. As with other descriptive typologies (e.g., Biagini et al., 2014; Smit and Skinner 2002; Gosnell et al., 2006), we do not intend to offer either a step-by-step guide nor method for evaluating drought management, preparedness, and/or response. And we do not offer relative weightings for the influence of each element, as these will vary by setting. We were not able to identify causal relationships between variables given our data, as one would expect from an explanatory typology. What we offer with this descriptive typology is a mechanism to parse the complexities of decision making into discrete elements, which can then be used by decision makers and researchers to improve their system-level understanding of how and by whom choices about drought are made.

Such increased understanding translates into developing more effective mental models of the overlapping problem spaces, actors, and decisions that interact to shape drought management in a particular location. A mental model is "a cognitive structure that forms the basis of reasoning, decision making, and, with the limitations … observed in the attitudes literature, behavior" (Jones et al., 2011, p. 1). The more complete and accurate a mental model someone possesses, the more prepared they are to respond to the complex situations they encounter in the world. Importantly, mental models "provide the mechanism through which new information is filtered and stored," which means they "evolve over time through learning" (Jones et al., 2011, p. 1). By creating a cognitive framework to classify drought decision making, the typology provides decision makers, funders, and scientists with a holistic understanding of past choices and a way to analyze how key elements are likely to influence present and future decisions.

2. Methods

This paper synthesizes findings from interdisciplinary research projects conducted in the western United States to generate a typology of drought decision making. Synthesis reveals generalizable patterns by expanding on distinct studies to elucidate the relationships that tie multiple datasets together (Magliocca et al., 2018; Pulver et al., 2018). Using a synthesis-based approach allows us to offer a more holistic description of the specific objectives, actors, choices, and interactions present in drought decision making.

2.1. Sampling strategy

Discussions at two drought-focused workshops held in Fort Collins, CO, USA, in 2016 and 2018, provided inspiration to create the typology. The first workshop was focused on drought social science but resulted in participants identifying the diverse ways they were conceptualizing drought decision making. As a result, the second workshop focused explicitly on identifying common themes among drought decision making across 18 research projects in the western United States. Twenty-nine participants from 15 disciplines, primarily social scientists but also including natural scientists and program administrators, participated in one or both workshops. Each social scientist represented one or more drought-focused research project(s).

Following the workshops, a smaller group of participants, the 11 authors of the present manuscript, completed additional synthetic analysis of 10 projects (Fig. 1; Table S1) to develop the typology described here. The sampling strategy, then, was purposive, both in spatially selecting cases that provided broad representation across the western United States and in identifying individual research projects that could richly contribute potential typology elements through their investigation of the social, institutional, cultural, and/or economic factors influencing drought management, preparedness, and/or response in particular locations. Each of the 10 projects included in the synthesis originally had been conducted by the authors as part of their individual research agenda. Projects varied in their objectives, methods, and analysis strategies; this heterogeneity provided the collaborative synthesis more robust insights than any single approach to methods or theory might, demonstrating that the four elements of the typology apply across different research sites and methodologies. All the included studies relied on primary data collection, which can be explored in more detail in the project summaries (Table S1, "Methods") and the authors' respective publications. Most of the projects also integrated natural science aspects (Table S1, "Research Approach").

2.2. Synthetic analysis

Each case was inductively re-analyzed to identify which of the potential elements identified during the workshops were most clearly represented in the data. Based on the results of this analysis and an iterative process of discussion over months, the team identified the four elements described below. Authors then wrote brief summaries of their cases based on the dominant elements identified, using this new insight to generate dimensions of each element (i.e., specific variables) that might represent finer grain features necessary to more robustly answer the question guiding the element. For example, the element of *problem framing* is guided by the question: How is the drought problem framed? To answer this question for a particular case, users would need to emphasize several dimensions: *issue focus* for decision making; the *temporal* and *spatial scale* to speak to the relative scope of a problem; the *type of drought* considered by participants; the extent to which *drivers and/or impacts* shaped understanding of the challenge to be solved; and whether or not the approach was from a *proactive or reactive* point of view. While other candidate dimensions were identified for each element, those described in Section III were identified commonly across cases where that element was most salient - and thus potentially generalizable. Dimensions of each element were iteratively revised based on group feedback and revisiting the data, with particular attention to whether dimensions were discrete categories or varied by degrees along a continuous spectrum. Finally, we tested the typology as a whole by applying it to each case and considering what we learned that was new or surprising. We summarize this analysis for five of the cases in the Supplemental Material (Supplemental Material, Testing the Typology).

3. Typology

In this section we present the four elements of a typology for decision making related to drought preparedness and response (Fig. 2). The first element focuses on how decision makers frame the problem of drought. The second element describes the actor(s) (individual or organizational) who make decisions, including dimensions of formal and informal power, as well as exclusion. The third element describes the actual choices made or actions taken. The fourth element describes how a given decision interacts with the decisions or actions of other actors.

For each element, we provide an explanation, a brief summary of relevant literature, and three to six key dimensions (Tables 1–4). These dimensions represent a simplified framework within each element for characterizing drought decision making based on a select, though necessarily incomplete, list of variables that provide a deeper understanding of drought decisions. The dimensions are presented in the form of a table that includes a description and brief example from our synthesized cases for each dimension. We also specify whether each dimension is a discrete or continuous variable. More detail about the cases from which the examples are drawn appears in the Supplemental Material and/or in the referenced publications.

3.1. Element 1: how is the drought problem framed?

Problem framing is the first element of the typology. Problem frames shape how individuals perceive issues and what they identify as problematic (Schön and Rein, 1994). A frame can be described as a "lens through which we perceive risks" — a way of approaching an event and understanding its consequences (Elliott, 2003, p. 215). Such lenses represent the attitudes and beliefs of decision makers (Schön and Rein, 1994). How drought is conceptualized, or framed, determines which aspects of the problem are addressed, where managers seek relevant knowledge, and which solutions are considered pertinent (Hisschemöller and Hoppe, 1995). Thus, the first element of the typology asks how the challenge of drought is understood by those responsible for addressing it and how it is understood by others who have an interest or "stake" in drought management (i.e., stakeholders). Is drought viewed as the primary issue, or does it emerge as an indirect consideration while addressing another problem, such as water supply or ecosystem restoration? How do managers define and operationalize their goals – as drought preparedness and/or drought response, or as another kind of challenge entirely? Is drought a short-term water availability challenge (i.e., the inverse of flood management)? Or, is it viewed as a part of longer-term phenomena (i.e., as a manifestation of climate change)? This element also encompasses questions of how drought is defined and what successful drought management looks like in a given setting.

Problem framing is intimately linked to problem definition. Schon and Rein (1994, p. 29) clarify the connection between problem framing and defining – or "formulating" – problems: "[Actors'] problem formulations and preferred solutions are grounded in different problem-setting stories rooted in different frames." Scholars disagree on what exactly constitutes a "problem," yet common definitions point to a "gap" (Hoppe, 2002), "substantial discrepancy" (Dery, 1984), or

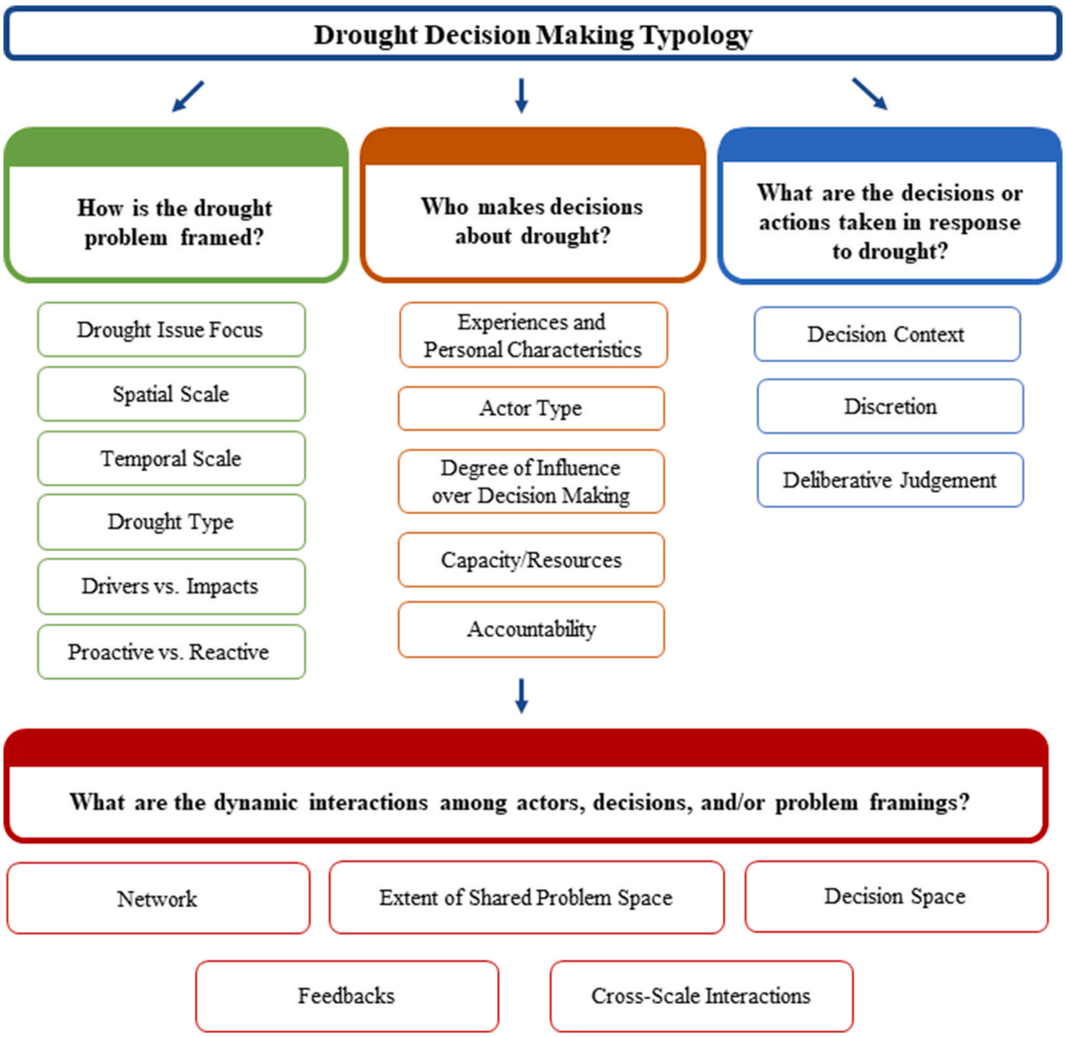

Fig. 2. Elements and dimensions of the typology for decision making related to drought preparedness and response.

"mis-match" (Woolley and Pidd, 1981) between current undesirable conditions and future desirable conditions. Broadly defining a problem as a discrepancy highlights the relative nature of problem definition since individuals have different ideas of what is or is not desirable (Hisschemöller and Hoppe, 1995). We use the word "problem" in reference to drought to emphasize the frequent mismatch between undesirable conditions during a drought and more desirable future conditions after drought recovery. Importantly, how someone frames and subsequently defines a problem influences how they will respond to it. Dery (1984, p. 17) observes that "problems may be defined in a number of ways, which will lead to entirely different solutions." How various problems and solutions are perceived shapes the type of management and policy solutions adopted (Elliott, 2003; Hisschemöller and Hoppe, 1995). For example, managers with different job roles may frame the causes and impacts of drought as more human-centered, more ecology-centered, or a combination of both (Case 2: Upper Missouri Headwaters; Cravens et al., 2021). The way someone frames drought can influence their approach to drought preparedness and affect which areas of impact receive greater attention and resources in drought planning and mitigation efforts (Cravens et al., 2021).

Understanding the dimensions of problem framing (Table 1) begins with assessing the presence or absence of drought as the *issue focus* for decision making. Whether conceived as a drought challenge or not, the *temporal* and *spatial scale* delineate the relative scope of a problem. Some framings focus on addressing a problem of limited spatial scale (e.g., providing water to a single municipality) or over a short time scale (e.g., ensuring that ranchers receive emergency forage relief this summer), while other frames concern relatively large spatial scales (e.g., river basins or states or regions) or a relatively long time scale (e.g., addressing water supply for the next twenty years). Which *type of drought* is being considered and the extent to which *drivers and/or impacts* are emphasized similarly shape understanding of the challenge to be solved. Finally, drought may be approached from a *proactive or reactive* point of view.

3.2. Element 2: who makes decisions about drought?

The second element of the typology describes the individual and institutional actors whose choices determine what is done regarding drought (Table 2). Decision makers may perceive and act upon the same climatological, hydrological, and ecological impacts of drought in different ways. Additionally, drought decisions are shaped by the characteristics and positions of individuals and groups of decision makers, requiring the recognition that various social structures and norms shape decision making. This second typology element concerns the concept of agency, or the "capacity of individual and corporate actors, with the diverse cultural meanings that they espouse, to play an independent causal role in history" (McLaughlin and Dietz, 2008, p. 105). Plummer and Armitage (2010) argue for an approach to understanding decision making that considers how people and groups of people both shape and are shaped by larger socio-cultural forces, and how actors' cognitive, emotional, and social experiences influence decision making. Individual decision makers

Table 1
Dimensions of the Problem Framing Element. The attributes column describes each dimension in greater detail. Attributes that represent discrete variables are separated by a comma while those that lie along a continuous spectrum are denoted with a dash. The final column provides an example from one of the synthesized cases to illustrate the dimension.

Dimension	Dimension Attributes	Example from a Case
Drought Issue Focus *Is drought the primary reason for the decision, or does it emerge as a secondary consideration while solving another problem, such as water supply, water quality, or ecosystem restoration?*	Primary, Secondary	The Montana State Water Plan and Montana Department of Natural Resources and Conservation have expressed interest in beaver mimicry and riparian restoration projects that promote groundwater recharge as a form of nature-based water storage solutions. While these projects can be beneficial in times of drought, discussions about natural water storage in Montana are primarily focused on the retention of high spring flows, groundwater recharge, and supporting late season streamflows in normal years or to offset changes in return flows due to changes in irrigation systems (Case 2: Upper Missouri Headwaters).
Spatial Scale *At which spatial scale is the problem understood?*	Local – Regional – National – International	The state of Oklahoma, facing the impacts of the catastrophic 2011–2013 drought, had to deal with the consequences of a patchwork of ways of framing drought, particularly given the dramatic east-west precipitation gradient that creates uneven drought impacts and vulnerabilities across the state. This drought demonstrated how the Oklahoma City Metro Area (pop. ~1.4 million) perceived drought as a long-term, "urban growth" problem, and how they approached "sustainability" via the purchase of water rights from the economically poor, but still water dependent, southeast of the state. Resilience, for the Metro Area, would come via water transfer rather than increased water-use efficiency or sustainably living within their water limits (Case 10: Oklahoma).
Temporal Scale *Is drought in this setting framed as a short-term problem (e.g., seasonal variability) or is it viewed as part of a longer phenomenon, i.e. as an intermediate manifestation of longer-term climate change?*	Short-term – Long-term	Some ranchers frame drought as a periodic occurrence while others think in terms of its impact on long-term outcomes and using drought response to enhance the resilience of grasslands and their operations. (Haigh and Knutson, 2013; Case 1: Great Plains).
Drought Type (Perspectives) *Which of the classic "types" of drought* (Wilhite and Glantz, 1985; Crausbay et al., 2017) *are part of the problem as it is understood in this context?*	Meteorological, Agricultural, Hydrological, Socioeconomic, Ecological	Water, rangeland, and non-rangeland land managers in the Upper Colorado River Basin use different indicators to understand the types of drought they are interested in (hydrological/meteorological, agricultural, and ecological, respectively) (Cravens, 2018; Case 7: Upper Colorado River Basin).
Drivers vs. Impacts *To what extent is drought understood by its causes versus its impacts?* (Redmond, 2002)	Drivers, Impacts	In the Rio Grande/Bravo basin, drought problem framings reflect two different — often contradictory — understandings of the drivers of drought: 1) physical systems as drivers impacting humans and ecosystems or 2) humans as drivers impacting physical systems and ecosystems (Koch et al., 2019; Case 9: Rio Grande Basin).
Proactive vs. Reactive *Is drought being addressed proactively before it occurs or reactively after it happens?*	Drought Response/Crisis Management, Drought Preparedness/Risk Management	Rangeland drought plans may focus heavily on working through bureaucratic permits and adapting facilities or water infrastructure, which must be started long before drought starts (Hawkes et al., 2018; Brugger et al., 2018). Or, plans may focus on the actions to be taken (e.g., destocking herds) once drought begins (Haigh and Knutson, 2013; Case 6: Ranch Decision Making in the Western United States).

operate within and across multiple institutions at various levels of governance and decision-making authority. To understand an individual's choices, then, it is also necessary to know something about their institutional position(s).

The *experiences and personal characteristics* dimension recognizes that actors are individuals, with unique personalities and life experiences they bring to bear on drought perceptions and choices. Decisions are made by multiple *actor types*, from individuals to families to collective organizations, such as an irrigation district or government agency. This dimension defines actors according to where they sit on a continuous spectrum between being an "individual-actor" and being part of a "collective-of-actors."

The *degree of influence over decision making* dimension describes the formal and informal power, responsibility, and/or agency that an actor (whether individual or collective) holds to determine drought preparedness or response actions. Notably, information providers, or other actors who lack official authority for a decision may provide analytical support or apply political pressure to decision makers. Influence occurs on a continuous spectrum from significant influence, where a decision is self-directed and has a notable impact on the broader system, to little or no influence, where an action is determined, for instance, by institutional rules or legal constraints. We draw on Giddens' (1984) work on structuration (and its foundations in the work of Pierre Bourdieu) in defining what counts as a "decision" among actors taken in response to drought. We argue that an actor's decisions can be understood as a function of structuring forces that constrain and guide the actions taken – organizational rules and cultural norms, legal constraints on what actions can or cannot be taken, drought plans that trigger "automatic" actions after reaching some threshold, etc. – as well as the agency of an individual who navigates a number of possible ways of fulfilling, circumventing, or even resisting these structuring forces (Gersick, 1991; Horan et al., 2011). Characterizing the real agency of an actor involved in drought decision making is critical because it can reveal the differences, for instance, between a federal agency deciding not to allow grazing on lands recovering from a multi-year drought and individual

Table 2
Dimensions of the Actor Element. The attributes column describes each dimension in greater detail. Attributes that represent discrete variables are separated by a comma while those that lie along a continuous spectrum are denoted with a dash. The final column provides an example from one of the synthesized cases to illustrate the dimension.

Dimension	Dimension Attributes	Example from a Case
Experiences and Personal Characteristics[a] *What aspects of individuals' backgrounds and personalities influence how they respond in the face of drought?*[a]	Experiences, Education, Social Networks, Values, Culture, Norms & Beliefs, Social Position/Identity	Cattle ranchers from different backgrounds, with various responsibilities, gender roles, and skills, and with different life histories, negotiate and navigate social, economic and ecological complexities of drought in diverse ways to sustain livestock operations on rangelands (Case 6: Ranch Decision Making in the Western United States).
Actor Type *Is an individual or a collective entity (e.g. an agency, an irrigation district) making the decision?*	Individual – Collective	In the Rio Grande/Bravo basin, actors range from individual farmers making decisions about their own properties and businesses, to entities making decisions on behalf of larger collectives (e.g., tribal, state, county, or municipal water managers and regional irrigation districts), to groups of decision-makers that form among individual actors or entities around temporary or specific objectives (e.g., senior water rights holders acting together to bring a legal case against the state regarding water adjudication) (Case 9: Rio Grande Basin).
Degree of Influence over Decision Making *To what degree are actors able to influence or enact decision-making?*	Little Influence – Much Influence	The San Luis Valley of Colorado is required to recharge over-extracted groundwater reserves by 2030. Under state rules, groundwater-pumping irrigators and municipalities must have state-approved plans in place to replace or retire groundwater withdrawals and reduce injury to senior surface water rights holders affected by groundwater depletion. Fearing that the state would impose one-size-fits-all rules on local irrigators to meet these goals, innovative subdistricts of the existing Rio Grande Water Conservation District were formed that allow local formulation of water management plans to meet the goals and spread the costs and risks across large groups of hydrologically-linked landowners. These subdistricts create a new space for formal decision-making where there had previously only been informal influence by concerned irrigators and ditch organizations (Case 9: Rio Grande Basin).
Capacity/Resources *What resources do actors have to engage in decision making? (i.e., financial, political, social, other)*	Low Capacity/Few Resources – High Capacity/Many Resources	In the Red Rock Watershed in Montana, different types of landowners exhibited different levels of financial, political, and social capacity. For example, amenity ranchers (i.e., landowners who do not rely on ranching for their primary income) were more willing to work with governmental and non-governmental organizations and were more likely to have formal, proactive drought plans when compared to traditional ranchers (i.e., full-time ranchers whose income is generated primarily from their operation). No traditional ranchers in this study had a formal, proactive drought plan. The relative lack of financial resources was cited as a barrier for implementing stream restoration projects or new drought mitigation practices among traditional ranchers (Moore, 2018) (Case 4: Red Rock Watershed).
Accountability *To what extent are decision makers held responsible for consequences of their decisions?*	No Consequences of Decisions – All Consequences of Decisions	Ranchers applied for increased numbers of well augmentation plan permits during the 2002–2005 drought in Colorado, a process regulated by the State Engineer. After senior water rights holders took the State to Water Court to stop these permits and rescind others because of injury they claimed done to them, ranchers were left with little recourse for obtaining new sources of supplemental water. Accountability for negative impacts to junior water rights holders was murky. On the one hand, senior water rights holders upheld their legal rights, which absolved them of responsibility for impacts to more junior water rights holders. On the other, the State Engineer and the Water Courts were responsible for rescinding well augmentation plan permits, which directly created consequences for ranchers. Yet these agricultural producers could not hold these institutions responsible for damage to their livelihoods either. Consequences of well permit decisions were not borne by those responsible for the decision itself but externalized to others (Henderson et al., 2021; Case 8: Southeast Colorado).

[a] For literature on these concepts, please see Ajzen (1991); Crenshaw (1991); Hitlin and Piliavin (2004); Kimmerer (2013); Knutson et al. (2011); Marshall (2015); Roche (2016); Tornikoski and Maalaoui (2019); Wilmer and Fernández-Giménez (2015).

farmers or ranchers choosing management practices. In the first case, the agency official may be constrained by government rules about grazing thresholds based on vulnerability assessments of public lands. In the latter case, landowners have the capacity to weigh tradeoffs and make reasoned decisions in relation to their own needs (Case 6: Ranch Decision Making in the Western United States).

The *capacity/resources* dimension recognizes that formal decision-making authority or agency may mean little in practice if it is not accompanied by sufficient capacity, including social capital (Putnam, 2000) and material resources. Finally, the *accountability* dimension emphasizes that those who make decisions and those who bear the consequences of decisions may or may not be one and the same. A mismatch between decision making capacity and being accountable for the consequences of decision making can occur in multiple ways. For instance, elected officials, civil servants, and non-governmental actors may be distanced from the consequences of their votes, policy action, or programs.

3.3. Element 3: what are the decisions or actions taken in response to drought?

Many definitions of what counts as a "decision" within a public administration context (Campbell and Clarke, 2018) focus on whether the actor made a conscious choice between options (Eilon, 1971; Kalra et al., 2014) and if the decision involved a process of deliberative judgment (Coles, 2002; Jones and Preston, 2010; Kowalski-Trakofler et al., 2003).[3] These two factors help identify the actors who make actual decisions, regardless of job title. For instance, irrigators would be viewed as drought decision makers if they 1) make a choice, such as between planting higher value, drought-sensitive crops and lower value, drought-resistant crops, and 2) the choice is based on a judgment of possible costs and benefits given different drought scenarios, the nature of agricultural markets, and so on. On the other hand, though irrigation district managers might make certain decisions regarding the everyday upkeep, monitoring, and operations of resources, they might not have the legal or bureaucratic authority to ultimately make choices regarding the release of water to water rights holders. Such managers may be legally bound to release water according to rules and regulations (e.g., seniority, water sharing agreements) regardless of their own judgments about the nature of that water transfer or the ultimate use of that water (Case 9: Rio Grande Basin). These actors are critical in drought preparedness or response, but their actions to release water might not meet the criteria of a drought "decision" per our definition. Indeed, in interviews with water, land, and fire managers in the Upper Colorado River Basin, respondents distinguished between whether or not they considered themselves to be "managing for drought" based on perceived control over decision making (Case 7: Upper Colorado River Basin; Cravens, 2018).

Drought decision making is complicated by the fact that the onset of drought is often difficult to detect and delineated by often-incompatible definitions of drought (*Drought Assessment, Management, and Planning, 1993*; also see *type of drought* dimension in Element 1). Indeed, it is this quality of drought that can result in a distinct form of decision making — the wait-and-see decision (Avriel and Williams, 1970; Riebsame, 1990). Reflecting what has been called "deep uncertainty" (Kalra et al., 2014), wait-and-see decisions are not based on an "ideal" set of responsive linear decisions that assume discrete triggers for actions (e.g., drought thresholds), but, rather, approach complex decision making as a stochastic problem that responds to the incomplete information the decision maker possesses.

Three dimensions describe aspects of the decision element (Table 3). The *decision context* dimension describes the various political, legal, economic, and cultural factors beyond drought that constrain and guide decision formulation, decision making, and the actions that are or can be taken as a result of those decisions. The *discretion* dimension reflects whether the decision or action is based on selecting between a wide variety of alternative actions or a more limited scope of actions. This permits one to distinguish management actions that are selected from many possible outcomes from actions taken based on a formalized algorithm or pre-determined, quantitative threshold, such as that specified in a drought plan. The *deliberative judgment* dimension indicates the extent to which the choice between different actions is informed by an explicit balancing of costs and benefits, broadly defined (Coles, 2002). As such, it is important to distinguish deliberative judgment – the application of conscious "System II" mental reflection (Kahneman, 2011) – from decision making that relies on less explicit consideration of options. Importantly, we do not take a normative stance on whether more deliberative judgement results in better decisions; professional intuition using "System I" processes (Kahneman, 2011) and "rules of thumb" has been shown to be critically important in diverse professional fields from forecasting avalanche risk to weather forecasting to pilots flying airplanes (Klein, 2011; Statham et al., 2018). Rather, we emphasize the range of discretion and deliberative judgment that may be associated with different decisions, to better characterize the drought decision-making process.

3.4. Element 4: what are the dynamic interactions among actors, decisions, and/or problem framings?

As presented thus far, the typology offers a simplified picture of reality: one actor with their own understanding of a problem, making one decision. But the real world is much more complex, with the actions and perceptions of any given actor both determining and being determined by the actions and perceptions of many other actors. These interactions influence how multiple, often competing objectives are weighed and whether they are acted upon, thereby directing, constraining, and/or generating new action pathways. Thus, understanding the complexity of real-world drought decision making requires a way to categorize and analyze the many kinds of interactions that can exist between actors, problem framings, and/or decisions. The typology's fourth element (Table 4) recognizes the diversity of these interactions. This element points to the interdependence of "environmental, cognitive, social, economic, geographic, and political" factors (White et al., 2009, p. 290), as well as temporal and spatial dimensions, in affecting how drought-related decisions and outcomes interact. Focusing on interactions offers a way to account for the unanticipated consequences and cascading effects of drought decisions (Kinzig et al., 2006). Specifically, we see the concept of interaction as recursive — one that shapes not only a specific decision but also the contextual apparatus that accompanies the decision and its outcomes.

Social scientists have developed various theories to make sense of the complexity of interactions in society and policy making. Each of these theoretical approaches suggests a different lens, or dimension, of interactions to consider. We emphasize that there are certainly additional dimensions of interactions that we have not identified. However, the list presented here begins to illustrate how multiple actors making decisions about drought may influence one another, constrain one another's action, and ultimately interact according to a logic that can be analyzed and understood.

The *network* dimension describes interactions (or the lack thereof) between multiple actors within a system. At the conceptual level, networks emphasize the importance of the patterns connecting people or other objects in a system (Borgatti et al., 2009). As a method, social network analysis provides a formal way to characterize relationships between people, introducing concepts like centrality (number of links of an individual actor) (Freeman, 1979) and network density (Scott, 1988). Network theory also emphasizes how connections influence the movement of resources or information within a system. For instance, the shape and extent to which a network is connected influences how actors find out about drought early warning information (Case 7: Upper Colorado River Basin; Cravens, 2018), how water is shared in times of drought through voluntary mechanisms (McNeeley, 2014), and whether collective learning takes place (Gerlak and Heikkila, 2011).

The *extent of shared problem space* dimension describes the interaction between various actors' problem framings. Conflict resolution and consensus-building theory suggests that the extent to which people share an understanding of a problem is a significant factor influencing their ability to collectively address it, making the development of a shared problem framing a frequent goal in consensus-building efforts (Susskind et al., 1999). Consensus about problem definition forms one end of a continuous spectrum, with conflict forming the other end. In the middle, actors hold different problem frames that are not necessarily contradictory, but may not acknowledge other points of view, such as the way ecological impacts of drought are often left out of drought planning discussions (e.g., Case 2: Upper Missouri Headwaters; McEvoy et al., 2018). At the conflict end of the spectrum, multiple views of a problem directly conflict with one another, which means that either the problem framing of those with the most power will prevail or taking action will be difficult until the contradictions are addressed (Freeman,

[3] In public policy and conflict resolution, (public) deliberation refers to a collaborative or group process that fosters thoughtful consideration of issues (Majone 1988). Deliberative judgement as discussed here is a cognitive process. While the two share underlying ideas, they are distinct concepts.

Table 3
Dimensions of the Decisions Element. The attributes column describes each dimension in greater detail. Attributes that represent discrete variables are separated by a comma while those that lie along a continuous spectrum are denoted with a dash. The final column provides an example from one of the synthesized cases to illustrate the dimension.

Dimension	Dimension Attributes	Example from a Case
Decision Context		
What contextual factors constrain and/or guide the actions taken?	Political, Legal, Economic, Cultural	The Montana decision context is constrained by the rigidity of the legal framework (i.e., prior appropriation doctrine). However, cultural and economic factors such as a strong sense of place and the changing economics of water-dependent livelihoods (i.e., from lower-value agricultural production to higher-value guiding and outfitting for anglers and recreationists) also shape how decisions are made. The politics related to threatened and endangered aquatic species management are an additional concern that shapes the decision context for senior and junior water rights holders (Cravens et al., 2021; Case 2: Upper Missouri Headwaters).
Discretion		
How much scope for decision making and/or acting does an actor(s) possess?	Flexible Process and Alternatives – Limited Choices	Like other drought plans in surrounding watersheds, the Beaverhead Drought Plan relies on predefined triggers for action. However, this 2016 plan is distinct in that it integrates triggers not only from streamflow and temperature but also a range of other indicators (including forecasted water supply, reservoir storage, and information from the U.S. Drought Monitor). For example, if the forecasted water supply in the main reservoir for August drops below 50,000 acre feet, then irrigation allotments are incrementally reduced by predefined amounts. The use of predefined triggers is an example of a plan with limited choice. In contrast the Blackfoot Drought Response Plan encourages the drought committee to examine several factors, but notes that "When all factors are considered, it is possible for stream flows and water temperatures to exceed trigger levels without the Drought Response being implemented" indicating a more flexible process (McEvoy et al., 2018 pg. 12; Case 3: Beaverhead Drought Planning).
Deliberative Judgement		
Does the actor(s) make a conscious choice between options? Or is the actor(s) using professional intuition?	Explicit Consideration of Alternatives (System II) – Professional Intuition (System I)	Along the Rio Grande, the U.S. Bureau of Reclamation is required to contribute to releasing water from upstream reservoirs to downstream water rights holders. However, the USBR is also tasked with protecting a number of endangered species and other ecological resources and habitats. While USBR managers release water according to a number of established protocols after a water rights holder "calls" for water, they also apply deliberative judgment regarding when and how to release the water in order to minimize negative and maximize positive impacts to the natural systems associated with the river. These decisions are not established in fixed protocols but involve professional judgments about what they could and ought to do rather than simply what they are required to do (Case 9: Rio Grande Basin).

1979).

The third and fourth dimensions of interactions are *decision spaces* and *feedbacks*. Actors, whether individuals or collectives, rarely act in isolation. Interactions between multiple actors and actions are critical to understand how *decision spaces* are created, recreated, and change (Otto-Banaszak et al., 2011). Decision spaces can be thought of as configurations of people, institutions, and ideas that guide or constrain how actors think about and negotiate drought decisions. They can also reflect the interactions between multiple decision spaces (e.g., when one agency's actions constrain that of another agency; Horne & O'Donnell, 2014; Papasozomenou and Zikos, 2009). Within decision spaces, *feedbacks* between actors, decisions, and problem frames in turn impact any of these, as well as the nature of a decision space itself. Feedbacks may reflect the dynamics within one decision space (e.g., one way of framing drought problems leads to degradation of habitat for aquatic species, which, in turn, leads to a re-framing of drought problems) or the dynamics among multiple decision spaces (e.g., the interaction between a city addressing per capita water use over time and a state agency addressing drought during a declared state of emergency)(Case 9: Rio Grande Basin). This dimension also includes the dynamics that dampen or facilitate the capacity to prepare for and respond to drought that emerge from interactions between different actors (e.g., when a state's water laws limit the capacity of a local actor to enact a drought plan that would ensure greater resilience to drought, at the cost of local water rights) (Kallis et al., 2009).

The final two dimensions emphasize that actors and the problems they see or actions they take all interact across space and time, sometimes in unanticipated ways. *Cross-scale interactions* describe how differences in spatiotemporal scales and resolutions (e.g. community, river basin, and regional scales) can have differential effects on actors (Peters et al., 2007).[4] Scales of space and resolution generate dynamics as individual decisions intersect within larger institutional decisions elsewhere (e.g., how many landowners' choices affect a watershed) or as decisions made by one group upstream in a river basin impact those downstream. Over time, as various actors and their choices interact, surprising outcomes or unintended consequences may result in other spaces distant from the initial decision space(s) (Dilling et al., 2017). Multiple dynamics of scale and resolution may be ongoing, creating interactive effects and externalities for the system that are difficult to track or that generate challenges characterized as maladaptation (Barnett & O'Neill, 2010).

The *path dependence* dimension emphasizes that decisions rarely occur absent historical context. Path dependency reflects the resistance to change from a historical norm and is often conceptualized as a barrier to change (Barnett et al., 2015). Similarly, particular problem framings or decision spaces may be more or less persistent, reflecting the durability of existing institutions or ways of understanding; a classic example that appeared in multiple cases we synthesized is how the legal framework provided by the prior appropriation doctrine (Thompson et al.,

[4] Cross-scale interactions are variously discussed in socio-economic literatures, with emphasis on power dynamics and resources between scales of actors (e.g. institutions and individuals) (Adger et al., 2005), between social and ecological systems at different resolutions or granularity (Scholes et al., 2013), and between different scales of time and space (Peters et al., 2007) – and combinations of these types. Here, we focus on cross-scale interactions in terms of spatiotemporal scales.

Table 4
Dimensions of the Interactions Element. The attributes column describes each dimension in greater detail. Attributes that represent discrete variables are separated by a comma while those that lie along a continuous spectrum are denoted with a dash. The final column provides an example from one of the synthesized cases to illustrate the dimension.

Dimension	Dimension Attributes	Example from a Case
Network *What kind of relationships exist among actors? To what extent does the network support or inhibit the flow of information and resources among actors?*	Weak Connections – Strong Connections	Beaver mimicry involves components including scientific inquiry and monitoring and also applied, practical management objectives. As a result, two distinct networks of actors emerge in understanding how beaver mimicry impacts ecological drought in riparian ecosystems. The first, scientific researchers, are hesitant and apprehensive to draw conclusions without substantial and long term monitoring data. The second network, managers and practitioners, utilize anecdotal information and locally available resources to verify benefits to their resources of concern. Information flows through these two networks of actors are restricted by (1) perceived credibility of conclusive information, (2) socially accepted legitimacy of information application, and (3) local relevance of anticipated application outcomes (Case 5: Beaver Mimicry).
Extent of Shared Problem Space *Do actors have the same understanding of the problem? To what extent are actors' framings of the problem contradictory or threatening to other actors?*	Consensus – Multiple But Not Contradictory – Conflict	The threat of the Arctic grayling being listed under the Endangered Species Act provides a shared problem space that motivates irrigators and anglers to collaborate via "shared sacrifice agreements." Some of these agreements are outlined in formal Candidate Conservation Agreements with Assurances plans that specify proactive stream restoration or water conservation measures for irrigators. Other agreements are outlined in less formal watershed drought plans that establish streamflow and water temperature thresholds at which irrigators will voluntarily reduce withdrawals and anglers will restrict fishing hours and access (McEvoy et al., 2018; Case 2: Upper Missouri Headwaters).
Decision Space *How do one actor's decisions constrain or enable another actor's range of possible choices?*	Enables Others – Constrains Others	Agricultural producers' decisions to apply for well augmentation permits, which are junior rights in the state of Colorado, were limited by senior surface water rights holders' decisions to petition the State Engineer. Given the magnitude and scope of the 3-year drought, producers who were denied augmentation permits or had them rescinded were left with few alternatives to sustain their businesses. Constraints on decision making in the moment had longer term consequences, as evidenced by the ongoing struggle producers have had in regaining their well augmentation permits (Henderson et al 2021; Case 8: Southeast Colorado).
Feedbacks *How do interactions between actors, actions, and decision spaces create dynamics that reinforce or dampen the effects of drought decisions and actions?*	Reinforce – Dampen	Decisions to shift away from heavy groundwater dependence in Colorado due to the state's requirements to recharge overexploited groundwater resources has meant a maximization of Rio Grande surface water use, reinforcing and exacerbating pressures on surface water users in New Mexico. The latter have responded by increasing their dependence on and investment in importing water from the Colorado River basin via the San Juan-Rio Chama diversion (Case 9: Rio Grande Basin).
Cross-Scale Interactions *To what extent do actors, decisions, and decision spaces interact across time and space?*	Discrete Decisions – Interdependent Decisions	In the Upper Missouri Headwaters basin, there are numerous agencies operating at various institutional and spatial scales whose management actions affect water availability and drought resiliency within the watershed. In addition to laws, policies and administrative programs, there are 33 plans that pertain to the area, but not necessarily much coordination between different levels and types of planning (McEvoy et al., 2018; Case 2: Upper Missouri Headwaters).

2018) shapes and constrains drought response. Path dependence literature suggests that historical context and continual reinforcement of trajectories matter in how they constrain action (e.g., Barnett et al., 2015). Path dependencies may be tacit and difficult to articulate and trace in a system, as for example, traditional decision making regarding forest management fails to account for the linkages between wildfires and water. This was the case in northern New Mexico where the 2011 Las Conchas wildfires led to flash flooding and soil erosion that deposited massive debris into rivers and creeks, leading to flow from portions of the watershed being cut off from the mainstem of the Rio Grande (Case 9: Rio Grande Basin; Thompson et al., 2016; Tillery et al., 2011). Legacy (path dependent) forest management practices had not accounted for the linked impacts of wildfire and the river which, in turn, impacted the water available for managing drought conditions downstream (Dahm et al., 2015). At other times, paths are transparent and easily knowable. For example, prior appropriation's "first in time, first in right" provision protects a farmer's senior water rights when demands are high on a particular river but may constrain the options of those with junior rights (Case 8: Southeast Colorado). As this example suggests, it is important to identify how historical context influences who gains and who loses, or how vulnerability changes over time (Erfurt et al., 2019).

4. Discussion and conclusions

Our typology asks four questions that together explain the key facets of drought decision making: *How is the drought problem framed? Who makes decisions about drought? What are the decisions or actions taken in response to drought? What are the dynamic interactions among actors, decisions, and/or problem framings?* Each element comprises multiple dimensions, providing sub-questions and specific variables to understand the nuances of that element (Tables 1–4). By unpacking the complexity of drought management, the typology permits drought managers, program and research funders, and natural and social scientists to assess the contours of a system and analyze how decisions to prepare for or respond to drought are made in specific contexts. In Table 5, we provide an example of the way the typology may be used to describe a particular drought management situation: junior water rights holders in Southeast Colorado responding to drought. In the Supplemental Material, there is a narrative description of the research from Case 8 summarized in Table 5. Comparing these two illustrates the way the typology simplifies a complex reality into discrete categories. Applying this typology allows one to avoid conflating water management with the greater complexity that is necessary to understand drought management as a system-level challenge. Greater system-level understanding facilitates a more robust mental model of the overlapping problem spaces, actors, and decisions that interact to comprise drought management.

Applying each element of the typology has the potential to yield distinct insights. Element 1 (problem framing) emphasizes that drought management approaches depend on how decision makers understand the challenge they are facing. Explicitly asking how different actors understand the problem may reveal shared or divergent assumptions as well as help decision makers resolve conflicts over planning or strategy development. Element 2 (actors) can reveal more nuanced understanding of decision maker and stakeholder backgrounds, experiences, and positions within the system, highlighting similarities and differences between types of drought managers. This element also reminds typology users that multiple types of actors make drought decisions in the same place. For instance, a researcher might focus on decisions made by individual ranchers, but the typology calls attention to how institutional decision making can be important in understanding individual actions. Element 3 offers two perspectives on decision making. Consideration of decision context appears in almost all relevant social science studies (a structural view of decision making); we add that explicitly analyzing where and how deliberative choice is exercised (a psychological view accounting for actor agency) increases ability to understand how context influences decision making. Element 4 (interactions) provides a way to address drought risk by parsing social and institutional complexity.

Together, the typology's four dimensions inform numerous planning and management processes. As a means of exploring social and institutional aspects of drought decision-making, the typology has immediate relevance for water, fire, and land managers; scientists; program and research funders; and communities seeking to more holistically and effectively understand and address drought management challenges. These users can apply the four guiding questions, with dimensions under each, to structure workshops, empirical social science research, or collaborative processes for a range of planning or management purposes. This may be of particular utility when managers or researchers are tasked with initiating collaborative planning in complex social settings, and when social or ecological relationships are changing rapidly. The typology offers a clear structure for guided inquiry, though the elements can be used in any order. For instance, a drought planner might have a fairly clear idea of the actors involved in preparing for drought in a watershed, so beginning with Element 2, actors, might help them identify underrepresented interests.

The outcome of this guided inquiry is greater system-level understanding, which facilitates a more robust mental model of the overlapping problem spaces, actors, and decisions that interact to comprise drought management. While improved mental models have broad relevance, use of the typology will likely play out differently for decision makers, funders, and scientists. For decision makers – whether water, fire or land managers, landowners, watershed groups, or others – greater understanding of one's place in the system translates into more effective action by revealing constraints, opportunities, and leverage points. The typology reveals dynamics of scale, context, and agency that may help decision makers identify sites of intervention for future drought. Understanding one's relationship to other actors in a system, for example, might reveal the limits of one's influence, or how a proposed alternative could magnify (good and bad) impacts on others. This greater understanding may be especially important for drought response in a crisis, when one must act from existing knowledge. For funding agencies and scientists, viewing drought management holistically can highlight gaps in scientific knowledge or program investments. For physical scientists, in particular, a mental model informed by the typology likely includes elements of people and society not present in their preexisting mental framework. Social scientists can use the typology as a tool in research design as a source of questions or variables to investigate.

A mental model of drought decision making that better reflects the complexities of actual practice provides four benefits. First, it provides users more holistic knowledge of possible constraints and opportunities that arise as one decision influences another. For an individual rangeland manager, for instance, a workshop using the typology might further understanding of the range of state and federal agencies providing drought information and resources.

Second, descriptive analysis of a past drought can illuminate current regimes of governance and possible interventions that might help decision makers avoid past mistakes, as well as anticipate or minimize tradeoffs, cascading effects, and unintended future consequences (Pahl-Wostl, 2009). By presenting a framework that is agnostic of time, the typology can be used to analyze longitudinal system changes, make comparisons across cases, and develop historical or contextual analogies. Such analog examples can then be compared to current conditions to guide ongoing decision making (Wilke and Morton, 2017), such as where new programs or policies are being introduced.

Third, placing decisions that both intentionally and unintentionally affect ecosystems and species into the same conceptual framework as agricultural and water supply actions helps illuminate whether and how ecological effects of drought (Crausbay et al., 2017) are accounted for in drought preparedness and response. Thus, using the typology can help planners, researchers, and funders identify the roles played by natural resource management in drought preparedness and response in a given system. This is a fruitful area for future research, as recognition of connections between drought and other natural resource decisions can lead to identifying previously unrecognized elements.

Finally, use of the typology, particularly in collaborative settings, has the potential to create a new shared mental model of drought for actors that enables both individual and social learning (Reed et al., 2010; Henderson et al., 2021), facilitating problem-solving from common starting points, as well as more sophisticated approaches to compromise (Cravens and Ardoin, 2016). For example, when scientists and practitioners share knowledge about their priorities and the barriers they face, an emerging drought management challenge such as "flash drought" will be better understood. Greater overall awareness of the wider system in which each is operating facilitates this collaborative learning process.

While typologies can aid thinking about system-level processes, no single framework can capture every salient feature, and all have limitations. As a descriptive typology, ours does not offer the causal explanation one would find in an explanatory typology; we consider this the next step for future research. Typologies are meant to simplify, yet simplification can overly constrain thinking and omit critical features (Bowker and Star, 2000). Our typology does not necessarily capture how decision makers' choices are influenced by other, often implicit social forces outside natural resource management, such as politics or markets. In developing a parsimonious typology, we made sometimes difficult decisions about which elements to highlight and exclude. Despite these limitations, we believe the typology offers a compelling framework to understand the most important factors shaping how and why drought-related decisions are made.

Our research is based in the western United States, a coherent ecoregion where aridity is an important factor, and one that shares many social and legal patterns (Jones et al., 2019). Despite the regional specificity of our research projects, our guiding goal in creating this typology was to provide a foundation for a methodology for generating typologies of drought decision making at multiple scales, within and across socio-cultural systems and hydrological, meteorological, or climatic environments. To use this methodology in that way, one would

Table 5
Illustration of applying the typology to summarize the decision-making experience of junior water rights holders in Case 8: Southeast Colorado. For more detail about this case, see the Supplemental Material.

Typology Dimension	Summary for Case 8: Southeast Colorado
Element 1: Problem Framing	
Drought Issue Focus	primary
Spatial Scale	regional
Temporal Scale	short term
Drought Type	all
Drivers vs. Impacts	impacts
Proactive vs. Reactive	reactive
Element 2: Who Made Decisions	
Experience or Personal Characteristics	not collected in this case
Actor Type	individual
Degree of Influence	little influence
Capacity/Resources	few resources
Accountability	some consequences
Element 3: Decisions in Response	
Decision Context	legal
Discretion	limited choices
Deliberative Judgement	explicit consideration of alternatives
Element 4: Dynamic Interactions	
Network	medium connections among individual ranchers
Extent of Shared Problem Space	consensus on problem (water scarcity)
Decision Space	impacts of decisions could threaten and/or constrain others' actions
Feedbacks	reinforcing
Cross-scale Interactions	interdependent

begin by answering the four questions posed in the elements above — *How is the drought problem framed? Who makes decisions about drought? What are the decisions or actions taken in response to drought? What are the dynamic interactions among actors, decisions, and/or problem framings?* The dimensions included within each of these broad questions permit one to give "local life" to the drought management systems and the socio-environmental systems that shape the local or regional context of systems under study. Quantifying and qualifying these dimensions ensures an understanding of discrete, place-based cases more reflective of the complexity involved in managing a drought. As such, the four core questions and their discrete dimensions are potentially globally relevant because they are built on a method of interpretation for generating a useable drought management typology. Regardless, we do not see this typology as exhaustive, but, rather, as a starting point. We invite others in the emerging field of drought social science to add to this typology based on their local experiences and regional research findings.

Funding sources

The workshops were funded by the U.S. Geological Survey North Central Climate Adaptation Science Center and National Climate Adaptation Science Center.

CRediT authorship contribution statement

Amanda E. Cravens: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Project administration. **Jen Henderson:** Methodology, Investigation, Writing – original draft, Writing – review & editing. **Jack Friedman:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Nina Burkardt:** Conceptualization, Methodology, Writing – original draft, Project administration. **Ashley E. Cooper:** Investigation, Writing – review & editing. **Tonya Haigh:** Methodology, Investigation, Writing – review & editing. **Michael Hayes:** Methodology, Investigation, Writing – review & editing. **Jamie McEvoy:** Conceptualization, Investigation, Writing – review & editing. **Stephanie Paladino:** Methodology, Investigation, Writing – review & editing. **Adam K. Wilke:** Methodology, Investigation. **Hailey Wilmer:** Methodology, Investigation, Writing – review & editing.

Declaration of competing interest

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

Acknowledgements

This typology was inspired and informed by discussions at the September 2016 Actionable Science Ecological Drought Workshop and June 2018 Drought Social Science Synthesis Workshop held at the U.S. Geological Survey's (USGS) Fort Collins Science Center. Thank you to attendees of both workshops for your enthusiastic participation and sharing of your insights in those early discussions, including Aparna Bamzai-Dodson (USGS), Tyler Beeton (Colorado State University), John Berggren (University of Colorado), Shawn Carter (USGS), Shelley Crausbay (Conservation Science Partners), Trevor Even (Colorado State University), Jill Lackett (Colorado State University), Shannon McNeeley (Colorado State University), Alison Meadow (University of Arizona), Lindsey Middleton (Colorado State University), Jeff Morisette (USGS), Dennis Ojima (Colorado State University), Robin O'Malley (USGS), Rachel Owen (University of Missouri, Columbia), Madeleine Rubenstein (USGS), Rudy Schuster (USGS) and Trisha Shrum (University of Vermont). We are grateful to Julia Goolsby for creating Figs. 1 and 2 and helping prepare the manuscript and citations and to Rebecca Nelson, Anne Siders, Aparna Bamzai-Dodson, Alisa Wade, and Mike Langston for reviews of earlier versions of this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wace.2021.100362.

References

Adger, W.N., 2006. Vulnerability. Global Environ. Change 16 (3), 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006.

Adger, W.N., Brown, K., Tompkins, E.L., 2005. The political economy of cross-scale networks in resource Co-management. Ecol. Soc. 10 (2) https://doi.org/10.5751/ES-01465-100209 art9.

Ajzen, I., 1991. The theory of planned behavior. Organ. Behav. Hum. Decis. Process. 50 (2), 179–211. https://doi.org/10.1016/0749-5978(91)90020-T (Theories of Cognitive Self-Regulation.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S.W., Semerci, A., Cobb, N., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manag. 259 (4), 660–684. https://doi.org/10.1016/j.foreco.2009.09.001 (Adaptation of Forests and Forest Management to Changing Climate.

Antwi-Agyei, P., Fraser, E.D.G., Dougill, A.J., Stringer, L.C., Simelton, E., 2012. Mapping the vulnerability of crop production to drought in Ghana using rainfall, yield and socioeconomic data. Appl. Geogr. 32 (2), 324–334. https://doi.org/10.1016/j.apgeog.2011.06.010.

Avriel, M., Williams, A.C., 1970. The value of information and stochastic programming. Oper. Res. 18 (5), 947–954. https://doi.org/10.1287/opre.18.5.947.

Ayres, L., Knafl, K.A., 2008. Typological analysis. In: The SAGE Encyclopedia of Qualitative Research Methods. SAGE Publications, Inc, p. 901, 901. http://sk.sagepub.com/reference/research/n472.xml.

Banerjee, O., Bark, R., Connor, J., Crossman, N.D., 2013. An ecosystem services approach to estimating economic losses associated with drought. Ecol. Econ. 91, 19–27. https://doi.org/10.1016/j.ecolecon.2013.03.022.

Barnett, J., Evans, L.S., Gross, C., Kiem, A.S., Kingsford, R.T., Palutikof, J.P., Pickering, C.M., Smithers, S.G., 2015. From barriers to limits to climate change adaptation: path dependency and the speed of change. Ecol. Soc. 20 (3) https://doi.org/10.5751/ES-07698-200305 art5.

Barnett, J., O'Neill, S., 2010. Maladaptation. Global Environ. Change 20 (2), 211–213. https://doi.org/10.1016/j.gloenvcha.2009.11.004.
Becker, S., Sparks, P., 2020. "It never rains in California": constructions of drought as a natural and social phenomenon. Weather Clim. Extrem. 100257. https://doi.org/10.1016/j.wace.2020.100257.
Biagini, B., Bierbaum, R., Stults, M., Dobardzic, S., McNeeley, S.M., 2014. A Typology of adaptation actions: a global look at climate actions financed through the Global Environment Facility. Global Environ. Change 25, 97–108. https://doi.org/10.1016/j.gloenvcha.2014.01.003.
Borgatti, S.P., Mehra, A., Brass, D.J., Labianca, G., 2009. Network analysis in the social sciences. Science 323 (5916), 892–895. https://doi.org/10.1126/science.1165821.
Bowker, G.C., Star, S.L., 2000. Sorting Things Out: Classification and its Consequences. MIT Press.
Brugger, J., Hawkes, K.L., Bowen, A.M., McClaran, M.P., 2018. Framework for a collaborative process to increase preparation for drought on U.S. public rangelands. Ecol. Soc. 23 (4) https://doi.org/10.2307/26796891.
Campbell, L., Clarke, P.K., 2018. Making Operational Decisions in Humanitarian Response: A Literature Review. https://doi.org/10.13140/rg.2.2.22634.82883.
Coles, C., 2002. Developing professional judgment. J. Continuing Educ. Health Prof. 22 (1), 3–10. https://doi.org/10.1002/chp.1340220102.
Collier, D., Laporte, J., Seawright, J., 2008. In: Box-Steffensmeier, J.M., Brady, H.E., Collier, D. (Eds.), Typologies: Forming Concepts and Creating Categorical Variables, vol. 1. Oxford University Press. http://oxfordhandbooks.com/view/10.1093/oxfordhb/9780199286546.001.0001/oxfordhb-9780199286546-e-7.
Collier, D., LaPorte, J., Seawright, J., 2012. Putting typologies to work: concept formation, measurement, and analytic rigor. Polit. Res. Q. 65 (1), 217–232. https://doi.org/10.1177/1065912912437162.
Cook, B.I., Cook, E.R., Smerdon, J.E., Seager, R., Williams, A.P., Coats, S., Stahle, D.W., Díaz, J.V., 2016. North American megadroughts in the common era: reconstructions and simulations: North American megadroughts in the common era. Wiley Interdis. Rev.: Clim. Chang. 7 (3), 411–432. https://doi.org/10.1002/wcc.394.
Crausbay, S.D., Ramirez, A.R., Carter, S.L., Cross, M.S., Hall, K.R., Bathke, D.J., Betancourt, J.L., Colt, S., Cravens, A.E., Dalton, M.S., Dunham, J.B., Hay, L.E., Hayes, M.J., McEvoy, J., McNutt, C.A., Moritz, M.A., Nislow, K.H., Raheem, N., Sanford, T., 2017. Defining ecological drought for the twenty-first century. Bull. Am. Meteorol. Soc. 98 (12), 2543–2550. https://doi.org/10.1175/BAMS-D-16-0292.1.
Cravens, A.E., 2018. How and why upper Colorado river basin land, water, and fire managers Choose to use drought tools (or not) [U.S. Geological Survey open file report](2018–1173). https://doi.org/10.3133/ofr20181173.
Cravens, A.E., Ardoin, N.M., 2016. Negotiating credibility and legitimacy in the shadow of an authoritative data source. Ecol. Soc. 21 (4), 14. https://doi.org/10.5751/ES-08849-210430.
Cravens, A.E., McEvoy, J., Zoanni, D., Crausbay, S.D., Ramirez, A., Cooper, A.E., 2021. Integrating ecological impacts: perspectives of drought in the upper Missouri river Headwaters, Montana, USA. Weather Clim. Soc. 13 (2), 363–376.
Crenshaw, K., 1991. Mapping the margins: intersectionality, identity politics, and violence against women of color. Stanford Law Rev. 43 (6), 1241. https://doi.org/10.2307/1229039.
Dahm, C.N., Candelaria-Ley, R.I., Reale, C.S., Reale, J.K., Van Horn, D.J., 2015. Extreme water quality degradation following a catastrophic forest fire. Freshw. Biol. 60 (12), 2584–2599.
de la Barrera, F., Barraza, F., Favier, P., Ruiz, V., Quense, J., 2018. Megafires in Chile 2017: monitoring multiscale environmental impacts of burned ecosystems. Sci. Total Environ. 637–638, 1526–1536. https://doi.org/10.1016/j.scitotenv.2018.05.119.
Dennison, P.E., Brewer, S.C., Arnold, J.D., Moritz, M.A., 2014. Large wildfire trends in the western United States, 1984–2011. Geophys. Res. Lett. 41 (8), 2928–2933.
Dery, D., 1984. Problem Definition in Policy Analysis. University of Kansas Press. https://journals.sagepub.com/doi/abs/10.1177/109821408600700308.
Dettinger, M., Udall, B., Georgakakos, A., 2015. Western water and climate change. Ecol. Appl. 25 (8), 2069–2093. https://doi.org/10.1890/15-0938.1@10.1002/(ISSN)1939-5582.ApplicationsCentennialPapers.
Dilling, L., Morss, R., Wilhelmi, O., 2017. Learning to expect surprise: hurricanes harvey, irma, maria, and beyond. J. Extrem. Events 4 (3), 1771001. https://doi.org/10.1142/S2345737617710014.
Drought Assessment, 1993. In: Wilhite, D.A. (Ed.), Management, and Planning: Theory and Case Studies: Theory and Case Studies. Springer US. https://www.springer.com/gp/book/9780792393375.
Dunham, J.B., Angermeier, P.L., Crausbay, S.D., Cravens, A.E., Gosnell, H., McEvoy, J., Moritz, M.A., Raheem, N., Sanford, T., 2018. Rivers are social–ecological systems: time to integrate human dimensions into riverscape ecology and management. Wiley Interdis. Rev.: Water 5 (4), e1291. https://doi.org/10.1002/wat2.1291.
Eilon, S., 1971. What is a Decision? In: Eilon, S. (Ed.), Management Control. Macmillan Education UK, pp. 135–162. https://doi.org/10.1007/978-1-349-01281-7_7.
Eisenack, K., Stecker, R., 2012. A framework for analyzing climate change adaptations as actions. Mitig. Adapt. Strategies Glob. Change 17 (3), 243–260. https://doi.org/10.1007/s11027-011-9323-9.
Elliott, M., 2003. Risk perception frames in environmental decision making. Environ. Pract. 5 (3), 214–222. https://doi.org/10.1017/S1466046603035609.
Erfurt, M., Glaser, R., Blauhut, V., 2019. Changing impacts and societal responses to drought in southwestern Germany since 1800. Reg. Environ. Change 19 (8), 2311–2323. https://doi.org/10.1007/s10113-019-01522-7.
Freeman, L.C., 1979. Centrality in social networks: conceptual clarification. Soc. Network. 2 (2), 215–239. https://doi.org/10.1016/0378-8733(79)90002-9.
Gerlak, A.K., Heikkila, T., 2011. Building a theory of learning in collaboratives: evidence from the everglades restoration program. J. Publ. Adm. Res. Theor. 21 (4), 619–644. https://doi.org/10.1093/jopart/muq089.
Gersick, C.J.G., 1991. Revolutionary change theories: a multilevel exploration of the punctuated equilibrium paradigm. Acad. Manag. Rev. 16 (1), 10. https://doi.org/10.2307/258605.
Giddens, A., 1984. In: The Constitution of Society: Outline of the Theory of Structuration. University of California Press. https://www.ucpress.edu/book/9780520057289/the-constitution-of-society.
Gosnell, H., Haggerty, J.H., Travis, W.R., 2006. Ranchland ownership change in the greater yellowstone ecosystem, 1990–2001: implications for conservation. Soc. Nat. Resour. 19 (8), 743–758. https://doi.org/10.1080/08941920600801181.
Gutiérrez, A.P.A., Engle, N.L., De Nys, E., Molejón, C., Martins, E.S., 2014. Drought preparedness in Brazil. Weather Clim. Extrem. 3, 95–106. https://doi.org/10.1016/j.wace.2013.12.001.
Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z.D., Wada, Y., Wisser, D., 2014. Global water resources affected by human interventions and climate change. Proc. Natl. Acad. Sci. Unit. States Am. 111 (9), 3251–3256. https://doi.org/10.1073/pnas.1222475110.
Haigh, T., Knutson, C., 2013. Roles of perceived control and planning in ranch drought preparedness. Great Plains Res. 23, 51–58.
Hawkes, K., McClaran, M.P., Brugger, B., Crimmins, M.A., Howery, L.D., Ruyle, G.B., Sprinkle, J.E., Tolleson, D.R., 2018. Guide to Co-developing Drought Preparation Plans for Livestock Grazing on Southwest National Forests.
Henderson, J., Dilling, L., Morss, R., Wilhelmi, O., Rick, U., 2021. We got in the pilot program to learn from it:" Features of Social Learning in Drought Contexts along the Arkansas River in Colorado. Weather, Climate. and Society 13 (4), 729–741. https://doi.org/10.1175/WCAS-D-20-0120.1.
Hinkel, J., Cox, M.E., Schlüter, M., Binder, C.R., Falk, T., 2015. A diagnostic procedure for applying the social-ecological systems framework in diverse cases. Ecol. Soc. 20 (1) https://doi.org/10.5751/ES-07023-200132.
Hisschemöller, M., Hoppe, R., 1995. Coping with intractable controversies: the case for problem structuring in policy design and analysis. https://www.taylorfrancis.com/.
Hitlin, S., Piliavin, J.A., 2004. Values: reviving a dormant concept. Annu. Rev. Sociol. 30 (1), 359–393. https://doi.org/10.1146/annurev.soc.30.012703.110640.
Hoppe, R., 2002. Cultures of public policy problems. J. Comp. Pol. Anal.: Res. Pract. 4 (3), 305–326. https://doi.org/10.1080/13876980208412685.
Horan, R.D., Fenichel, E.P., Drury, K.L.S., Lodge, D.M., 2011. Managing ecological thresholds in coupled environmental–human systems. Proc. Natl. Acad. Sci. U.S.A. 108 (18), 7333–7338. https://doi.org/10.1073/pnas.1005431108.
Horne, A., O'Donnell, E., 2014. Decision making roles and responsibility for environmental water in the Murray-Darling Basin. Aust. J. Water Resour. 18 (2) https://doi.org/10.7158/W12-032.2014.18.2.
Iglesias, A., Garrote, L., Cancelliere, A., Cubillo, F., Wilhite, D.A., 2009. Coping with Drought Risk in Agriculture and Water Supply Systems: Drought Management and Policy Development in the Mediterranean. Springer Science & Business Media.
Jencso, K., Parker, B., Downey, M., Hadwen, T., Hoell, A., Rattling Leaf, J., Edwards, L., Akyuz, A., Kluck, D., Peck, D., Rath, M., Syner, M., Umphlett, N., Wilmer, H., Barnes, V., Clabo, D., Fuchs, B., He, M., Johnson, S., Kimball, J., Longknife, D., Martin, D., Nickerson, N., Sage, J., Fransen, T., 2019. Flash Drought: Lessons Learned from the 2017 Drought across the U.S. Northern Plains and Canadian Prairies. NOAA National Integrated Drought Information System.
Jones, K., Abrams, J., Belote, R.T., Beltrán, B.J., Brandt, J., Carter, N., Castro, A.J., Chaffin, B.C., Metcalf, A.L., Roesch-McNally, G., 2019. The American West as a social-ecological region: drivers, dynamics and implications for nested social-ecological systems. Environ. Res. Lett. 14 (11), 115008. https://doi.org/10.1088/1748-9326/ab4562.
Jones, N., Ross, H., Lynam, T., Perez, P., Leitch, A., 2011. Mental models: an interdisciplinary synthesis of theory and methods. Ecol. Soc. 16 (1), 1–13. https://doi.org/10.5751/ES-03802-160146.
Jones, R.N., Preston, B., 2010. *Adaptation and risk management* [Monograph](15). (Climate change working ppaer. http://www.vu.edu.au/research.
Kachergis, E., Derner, J.D., Cutts, B.B., Roche, L.M., Eviner, V.T., Lubell, M.N., Tate, K. W., 2014. Increasing flexibility in rangeland management during drought. Ecosphere 5 (6), 1–14. https://doi.org/10.1890/ES13-00402.1.
Kahneman, D., 2011. Thinking, Fast and Slow. Macmillan.
Kallis, G., 2008. Droughts. Annu. Rev. Environ. Resour. 33 (1), 85–118. https://doi.org/10.1146/annurev.environ.33.081307.123117.
Kallis, G., Kiparsky, M., Norgaard, R., 2009. Collaborative governance and adaptive management: lessons from California's CALFED Water Program. Environ. Sci. Pol. 12 (6), 631–643. https://doi.org/10.1016/j.envsci.2009.07.002.
Kalra, N., Hallegatte, S., Lempert, R., Brown, C., Fozzard, A., Gill, S., Shah, A., 2014. Agreeing on robust decisions: new processes for decision making under deep uncertainty. http://agris.fao.org/agris-search/search.do?recordID=US2014601281.
Kim, H., Park, J., Yoo, J., Kim, T.-W., 2015. Assessment of drought hazard, vulnerability, and risk: a case study for administrative districts in South Korea. J. Hydro-environ. Res. 9 (1), 28–35. https://doi.org/10.1016/j.jher.2013.07.003.
Kimmerer, R.W., 2013. Braiding Sweetgrass: Indigenous Wisdom, Scientific Knowledge and the Teachings of Plants. Milkweed Editions.
Kinzig, A.P., Ryan, P., Etienne, M., Allison, H., Elmqvist, T., Walker, B.H., 2006. Resilience and regime shifts: assessing cascading effects. Ecol. Soc. 11 (1), 23. https://doi.org/10.5751/ES-01678-110120.
Klein, G.A., 2011. Streetlights and Shadows: Searching for the Keys to Adaptive Decision Making. MIT Press.
Knutson, C.L., Haigh, T., Hayes, M.J., Widhalm, M., Nothwehr, J., Kleinschmidt, M., Graf, L., 2011. Farmer perceptions of sustainable agriculture practices and drought risk reduction in Nebraska, USA. Renew. Agric. Food Syst. 26 (3), 255–266. https://doi.org/10.1017/S174217051100010X.

Koch, J., Friedman, J.R., Paladino, S., Plassin, S., Spencer, K., 2019. Conceptual modeling for improved understanding of the Rio Grande/Río Bravo socio-environmental system. Socio-Environ. Syst. Modell. 1, 16127. https://doi.org/10.18174/sesmo.2019a16127, 16127.

Kohl, E., Knox, J.A., 2016. My drought is different from your drought: a case study of the policy implications of multiple ways of knowing drought. Weather Clim. Soc. 8 (4), 373–388. https://doi.org/10.1175/WCAS-D-15-0062.1.

Kowalski-Trakofler, K.M., Vaught, C., Scharf, T., 2003. Judgment and decision making under stress: an overview for emergency managers. Int. J. Emerg. Manag. 1 (3), 278. https://doi.org/10.1504/IJEM.2003.003297.

Li, Y., Ye, W., Wang, M., Yan, X., 2009. Climate change and drought: a risk assessment of crop-yield impacts. Clim. Res. 39, 31–46. https://doi.org/10.3354/cr00797.

Magliocca, N.R., Ellis, E.C., Allington, G.R.H., de Bremond, A., Dell'Angelo, J., Mertz, O., Messerli, P., Meyfroidt, P., Seppelt, R., Verburg, P.H., 2018. Closing global knowledge gaps: producing generalized knowledge from case studies of social-ecological systems. Global Environ. Change 50, 1–14. https://doi.org/10.1016/j.gloenvcha.2018.03.003.

Majone, G., 1988. Policy analysis and public deliberation. In: The Power of Public Ideas. Harvard University Press, Cambridge, MA.

Marshall, N.A., 2015. Adaptive capacity on the northern Australian rangelands. Rangel. J. 37 (6), 617. https://doi.org/10.1071/RJ15054.

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), 14. https://doi.org/10.3390/resources7010014.

McLaughlin, P., Dietz, T., 2008. Structure, agency and environment: toward an integrated perspective on vulnerability. Global Environ. Change 18 (1), 99–111. https://doi.org/10.1016/j.gloenvcha.2007.05.003.

McLeman, R., Mayo, D., Strebeck, E., Smit, B., 2008. Drought adaptation in rural eastern Oklahoma in the 1930s: lessons for climate change adaptation research. Mitig. Adapt. Strategies Glob. Change 13 (4), 379–400. https://doi.org/10.1007/s11027-007-9118-1.

McNeeley, S.M., 2014. A "toad's eye" view of drought: regional socio-natural vulnerability and responses in 2002 in Northwest Colorado. Reg. Environ. Change 14 (4), 1451–1461. https://doi.org/10.1007/s10113-014-0585-0.

Moore, M.A., 2018. Thesis. In: Understanding Rancher's Beliefs and Behaviors Regarding Drought and Natural Water Storage in Southwest Montana. Montana State University - Bozeman, College of Letters & Science. https://scholarworks.montana.edu/xmlui/handle/1/15094.

Moser, S.C., Ekstrom, J.A., 2010. A framework to diagnose barriers to climate change adaptation. Proc. Natl. Acad. Sci. Unit. States Am. 107 (51), 22026–22031. https://doi.org/10.1073/pnas.1007887107.

Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world's large river systems. Science 308 (5720), 405–408. https://doi.org/10.1126/science.1107887.

NOAA National Centers for Environmental Information, 2020. U.S. Billion-dollar Weather and Climate Disasters. https://doi.org/10.25921/stkw-7w73.

Ostrom, E., 2007. A diagnostic approach for going beyond panaceas. Proc. Natl. Acad. Sci. Unit. States Am. 104 (39), 15181–15187. https://doi.org/10.1073/pnas.0702288104.

Ostrom, E., 2010. Beyond markets and states: polycentric governance of complex economic systems. Am. Econ. Rev. 100 (3), 641–672. https://doi.org/10.1257/aer.100.3.641.

Otto-Banaszak, I., Matczak, P., Wesseler, J., Wechsung, F., 2011. Different perceptions of adaptation to climate change: a mental model approach applied to the evidence from expert interviews. Reg. Environ. Change 11 (2), 217–228. https://doi.org/10.1007/s10113-010-0144-2.

Pahl-Wostl, C., 2009. A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. Global Environ. Change 19 (3), 354–365. https://doi.org/10.1016/j.gloenvcha.2009.06.001.

Pahl-Wostl, C., 2015. Water governance in the face of global change. In: Water Governance In the Face of Global Change: From Understanding to Transformation, pp. 1–287. https://doi.org/10.1007/978-3-319-21855-7.

Pandey, S., Bhandari, H.S., Hardy, B., 2007. Economic costs of drought and rice farmers' coping mechanisms: a cross-country comparative analysis. Int. Rice Res. Inst.

Papasozomenou, R., Zikos, D., 2009. Linking perceptions and water management: reflections from Cyprus. WSEAS Trans. Environ. Dev. 5 (12), 10.

Pederson, G.T., Gray, S.T., Fagre, D.B., Graumlich, L.J., 2006. Long-duration drought variability and impacts on ecosystem services: a case study from glacier national park, Montana. Earth Interact. 10 (4), 1–28. https://doi.org/10.1175/EI153.1.

Peters, D.P.C., Bestelmeyer, B.T., Turner, M.G., 2007. Cross–scale interactions and changing pattern–process relationships: consequences for system dynamics. Ecosystems 10 (5), 790–796. https://doi.org/10.1007/s10021-007-9055-6.

Plummer, R., Armitage, D., 2010. Integrating perspectives on adaptive capacity and environmental governance. In: Adaptive Capacity and Environmental Governance. Springer Science & Business Media.

Pulver, S., Ulibarri, N., Sobocinski, K.L., Alexander, S.M., Johnson, M.L., McCord, P.F., Dell'Angelo, J., 2018. Frontiers in socio-environmental research: components, connections, scale, and context. Ecol. Soc. 23 (3), 22. https://doi.org/10.5751/ES-10280-230323.

Putnam, R.D., 2000. Bowling Alone: the Collapse and Revival of American Community. Simon and Schuster.

Redmond, K.T., 2002. The depiction of drought. Bull. Am. Meteorol. Soc. 83 (8), 1143–1148. https://doi.org/10.1175/1520-0477-83.8.1143.

Reed, M.S., Evely, A.C., Cundill, G., Fazey, I., Glass, J., Laing, A., Newig, J., Parrish, B., Prell, C., Raymond, C., Stringer, L.C., 2010. What is social learning? Ecol. Soc. 15 (4), 10. https://doi.org/10.5751/ES-03564-1504r01.

Rey, D., Holman, I.P., Knox, J.W., 2017. Developing drought resilience in irrigated agriculture in the face of increasing water scarcity. Reg. Environ. Change 17 (5), 1527–1540. https://doi.org/10.1007/s10113-017-1116-6.

Riebsame, W.E., 1990. Anthropogenic climate change and a new paradigm of natural resource planning. Prof. Geogr. 42 (1), 1–12. https://doi.org/10.1111/j.0033-0124.1990.00001.x.

Roche, L.M., 2016. Adaptive rangeland decision-making and coping with drought. Sustainability 8 (12), 1334. https://doi.org/10.3390/su8121334.

Scholes, R., Reyers, B., Biggs, R., Spierenburg, M., Duriappah, A., 2013. Multi-scale and cross-scale assessments of social–ecological systems and their ecosystem services. Curr. Opin. Environ. Sustain. 5 (1), 16–25. https://doi.org/10.1016/j.cosust.2013.01.004.

Schön, D.A., Rein, M., 1994. Frame Reflection: toward the Resolution of Intractable Policy Controversies. Basic Books.

Scott, J., 1988. Social network analysis. Sociology 22 (1), 109–127. https://doi.org/10.1177/0038038588022001007.

Simelton, E., Fraser, E.D.G., Termansen, M., Forster, P.M., Dougill, A.J., 2009. Typologies of crop-drought vulnerability: an empirical analysis of the socio-economic factors that influence the sensitivity and resilience to drought of three major food crops in China (1961–2001). Environ. Sci. Pol. 12 (4), 438–452. https://doi.org/10.1016/j.envsci.2008.11.005.

Smit, B., Burton, I., Klein, R.J.T., Wandel, J., 2000. An anatomy of adaptation to climate change and variability. Societal Adaptation to Climate Variability and Change. Springer, pp. 223–251.

Smit, B., Skinner, M.W., 2002. Adaptation options in agriculture to climate change: a typology. Mitig. Adapt. Strategies Glob. Change 7, 85–114. https://doi.org/10.1023/A:1015862228270.

Statham, G., Haegeli, P., Greene, E., Birkeland, K., Israelson, C., Tremper, B., Stethem, C., McMahon, B., White, B., Kelly, J., 2018. A conceptual model of avalanche hazard. Nat. Hazards 90 (2), 663–691. https://doi.org/10.1007/s11069-017-3070-5.

Susskind, L.E., McKearnen, S., Thomas-Lamar, J., 1999. The Consensus Building Handbook: A Comprehensive Guide to Reaching Agreement. SAGE Publications.

Thompson, B.H., Leshy, J.D., Abrams, R.H., Zellmer, S.B., 2018. Legal Control of Water Resources, Cases and Materials, 5th, 6 edition. West Academic Publishing.

Thompson, M.P., Freeborn, P., Rieck, J.D., Calkin, D.E., Gilbertson-Day, J.W., Cochrane, M.A., Hand, M.S., 2016. Quantifying the influence of previously burned areas on suppression effectiveness and avoided exposure: a case study of the Las Conchas Fire. Int. J. Wildland Fire 25 (2), 167–181.

Tillery, A.C., Darr, M.J., Cannon, S.H., Michael, J.A., 2011. Postwildfire Preliminary Debris Flow Hazard Assessment for the Area Burned by the 2011 Las Conchas Fire in North-Central New Mexico. US Department of the Interior, US Geological Survey.

Tornikoski, E., Maalaoui, A., 2019. Critical reflections – the theory of planned behaviour: an interview with icek ajzen with implications for entrepreneurship research. Int. Small Bus. J.: Researching Entrepreneurship 37 (5), 536–550. https://doi.org/10.1177/0266242619829681.

Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J., 2014. Global warming and changes in drought. Nat. Clim. Change 4 (1), 17–22. https://doi.org/10.1038/nclimate2067.

van Dijk, A.I.J.M., Beck, H.E., Crosbie, R.S., de Jeu, R.A.M., Liu, Y.Y., Podger, G.M., Timbal, B., Viney, N.R., 2013. The Millennium Drought in southeast Australia (2001-2009): natural and human causes and implications for water resources, ecosystems, economy, and society. Water Resour. Res. 49 (2), 1040–1057. https://doi.org/10.1002/wrcr.20123.

Van Loon, A.F., Gleeson, T., Clark, J., Van Dijk, A.I.J.M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A.J., Tallaksen, L.M., Uijlenhoet, R., Hannah, D.M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N., Van Lanen, H.A.J., 2016. Drought in the anthropocene. Nat. Geosci. 9 (2), 89–91. https://doi.org/10.1038/ngeo2646.

Vogel, C., Olivier, D., 2019. Re-imagining the potential of effective drought responses in South Africa. Reg. Environ. Change 19 (6), 1561–1570. https://doi.org/10.1007/s10113-018-1389-4.

Wall, T.U., Brown, T.J., 2015. In: Wildfire and Drought: Impacts on Wildfire Planning, Behavior and Effects. Desert Research Institute. https://www.drought.gov/drought/sites/drought.gov.drought/files/media/rpt_Wildfire_Drought_final_Oct_2015_Boise.pdf.

White, S.S., Brown, J.C., Gibson, J., Hanley, E., Earnhart, D.H., 2009. Planting food or fuel: developing an interdisciplinary approach to understanding the role of culture in farmers' decisions to grow second-generation, biofuel feedstock crops. Comp. Technol. Tran. Soc. 7 (3), 287–302. https://doi.org/10.1353/ctt.0.0038.

Wilhite, D., Hayes, M., Knutson, C., Wilhite, D., 2005. Drought preparedness planning: building institutional capacity. In: Wilhite, D. (Ed.), Drought and Water Crises: Science, Technology, and Management Issues, vol. 107. CRC Press, pp. 93–136. http://www.crcnetbase.com/doi/abs/10.1201/9781420028386.ch5.

Wilhite, D.A., 1997. Responding to drought: common threads from the past, visions for the future 1. JAWRA J. Am. Water Resour. Assoc. 33 (5), 951–959. https://doi.org/10.1111/j.1752-1688.1997.tb04116.x.

Wilhite, D.A., Glantz, M.H., 1985. Understanding: the drought phenomenon: the role of definitions. Water Int. 10 (3), 111–120. https://doi.org/10.1080/02508068508686328.

Wilhite, D.A., Sivakumar, M.V.K., Pulwarty, R., 2014. Managing drought risk in a changing climate: the role of national drought policy. Weather Clim. Extrem. 3, 4–13. https://doi.org/10.1016/j.wace.2014.01.002.

Wilhite, D.A., Vanyarkho, O.V., 2000. Chapter 18 drought: pervasive impacts of a creeping phenomenon. In: Drought: A Global Assessment, vol. 1. Routledge, p. 15.
Wilke, A.K., Morton, L.W., 2017. Analog years: connecting climate science and agricultural tradition to better manage landscapes of the future. Clim. Risk Manag. 15, 32–44. https://doi.org/10.1016/j.crm.2016.10.001.
Wilmer, H., Fernández-Giménez, M.E., 2015. Rethinking rancher decision-making: a grounded theory of ranching approaches to drought and succession management. Rangel. J. 37 (5), 517–528. https://doi.org/10.1071/RJ15017.
Woolley, R.N., Pidd, M., 1981. Problem structuring — a literature review. J. Oper. Res. Soc. 32 (3). https://www.tandfonline.com/doi/abs/10.1057/jors.1981.42.

Supplemental Material for "A Typology of Drought Decision Making: Synthesizing Across Cases to Understand Drought Preparedness and Response Actions"

Journal Title: Weather and Climate Extremes

Corresponding author: Amanda E. Cravens, U.S. Geological Survey, aecravens@usgs.gov

Authors: A.E. Cravens, J. Henderson, J. Friedman, N. Burkardt, A.E. Cooper, T. Haigh, M. Hayes, J. McEvoy, S. Paladino, A. Wilke, H. Wilmer

Contents

Table S1: Social Science Case Study Research Projects Synthesized

Case ID	Project Title	Location	Project Objectives	Methods	Team Members *(paper authors in bold)*	Research Approach(es)	Project Products	Project Funding
Case 1: GREAT PLAINS	Operationalization and Measurement of Adaptive Capacity: Agriculture and Drought in the U.S. Great Plains	U.S. Great Plains	Understand drought mitigation and response in terms of agricultural producers' adaptive capacity.	Random sample surveys of range-based livestock producers in the Northern Great Plains region following the 2012 and 2016 droughts.	C.D. Allen, M.E. Burbach, **T.R. Haigh, M.J. Hayes,** C.L. Knutson, A. Mucia, J.A. Otkin, W. Schacht, A. Smart, J. Volesky	Disaster risk and vulnerability; adaptive capacity; behavioral motivation	Haigh et al. (2019a); Haigh et al. (2019b), Haigh (2019c)	Natural Resources Conservation Service; University of Nebraska-Lincoln; U.S. National Oceanic and Atmospheric Administration
Case 2: UPPER MISSOURI HEADWATERS	Human Dimensions of Ecological Drought in the Upper Missouri Headwaters, Montana	Upper Missouri Headwaters (UMH) Basin, southwestern Montana	Understand how drought's impact on ecosystems affects human communities, including (a) how stakeholders and managers perceive and respond to drought, (b) by whom and under which laws or policies ecologically available water is governed, (c) responses to drought in the UMH, and (d) ecosystem services impacted by drought in the region.	Mixed methods project including: (1) interviews with partners of the Montana demonstration project of the National Drought Resilience Project (NDRP); (2) document analysis of all plans (drought, land management, hazard, etc.) that pertain to the study region to understand how they do or do not address ecologically available water; and (3) ecosystem services inventory workshop. Analysis informed by the Ecological Drought Framework developed by the working group.	D.J. Bathke, S.D. Crausbay, **A.E. Cravens, T.R. Haigh, M.J. Hayes,** T. Jedd, **J. McEvoy**, M. Podebradska, N. Raheem, A. Ramirez, SNAPP Ecological Drought Working Group (Working Group Pls: S.L. Carter, M.S. Cross, K.R. Hall), E. Wickham, D. Zoanni	Institutional analysis; human-environment geography; terrestrial ecology, rural sociology; political science; drought planning	Cravens et al. (2021); McEvoy et al. (2018); Raheem et al. (2019)	U.S. Geological Survey Climate Adaptation Science Center; Science for Nature and People Partnership (SNAPP)
Case 3: BEAVERHEAD DROUGHT PLANNING	The Beaverhead Watershed Drought Resiliency Plan	Beaverhead Watershed, southwestern Montana	Develop a drought plan that provides the framework for proactive drought risk management across the watershed.	Collaborative planning process that included multiple public stakeholder engagements and individual meetings with key stakeholders.	C. Carparelli, **T.R. Haigh, M.J. Hayes**, National Drought Mitigation Center, C.J. Stiles, E. Wickham	Natural resources/drought planning	Carparelli (2016); Stiles and Wickham (2019)	U.S. Bureau of Reclamation
Case 4: RED ROCK WATERSHED	Understanding Ranchers' Beliefs and Behaviors Regarding Drought and Natural Water Storage in Southwest Montana	Red Rock Watershed, southwestern Montana	Understand ranchers' perceptions of drought and their beliefs and behaviors towards adoption of two natural water storage strategies: flood irrigation and beaver mimicry projects.	Semi-structured qualitative interviews of landowners and ranch managers. Key informants helped develop a list of interviewees, expanded using a snowball sampling technique. Literature on the theory of planned behavior and amenity land ownership informed analysis.	M.A. Moore, **J. McEvoy**	Human-environment geography; theory of planned behavior	Moore (2018)	The Nature Conservancy
Case 5: BEAVER MIMICRY	Actionable Science for Ecological Drought Adaptation: The Case of Beaver-Related Restoration	Colorado, Montana, Utah, Oregon	Understand the characteristics that make science actionable for water resource management in the context of beaver mimicry.	Ethnographic conversations with scientists and resource managers/practitioners focused on re-introduction of woody debris for stream and wetland restoration.; qualitative analysis.	A. Bamzai-Dodson, **A.E. Cravens,** T. Pfaeffle, **A.K. Wilke**	Sociology, science and technology studies	Products in preparation	U.S. Geological Survey Climate Adaptation Science Center

Case 6: RANCH DECISION MAKING IN THE WESTERN UNITED STATES	Drought Decision Making in Western U.S. Ranches	Colorado; Wyoming; western United States	Identify ranching strategies to increase adaptive capacity and compare management practices across the western United States.	Synthesis of existing literature and case-studies built from interviews with ranchers related to decision making, grazing management, forage management, and other decisions.	**H. Wilmer** and coauthors	Rangeland ecology; social-ecological systems	Wilmer et al. (2018); Wilmer and Fernández-Giménez (2015, 2016a); Wilmer et al. (2019)	National Institute of Food and Agriculture; Agricultural Research Service
Case 7: UPPER COLORADO RIVER BASIN	Drought Decision Support in the Upper Colorado River Basin	Upper Colorado River Basin (western Colorado)	Identify the scientific information that various types of land, water, and fire managers need to respond to drought in western Colorado. Understand how managers incorporate this information into decision making.	Interviews with known and prospective tool users of drought early warning information in the study area, as well as providers of drought information and tools. Researcher also participated as a participant-observer in Colorado Climate Center drought early warning biweekly updates.	**A.E. Cravens**, N.J. Doesken, J. Lukas	Institutional analysis; learning sciences; climatology	Cravens (2018)	U.S. Geological Survey
Case 8: SOUTHEAST COLORADO	Unintended Consequences, Social Learning, and Adaptation to Drought in Southeast Colorado	Arkansas River Basin, Colorado	Understand how decisions about drought at different scales trigger unintended consequences and possible social learning in light of identified vulnerabilities and resilience.	Interviews based on purposive and snowball sampling in urban and rural areas recently exposed to significant drought. Additional discourse analysis and interviews informed by theoretical sampling.	L. Dilling, **J. Henderson**, R.E. Morss, U. Rick, O. Wilhelmi	Science and technology studies; atmospheric and climate sciences; geography; NOAA RISA (Western Water Assessment)	Henderson et al. (2021)	Cooperative Institute for Research in Environmental Sciences (CIRES)
Case 9: RIO GRANDE BASIN	Improving Resilience for the Rio Grande Coupled Human-Natural System	Rio Grande Basin (Colorado to the Gulf of Mexico and portions of Mexico)	Understand how stakeholders perceive ecosystem services and identify capacity to sustainably manage river waters. Identify what shapes Rio Grande decision making and water management. Provide directed adaptation and management knowledge.	Initial sampling strategy guided by purposive sampling, focused on water managers. Informational interviews and secondary sources helped delineate distinct sections within the basin. Snowball sampling used to identify additional interviewees; ethnographic methods in each section helped capture variation in key water management practices.	**J.R. Friedman**, K. Hanson, J. Koch, **S. Paladino**, S. Plassin, J.R. Ziolkowska	Social science (anthropology, geography, and economics); collaborative systems modelling	Koch et al. (2019); Plassin et al (2020); Plassin et al. (2021)	U.S. Geological Survey Climate Adaptation Science Center
Case 10: OKLAHOMA	Adapting Socio-ecological Systems to Increased Climate Variability	Oklahoma	Understand how stakeholders perceive "natural" systems and identify drought adaptations to climate change (drought). Understand how different socio-ecological systems adapt to climate change impacts.	Community-based research approach; cross-sampled water managers, agricultural stakeholders, businesses, tribal representatives, conservation groups, etc.	**J. Friedman**, M. Stanton, T.N. VanWinkle	Environmental and psychological anthropologists	Doughty et al. (2018); Gray et al. (2019); VanWinkle and Friedman (2017, 2018, 2019)	National Science Foundation

Examples of Testing the Typology by Applying to Cases

To illustrate in greater detail than possible within the length confines of the manuscript, this section describes how the typology's four elements manifested in five of the case study projects we synthesized. Our goal is to demonstrate how we used this analysis to test the particular typology elements we selected in the course of our synthesis analysis.

Case 2: Human Dimensions of Ecological Drought in the Upper Missouri Headwaters, Montana

Case Summary

As part of a Science for Nature and People Partnership (SNAPP) Working Group, this project brought together a group of interdisciplinary scientists to study ecological drought. While previous research has focused extensively on hydrological, agricultural, and municipal impacts of drought, little attention has been given to the ecological impacts of drought and how drought affects the ecosystem services on which human communities rely. The Working Group defined ecological drought as "an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems" (Crausbay et al., 2017, p. 2544) and developed an ecological drought framework that considers both the physical and human drivers of drought. The Working Group focused their ecological drought research in the Upper Missouri Headwaters (UMH) Basin in southwestern Montana where a National Drought Resiliency Partnership (NDRP) pilot project was underway. The goal of the NDRP was to "leverage and deliver technical, human and financial resources to help address drought" through collaborations with federal, state, and local stakeholders (Montana Drought Demonstration Partners, 2015, p. 2). Members of the SNAPP Working Group conducted 44 interviews with stakeholders of the NDRP, analyzed watershed drought plans and other relevant planning documents, and hosted an ecosystem services elicitation workshop. The UMH vignettes presented in this paper draw on the insights learned from the social science component of the Working Group's research.

Element 1: Problem Framing

Central to this research project was an examination of the degree to which UMH resource managers and stakeholders are aware of - and monitor and plan for - the ecological impacts of drought. In other words, to what degree is the problem of drought framed as ecological drought? Our interviews indicate that most NDRP stakeholders define drought in an integrated fashion that includes both natural and human communities. However, when we analyzed the specific impacts each interviewee mentioned, we found that some participants focused more on ecological impacts while others focused more on non-ecological impacts. We interpret this to mean that while interviewees may conceptualize the overall problem of drought to include ecological impacts, their roles and other constraints may require them to address either ecological or non-ecological aspects of that problem on a day-to-day basis (Cravens et al., 2021).

Our in-depth analysis of five watershed drought plans indicated that the plans do account for some ecological impacts. However, the ecological drought problem is framed narrowly in terms of impacts to fish with little attention given to other ecological drought impacts (McEvoy et al., 2018).

Following Van Loon et al. (2016) as well as Crausbay et al. (2017), our analyses also focused on the degree to which the problem of drought was framed as being driven by physical factors, human factors, or both. In our interviews, we found that individuals framed drought as a phenomenon with diverse drivers including physical landscape attributes and meteorological conditions, as well as human management of land and water resources. Interviewees also noted the importance of interactions between drivers and highlighted the role climate change plays in exacerbating drought (Cravens et al., 2021).

Element 2: Actors

This project examined an innovative and nascent partnership for drought planning (i.e., the Montana pilot project of the National Drought Resiliency Partnership) and thus drew a sample frame to capture stakeholders from organizations participating in the NDRP (see Raheem et al., 2019 for details). When asked about their respective roles in drought management, some interviewees described the drought decisions for which they are responsible (e.g., local watershed group member calling for voluntary irrigation reductions). Other interviewees indicated they do not see themselves as drought "decision-makers", but rather as providing support to those who make decisions. Thus, they have fairly limited agency for directly influencing drought decisions (e.g., environmental non-profit staff providing information to landowners). Some interviewees occupy a middle ground (e.g., a Bureau of Land Management employee administering a grazing plan implemented by individual rancher permittees).

Many of the interviewees noted the important role that actors in local watershed groups and local watershed planners play in drought planning at the local watershed level. However, the most commonly noted constraint for these actors was financial resources. Lack of funding was seen as a barrier to the long-term capacity for local watershed groups to effectively develop and implement drought plans.

In terms of accountability, our research made a distinction between informal watershed drought plans and Candidate Conservation Agreements with Assurances (CCAAs), which are formal agreements between the U.S. Fish and Wildlife Service and non-Federal entities, including irrigators. The CCAAs create greater accountability with a mechanism to enforce conservation agreements through the Federal Endangered Species Act (i.e., if the agreement is not followed, additional restrictions can be imposed). Conversely, informal watershed drought plans lack formal enforcement mechanisms and rely on social norms and voluntary collaboration to implement the conservation agreements.

Element 3: Decisions in Response

Our analysis of five watershed drought plans found that these plans rely on predetermined thresholds (primarily streamflow level and water temperature) that trigger a voluntary reduction in irrigation withdrawals and/or angling restrictions and river closures (McEvoy et al., 2018). At first pass, it appears there is not much room for discretion and that drought decisions based on these pre-existing thresholds outlined in the plan would be rather rigid and formal. However, the Blackfoot Drought Response Plan[1] gives decision-makers much greater discretion by instructing the drought committee to look beyond established streamflow and water temperature thresholds and consider a variety of other factors (e.g., season, water demand, climatic conditions, weather forecasts, and general conditions) before making a decision (McEvoy et al., 2018). An interview with a member of this drought committee confirmed that, in practice, they have a great deal of discretion when deciding if - and when - to call for voluntary irrigation and angling restrictions. The Montana decision context influences how this discretion is applied. Key factors include the legal framework (prior appropriation as applied under Montana state law), as well as a strong sense of place and tradition of outdoor recreation among residents and the relative balance of economic power between agriculture (lower value than in much of the West) and guiding or outfitting (higher value than in much of the West, especially on the world-class “blue ribbon” trout streams) (McEvoy et al., 2018).

Element 4: Dynamic Interactions

This case study reveals several examples of dynamic interactions. Our analysis of five drought plans highlighted cross-scale interactions in drought planning. For example, the Beaverhead Watershed Drought Resiliency Plan mentioned several other resource management plans that have drought-related components and/or implications for ecological drought planning (e.g., U.S. Forest Service National Forest Plans, State Water Plans, Watershed Restoration Plans, County Pre-Disaster Mitigation Plans, etc.). These additional plans broaden the scope of the ecological impacts that are monitored and managed. Additionally, these plans highlight the interactions between water temperature, water quality, pathogen outbreaks, invasive species, resource degradation, and wildfire that need to be considered in drought planning (McEvoy et al., 2018). Given the importance of cross-scalar and cross-institutional interactions, we are in the process of analyzing the wider range of federal, state, and local laws, policies, administrative programs and plans that affect the availability of water to ecosystems in times of drought in the UMH in order to map the institutional landscape that shapes drought preparedness and response.

By examining the ongoing Montana demonstration project, our case study highlights the importance of network interactions in drought planning. The goal of the NDRP is to coordinate and leverage various federal, state, and local resources to improve drought responses. The partnership made federal and state resources available to local communities to prepare for - and mitigate - drought impacts (Cravens et al., 2021). The list of Montana demonstration project partners includes 49 different organizations involved in drought management in the UMH.

Lastly, this case highlights dynamic interactions in a shared problem space. The threat of the fluvial artic grayling becoming listed as a threatened or endangered species provided motivation for irrigators, anglers, state wildlife officials, and the federal Environmental Protection Agency to work together to mitigate drought in various watersheds in the UMH.

[1] Note that the Blackfoot Watershed is outside the Upper Missouri Headwaters Basin; it is included in the analysis of local watershed drought plans as it is recognized throughout the state of Montana as an innovative, successful example. See McEvoy et al 2018 for details.

Case 3: The Beaverhead Watershed Drought Resiliency Plan

Case Summary

Drought risk management strategies are promoted as the keys to reduce the potential for impacts resulting from future drought events. While responses during a drought event, often called “crisis management”, are necessary, the proactive nature of mitigation activities and policies associated with risk management and implemented before droughts occur provide the opportunities to reduce drought vulnerabilities in a location or region. For example, the Integrated Drought Management Programme (IDMP) has recently advocated a three “pillar” approach for drought risk management (World Meteorological Organization Global Water Partnership, 2014). Pillar 1 covers drought monitoring and early warning. Pillar 2 emphasizes impact and vulnerability assessments to identify who and what are most vulnerable to droughts and why. The third pillar, Pillar 3, deals with the response and mitigation management strategies that take place either during or before a drought event, respectively, to reduce drought impacts.

Similarly, the U.S. Bureau of Reclamation (USBR), which funds drought contingency planning in the western U.S., requires six elements for any funded drought planning project (USBR, 2019); these required elements align quite closely with the three pillars. Drought planning can take place at any jurisdictional level and, in the United States, this has often been at the state level. However, in recent years, there has been more interest in drought planning at the municipal, basin, tribal, and individual rancher levels. In 2015, the Beaverhead Watershed in southwest Montana undertook a proactive drought planning process to develop the Beaverhead Watershed Drought Resiliency Plan (BWDRP) (Carparelli, 2016). This step coincided with activities associated with the National Drought Resilience Partnership taking place at the time in Montana and funding opportunities available through the USBR’s WaterSMART program.

The Beaverhead Watershed within the Upper Missouri River Basin is one of the main tributaries for the Jefferson River, which eventually joins with the Madison and Gallatin Rivers to form the Missouri River Headwaters at Three Forks, Montana. The Beaverhead Watershed has numerous stakeholders that rely heavily on the water resources within the basin, including agriculture, recreation, tourism, municipal water use, and a wide variety of ecological resources. Food production, particularly beef production, is the most important economic factor for the watershed, while angling recreation and tourism are also very important components of the local economy. The watershed’s climate is highly variable and wildfire is a key ecosystem issue for the region. Following the development of the BWDRP, the National Drought Mitigation Center (NDMC) collected information about the planning process now featured on the Climate Resilience Toolkit (Stiles & Wickham, 2019).

Element 1: Problem Framing

The central premise of drought risk management is that the proactive drought planning process provides a framework for decision making and that drought impacts are reduced in the long run compared to a more ad-hoc crisis management approach. This particular paradigm is very important to consider for framing any drought planning process. This approach includes strategies for drought early warning and assessment, identifying vulnerabilities and taking steps to reduce those vulnerabilities, which the disaster management community calls “mitigation”. Risk management also includes plans for responding during drought events with efficient and timely actions. The USBR recognizes these components of risk management and BWDRP specifically incorporates the six USBR requirements for drought resiliency plans: Operational and Administrative Framework, Drought Monitoring, Vulnerability Assessment, Mitigation Actions, Response Actions, and Plan Update Process. In addition to being consistent with the framing context covered by the IDMP and USBR, the process also largely followed other legacy drought risk management approaches (Svoboda et al., 2011; Wilhite et al., 2005).

The Beaverhead Watershed sits within the Rocky Mountains of southwestern Montana. The climate in this region shifts from alpine conditions with potentially heavy winter season snowfalls in the highest elevations to late spring/early summer peaks in both precipitation and streamflows in the watershed's valleys. Droughts are a normal part of climate across the region. Because droughts affect the region from a variety of meteorological, agricultural, hydrological, and ecological perspectives, all aspects of the hydrological cycle need to be monitored in order to understand the drought characteristics, including snowpack, precipitation, streamflows, groundwater, soil moisture, reservoir levels, and vegetation conditions. The BWDRP observes that several trends are noticeable as a result of climate change across the watershed, including earlier and lower peak snowmelt runoffs in streamflows, warmer stream temperatures, increased evapotranspiration, and increased pressure from weeds and invasive plant species (Carparelli, 2016). These factors lead to increased competition for the limited water resources across the region, which drought events exacerbate.

Element 2: Actors

The development of the BWDRP was initiated and led by Chris Carparelli, a member of the AmeriCorps-Big Sky Watershed Corps program. The Beaverhead Conservation District (BCD) and the Beaverhead Watershed Committee (BWC) cohosted Mr. Carparelli, who was based within the Beaverhead Watershed in Dillon, MT. The BCD and BWC supervised the overall planning process, along with consultation with the Beaverhead County Drought Task Force (BWDTF). These three groups are comprised of numerous stakeholders across the Beaverhead Watershed, including landowners, agricultural and livestock producers and businesses, business owners, anglers and outfitters, conservation groups, governmental agencies, and local citizens.

The BWDRP development process was specifically designed as a collaborative effort between multiple governmental agencies, non-governmental organizations (NGOs), and local stakeholders given the wide variety of drought-related actors and types of impacts within the watershed. For this reason, stakeholder engagement was fundamental to the process to incorporate the unique stakeholder needs and perspectives into the plan. The engagement was iterative; Mr. Carparelli convened a series of public meetings, and meetings were scheduled with key stakeholders. Multiple federal, state and local governmental organizations provided support and input into the plan development process. At the federal level, this included the local office of the Natural Resources Conservation Service based in Dillon. It also included the Bureau of Land Management for agricultural and grazing information, as well as multiple other federal agencies. At the state level, two agencies responsible for important water management-related decisions, the Montana Department of Natural Resources and Conservation and the Montana Department of Fish, Wildlife and Parks, both provided important input and support. Multiple other state and local organizations were also involved. The BWDRP provides a long list of stakeholders and documents their potential roles and contributions within the plan.

Element 3: Decisions in Response

Once committed to the proactive drought planning paradigm, the planning process stepped through the identification of local vulnerabilities, mitigation strategies to reduce those vulnerabilities, and response actions taken during droughts to address the impacts resulting from such vulnerabilities. These drought plan components evolved directly out of the stakeholder engagements. The BWDRP identifies five drought vulnerability issues, and then recommends both mitigation and response strategies are made to address those vulnerabilities. It is important to note, however, that the plan also highlights existing mitigation and response actions and strategies that are already in place, and the context around the decisions for those particular activities.

For implementation during future drought events, the BWDRP could potentially become an appendix within the Beaverhead County Hazard Mitigation Plan. The Beaverhead County Drought Task Force meets monthly from March through October each year and can use the BWDRP as a reference. However, there is no operational or administrative framework to mandate activities identified within the plan or hold agencies accountable. Therefore, the implementation of the roles and responsibilities identified are ultimately the responsibility of the agencies and stakeholders active in the watershed. The BWDRP does suggest a plan evaluation process that might be followed to assess and update the various sections of the plan and how the vulnerability, mitigation, and response issues are being addressed.

Element 4: Dynamic Interactions

One important element highlighted by the BWDRP is that coordination between agencies, other planning processes, and other potential hazards at all scales is necessary and highly valuable for proactive drought risk management. The plan highlights multiple Interagency Coordination Groups that consider drought as a primary or secondary issue to address. A list of multiple planning documents at various scales is also provided, and these documents directly or indirectly address drought issues in the watershed. For example, there is the Beaverhead County Pre-Disaster Mitigation Plan, the East Bench Irrigation District-Clark Canyon Water Supply Company Drought Management Plan, and the Montana Drought Response Plan, among many others, that all cover aspects and issues important to the watershed and the broader region. The BWDRP recommends that the Beaverhead County Pre-Disaster Mitigation Plan, which covers a wide range of potential hazards to affect the county, incorporates the BWDRP as an appendix during its 2016 revision to assist with this coordination need. The BWDRP also discusses the importance and role of water rights in any decision making within the watershed. These policy-oriented interactions illustrate the complexity regarding drought- and water-related issues in the western United States and demonstrate the need for coordination between organizations within the Beaverhead Watershed.

Case 6: Ranch Decision Making in the Western United States

Case Summary

Ranchers in the western United States manage forage resources for livestock grazing systems across a matrix of heterogeneous rangelands, pasturelands, and forage crop land uses, often in highly variable and uncertain climatic, social and economic conditions. Flexible, extensive livestock production can be well adapted to drought and variable weather when managers have the flexibility to respond to large swings in forage resources (Derner & Augustine, 2016). Many ranching communities have production systems developed over generations which anticipate drought disturbance and employ operational and strategical decisions to enhance flexibility and balance livestock production livelihoods with rangeland ecosystem variability (Haigh et al., 2019b; Kachergis et al., 2014; Wilmer & Fernández-Giménez, 2015). However, even highly flexible operations and ranching communities can be vulnerable to extremely variable precipitation and drought (Derner et al., 2018).

When extreme events are coupled with dynamic social, political, and economic contexts, drought can drive short and long-term financial and ecological challenges for ranchers (Hamilton et al., 2016). Drought creates spatial and temporal variability in forage resources which can impact livestock weight gains and reproductive rates, operational costs, and thus financial viability. At the same time, these ecological and economic impacts can affect personal and social well-being, and the persistence of family ranch operations and larger scale land use patterns over the long-term (Gutmann, 2018). The body of social science describing rancher decision-making and the social, ecological and economic impacts is growing rapidly (Bruno et al., 2020). Here we synthesize findings of multiple qualitative and quantitative studies published elsewhere which offer insights into how ranchers experience and navigate drought decision-making relative to our framework (Kachergis et al., 2014; Roche, 2016; Wilmer et al., 2018; Wilmer & Fernández-Giménez, 2015, 2016a, 2016b; Wilmer et al., 2019).

Element 1: Problem framing

Ranch family businesses experience drought as interacting climate, ecological and social events. Drought impacts forage resources and rangeland ecological outcomes, animal health and production, water availability and distribution, input costs, income, labor requirements, and also ranchers' sense of agency and, in some cases, well-being. Thus, ranchers describe drought as a complex social-ecological problem that ripples through multiple aspects of their operations. The threat of drought, and whether or not drought is viewed as a relatively uncommon threat or an anticipated aspect of historical system variation, varies by ranchers' personal and operational experience, ecological context and geographic setting. Ranchers running cattle in Southern Arizona may perceive frequent drought as a "normal" part of ranching (Wilmer & Fernández-Giménez, 2015), while those in semi-arid environments in the Western Great Plains of Colorado and Wyoming may see drought as a less common and more challenging experience (Haigh et al., 2019a; Kachergis et al., 2014). Because ranchers often express close place attachment and relational responsibility to ranch ecosystems, drought is an emotional and ethical experience that shapes how ranchers see themselves and their role in eco- and food systems (Wilmer et al., 2019). Put another way, drought is an economic and ecological risk for ranchers, but it is also part of the complexity and uncertainty they must deal with in order to live, on their terms, good, moral lives as food producers and stewards of the land.

Element 2: Actors

Ranchers are often targeted as the focus of social and rangeland science because of their ownership of or influence over vast areas of rangeland ecosystems in public and private lands. In reality, the placement of cattle and other management practices often involves formal or informal negations among multiple actors, even at the ranch scale. Family members of multiple generations and genders shape operational goals, strategic decisions and management actions, and these roles change over the lifetime of the ranch and rancher (Wilmer & Fernández-Giménez, 2016a, 2016b). Non-owners (herders and hired managers), non-white ranchers, women, and absentee landowner ranchers (who are often of higher economic status than surrounding communities) have received less attention in the literature as decision makers than white, male heads-of household (Bruno et al., 2020; Epstein et al., 2019; Pilgeram, 2007; Sayre, 2018). Finally, personal backgrounds, characteristics and past experiences with drought can influence how individual ranchers perceive drought and climate variability, with increased experience with drought sometimes leading to decreased willingness to implement adaptive changes for future droughts (Marshall & Smajgl, 2013), and life histories shaping various roles and approaches over the course of a ranch and a rancher (Wilmer & Fernández-Giménez, 2016b).

Element 3: Decisions in response

Ranchers in the western United States have various managerial, operational, strategic, and tactical choices available to them to anticipate and respond to drought, though their capacity to do so may be constrained by various ecological, economic, and regulatory contexts (McClaran et al., 2015). Knutson and Haigh (2013) and Derner and Augustine (2016) outline frameworks for adaptive ranch management in the face of drought, noting the importance of anticipating, monitoring, and tracking precipitation variability, of setting key decision "triggers" for adaptive management, and of maintaining flexible stocking approaches that enable ranchers to use spatial variability to offset temporal variability in rainfall and/or reduce or expand herd size as needed with less financial strain. Economic models suggest cow-calf operators may find additional flexibility by adding yearling or additional replacement heifers to their operation to facilitate stocking rate reductions (Hamilton et al., 2016; Torell et al., 2010). In addition to moving drought risk over space by improving water infrastructure across extensive pastures or leasing pasture, storing hay or other forage, market-based approaches such as insurance may provide additional adaptive capacity for ranchers. However, it is well-accepted that the combination of approaches needed to reach various production and ecological goals is highly context specific. In range management, the timing of drought response, specifically reducing stocking rates, has been an area of study because delayed response can have negative economic and ecological outcomes. Haigh et al. (2019a) noted that ranchers in the Northern Plains responded to environmental cues during a recent (2016) flash drought, but had a delayed response compared to when drought conditions emerged. Haigh et al. (2021) found that ranchers with specific if-then plans for drought and on-farm monitoring practices were able to overcome situational uncertainty and avoid delayed response to drought.

Element 4: Dynamic interactions

Even at the ranch scale, interactions among multiple scales and sources of complexity can constrain and motivate adaptive management (Fernández-Giménez et al., 2019). Beef and sheep operations in the western United States are part of larger meat and fiber systems and global economic structures and are under a variety of regulatory constraints. As such, drought decision-making may be enhanced or constrained by multiple scales of policy, social, and climatic processes. Ranchers often lease private lands or contract cattle for custom grazing from other ranchers and rely on permits to graze publicly held lands, and so collaborate with other managers to graze in accordance with these contexts. The role of these other actors and regulatory frameworks can greatly increase the complexity and reduce the flexibility of drought decision-making in ranching (McClaran et al., 2015).

Case 8: Unintended Consequences, Social Learning, and Adaptation to Drought in Southeast Colorado

Case Summary

The years 2002-2005 was a drought of record for many communities in Colorado. To better understand some of the drought-related interactions among and between actors during that time, in 2017 researchers in the Regional Integrated Sciences and Assessments program and University of Colorado, Boulder, conducted semi-structured interviews with 20 individuals representing various sectors throughout Southeastern Colorado, and they attended 4 conferences, workshops, and meetings focused on water and drought in the Arkansas River Basin (see methods in Henderson et al. (in press)). The following example is from unpublished data taken from this study and focuses on one set of decisions made mid-drought by the Colorado Office of the State Engineer about well water use that created unintended consequences within the system that still reverberate today (J. Henderson, Texas Tech University, unpublished data, December 2020).

Element1: Problem Framing

Those interviewed initially framed the problem reactively, in two interrelated ways. First, they identified a tension in Colorado between urban and rural communities where the former communities are increasing in population, straining water availability in an arid climate, and the latter are struggling to maintain their agricultural heritage. One interviewee explained that there were “not a lot of administrative changes” over the years “and [population] growth was sort of manageable and a lot of the communities, especially the older front range communities, had a long standing water supply that was adequate. And then we had a historic drought in 2002.” The magnitude of the drought, exacerbated by its continuation over multiple years, triggered a breakdown between individuals and collective actors (i.e. agencies and irrigation districts), revealing flaws in the administration of water that weren’t evident until the system was stressed. The scale of this problem was defined by interlinkages between river basins on both the east and west slopes and municipalities along the Front Range; participants focused primarily on the longer-term issue of population in their analysis of the problem's causes – not so much an issue of drought, then, but of water distribution.

The second frame that emerged in the data is a legal one, focused on water rights. As Colorado is a state governed by the doctrine of prior appropriation, or "first in time, first in right," drought often triggers various calls along a river basin by those who hold the most senior water rights, leaving junior rights holders and those without rights in a precarious position (Tarlock, 2000). In Colorado, groundwater and surface water are interlinked legally along a river, though almost all well rights are junior to surface water rights (Fischer & Ray, 1978). Any action taken that might injure a senior water rights holder's amount, timing, or water flow is forbidden and compels legal action to stop it. Because the legal system preserves their water use in times of scarcity at the expense of more junior appropriators, senior water rights holders often have a greater ability to meet their water needs during drought. Water rights highlight the acute nature of water scarcity during a temporary anomaly in the climate (e.g. drought), which might otherwise be manageable during years of "normal" precipitation and river flows. In this sense, then, the 2002-2005 drought started as a meteorological and hydrologic drought but transitioned in its second year to include agricultural drought (Wilhite & Glantz, 1985). Problem framings, then, are not always singular but multiple, and are dynamic in how they shift or are replaced as droughts change.

Element 2: Actors

Actors in this case include both individual agricultural producers, the state engineer, and the water court system. In Colorado, new groundwater users must obtain approval of a well augmentation plan that describes a method for replacing all depletions that affect surface water so as not to injure more senior water rights holders. Well augmentation plan permits are administered by the state engineer on a year-to-year basis (Hannay, 1980; Hobbs, 2007). As an institutional actor, the State bore the responsibility for maintaining the rules of prior appropriation to mitigate any injury to senior rights holders. Interviewees noted that before the 2002 drought, the system of water administration and oversight by the State seemed to be working fine. The State had been approving a significant number of augmentation plans in the years leading up to 2002 because there was sufficient water in the system to serve both senior (surface water) and junior (ground) water rights holders. An interviewee noted that "2002 set off a whole bunch of legal and administrative changes that rippled through the system for a while as people were trying to adjust to a significant multi-year drought." Early in the drought, well water gave junior water rights holders more agency in decisions made in response to drought for their own businesses; however, others' agency eventually superseded their own. In part, the drought itself exhibited agency in shaping decisions as it stretched from its first to its second and then third year, transitioning from a meteorological to hydrological and finally agricultural drought. This later framing emerged over time as a dominant framing of the problem, complicating water availability for both municipalities and agricultural producers.

By the second year of the drought, 2003, senior rights holders for surface water noticed that rivers were impacted by the proliferation of well augmentation plans, with lower flows than expected. This change in individual water rights along the river basin collectively constituted injury. As one interviewee explained, "Finally, the senior water rights holders said 'State, you can't approve these [plans] anymore. You don't have the authority.' And they took them to court." Decisions made in response to drought during its early years reflected a collection of individual and state actors triaging water shortages to keep agricultural businesses solvent. Wells allowed producers and the state joint capacity to maintain producers' livelihoods. It became clear as the drought continued, however, that senior water rights holders' agency to control drought decisions supplanted even that of the State's, with the courts maintaining ultimate accountability for ensuring prior appropriation enforcement. This example demonstrates how individual legal authority and the attendant resources of power and privilege of more senior water rights holders might overturn collective agency in experiencing drought. Further, it illustrates that those who have high capacity may not also have commensurate responsibility for the consequences of their decisions. It's unclear in this case how past experiences, backgrounds, personalities, and social networks affected drought responses, in part because such questions were not asked during interviews nor observed during community activities.

Element 3: Decisions in Response

In response to the length of the drought, more agricultural producers began to apply for well augmentation plans, relying almost exclusively on ground water. Groundwater is often used as a supplement rather than as the main source of water in their operations. When the drought stretched into its second year, 2003, the state engineer chose to continue to approve well augmentation plans, even as users were unable to replace their depletions. In part, applications continued because ongoing meteorological and hydrological drought made supplemental water crucial to producers' operations and replacements nearly impossible. The State's decision to continue to approve such plans could be seen as an issue of deliberative judgement, one that balances a more judicial issuance of plans in non-drought years with the survival of individual businesses in a multi-year drought.

Intervention by the courts in State operations was a response to a secondary issue emerging from drought, one motivated by complaints from individual senior water rights holders. While the court's response to stop well augmentation plans was not done directly in response to the drought itself, it was in response to other decisions that were. The economic context of the State's decisions – potential negative consequences for businesses unable to secure sources of water – and perhaps the political pressure to maintain the viability of agricultural heritage in the basin initially prompted excessive plan approvals. However, the legal context of prior appropriation left little discretion to the State or to junior water rights holders to make decisions in their collective best interests. That is, the decision context transitioned from a conscious decision to support producers economically (and perhaps politically) to the binary of a legal trigger of injury/no injury done to senior rights holders. Responses to drought in this case were spatially localized, involving only one river basin and a subset of producers within the state, and the time horizon for such decisions was short-term – involving the acute need for water in an unexpected multi-year drought. Unforeseen at the time were the ways the interactions of these actors and decisions generated cascading implications for the larger system over the next decade.

Element 4: Dynamic Interactions

Interactions between individual and institutional actors and their respective decision spaces created immediate and long-lasting feedbacks in the system. Interviewees noted that the State's decision to increase well augmentation plan permits during the first two years of the drought (2002-2003) meant that more groundwater was being used than normal, which created the possibility for agricultural producers to continue their operations during the water crisis. Actors involved in the network were not as well integrated as they perhaps believed given that surface water rights holders were not aware of the State's plans until their water was affected, a delay caused by attenuations in aquifer depletions. Unaccounted for in this network was the ecology of the water, its movement and participation in outcomes of decisions.

Cross-scale interactions generated unexpected consequences when water taken from wells resulted in significant reductions in surface water elsewhere in the system, triggering interventions by senior water rights holders that forced the cessation and rescinding of well augmentation permits by the State. Legal recognition of senior water rights revealed conflicts in the extent of shared problem spaces that preserved economic solvency for those with power but not for others. One interviewee pointed to continued impacts: "It's probably starting to slow down but for ten years after 2003, farm groups were coming with adjudicated augmentation plans and trying to recapture the ability to use their pumps." Unanticipated feedbacks occurred throughout the basin, dampening the ability of some producers to maintain their stock or recapture the ability to use their pumps after the drought had ended.

Case 9: Improving Resilience for the Rio Grande Coupled Human-Natural System

Case Summary

The Rio Grande is, first and foremost, a system that operates based on the storage of snowmelt water from the southern Rocky Mountains. The "economics" of this storage means that the system is generally buffered from the worst effects of the early stages of a drought because there is always water "left in the bank" in reservoirs for future need. Thus, one drought year has little catastrophic impact on the Rio Grande system; in contrast, in a system that has limited water storage capacity and relies heavily on direct precipitation, one drought year can lead to the loss of crops, livelihood, and habitat destruction. What little flow there was in the Rio Grande during 2017-2018 was almost entirely consumed before it left Colorado, thus, Colorado was not required to deliver any significant quantity of water to New Mexico. By extension, this affected the delivery of water from Elephant Butte to southern New Mexico and Texas, forcing downstream users to rely almost entirely on their own stored water reserves during 2018. This drought management case will describe the challenges, responses, and systems at play in the Colorado through the Middle Rio Grande region of New Mexico.

Element 1: Problem Framing

We use the dates "2017-2018" to designate the drought described here to capture both the meteorological drought and the human perception of drought, at that time. The drought began, meteorologically, in 2017, when some of the lowest recorded snowfall quantities occurred in the southern Rockies. However, because people in the area have experienced years when – as they described it – they had massive snowfall amounts "late in the season," there was little reason to believe that they might be facing a year with little spring runoff until the 2018 spring actually came and they found that they had little-to-no surface water being added into their storage systems. From a human perception standpoint, most people referred to this as "the drought of 2018," even though the precipitation deficit that began in 2017 (with a lack of snowfall during the winter of 2017-2018) caused the lack of water in 2018.

Element 2: Actors

Colorado has the rights to the majority of the surface water flowing in the Rio Grande, the vast majority of which goes to irrigate agriculture in the San Luis Valley (SLV). However, the SLV is also, historically, the site of unsustainable over-extraction of groundwater in the region. Due to unsustainable groundwater extraction in the region, the state of Colorado has threatened to suspend the groundwater wells licensed to pump in the SLV (as the State had already done in the South Platte region) if the SLV did not address the groundwater deficit in the region. In response, local groups created a number of self-governing "sub-districts" responsible for managing and incentivizing conservation efforts to fallow land, increase efficiency, and other efforts focused on recharging the groundwater supply. Between 2010-2017, the Rio Grande Water Conservancy District Special Improvement District #1's efforts resulted in recharging 350,000 acre feet of water to the basin, leading to narratives[2] about the success of self-government to solve water problems in the West. However, to get a sense of the impacts of the 2017-2018 drought, irrigators were forced to shift from conjunctive surface/groundwater strategies to exclusively relying on groundwater during the 2018 growing season, meaning that, although more than seven years of conservation had recharged 350,000 acre feet, one year of drought drew down 200,000 of those acre feet of water. Given that the SLV sub-districts are mandated to return over 1,000,000 acre feet of groundwater by 2030, this is a devastating blow to the region that could impact both its sovereignty and the livelihoods of the people who live in the region.

New Mexico's challenges and responses to the 2017-2018 drought were different, though there are certain similarities when we consider management for agriculture/irrigators. Federal water managers – particularly the Bureau of Reclamation (USBR) – play a critical role in managing water in the northern half of New Mexico's Rio Grande. USBR's primary mandate in the region is to ensure environmental flows and to assure the flow of water to New Mexico's prior and paramount (P&P) water rights holders, the Native American Pueblos in New Mexico. Several decades prior, the City of Albuquerque shifted away from relying solely on groundwater (due to risks of subsidence), and has since relied on conjunctive use of surface water rights from both the Rio Grande and from water imported through the San Juan-Chama diversion, which draws in water from outside of the basin in southwest CO. The Middle Rio Grande Conservancy District is a regional water management organization that manages the release, distribution, and monitoring of water to the agricultural irrigators from areas just north of Albuquerque all the way south to Elephant Butte Reservoir. Composing some 70,000 irrigated acres, the MRGCD relies heavily on water that is held in El Vado Reservoir near the Colorado border on the Rio Chama. El Vado Reservoir was built by the MRGCD in 1935, but has been owned by the U.S. Bureau of Reclamation since the 1950s. Water is released from El Vado when irrigators who own water rights make a "call" on the water, meaning that it flows nearly 300 miles to reach some of the southern-most water users.

[2] See Blankenbuehler 2016 for an example.

Element 3: Decisions in Response

Colorado: From a drought management standpoint, situations like those found in the SLV are deeply troubling because they leave managers with few-if-any options – before, during, or after a drought. Long-term conservation successes were almost entirely wiped out in a single drought. Successful measures to recharge groundwater were erased as irrigators were forced to take extreme actions to save their crops and livelihoods. While the goal of the SLV sub-district management has been to create a system that uses less water to ensure that the whole system is more resilient to stressors and more adaptive to new climate-driven fluctuations, the drought of 2017-2018 showed that even a one-year drought can reveal fatal flaws in a resource/drought management plan that does not take aggressive action to address the core problems in a system.

New Mexico: Challenges and responses to the 2017-2018 drought were different in the northern half of the Rio Grande in New Mexico, although agricultural and irrigation management similarities exist. Federal water managers from the USBR were able to release water that had been stored from the previous year (2017 snowmelt water) to meet the needs of the Pueblos and for Endangered Species Act (ESA)-listed species habitat – and it did so without too many problems. Indeed, even though there was little-to-no water entering the reservoirs in northern New Mexico from Colorado, the "bank" of water from the previous year was adequate enough so that there was no observable impact on P&P needs, uses, and consumption of water.

Albuquerque: During 2017-2018, Albuquerque had a choice between drawing 100% of their water from groundwater or releasing surface water imported from the Colorado River system as part of the San Juan-Chama Project and stored upstream in reservoirs, relying on a modified conjunctive use strategy. The city chose the latter, though not without some "internal" objections. Some managers suggested to us that there would have been great "psychological" value because the Rio Grande would have run dry through the city of Albuquerque (something that has not occurred, according to interviewees, "in several decades"), forcing residents and surrounding communities to actually face the visceral consequences of drought without actually going without municipal water (since it still would have been provided via groundwater). However, this approach was not seriously considered due to the political costs of letting the river go dry when the city had stored water, as well as concerns for the environmental costs of letting the riverine habitat dry up, which would have led to the loss of substantial populations of ESA-protected Rio Grande Silvery Minnow.

MRGCD**:** Similar to other actors in this system, the MRGCD was able to meet the water needs of the irrigators that compose the 70,000 acres of land under its purview. However, by the end of 2018, representatives from the MRGCD estimated that they only had 1,000 acre feet in stored water remaining in El Vado Reservoir. They assumed that they would be able to capture "a few thousand more" throughout the year, even without substantial snowpack, by drawing on unused water reserved for the Pueblos' use stored in either El Vado or Heron Reservoirs (something they were able to do in Oct. 2018). However, if a drought comparable to 2017-2018 continued for one more year, it would lead to significant "shared suffering" among all of the irrigators for which the MRGCD manages water.

Element 4: Dynamic Interactions

The situation with the environmental flows – primarily those necessary to keep the river wet enough to maintain the habitat for the ESA-listed Rio Grande Silvery Minnow – was complicated and involved a joint effort between the MRGCD, the USBR and the City of Albuquerque. In cooperation with the city of Albuquerque, which already voluntarily commits a certain amount of its surface water rights to ensure environmental flows for riparian habitat and ESA protection, the USBR and the MRGCD worked to optimize the releases of water to benefit ESA species.

In other words, if all parties agreed to the releases of water, then the Rio Grande would remain a flowing river across these managed reaches, reducing water losses across the system. Similarly, all actors agreed that, if there wasn't a shared vision and will to ensure that releases were timed to reduce water loss to any one entity, it was unlikely that there would have been much will to continue to focus on environmental flows given the increasing recognition, by late-February, that snowpack in the southern Rocky Mountains would not benefit from a late heavy snow season and that the region would be facing drought deficits.

References

Bruno, J. E., Jamsranjav, C., Jablonski, K. E., Dosamantes, E. G., Wilmer, H., & Fernández-Giménez, M. E. (2020). The landscape of North American Rangeland Social Science: A Systematic Map. *Rangeland Ecology & Management*, *73*(1), 181-193. https://doi.org/10.1016/j.rama.2019.10.005

Carparelli, C. (2016). *Beaverhead Watershed Drought Resiliency Plan*. http://www.beaverheadwatershed.org/?s=Beaverhead+Watershed+Drought+Resiliency+Plan

Crausbay, S. D., Ramirez, A. R., Carter, S. L., Cross, M. S., Hall, K. R., Bathke, D. J., Betancourt, J. L., Colt, S., Cravens, A. E., Dalton, M. S., Dunham, J. B., Hay, L. E., Hayes, M. J., McEvoy, J., McNutt, C. A., Moritz, M. A., Nislow, K. H., Raheem, N., & Sanford, T. (2017). Defining Ecological Drought for the Twenty-First Century. *Bulletin of the American Meteorological Society*, *98*(12), 2543-2550. https://doi.org/10.1175/BAMS-D-16-0292.1

Cravens, A. E. (2018). *How and Why Upper Colorado River Basin Land, Water, and Fire Managers Choose to Use Drought Tools (or Not)* [Open File Report](2018–1173). https://doi.org/10.3133/ofr20181173

Cravens, A. E., McEvoy, J., Zoanni, D., Crausbay, S. D., Ramirez, A., & Cooper, A. E. (2021). Integrating Ecological Impacts: Perspectives of Drought in the Upper Missouri River Headwaters, Montana, USA. *Weather, Climate, and Society*, *13*(2), 363-376.

Derner, J., Briske, D., Reeves, M., Brown-Brandl, T., Meehan, M., Blumenthal, D., Travis, W., Augustine, D., Wilmer, H., Scasta, D., Hendrickson, J., Volesky, J., Edwards, L., & Peck, D. (2018). Vulnerability of grazing and confined livestock in the Northern Great Plains to projected mid- and late-twenty-first century climate. *Climatic Change*, *146*(1), 19-32. https://doi.org/10.1007/s10584-017-2029-6

Derner, J. D., & Augustine, D. J. (2016). Adaptive Management for Drought on Rangelands. *Rangelands*, *38*(4), 211-215. https://doi.org/10.1016/j.rala.2016.05.002 (Drought on Rangelands: Effects and Solutions)

Doughty, R., Xiao, X., Wu, X., Zhang, Y., Bajgain, R., Zhou, Y., Qin, Y., Zou, Z., McCarthy, H., Friedman, J., Wagle, P., Basara, J., & Steiner, J. (2018). Responses of gross primary production of grasslands and croplands under drought, pluvial, and irrigation conditions during 2010–2016, Oklahoma, USA. *Agricultural Water Management*, *204*, 47-59. https://doi.org/10.1016/j.agwat.2018.04.001

Epstein, K., Haggerty, J. H., & Gosnell, H. (2019). Super-rich landowners in social-ecological systems: Opportunities in affective political ecology and life course perspectives. *Geoforum*, *105*, 206-209. https://doi.org/10.1016/j.geoforum.2019.05.007

Fernández-Giménez, M. E., Augustine, D. J., Porensky, L. M., Wilmer, H., Derner, J. D., Briske, D. D., & Stewart, M. O. (2019). Complexity fosters learning in collaborative adaptive management. *Ecology and Society, 24*(2). https://doi.org/10.2307/26796952

Fischer, W. H., & Ray, S. B. (1978). *A Guide to Colorado water law* (5).

Gray, B. J., Gill, D. A., & Friedman, J. R. (2019). Analogies and Natural Cycles in Climate Change Skepticism. *Human Organization, 78*(3), 181-191. https://doi.org/10.17730/0018-7259.78.3.181

Gutmann, M. P. (2018). Beyond Social Science History: Population and Environment in the US Great Plains. *Social Science History, 42*(1), 1-27. https://doi.org/10.1017/ssh.2017.43

Haigh, T. R., Otkin, J. A., Mucia, A., Hayes, M., & Burbach, M. E. (2019a). Drought Early Warning and the Timing of Range Managers' Drought Response. *Advances in Meteorology*. https://www.hindawi.com/journals/amete/2019/9461513/

Haigh, T. R., Schacht, W., Knutson, C. L., Smart, A. J., Volesky, J., Allen, C., Hayes, M., & Burbach, M. (2019b). Socioecological Determinants of Drought Impacts and Coping Strategies for Ranching Operations in the Great Plains. *Rangeland Ecology & Management, 72*(3), 561-571. https://doi.org/10.1016/j.rama.2019.01.002

Haigh, T. (2019c). *Rangeland Management during Drought: Assessing Social-Ecological and Cognitive Indicators of Ranchers' Adaptive Capacity*. [Doctoral dissertation, University of Nebraska - Lincoln].

Haigh, T., Hayes M., Smyth, J., Prokopy, L., Francis, C., & Burbach, M. (2021). Ranchers' use of drought contingency plans in protective action decision-making. *Rangeland Ecology & Management*, 74, 50-62. https://doi.org/10.1016/j.rama.2020.09.007.

Hamilton, T. W., Ritten, J. P., Bastian, C. T., Derner, J. D., & Tanaka, J. A. (2016). Economic Impacts of Increasing Seasonal Precipitation Variation on Southeast Wyoming Cow-Calf Enterprises. *Rangeland Ecology & Management, 69*(6), 465-473. https://doi.org/10.1016/j.rama.2016.06.008

Hannay, F. (1980). Recent Developments in Colorado Groundwater Law. *Denver Law Journal, 58*(4), 801-824. https://heinonline.org/HOL/P?h=hein.journals/denlr58&i=835

Henderson, J., Dilling, L., Morss, R., Wilhelmi, O., & Rick, U. (2021). "We got in the pilot program to learn from it:" Features of Social Learning in Drought Contexts Along the Arkansas River in Colorado. *Weather, Climate, and Society*, *13*(4), 729-741.

Hobbs, G. (2007). *An Overview of Colorado Groundwater Law* (Colorado Ground-Water Association Newsletter, Issue. https://elbertcounty.net/blog/wp-content/uploads/2007/10/hobbs_in_cgwa_summer_2007_.pdf

Kachergis, E., Derner, J. D., Cutts, B. B., Roche, L. M., Eviner, V. T., Lubell, M. N., & Tate, K. W. (2014). Increasing flexibility in rangeland management during drought. *Ecosphere, 5*(6), 1-14. https://doi.org/10.1890/ES13-00402.1

Knutson, C., & Haigh, T. (2013). A Drought-Planning Methodology for Ranchers in the Great Plains. *Rangelands, 35*(1), 27-33. https://doi.org/10.2111/RANGELANDS-D-12-00075.1.

Koch, J., Friedman, J. R., Paladino, S., Plassin, S., & Spencer, K. (2019). Conceptual modeling for improved understanding of the Rio Grande/Río Bravo socio-environmental system. *Socio-Environmental Systems Modelling, 1*, 16127-16127. https://doi.org/10.18174/sesmo.2019a16127

Marshall, N. A., & Smajgl, A. (2013). Understanding Variability in Adaptive Capacity on Rangelands. *Rangeland Ecology & Management, 66*(1), 88-94. https://doi.org/10.2111/REM-D-11-00176.1

McClaran, M. P., Butler, G. J., Wei, H., & Ruyle, G. D. (2015). Increased preparation for drought among livestock producers reliant on rain-fed forage. *Natural Hazards, 79*(1), 151-170. https://doi.org/10.1007/s11069-015-1834-3

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), 14. https://doi.org/10.3390/resources7010014

Montana Drought Demonstration Partners. (2015). *A Workplan for Drought Resilience in the Missouri Headwaters Basin: A National Demonstration Project*. http://dnrc.mt.gov/divisions/water/management/docs/surface-water-studies/workplan_drought_resilience_missouri_headwaters.pdf

Moore, M. A. (2018). *Understanding rancher's beliefs and behaviors regarding drought and natural water storage in southwest Montana* [Thesis, Montana State University - Bozeman, College of Letters & Science]. https://scholarworks.montana.edu/xmlui/handle/1/15094

Pilgeram, R. (2007). 'Ass-kicking' Women: Doing and Undoing Gender in a US Livestock Auction. *Gender, Work & Organization, 14*(6), 572-595. https://doi.org/10.1111/j.1468-0432.2007.00372.x

Plassin, S., Koch, J., Paladino, S., Friedman, J.R., Spencer, K., & Vache, K (2020). A Socio-Environmental Geodatabase for Integrative Research in the Transboundary Rio Grande/Río Bravo Basin. *Scientific Data, 7*, 80. https://doi.org/10.1038/s41597-020-0410-1.

Plassin, S., Koch, J., Wilson, M., Neal, K., Friedman, J.R., Paladino, S., & Worden, J. (2021). Multi-scale fallow land dynamics in a water-scarce basin of the U.S. Southwest. *Journal of Land Use Science, 16*(3), 291-312. https://doi.org/10.1080/1747423X.2021.1928310.

Raheem, N., Cravens, A. E., Cross, M. S., Crausbay, S., Ramirez, A., McEvoy, J., Zoanni, D., Bathke, D. J., Hayes, M., Carter, S., Rubenstein, M., Schwend, A., Hall, K., & Suberu, P. (2019). Planning for ecological drought: Integrating ecosystem services and vulnerability assessment. *Wiley Interdisciplinary Reviews: Water*, e1352. https://doi.org/10.1002/wat2.1352

Roche, L. M. (2016). Adaptive Rangeland Decision-Making and Coping with Drought. *Sustainability, 8*(12), 1334. https://doi.org/10.3390/su8121334

Sayre, N. F. (2018). Race, Nature, Nation, and Property in the Origins of Range Science. In R. Lave, C. Biermann, & S. N. Lane (Eds.), *The Palgrave Handbook of Critical Physical Geography* (pp. 339-356). Springer International Publishing. https://doi.org/10.1007/978-3-319-71461-5_16

Stiles, C. J., & Wickham, E. (2019). *Drought Resiliency Planning Prepares Stakeholders for New Conditions*. https://toolkit.climate.gov/case-studies/drought-resiliency-planning-prepares-stakeholders-new-conditions

Svoboda, M., Smith, K. H., Widhalm, M., Woudenberg, D., Knutson, C., Angel, J., Spinar, M., Shafer, M., McPherson, R., & Lazrus, H. (2011). Drought-Ready Communities: A Guide to Community Drought Preparedness. 55.

Tarlock, D. (2000). Prior appropriation: Rule, principle, or rhetoric? *North Dakota Law Review, 76*, 881-910.

Torell, L. A., Murugan, S., & Ramirez, O. A. (2010). Economics of Flexible Versus Conservative Stocking Strategies to Manage Climate Variability Risk. *Rangeland Ecology & Management, 63*(4), 415-425. https://doi.org/10.2111/REM-D-09-00131.1

USBR. (2019). *WaterSMART Drought Response Program Framework*. https://www.usbr.gov/drought/docs/2019/FY19DroughtResponseProgramFramework.pdf

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N., & Van Lanen, H. A. J. (2016). Drought in the Anthropocene. *Nature Geoscience, 9*(2), 89-91. https://doi.org/10.1038/ngeo2646

VanWinkle, T. N., & Friedman, J. R. (2017). What's good for the soil is good for the soul: scientific farming, environmental subjectivities, and the ethics of stewardship in southwestern Oklahoma. *Agriculture and Human Values, 34*(3), 607-618. https://doi.org/10.1007/s10460-016-9750-z

VanWinkle, T. N., & Friedman, J. R. (2018). American Indian Landowners, Leasemen, and Bureaucrats: Property, Paper, and the Poli-Technics of Dispossession in Southwestern Oklahoma. *American Indian Quarterly, 42*(4), 508-533. https://www.jstor.org/stable/10.5250/amerindiquar.42.4.0508

VanWinkle, T. N., & Friedman, J. R. (2019). Between Drought and Disparity: American Indian Farmers, Resource Bureaucracy, and Climate Vulnerability in the Southern Plains. *Journal of Agriculture, Food Systems, and Community Development, 9*(B), 53-68. https://doi.org/10.5304/10.5304/jafscd.2019.09B.022

Wilhite, D., Hayes, M., Knutson, C., & Wilhite, D. (2005). Drought Preparedness Planning: Building Institutional Capacity. In D. Wilhite (Ed.), *Drought and Water Crises: Science, Technology, and Management Issues* (Vol. 107, pp. 93-136). CRC Press. http://www.crcnetbase.com/doi/abs/10.1201/9781420028386.ch5

Wilhite, D. A., & Glantz, M. H. (1985). Understanding: the Drought Phenomenon: The Role of Definitions. *Water International, 10*(3), 111-120. https://doi.org/10.1080/02508068508686328

Wilmer, H., Augustine, D. J., Derner, J. D., Fernández-Giménez, M. E., Briske, D. D., Roche, L. M., Tate, K. W., & Miller, K. E. (2018). Diverse Management Strategies Produce Similar Ecological Outcomes on Ranches in Western Great Plains: Social-Ecological Assessment. *Rangeland Ecology & Management, 71*(5), 626-636. https://doi.org/10.1016/j.rama.2017.08.001 (Integrated Social-Ecological Approaches to Silvopastoralism)

Wilmer, H., & Fernández-Giménez, M. E. (2015). Rethinking rancher decision-making: a grounded theory of ranching approaches to drought and succession management. *The Rangeland Journal, 37*(5), 517-528. https://doi.org/10.1071/RJ15017

Wilmer, H., & Fernández-Giménez, M. E. (2016a). Some years you live like a coyote: Gendered practices of cultural resilience in working rangeland landscapes. *Ambio, 45*(3), 363-372. https://doi.org/10.1007/s13280-016-0835-0

Wilmer, H., & Fernández-Giménez, M. E. (2016b). Voices of Change: Narratives from Ranching Women of the Southwestern United States. *Rangeland Ecology & Management, 69*(2), 150-158. https://doi.org/10.1016/j.rama.2015.10.010

Wilmer, H., Fernández-Giménez, M. E., Ghajar, S., Taylor, P. L., Souza, C., & Derner, J. D. (2019). Managing for the middle: rancher care ethics under uncertainty on Western Great Plains rangelands. *Agriculture and Human Values, 37*, 699-718. https://doi.org/10.1007/s10460-019-10003-w

World Meteorological Organization Global Water Partnership. (2014). *National drought management policy guidelines: a template for action* (D. A. Wilhite, Ed.).