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Review

Unfamiliar Territory: Emerging Themes for Ecological Drought Research and Management

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SUMMARY

Novel forms of drought are emerging globally, due to climate change, shifting teleconnection patterns, expanding human water use, and a history of human influence on the environment that increases the probability of transformational ecological impacts. These costly ecological impacts cascade to human communities, and understanding this changing drought landscape is one of today's grand challenges. By using a modified horizon-scanning approach that integrated scientists, managers, and decision-makers, we identified the emerging issues in ecological drought that represent key challenges to timely and effective responses. Here we review the themes that most urgently need attention, including novel drought conditions, the potential for transformational drought impacts, and the need for anticipatory drought management. This horizon scan and review provides a roadmap to facilitate the research and management innovations that will support forward-looking, co-developed approaches to reduce the risk of drought to our socio-ecological systems during the 21st century.

INTRODUCTION

Many grand environmental challenges, from global food security to sustainable development, are exacerbated by natural hazards and disasters, the vast majority of which are water related.[1] Drought is the leader among physical hazards in terms of consequences, with 2 billion people affected and 11 million deaths since 1900.[2] There is no agreed upon precise definition of drought;[3] however, it is functionally understood as a temporary aberration in climate that results in insufficient water to meet the requirements of people and nature.[4,5] Historically, the frequency, intensity, duration, and extent of droughts were determined primarily by the variability in large-scale climate drivers that include sea-surface temperatures in major oceanic basins, ocean–atmosphere interactions such as the El Niño–Southern Oscillation (ENSO), internal atmospheric variability, and land–atmosphere feedbacks.[6,7] Typically these meteorological drought processes would trigger a drought onset through a deficit in precipitation. The drought could then intensify if that deficit continues to grow or other factors such as temperature, winds, radiation, and/or humidity exacerbates the effects.[8] Now, drought is entering unfamiliar territory. Today, droughts are increasingly influenced by combinations of anthropogenic climate change, increasing human water use, and expanding land-use change.[7,9–12] As a result, novel forms of drought are emerging globally, challenging our ability to anticipate and manage drought impacts.

These novel forms of drought threaten ecosystems (Figure 1). As a result, ecological droughts (Figure 1B), or droughts that drive perceptible ecosystem changes and reductions in the services they provide,[13–16] are increasingly evident: for example, as widespread fish kills in streams of the western United States,[17] massive elephant mortality in Africa,[18] collapse of hydrological ecosystems in Australia,[19] and widespread wildfire and tree

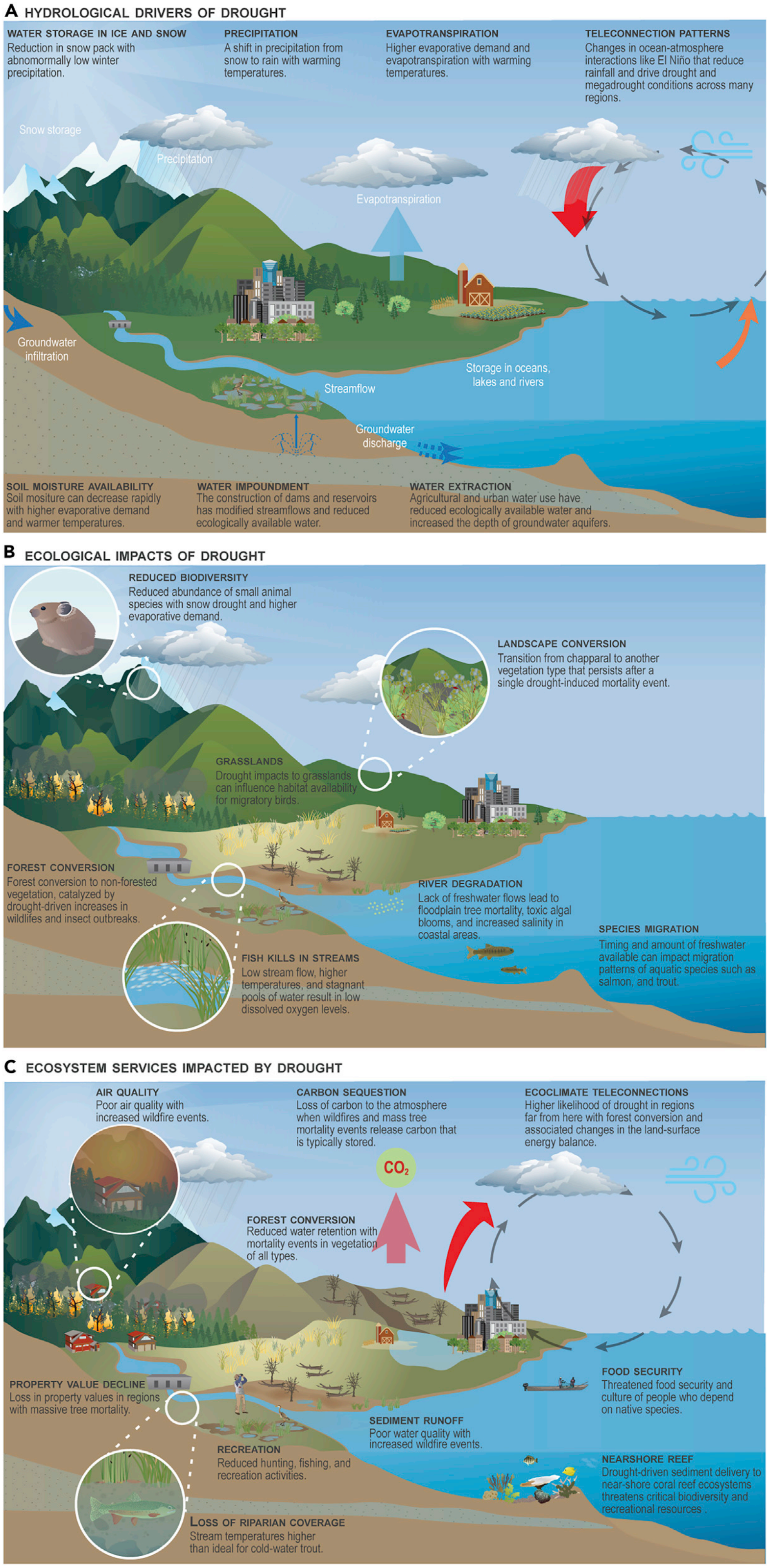


Figure 1. Depiction of Ecological Drought

(A–C) Depiction of (A) the hydrological drivers of novel drought conditions, (B) ecological drought impacts, and (C) the ecosystem services that are altered or lost with ecological drought impacts.

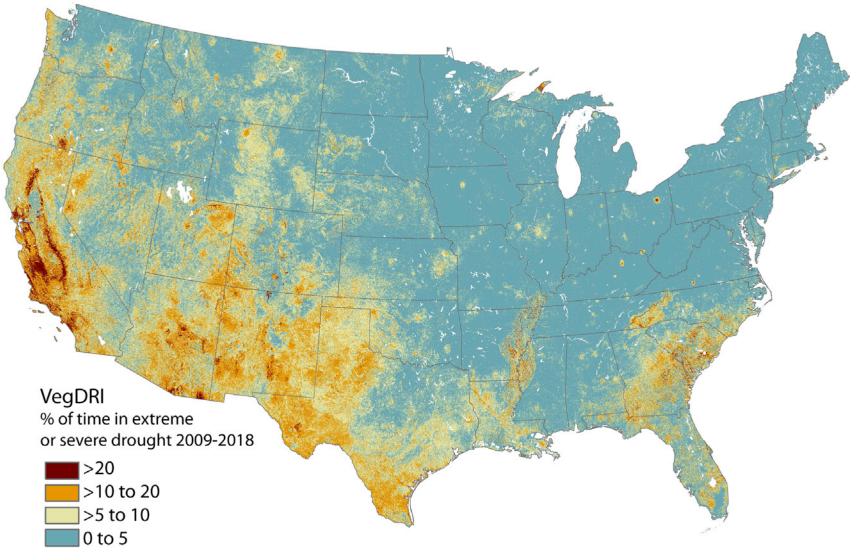


Figure 2. Footprint of Recent Drought Impacts

The footprint of recent drought-induced impacts to vegetation, represented as the percent of time vegetation has been under severe or extreme drought stress since mid-2009, based upon the near-real-time weekly depiction of drought-induced vegetation stress across the contiguous United States from the Vegetation Drought Response Index (VegDRI, https://vegdri.unl.edu/).

mortality events[20] that threaten to convert forests to non-forested vegetation types.[21] The footprint of ecological drought can be large, for example in the last decade in the contiguous United States, much of the vegetation in southern and western regions has been under extreme or severe drought stress for more than 10%–20% of the time (Figure 2). Ecological droughts like these are becoming more commonplace as anthropogenic climate change drives more extreme high temperatures, greater evaporative demand (a "thirstier" atmosphere), faster onset, longer duration, and altered timing of drought conditions that cross ecological thresholds, e.g., Smith[13,14] and Allen et al.[20] Meanwhile, growing human populations are adapting by modifying hydrological processes through extracting and impounding water, creating the potential to drive drought conditions either in concert with, or independent of climate-driven drought (Figure 1A; e.g., Van Loon et al.[12]). These relatively new drivers of drought exposure interact with a legacy of historical land use and natural resource management (e.g., fire suppression, invasive species) that affect the sensitivity of ecosystems to drought impacts.[22–24] To add insult to injury, ecological recovery processes after drought are now occurring under unfamiliar climates, resulting in potentially irreversible shifts in the species composition of plants and animals that recolonize after drought, i.e., transformational drought impacts (e.g., Smith,[13,14] Crausbay et al.,[16] and Jacobsen and Pratt[25]). In this way, drought joins an array of pathways, including other disturbances like wildfire,[26] for how climate change can drive widespread ecological transformation.

Drought impacts to ecosystems cascade through social-ecological systems as the services ecosystems offer to people are severely altered or lost (Figure 1C). For example, the "Millennium Drought" (2002–2010) in Australia caused unanticipated losses to key services provided by hydrological ecosystems in the Murray–Darling basin, exceeding 800 million AUD, as resources were spent to replace these services and adapt to transformational drought impacts.[19] In regions with chronic issues related to food security, access to clean drinking water, and/or infectious disease outbreaks, droughts can exacerbate these problems and precipitate and deepen public health crises. Drought impacts to vegetation, from widespread forest mortality to massive wildfires and vegetation conversion, alter regulating services like soil stability, carbon storage, water quality, and water retention.[27] Healthy ecosystems also support livelihoods, and provide a foundation for economic maintenance and growth. For example, the United States Bureau of Economic Analysis found that in 2017, outdoor recreation grew faster than the United States economy as a whole and accounted for $427 billion (2.2%) of the nation's gross domestic product.[28] Given our changing drought landscape, and the clear connection between ecological drought, ecosystem services, and healthy economies (Figure 1; e.g., Raheem et al.[27]), managing these unfamiliar forms of drought and the costly ecological impacts that cascade to human communities is an emerging grand challenge.

We used a modified (two-phase) horizon-scanning approach to understand the context and constraints that underlie the emerging challenge of managing ecological drought in the 21st century (Box 1, also see Note S1). Horizon scanning is a systematic approach for exploring a topic that is looming, so that the needed engagement is identified early.[29] Our horizon-scanning approach integrates insights from stakeholders, decision-makers, and scientists to effectively facilitate the science and management innovations that are needed to reduce the risks of drought to our social-ecological systems. We found consensus on three emerging themes in ecological drought that need immediate attention: (1) novel drought conditions, (2) transformational drought impacts, and (3) anticipatory drought management. This review aims to provide a more in-depth discussion of key research and management gaps around these three themes that emerged from our horizon-scanning process.

NOVEL DROUGHT CONDITIONS

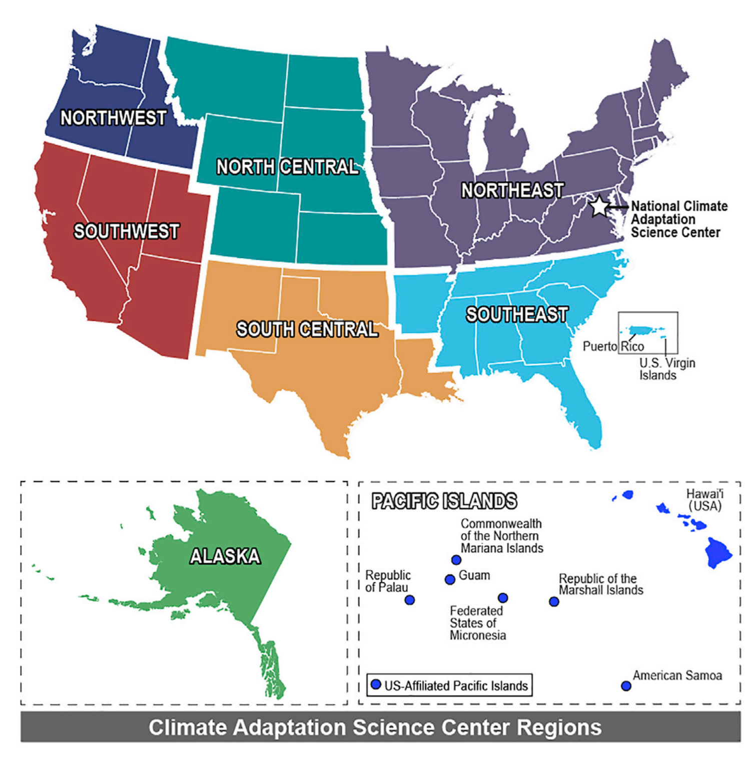
Our first theme focuses on novel forms of drought and the need for a broader perspective on the diverse drivers of today's water deficits. Here we focus on how anthropogenic climate change, changing teleconnection patterns, and human water and land use drive unfamiliar drought conditions.

Novel Forms of Drought with Climate Change

Anthropogenic climate change is altering drought through increased temperature, associated increases in evaporative demand, and/or decreased precipitation or altered precipitation

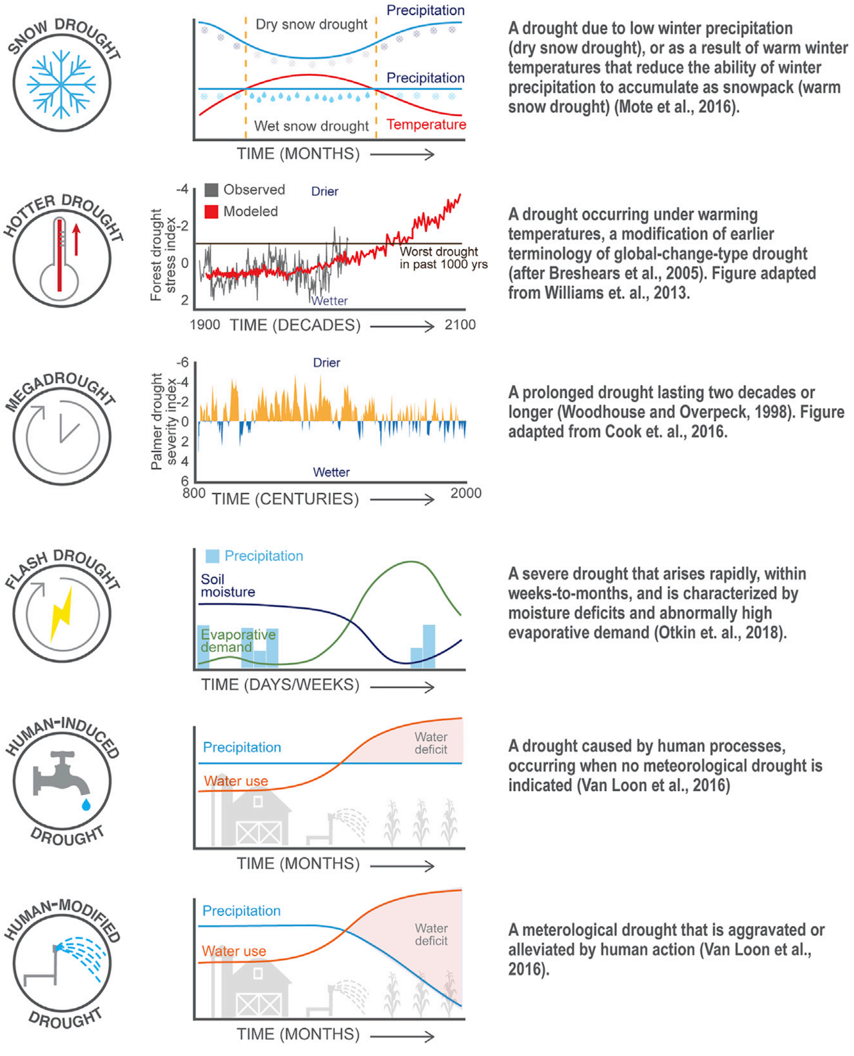
Box 1. A Co-produced Horizon-Scanning Approach to Facilitate the Science and Management Innovations Needed for 21st-century Droughts

Horizon scanning is a systematic approach for exploring an emerging topic that is looming, with the goal of identifying opportunities early enough to facilitate the needed engagement by scientists, managers, and policy makers.[27] Horizon scans engage scientific experts, through interviews, questionnaires, or workshops, and can integrate state-of-science reviews that identify key research gaps to effectively highlight emerging issues before they become costly surprises.[27] Horizon scans are often conducted only with expert scientists, but we included scientists, managers, and decision-makers together to root our horizon scan in the values of co-production, or co-creation of knowledge,[30,31] user-centered design, or human-centered design. Today's grand challenges are more effectively met when scientists, managers, and decision-makers engage collaboratively to develop the needed innovations to solve critical, emerging problems.



We carried out a two-phase, modified horizon scan with the United States Geological Survey's National Climate Adaptation Science Center by first convening a series of regional workshops with expert drought scientists, managers, and decision-makers to reveal the emerging topics in ecological drought. These workshops were held in each of the eight Regional Climate Adaptation Science Centers (CASCs), which cover the entire continental United States, Hawai'i, Alaska, the United States Affiliated Pacific Islands, and the United States Caribbean (map below—the eight-region CASC network covers the entire continental United States, Alaska, Hawai'i, the United States Affiliated Pacific Islands, and the United States Caribbean). Although these workshops and the pool of expert scientists, managers, and decision-makers were all centered in the United States, they do encompass a wide range of ecosystem types and drought regimes represented globally. We followed regional workshops with a survey to workshop attendees to rank these topics that the workshops generated, as well as provide additional emerging topics. We used a mini-Delphi technique with a subset of respondents to gain consensus on the highest-ranked topics (see Note S1). Finally, we integrated a literature review with this horizon-scanning approach to identify key research and management gaps for each high-ranking topic.

timing (Figures 1A and 3; e.g., Dai[32] and Naumann et al.[33]). Warming exacerbates drought through effects on (1) evaporative demand, (2) partitioning between latent and sensible heat fluxes, (3) phase change of water (i.e., snow to rain, snowmelt), and (4) changing atmospheric circulation, particularly in summer,[34] resulting in an increase in snow droughts, hotter droughts, and flash droughts (Figures 1 and 3). Through these processes, rising temperatures associated with climate change are projected to affect drought frequency, severity, duration, seasonality, and geographic extent of affected areas in ways that deviate from the instrumental and proxy records of the past millennium.[9,33,35]



A drought due to low winter precipitation (dry snow drought), or as a result of warm winter temperatures that reduce the ability of winter precipitation to accumulate as snowpack (warm snow drought) (Mote et al., 2016).

A drought occurring under warming temperatures, a modification of earlier terminology of global-change-type drought (after Breshears et al., 2005). Figure adapted from Williams et. al., 2013.

A prolonged drought lasting two decades or longer (Woodhouse and Overpeck, 1998). Figure adapted from Cook et. al., 2016.

A severe drought that arises rapidly, within weeks-to-months, and is characterized by moisture deficits and abnormally high evaporative demand (Otkin et. al., 2018).

A drought caused by human processes, occurring when no meteorological drought is indicated (Van Loon et al., 2016)

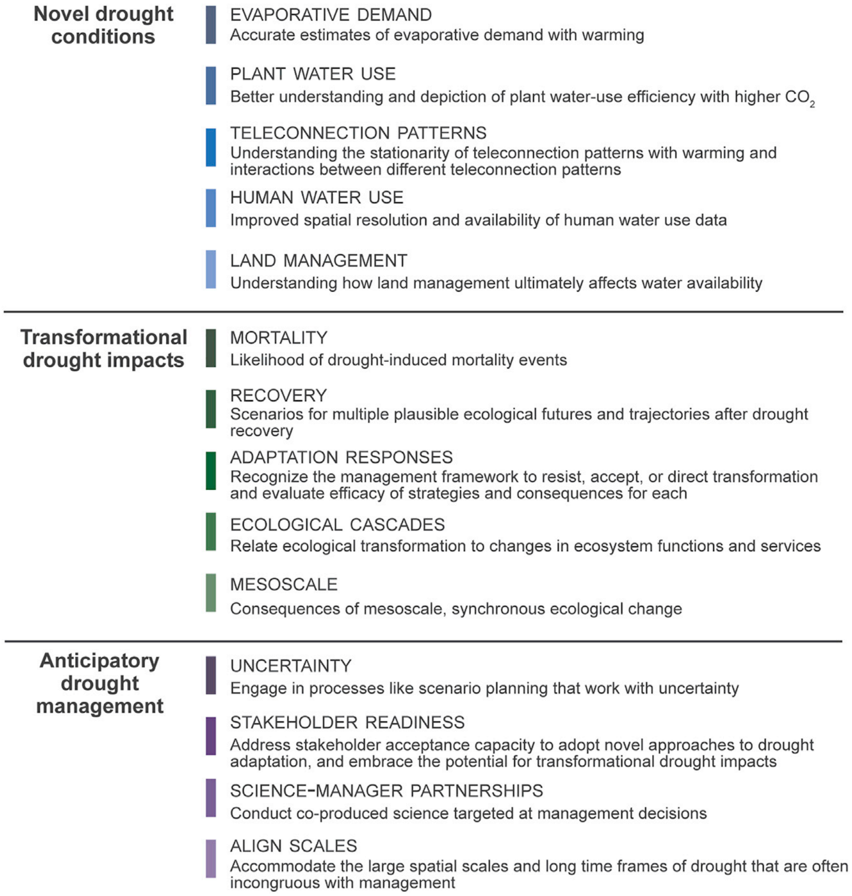
A meterological drought that is aggravated or alleviated by human action (Van Loon et al., 2016).

Figure 3. Definitions of Various Novel Drought Conditions

Definitions and graphic depictions for novel drought conditions including snow drought, hotter drought, megadrought, flash drought, and human-modified or human-induced drought. Figure for hotter drought is adapted with permission from Williams et al.,[36] which combines tree-ring records across the southwestern United States from 1,000–2,007 CE to develop an index of annual forest stress that integrates rainfall and temperature. The horizontal line in the hotter drought figure references Forest Drought-Stress Index (FDSI) values from the most severe megadrought in the southwestern United States over the past 1,000 years (1572–1587). Figure for megadrought is adapted with permission from Cook et al.,[37] which compiles tree-ring records across multiple regions in North America to provide average Palmer Drought Severity Index (PDSI) time series from the updated version of the North American Drought Atlas, and this example time series is for the United States Central Plains.

Snow drought, a reduction in how much and how long winter (cold-season) precipitation is stored as snow (Figure 3), can occur as a result of low winter precipitation (*dry* snow drought) or when precipitation amounts are unchanged, but warmer winter temperatures prevent winter precipitation from accumulating as a snowpack (*warm* snow drought). Dry snow droughts have become more frequent, more severe, and longer in duration in certain regions, such as the Pacific Northwest United States[38] Warm snow droughts occur with shifts in the phase of precipitation from snow to rain, changes in the timing of accumulation (e.g., later accumulation), and earlier spring melt.[39] Climate models project an increasing likelihood of warm snow droughts under climate change.[40,41] Collectively, dry and warm snow droughts can drive pronounced impacts on (1) freshwater ecosystems by influencing the seasonality and amount of runoff [42–44] and subsurface recharge that contributes significantly to streamflow in summer or low flow periods[45,46] as well as (2) terrestrial ecosystems, such as increasing wildfire risk, with potential for feedback loops, as burned areas are more likely to experience warm snow droughts due to loss of thermal protection of snowpack by the forest canopy.[47–49] Wildlife species that depend on snow for thermal protection or other habitat functions (subnivean habitats)[50,51] or winter camouflage, and recreational values associated with snow pack, are additional key risks associated with this emerging change in drought regimes.

Although the concept of *hotter droughts* (Figure 3) under climate change might not be surprising, this topic is an emerging focus because hotter droughts can have broad-reaching consequences for ecosystems. First, hotter temperatures exacerbate droughts driven by the natural variability of rainfall. For example, the 2013–2016 Caribbean drought was associated with an El Niño-driven lack of rainfall, which is not unusual in the region.[52] The novel aspect of this Caribbean drought was that it emerged as the most severe and most extensive drought on record since at least 1950, and perhaps the past century, because of temperature-driven increases in evaporative demand.[52] Recent hotter droughts with increases in evaporative demand have crossed ecological thresholds: for example, noticeably increasing tree mortality in several regions across the globe, and increasing the global likelihood of tree mortality when and where water is limiting.[20,36] Rising global surface temperatures will increase vapor pressure deficit (VPD, the difference between the saturation vapor pressure and the actual vapor pressure) in a nonlinear way, where VPD is increasingly higher with warming temperatures.[53] Increased VPD substantially affects basic plant and animal physiological processes, leading to increased mortality.[54,55] Warmer air temperatures will also lead to earlier green-up in vegetation and therefore increased water uptake by plants (actual evapotranspiration) that, in the absence of increased precipitation, will promote lower soil moisture during the current peak of the growing season.[56,57] These increasing soil moisture deficits could in turn reduce actual evapotranspiration, which will further increase sensible heat fluxes, ambient



Novel drought conditions

EVAPORATIVE DEMAND
Accurate estimates of evaporative demand with warming

PLANT WATER USE
Better understanding and depiction of plant water-use efficiency with higher CO_2

TELECONNECTION PATTERNS
Understanding the stationarity of teleconnection patterns with warming and interactions between different teleconnection patterns

HUMAN WATER USE
Improved spatial resolution and availability of human water use data

LAND MANAGEMENT
Understanding how land management ultimately affects water availability

Transformational drought impacts

MORTALITY
Likelihood of drought-induced mortality events

RECOVERY
Scenarios for multiple plausible ecological futures and trajectories after drought recovery

ADAPTATION RESPONSES
Recognize the management framework to resist, accept, or direct transformation and evaluate efficacy of strategies and consequences for each

ECOLOGICAL CASCADES
Relate ecological transformation to changes in ecosystem functions and services

MESOSCALE
Consequences of mesoscale, synchronous ecological change

Anticipatory drought management

UNCERTAINTY
Engage in processes like scenario planning that work with uncertainty

STAKEHOLDER READINESS
Address stakeholder acceptance capacity to adopt novel approaches to drought adaptation, and embrace the potential for transformational drought impacts

SCIENCE-MANAGER PARTNERSHIPS
Conduct co-produced science targeted at management decisions

ALIGN SCALES
Accommodate the large spatial scales and long time frames of drought that are often incongruous with management

Figure 4. Science and Management Gaps for Ecological Drought
The science and management gaps that need to be addressed, based on our review of the three themes that emerged from our modified horizon scan: (1) novel drought conditions, (2) transformational drought impacts, and (3) anticipatory drought management.

temperatures, and evaporative demand as the growing season progresses.[58] As a consequence, hotter seasonal droughts will occur when drier soils encounter unusual precipitation deficits.[59] Ultimately, hotter drought has substantial impacts on ecosystems through higher evaporative demand, increased VPD, and reduced soil moisture.

Another manifestation of droughts that have received much attention recently are flash droughts, which are characterized by "sudden onset and rapid intensification of drought conditions with severe impacts."[60,61] Although flash droughts (Figure 3) are not necessarily associated with anthropogenic climate change, it is likely that these events will occur more frequently in a warmer climate, suggesting an emerging need for improved drought preparation. The predominant characteristic of flash droughts is their rapid rate of intensification, developing from near-normal to extreme conditions within weeks to months[60–62] that can even develop within a water year (Oct 1–Sept 30) with above-normal precipitation.[44] These events are typically driven by greater than normal evaporation caused by high atmospheric evaporative demand (VPD, potential evapotranspiration, and precipitation minus potential evapotranspiration) and solar radiation (low cloudiness), which leads to a rapid depletion of soil moisture.[61] Although flash droughts develop rapidly, they are not necessarily short in duration and could last as long as arid meteorological conditions persist. For drought management and preparedness in the 21st century, the separate classification of flash droughts is particularly relevant because of the rapid development and potential surprise they present when precipitation levels are normal.

Megadroughts[63] (Figure 3) are droughts lasting for at least two decades, and although they have not been part of Earth's recent instrumental history, they are of increasing concern. Some close approximations to a megadrought have occurred in the recent historical record. For example, the 1930s Dust Bowl drought in the United States lasted approximately eight years, and the combined effects from drought and land-management practices resulted in severe drought conditions that affected more than 400,000 km^2.[64] Crops were destroyed, grasslands were lost, livestock suffocated from dust, people were sickened with "dust pneumonia," and ultimately over 2.5 million people migrated westward out of the Plains states.[65] Megadroughts, like the near megadrought of the Dust Bowl, can cover multiple regions and manifest as pancontinental drought.[66–68] Now, evidence from general circulation models (GCMs) suggest that warming from climate change is increasing evaporative demand and adding substantially to the likelihood of megadrought in some regions in the next few decades.[7,69,70] A recent study of summer soil moisture conditions by Williams et al.[71] found that the 2000–2018 period in southwestern North America was the driest 19-year period since the megadrought of the late 1500s. Their estimation finds near-equal contributions from natural variability and anthropogenic warming to the severity of the 2000–2018 drought.

Filling knowledge gaps is critical to adequately anticipate future novel drought conditions in a warming world (Figure 4). First, a better understanding of how to accurately estimate evaporative demand given likely changes in water and energy balance under current and future warming is critical.[72–76] Drought projections are highly sensitive to the different ways of measuring evaporative demand, specifically whether the formulation for potential evapotranspiration is energy only, temperature based, or physically based.[75,77] It is well recognized that evapotranspiration is a considerable energy sink, and energy balance calculations in climate models take this into account when estimating temperature changes and consequently VPDs.[78] When those temperature estimates are applied after the fact in a hydrological model, the effects of climate change on evapotranspiration and ultimately soil moisture are overestimated, sometimes quite substantially.[77,79] Importantly, hotter temperatures and higher evaporative demand have direct physiological effects on plant and animal species[54,55] that are distinct from the effects of reduced soil moisture. Although temperature effects could be secondary to the primary drought effect,[80] the added stress of temperature can be important, e.g., Adams et al.[81], emphasizing the need for tools that help land managers anticipate this novel form of drought. Second, our understanding of future drought is limited by our understanding of how vegetation responds to drought given elevated CO_2, because this key driver of climate change is also an important plant resource, and when its concentration increases, plants can potentially respond in ways that increase their water-use efficiency.[57,73,74,82,83] Whether or not models incorporate an effect of CO_2 on a plant's water-use efficiency can fundamentally change the predicted impact of climate change on future drought occurrence.[84] Wider use of the emerging trait- and process-based models of how plants optimize carbon gain and hydraulic risk could provide a way forward.[85–87]

Altered Teleconnection Patterns

Drought is an inherent part of the climate system, often driven by familiar and recurring patterns of atmospheric pressure and ocean circulation anomalies that span vast geographies, i.e., teleconnection patterns. Perhaps the most well-known teleconnection pattern, ENSO, drives drought across more than twice the land area in the global tropics during strong versus weak El Niño events.[88] Understanding the link between teleconnection patterns and global weather patterns has allowed us to successfully predict drought for decades, e.g., Ropelewski and Halpert.[89] However, recent research suggests broad changes to teleconnection patterns with recent warming of the lower atmosphere and sea surface.[90–93] There is an indication that extreme ENSO events could become more frequent with warming,[94] and evidence of a doubling in the frequency of extreme El Niño events, with little to no change in extreme La Niña frequency under 1.5°C of warming.[93] Further, ENSO-driven climate variations are likely to affect larger areas than they have during the historical record.[92] Changes in these teleconnection patterns can result in broad changes to drought frequency, intensity, spatial extent, and duration and can result in greater spatiotemporal synchrony in biological processes with the potential to destabilize ecosystems.[95]

Importantly, changing teleconnection patterns can also alter the potential for megadrought in the 21st century. Because megadroughts are unprecedented in the historical instrumental record, it is difficult to understand what drives them. But megadroughts were common during some time periods in the paleorecord, which provides important insights. There was a strong clustering of multidecadal megadrought events in the western United States during the Medieval Climate Anomaly, a warm period ~1,000 years ago. Megadroughts in paleorecords across the western United States are consistently associated with 10- to 30-year periods of frequent cool ENSO (La Niña) conditions as well as a persistently warm Atlantic Multidecadal Oscillation, and given a sufficiently long period of time, these events are inevitable.[69,96–98] Evidence from paleorecords suggests that internal climate variability and teleconnection patterns play the strongest role in megadrought occurrence, and broad-scale temperature changes, like the Earth is experiencing now, are not necessarily associated.[67,68,98] Understanding the likelihood of megadrought exemplifies the challenges and complexities of anticipating and managing novel droughts in the 21st century. Despite the paleoclimatological evidence that megadrought is primarily controlled by teleconnection patterns, the likelihood of megadrought has largely been analyzed as a function of increased evaporative demand with a warming climate.[70] Yet, as we discussed above, our ability to accurately estimate evaporative demand in a warming world is limited, and it is unknown how changes in evaporative demand might interact with changing teleconnection patterns. Further, the potential to provide accurate projections of future teleconnection patterns themselves is also limited.

Targeted science that fills the gaps around our understanding of teleconnection patterns is critical to adequately anticipate novel drought regimes, especially the occurrence of megadrought (Figure 4). First, the ability of GCMs to capture interannual climate variability is inconsistent, and these simulation biases partly explain the large spread in future projections.[94,99] To address this need, a recent workshop called for coordinated simulations, an ENSO Model Intercomparison Project, to better understand ENSO in a warmer climate.[100] Second, different modes of variability (e.g., ENSO versus Pacific Decadal Oscillation [PDO]) could interact with each other to enhance or dampen the effects on rainfall and temperature. In Hawai'i, for example, the magnitude of winter dryness during El Niño events is enhanced when the PDO is in the positive phase.[101] Third, teleconnection patterns across different geographic regions might not be stationary but instead variable with multidecadal changes in the tropical Pacific, with implications for our ability to continue successfully using teleconnections to forecast drought.[102,103]

Expanding Human Footprint Exacerbates Drought

Human influences are driving the emergence of novel droughts. Frameworks for drought must include the human role in mitigating or enhancing water availability, because water deficits are a complex interaction between human inflows, outflows, and storage.[12,104] These *human-induced/modified droughts* (Figure 3) are becoming increasingly common. For example, although the Millennium Drought in Australia was ENSO induced, groundwater extraction and river regulation contributed strongly to the water deficits that led to costly ecological impacts.[105] Similarly, in the United States High Plains and California's Central Valley, most of the groundwater extraction occurs during drought[106] and exacerbates drought magnitude.[107] Recent modeling suggests that human water use might outweigh the impacts of climate change on water availability in many systems globally.[10] In addition, human land use and land change can affect water availability. Management decisions related to forest structure, invasive species control, or conversion to alternative vegetation types shape future water availability during drought.[108,109]

Understanding how human water and land use might alter drought regimes and water availability is crucial for decision-making, because human activities are under our direct control. However, information gaps that include data availability and uncertainty in how land use affects water availability can hamper decision-making (Figure 4). Although it seems intuitive that

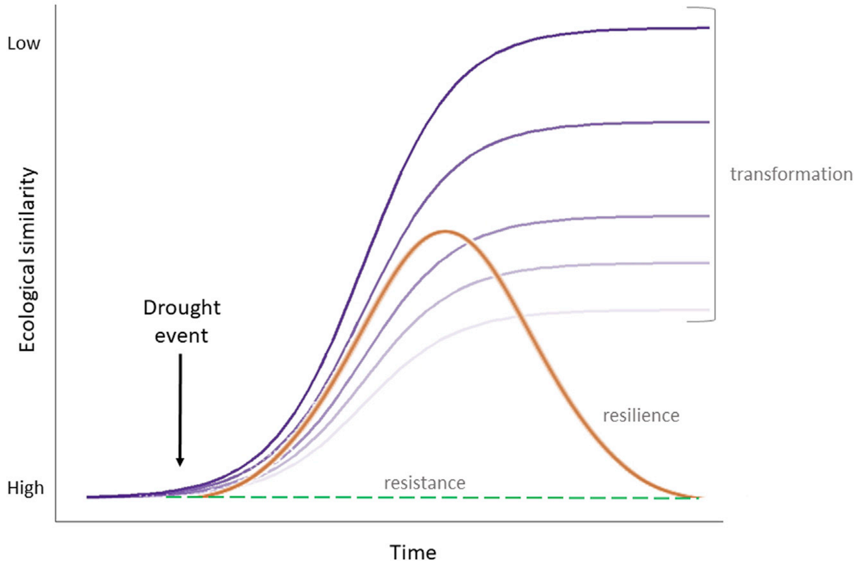


Figure 5. Depiction of Ecosystem Response to Drought

Conceptual depiction of potential ecosystem response to drought. Resistance (green) to drought occurs when the pre-drought ecosystem remains unchanged and the pre- and post-drought ecosystems are the same. Resilience (orange line) after drought is a measure of a system's ability to absorb drought and reorganize through successional processes, so that after the drought event, the post-drought ecosystem is highly similar to the pre-drought state (e.g., pinyon recruitment and growth after widespread pinyon mortality in a pinyon-juniper woodland). Transformation (purple lines) is characterized by an ecosystem not returning to pre-drought conditions but instead finding equilibrium around a new state with low similarity to the pre-drought state (e.g., pinyon-juniper woodland converting to sagebrush after drought).

accounting for human water use will lead to more effective drought preparation and mitigation strategies, incorporating water-use data remains a persistent challenge given the associated uncertainties and coarse spatial and temporal resolution at which these data are available.[110] Also, though some linkages between land cover change and the hydrologic cycle are well recognized (e.g., the effects of impervious surface on infiltration), others are much less understood (e.g., how alteration of vegetation type influences hydrology). More studies are needed to understand the links between natural resource management, ecosystem structure and function, and water supply. Overall, a greater research focus is needed on how and when human activities, including land management, exacerbate drought (e.g., Thomas et al.,[107] Roser-Renouf et al., [111] and Dunham et al.[112]).

TRANSFORMATIONAL DROUGHT IMPACTS

Our second theme focuses on ecological impacts from drought that are transformative, i.e., an irreversible shift in ecological states characterized by fundamentally different species composition, structure, and function. Climate change is driving widespread ecological transformation,[113] which can unfold through various mechanisms and at various rates. But disturbances like wildfire and drought are currently triggering abrupt ecological transformations[26,114] that challenge managers to make rapid decisions about whether and how to resist, accept, or direct such sweeping transformation.[115]

Drought Resilience and Resistance Is Overwhelmed

Drought has shaped ecological patterns, processes, and evolutionary adaptations in ecological systems worldwide.[116–118] As a result, ecosystems and their resident species are often resistant or resilient to drought, through characteristics and processes that minimize or counteract a drought's effect on demographic characteristics (mortality and recruitment rates), and result in long-term stability and high similarity of ecological communities through time (Figure 5; e.g., Lloret et al.[114]). Characteristics that can minimize drought-induced impacts at the individual and population levels include tolerance, plasticity, avoidance, and genetic/phenotypic variability, such as unique hydraulic traits in island plants.[119] At the landscape/ecosystem level, exposure to drought has shaped ecotypic variation across species ranges,[120] whereas topographic and geologic factors interact with climate drivers to create differences in microclimate, allowing some locations to maintain access to ecologically available water during drought, and thus act as hydrologic refuges.[121] Any process that minimizes the initial impact (i.e., resistance, Figure 5) or enhances the post-drought recruitment, succession, or recovery and ensures a return to the pre-drought ecological community (i.e., resilience, Figure 5) will have a stabilizing effect on the ecosystem.[122] Conditions that overwhelm these processes of resistance/resilience will change the ecological community assemblage, structure, and function in a way that persists and is difficult to reverse, i.e., transformational drought impacts (Figures 1B and 5; e.g., Jacobsen and Pratt[25] and Briske et al.[123]).

The processes of resistance and resilience in ecological communities to today's droughts can be overwhelmed by anthropogenic climate change. First, climate change creates novel drought exposures that increase the risk of high-magnitude ecological responses (e.g., Smith[13,14]). These novel exposures could occur in unexpected places; for example, analyses based on the Community Earth System Model (CESM1[124]) show that by the mid-21st century, between 100%–400% increase in the exceedance probability of a severe soil moisture drought (i.e., below 5th percentile value in the historical period) will occur (Figure 6A) in regions that don't normally experience strong drought (Figure 2). Second, warming is also enhancing other disturbance patterns, such as fire, pest, and pathogen outbreaks that also increase the likelihood of mortality events. For example, wildfire has affected tens of millions of acres in the contiguous United States (Figure 6B), and climate change now synchronizes wildfires[125,126] and increases fuel aridity.[127] In addition, climate change alters the life cycles and distribution of insect outbreaks and increases the prevalence or effectiveness of endemic diseases.[128] Now, climate change essentially promotes "stress complexes" of interacting disturbances across large spatial scales[128,129] that fundamentally transform ecosystems and

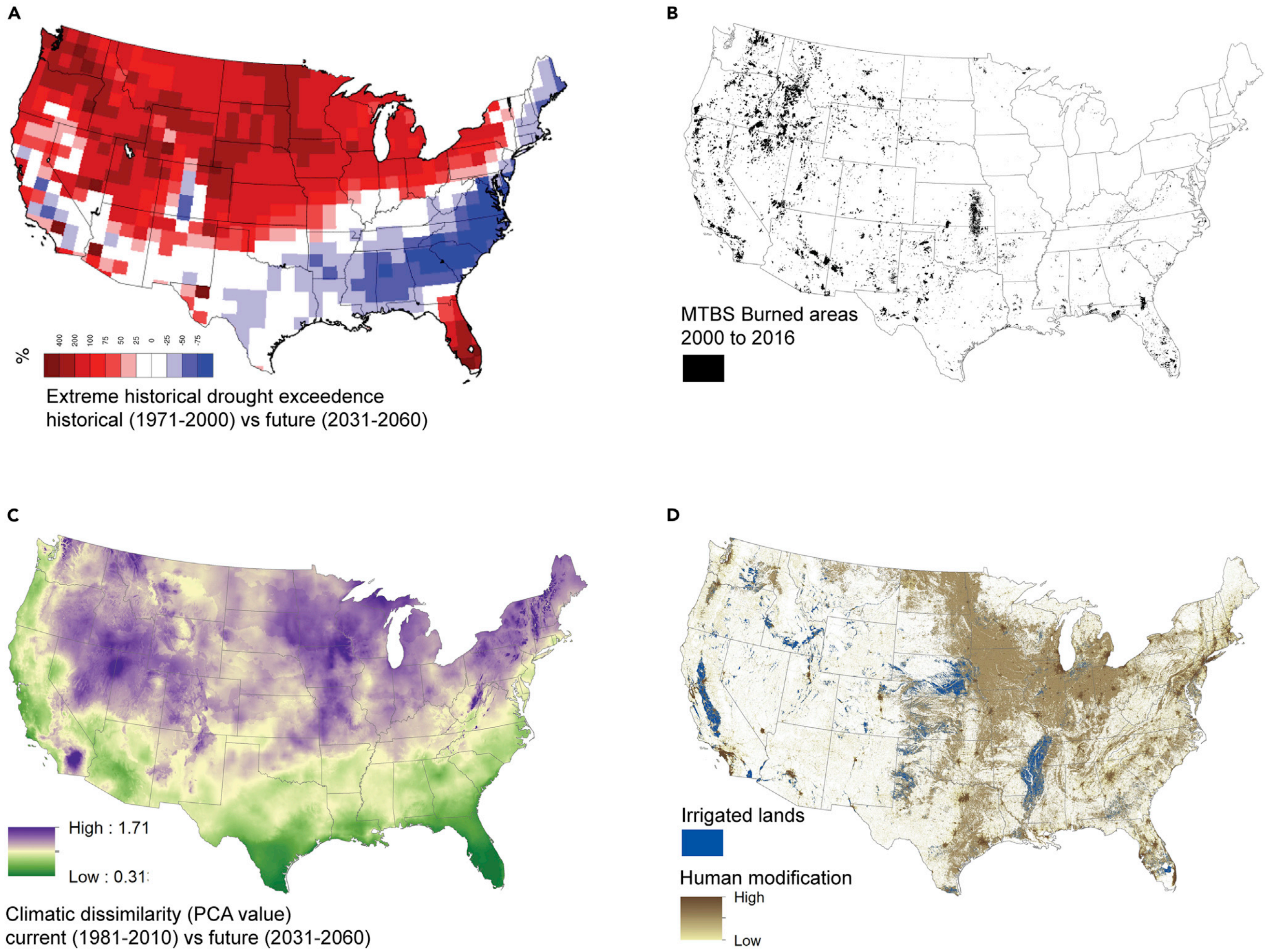


Figure 6. Factors Leading to Transformational Drought Impacts

Potential factors leading to transformational drought impacts.

(A) The potential future drought magnitude, represented as percent drought exceedance (based on our own analysis with CESM1[124]).

(B) Burned area since 2000 (MTBS[134]).

(C) Degree of climate change expected under RCP 8.5, represented as dissimilarity between recent climate normals and that of mid-21st century (2031–2060), considering temperature and precipitation simultaneously.[135]

(D) Degree of landscape modification by humans (browns)[136] and irrigated lands (blue).[137]

To represent future drought magnitude (A), we conducted an analysis of large ensemble experiments of the Community Earth System Model (CESM1[124]), which incorporates plants' response to elevated atmospheric CO_2. We then calculated the percent that mid-21st century (2031–2060) soil moisture during summer is projected to exceed historical (1971–2000) thresholds of soil moisture drought (5th percentile) in the contiguous United States.

challenge adaptation.[126,130] Third, and perhaps most importantly, the climate context in which ecosystems recover from drought is changing. For example, climate models show that some regions in the contiguous United States will experience very different climates by mid-century (Figure 6C). During such times of strong directional climate change, where the climate context during post-drought recovery is quite different from historical climate normals (high climate dissimilarity, Figure 6C), new successional pathways can be initiated after disturbance to catalyze a persistent state change in vegetation,[131,132] making ecological transformation more likely following droughts in the 21st century, even if the triggering drought was not extreme.[133]

Aspects of human water use, land use, and natural resource management can also overwhelm ecological processes of resistance and resilience, e.g., van Dijk et al.[105] The human footprint on land and water is pervasive, but of course regionally variable: for example, centered in the central and eastern portions of the United States (Figure 6D). Human use of water lowers ecologically available water, locally and regionally, especially during drought, to contribute to novel drought conditions. In aquatic systems, increased groundwater extraction and surface-water withdrawals during drought can lower stream flow, disconnect pool networks, and increase stream intermittency, impeding native fish populations' drought resilience.[105,138,139] Land use such as livestock grazing can exacerbate changes in grassland community structure after drought,[140] and resistance or resilience to drought can be highly dependent on management intensity.[141] Natural resource management can also inadvertently increase ecosystem sensitivity to drought. For example, decades of wildfire exclusion in forests has altered community composition and increased stem density,[22,142] resulting in increased tree mortality rates during drought.[23] In addition, human-assisted spread of invasive species could predispose systems to vegetation type conversion through, for example, a drought-induced invasion of cheatgrass in the western United States, which persists as it promotes an increased fire cycle,[143] or through the strong negative role of herbivory by non-native animals that disrupts recovery processes.[144]

Anticipating when and where processes that maintain ecological stability will be overwhelmed, and drought-induced ecological transformation might occur, requires filling some diverse science gaps (Figure 4). First, research is needed to address when and where mortality events might occur given the effects of novel drought conditions, interacting disturbance, and human land and water use (Figure 6) on multiple landscape, demographic, and physiological processes related to mortality. Second, innovative science is needed to determine which unfamiliar species might recruit and stabilize after drought, given ongoing climate trends, non-native species pressure, etc. The ecological state changes depicted in purple hues in Figure 5, where there is low similarity between the pre- and post-drought ecological communities, could take on various shapes and could be characterized by several different assemblages of species. Predicting the shape and character of the ecological trajectory and the many plausible endpoints for ecological communities requires understanding how complex and diverse underlying patterns and processes, especially those portrayed in Figure 6, will affect ecological community assembly and result in unfamiliar post-drought ecosystems. Overall, ecological drought science must grow to support the complex decisions managers will make about whether to resist, accept, or direct[115] the new ecological states that arise after drought. In particular, understanding whether typical management tactics to resist transformation might fail, or when natural resource management could direct the trajectory of an ecosystem, e.g., toward a particular form of ecological transformation, or a resilient ecosystem instead of one that was tending toward transformation (Figure 5), is a fundamental management need.

Cascading Transformational Drought Impacts

Transformational drought impacts cascade to have widespread and important consequences for biodiversity and ecosystem processes. Disturbances like drought are proving to be one mechanism for the species range shifts and biome shifts expected with ongoing climate change.[114,145] The loss or replacement of valued ecosystem components such as pinyon pine,[146] wild salmon and trout,[147,148] or sage grouse[149] after drought represents a cultural or recreational loss to diverse groups of people. These losses and strong turnover in the ecological community also alters ecosystem processes in ways that affect goods and services people rely upon (Figure 1C). For example, water yields in some drought-vulnerable ecosystems decreased after conversion from woodland to grassland.[150,151] After fires and associated debris flows, loss of riparian canopy and negligible or slow recovery can yield stream temperatures higher than ideal for cold-water trout,[147,152,153] and sediment delivery to near-shore coral reef ecosystems in the Pacific Islands threatens critical biodiversity and recreational resources.[154] Loss of nutrients and soil in post-fire wind erosion events mark a more fundamental loss to the kinds of ecosystems that support production of valued services.[155]

Further, when drought transforms vegetation to a new state, it can also alter regional climate in another location through ecoclimate teleconnections (Figures 1B and 1C), where vegetation characteristics in one location can drive the meteorology in another location.[11] Like deforestation, afforestation, or new agricultural crops, ecological transformation of vegetation can alter the land-surface energy balance through changes in albedo, evapotranspiration, and roughness, which creates feedbacks that can alter future climate and drought probabilities in regions far afield.[11,156] Additionally, 21st century droughts have larger spatial footprints that promote spatiotemporal synchrony in ecological processes over large mesoscales (10^4 to 10^6 km^2).[95,157] Therefore, transformational drought impacts can lead to rapid, large-scale change in ecological processes that could facilitate the synchronous movement of species better suited for 21st century climates, a synchronous spread of non-native species, or a synchronous loss in ecosystem services, with sweeping implications for biodiversity conservation and human well-being. Finally, extreme widespread ecological drought response can elicit widespread socio-economic response, e.g., the Dust Bowl, and trigger institutional and social change, e.g., the Soil Conservation Act of 1935 in the United States or the Commonwealth Water Act of 2007 in Australia.

Two major gaps stand in the way of understanding how these costly ecological impacts will cascade to human communities, biodiversity conservation, and even regional climate (Figure 4). First, more work is needed to anticipate the changes and dynamics in ecosystem function[80] and services that transformational drought impacts will bring. A greater understanding of how ecosystem health and dynamics link to human institutions, policies, and well-being is also needed to facilitate the consideration of trade-offs between human and ecosystem water needs in drought policy. General frameworks exist for categorizing ecosystem services[158] but have only rarely been applied to drought specifically.[27] Second, a new focus on the consequences of rapid, synchronous, and mesoscale phenomena that accompany transformational drought impacts, but are seldom considered in ecology, is urgently needed. In particular, understanding how transformational drought impacts can act as the event that ushers in the biome and species range shifts we expect with climate change,[145] how vegetation conversion creates ecoclimate teleconnections that alter weather in other locations, and how widespread ecosystem change alters ecosystem function, synchronously, on a mesoscale is needed.

ANTICIPATORY DROUGHT MANAGEMENT

Novel drought conditions and transformational drought impacts are increasingly likely prospects, which leads to our third theme, focused on how to successfully manage water and ecosystems in such unfamiliar territory. We identified several gaps that need to be addressed before managers can practice anticipatory drought management (Figure 4).

Anticipating Ecological Drought despite Uncertainty

Unfamiliar terrain is naturally accompanied by uncertainty. In the sections above, we laid out many of the scientific gaps that must be filled before managers can anticipate novel drought conditions or transformational drought impacts (Figure 4). As scientists turn their focus toward addressing the scientific uncertainties inherent to 21st century drought, recognizing how scientific support can target decision-making is key.[112,159] In practice, management uncertainty comes into play when confronting decisions about *when* to act (action thresholds), decisions involving *existing* action alternatives, and decisions to identify *new* opportunities in this unfamiliar territory.[160] Further, managers dealing with ecological transformation are working in a new management paradigm, to resist, accept, or direct the new ecological states.[115,161,162] It is clear that in practice, there are real limits to how far the scientific uncertainty around these complex and inherently unpredictable topics can be reduced; therefore managers must make decisions despite uncertainty. Managers have of course always worked with uncertainty, but to help work with the kinds of uncertainty and complexity associated with climate change, resource managers are increasingly using processes like scenario planning[163,164] and climate-smart conservation principles and approaches.[165] These approaches were crafted for climate change but can also help managers address novel droughts and transformational drought impacts through a systematic process of considering the direct and indirect effects of drought, with outcomes that include re-evaluating and, where necessary, updating existing management goals that are judged to be unrealistic in light of anticipated rapid changes.

Stakeholder Readiness

Success in adapting to unfamiliar territory for ecological drought hinges on stakeholder readiness.[166] Moving beyond the status quo to adopt novel approaches to drought adaptation, and to embrace the potential for transformational drought impacts, comes with the challenge of building public and agency support[162,167,30] but is greatly needed to meet management objectives in the 21st century. From the perspective of human dimensions, this stakeholder readiness could be framed in terms of "acceptance capacity."[168] Carpenter et al.[168] considered acceptance capacity in terms of individual knowledge, beliefs, and attitudes in relation to economic, social, and environmental conditions. Addressing "acceptance capacity" starts with recognizing that stakeholders have different perceptions of climate change and drought, and that effective means of engaging them can vary accordingly.[111]

A related challenge for scientists is to acknowledge the need to meaningfully engage stakeholders, even when stakeholder views are not in alignment with the most credible science.[31] Cash and co-authors[31] emphasize the equal importance of credibility of scientific evidence and technology, salience (relevance and timeliness of issues to stakeholders), and legitimacy (respectful of divergent stakeholder values and beliefs). In short, simply handing science off to stakeholders in a "loading dock" approach is unlikely to lead to outcomes that improve decisions about novel drought or transformational drought impacts. Instead, crafting authentic science–manager partnerships where scientists collaboratively engage stakeholders to co-develop or to co-produce science[159,169] is likely to be more successful in navigating unfamiliar territory. Fortunately, there has been much work on this topic, and useful guidance for both scientists and stakeholders exists.[170–172]

Incongruent Scales of Drought and Management

In the 21st century, drought can cover a larger area, last for a longer time, arise more rapidly, and promote synchrony in ecological dynamics over mesoscales.[95] These spatial and temporal scales of drought and ecological response arguably do not align with scales that are typical of natural resource management.[173] As with any ecological phenomena, the social and ecological complexity of managing drought increases with extent,[174] and the spatial footprint of drought generally now extends over multiple jurisdictions.[175] Salient time frames for drought recovery extend beyond the tenure of individual careers and the typical duration of organizational structures, political, and funding cycles. A more fundamental challenge stems from the fact that people tend to discount future costs and risks, relative to the present.[176,177] All of these scale-related factors reduce the focus on the most-needed larger spatial and longer temporal scales for management planning and actions. Consequently, management responses to drought and other disturbances tend to be limited in scope and necessarily more reactive than proactive. Scientific tools to support more proactive or anticipatory management have advanced considerably, but more progress is needed to incorporate this information into practice.[178] Each of these aspects of scale poses major challenges, but the first step to success is to acknowledge and develop plans for addressing them explicitly.[179]

OUTLOOK AND CONCLUSIONS

Horizon scans are great opportunities to determine the direction of future work (e.g., Kennicutt et al.[180]), and as we enter unfamiliar territory with an array of 21st century concerns, they are increasingly needed. Horizon scanning is a systematic approach for exploring an emerging challenge that is too nascent for a traditional systematic review process.[29] But, to effectively facilitate all of the science and management innovations that are needed to address the grand challenges we face today, horizon scans must go beyond purely scientific perspectives. Our horizon-scanning approach integrates stakeholders, decision-makers, and scientists to steer the direction of future work in a concerted way in order to reduce the rising risk of drought (Box 1; see Note S1). The many grand challenges that are looming today can be facilitated more effectively with this kind of co-produced process that identifies the emerging science and management gaps that must be filled to minimize social-ecological risks.

In order to effectively manage droughts of the 21st century, multiple science and management gaps must be met (Figure 4). Our horizon scan provides a roadmap for addressing the emerging themes that need the most immediate attention: (1) novel drought conditions, (2) transformational drought impacts, and (3) anticipatory drought management (Box 1; see also Figures S1 and S2, Table S1, and Note S1). As we move into this unfamiliar territory of novel drought conditions, being able to anticipate novel droughts requires new investments in understanding evaporative demand and teleconnection patterns in a warming world and how human land use and direct water use exacerbate drought conditions. There are also multiple opportunities in ecological science to better predict when and where drought might overwhelm versus facilitate the ecological processes that promote resilience or resistance, how drought recovery processes will change with climate change, and how effective new or existing adaptation strategies might be. Understanding the consequences of novel drought and transformational drought impacts, and therefore how important it is to take proactive actions and make decisions involving difficult trade-offs and uncertain outcomes, will require greater understanding of how rapid changes in mesoscale ecological dynamics ultimately cascade to people and nature, sometimes catastrophically (e.g., the destructive 2018 Camp Fire in Paradise, California, USA, or the 2020 megafires in eastern Australia). Finally, anticipatory management of novel drought conditions will require addressing scientific uncertainty in a way that is targeted toward real decision-making processes and will benefit from structured decision-making processes, like scenario planning, that are meant to work with uncertainty.[164] Stakeholder readiness to accept the notion that we are in novel drought territory, and authentic science-manager partnerships that co-develop science will both be key to putting well-targeted science into action. In addition, the increased spatial and temporal synchrony that accompanies climates and droughts of the future increases risks of drought impacts across very broad scales. Reducing or managing this synchrony will require large-scale collaborative partnerships that cross jurisdictional boundaries and challenge the traditional temporal and spatial scales of management.

Drought is a billion-dollar, global disaster. The science and management gaps that need to be filled to manage novel droughts and transformational drought impacts are diverse and many (Figure 4), and each are important globally. This horizon scan aims to direct new and synthesized science and encourage new management and adaptation paradigms that provide co-developed, forward-thinking approaches to all types of novel drought conditions (Figure 3). In particular, it is important to recognize that the expanding human footprint can be a strong driver of novel drought conditions and is potentially one of the most effective levers available to managers. History shows that major policies and programs often emerge after transformational ecological dynamics cascade to human communities. The Millennium Drought in Australia, the 1950s drought-induced fires in the western United States, and the 1930s drought-induced dust storms in the central United States were all followed by policy changes that persist today. Now is the time to recognize that dramatic transformational events create an opportunity to rapidly shift public impressions and resulting resource management and policy paradigms, and this co-produced horizon scan provides a roadmap for how both science and management can be ready.

Resource Availability

Lead Contact

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Shelley Crausbay (shelley@csp-inc.org).

Materials Availability

This study did not generate new unique materials.

Data and Code Availability

Results from the online survey that supported our horizon-scanning process and Figures S1 and S2 are available on Mendeley: DOI: https://doi.org/10.17632/5sx5k2cvwn.1.

Source data for Figure 2 is from the Vegetation Drought Response Index, or VegDRI, https://vegdri.unl.edu/, a weekly depiction of vegetation stress across the contiguous United States, co-developed by the National Drought Mitigation Center (NDMC), the United States Geological Survey's National Center for Earth Resources Observation and Science (EROS), and the High Plains Regional Climate Center (HPRCC). Archived data are freely available at USGS's Earth Explorer https://earthexplorer.usgs.gov/. We considered "extreme" and "severe" drought categories, and cutoffs for drought categories can be found here: https://lta.cr.usgs.gov/VegDRI. The code for compiling the archived VegDRI maps for this figure can be found at DOI: https://doi.org/10.5281/zenodo.3998120.

Figure 3's hotter drought graphic was adapted from Williams et al. (2013),[36] with permission from Springer Nature, available at https://doi.org/10.1038/nclimate1693 and Figure 3's megadrought graphic was adapted from Cook et al. (2016),[37] with permission from John Wiley and Sons available at https://doi.org/10.1002/wcc.394.

Data and code for Figure 6A, historical drought exceedance, can be found at DOI: https://doi.org/10.5281/zenodo.3998120.

Source data for Figure 6B, the footprint of recent fires, are freely available from MTBS: https://www.mtbs.gov/viewer/index.html. Source data for Figure 6C, absolute climatic dissimilarity for RCP 8.5 2050's, are freely available from AdaptWest: https://adaptwest.databasin.org/pages/climatic-dissimilarity. Source data for Figure 6D, human footprint, are freely available on Data Basin: https://databasin.org/datasets/110a8b7e238444e2ad95b7c17e889b66#, and the data for irrigation are freely available from the USGS: https://earlywarning.usgs.gov/usewem.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.08.019.

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