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REVIEW

Existing Challenges and Opportunities for Advancing Drought and Health Research

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Abstract

Purpose of Review Drought is one of the most far-reaching natural disasters, yet drought and health research is sparse. This may be attributed to the challenge of quantifying drought exposure, something complicated by multiple drought indices without any designed for health research. The purpose of this general review is to evaluate current drought and health literature and highlight challenges or scientific considerations when performing drought exposure and health assessments.
Recent Findings The literature revealed a small, but growing, number of drought and health studies primarily emphasizing Australian, western European, and US populations. The selection of drought indices and definitions of drought are inconsistent. Rural and agricultural populations have been identified as vulnerable cohorts, particularly for mental health outcomes.
Summary Using relevant examples, we discuss the importance of characterizing drought and explore why health outcomes, populations of interest, and compound environmental hazards are crucial considerations for drought and health assessments. As climate and health research is prioritized, we propose guidance for investigators performing drought-focused analyses.

Keywords Drought · Exposure assessment · Climate change · Natural disasters · Public health

Introduction

The public health impacts of extreme weather and climate events are well documented [1, 2]. The best-studied natural disasters, such as heat waves [3–5], cyclonic storms [6–8], wildfires [9–11], and floods [12], tend to have abrupt onsets with noticeable high impact. These events develop rapidly and result in short-term acute effects with regionally persisting consequences. However, it is the slow to evolve and persistent drought that is considered the most far-reaching natural disaster and a major contributor to climate-related health effects [13, 14].

In the most basic sense, drought is a precipitation deficit resulting in water shortages that impact soil, hydrology, or water supply [15]. In the past 40 years, drought has likely impacted more people worldwide than any other natural disaster [16] and has caused an estimated 60% of all extreme weather deaths, despite representing only 15% of natural disasters [17]. In the United States, a 2012 pan-continental drought affected over 150 million people and covered nearly two-thirds of the country [15, 18, 19], while California experienced its worst 3-year dry spell in 1200 years from 2013 to 2015 [19, 20]. Central South America had one of its most severe and prolonged drying spells from 2019 to 2022 that peaked with record-breaking dry conditions over two standard deviations below normal soil moisture [21]. And from 2014 to 2018, Europe experienced a prominent and prolonged drought period that was exceptional not in annual severity, but for its 5-year duration that cost billions (€) in

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farming losses [22]. As an environmental hazard, drought exhibits a set of characteristics unique from other natural disasters. Drought is typically slow evolving and can persist across months and years with impacts that linger after an event has terminated [23]. Drought also has complex spatial and temporal boundaries, which can lead to disagreement over severity and extent [15, 24–26]. As a society, there is a tendency to downplay the consequences of drought or overlook them entirely since these events rarely result in the highly visible structural damage typically associated with other natural disasters.

Drought causes adverse health outcomes through multiple direct and indirect pathways. Drought exacerbates harmful environmental exposures, including increased dust [27•, 28, 29], extreme heat [30••, 31••, 32], wildfire prevalence and smoke [33–35], and changes in allergen composition [36, 37]. Drought is perhaps best known for its impacts on psychosocial stress and mental health [38, 39, 40•, 41]. Australian studies have identified drought events to be associated with increased stress, depression, and suicide [39, 42–44, 45•, 46]. The largest mental health risks were observed in males from rural communities [42, 45, 47], *Vibrio* prevalence in estuarine environments [48, 49], and the incidence of coccidioidomycosis, when drought follows wet conditions [50•, 51].

Our understanding of the detailed relationship between drought and health is still limited, despite its broad consequences [24, 52, 53••, 54•, 55••, 56]. Additionally, it is likely that drought exacerbates the health risks from other extreme weather events, such as dust storms, wildfires, and heat waves. Federal agencies and public health practitioners are tasked with creating appropriate drought early warning systems and risk mitigation plans; however, to effectively carry out this task, it is crucial to understand the intricate characteristics of drought and how they affect health. The complexity of this problem underscores the need for multifaceted approaches to address this threat.

The objective of this integrative review is to examine recent literature and expand the discussion of challenges related to public health and drought research. We will emphasize the considerations that go into selecting a drought metric, including drought exposure characteristics, identifying at-risk populations, co-occurrence with other environmental hazards, and how these factors play into evaluating a disease. This approach is outlined in a conceptual framework to guide investigators performing drought and health epidemiological research (Fig. 1). We illustrate some of these issues using US drought data, provide relevant examples from the literature, and outline opportunities and new drought and health research needs.

Challenges in Characterizing Drought Exposure

A key challenge for assessing the health effects of drought lies with effective characterization of exposure. However, unlike air pollution or temperature, drought is not easily quantified. Instruments cannot directly measure drought, so

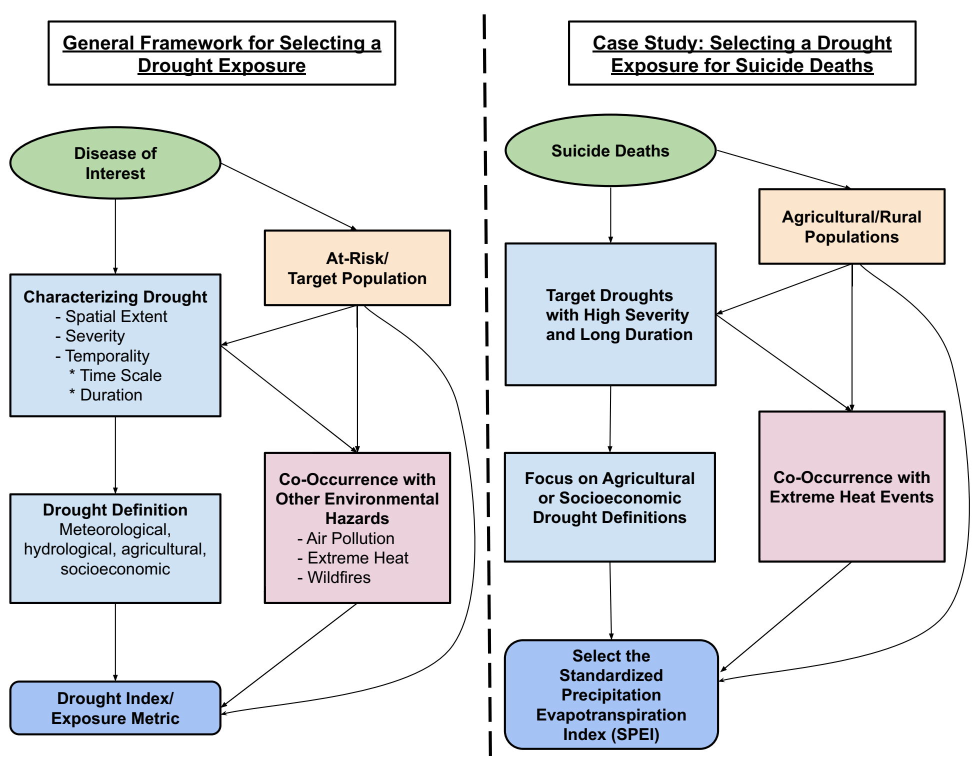

Fig. 1 Guiding framework of factors to consider when performing drought and health research. The left side is a general framework for drought and health investigations, while the right side outlines the process using suicide as a case study

meteorologists rely on atmospheric and environmental surrogates, such as precipitation, groundwater, or soil moisture. Drought indicators combine multiple surrogates to compare current conditions against a long-term average or "normal," which is typically location specific, making drought in the arid Southwestern United States different from drought in the humid Southeastern United States [57]. Drought is additionally complicated by four unique types: meteorological, agricultural, hydrological, and socioeconomic droughts. These drought types are associated with a particular kind of water-related deficit. Meteorological drought is a lack of precipitation, agricultural drought is a lack of soil moisture to the extent that crop growth and production are negatively affected, hydrological drought is a measure of surface and groundwater availability, while socioeconomic drought is defined as a negative supply related to water demand resulting in economic burden [25]. Socioeconomic drought is the most severe drought stage and considers the wider societal and economic impacts of prolonged meteorological, agricultural, and hydrological drought conditions. This type of drought can lead to water shortages for communities, increased competition for water resources, and significant economic losses in agriculture, industry, and other sectors. Other meteorological conditions, such as temperature, may exacerbate the severity and impacts of drought [23], while anthropogenic water use may amplify drought conditions [58, 59].

The necessity of multiple drought definitions stems from the many stakeholders affected by drought conditions. Drought causes environmental, social, and economic impacts that can be local or far reaching. Therefore, a universally accepted drought definition has proved elusive, if not unobtainable. Currently, around 150 drought indices exist, each designed to measure a specific phenomenon of drought with their own strengths and limitations [26, 57, 60]. No drought indices have been designed for human health research, and there is no "best" drought measure for epidemiological applications [15]. Therefore, selecting a drought exposure metric should rely on its ability to capture features that likely influence health-related vulnerability: severity, spatial extent, and temporality, including timescale and duration.

Severity of Drought

The severity of drought refers to the magnitude of a water deficit compared to normal conditions. It is frequently assessed, and more severe drought has been associated with elevated mortality and disease [42, 61–63, 64•, 65]. However, drought metrics employ varying scales to quantify "severity" and that complicates the comparison of health effects across studies. For example, in studies of drought and mortality, Berman et al. used exposures from the US Drought Monitor (USDM) for their US-based study, which reports five categories of drought severity, while Salvador et al. and Wang et al. employed standardized precipitation indices (SPI) that report drought as standard deviations below or above the long-term precipitation mean for their studies in Spain and northwest China, respectively. While these three studies all examined the same exposure and health outcome, comparability and meta-analysis across them are complex as drought severity and magnitude were quantified so differently.

An additional consideration is that droughts are typically long-term events compared to other climate-related or meteorological disasters, where dry conditions begin, severity increases, and then improves back to baseline. A single drought event will therefore experience the same severity at least twice, which can add complexity to evaluating continuous exposure risk. In a randomly selected county, we demonstrate this phenomenon using USDM data for Jasper County, IA (Fig. 2). In a 6-year time frame, we observe three separate drought periods that achieved moderate, severe, or extreme drought conditions (August 2011–November 2011; June 2012–April 2013; August 2013–April 2014), which may

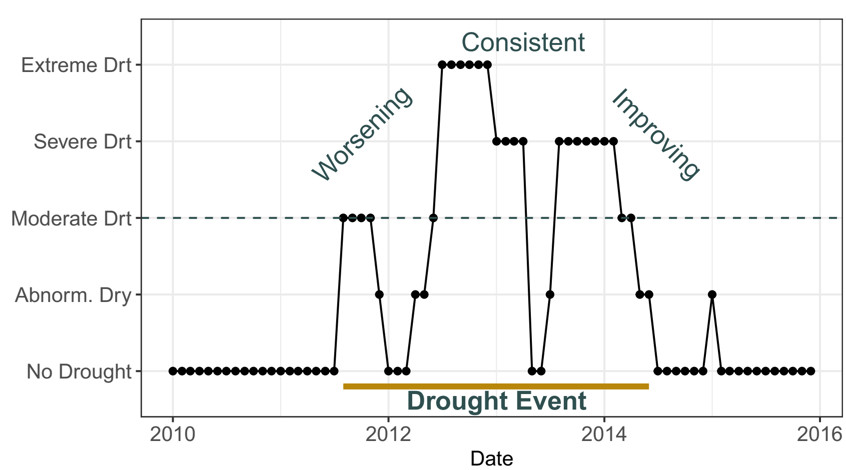

Fig. 2 US Drought Monitor conditions for Jasper County, IA, from 2010 to 2016. The dashed line highlights months with moderate drought conditions during this period

be considered a single long-term drought event. Moderate drought is recorded for both June 2012 and April 2013, but should these have the same health risk in the same drought event? June 2012 "moderate drought" relates to early stages of the drought event, when environmental conditions are worsening, but individual and community resilience are still high. However, in April of 2013, the moderate drought condition represents the consequence of 11 months of continuous, yet now improving drought, and may be associated with far different health risks than moderate drought during the early portion of an event. Researchers have to carefully consider if a drought severity measure should be evaluated as a continuous environmental exposure [64•, 66] or if categorical events stratified by drought severity [61] with different worsening or improving conditions are more appropriate.

Spatial Extent of Drought

Spatial extent refers to the total geographic area considered a drought event. It may be an important exposure characteristic because larger droughts place greater demands on natural resources and human systems. However, there is little research looking at drought size and associated health risks. Measuring the extent of droughts may be complicated by the spatial resolution of drought data, which can range from data storage pixels to hydrologic watersheds to continuous spatial polygons. Dai discusses the challenges of deriving drought indices using data from multiple spatial scales, particularly with historical weather data where inputs can be missing or sparse [109]. Differences in data units for drought indices can make spatial comparisons of events difficult, notably in the transition between wet and dry conditions and at geographic margins [57]. From an epidemiological standpoint, the varying extents of drought events due to metric choice can lead to exposure misclassification and a bias toward the null.

Temporality of Drought: Timescale and Duration

The temporality of environmental hazards represents a key piece of the exposure assessment pathway. Observational studies, particularly for ubiquitous environmental hazards like air pollution or heat, rely on the precise evaluation of cumulative time-dependent exposures during a follow-up period [67]. However, evaluating drought requires the consideration of two time-related characteristics. First is the timescale of a drought condition. Drought is defined as current dryness compared to normal conditions, but "current" could be interpreted as conditions over the past week, month, or even year. Dracup et al. states "selection of the averaging period for a particular drought study is dependent almost entirely on the purpose for which the study is intended." Most drought research commonly uses either 1-month, 3-month, 6-month, or 12-month intervals, which would capture short-term, seasonal, moderate, and long-term drought conditions [39, 40•, 64•, 66, 68]. However, interval choice has major consequences for the frequency, trend, and duration of drought over the same period of time.

To highlight the phenomenon of drought timescales, we pulled the Standardized Precipitation Evapotranspiration Index (SPEI) for Wichita, KS, from 1995 to 2012 at 1-, 3-, and 12-month timescales (Fig. 3) [69, 70]. We observe that a 1-month timescale produces frequent drought measures of short duration with rapid fluctuation between wet and dry conditions, whereas timescales of 6 and 12 months have distinct events of longer duration. In choosing a drought timescale, researchers should consider the development of their disease and whether this depends on rapid or longer-term persistent drought.

The second time-related characteristic refers to the more familiar duration of exposure or length of a drought period. If we consider a time series of a drought index, estimating the duration of a drought exposure involves truncating our data into periods/events of drought and non-drought [71]. However, drought is complicated by its "creeping effect," so the exact onset and termination are difficult to determine. Furthermore, depending on the drought definition or index, events can be out of sync with one another. Meteorological and agricultural droughts can develop in short time periods but can be lagged by hydrological or socioeconomic droughts as water deficits work their way through the system. During the same time period, a specific location may be considered a drought under one metric, but a non-drought using a different metric. This variability is further exacerbated by geographic location, where correlations between different drought measures may be impacted by local weather conditions such as cold drought during winter conditions [72]. Drought requires us to consider not only the severity but also the factors related to the timing and duration of a drought event to effectively elucidate potential health risks.

Health Effects and Drought Exposure

Drought has been associated with several health effects, highlighting the multiple pathways to impact people and the environment. In a systematic review, Stanke et al. categorized drought health effects as (1) nutritional deficiencies, (2) water-related disease, (3) airborne and dust-related disease, (4) vector-borne disease, (5) mental health effects, and (6) other outcomes, which include injury, heat waves and wildfires, migration, and infrastructure damage. Similar reviews have focused on comprehensive [55••] and specific drought health effects, including mental health [24] and vector-borne disease [53••]. Drought and human health were also an area of focus in the US Global Change Research

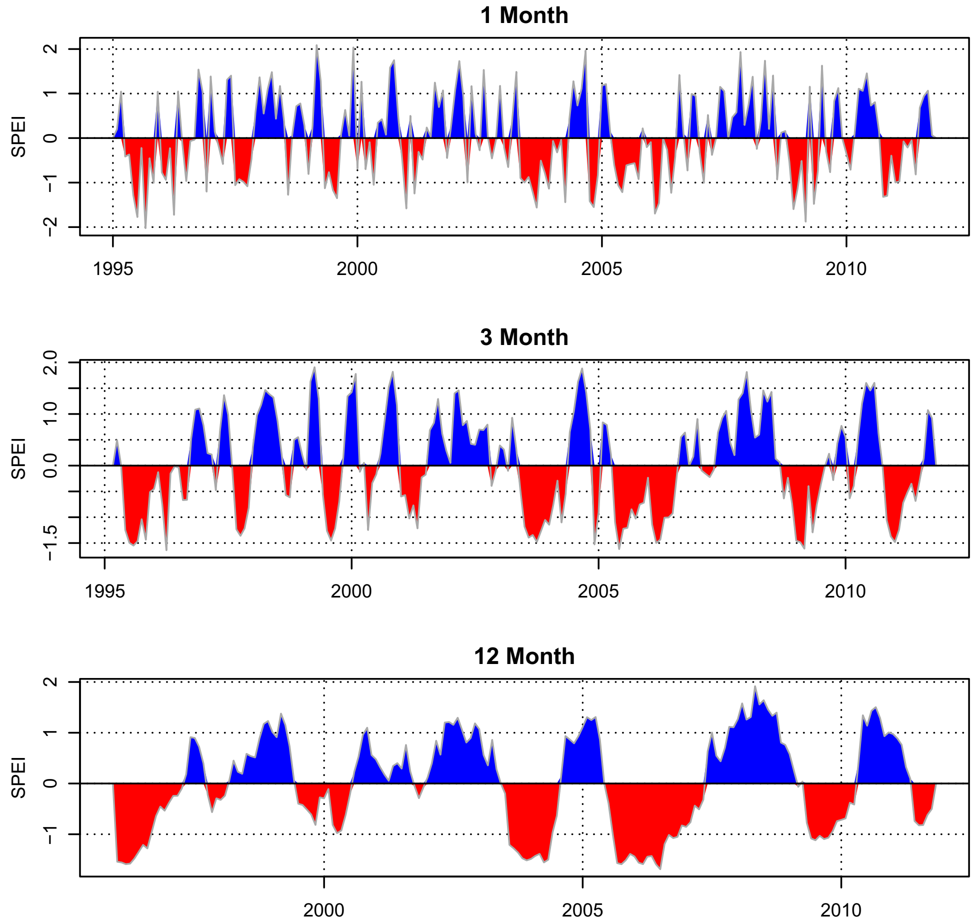

Fig. 3 Drought conditions measured with the Standardized Precipitation Evapotranspiration Index (SPEI) in Wichita, KS, using timescales of 1, 3, and 12 months. Positive SPEI indicates wetter than normal conditions (blue), and negative SPEI indicates dryer than normal conditions (red)

Program special report released in 2016 [73]. While these systematic reviews discuss many studies, a universal theme is that a comprehensive understanding of the drought and health relationship is still limited. Published research varies in study design and quality, and health effects from drought are likely under-recognized and under-reported. Limited papers quantify the direct association between drought and health, and separating effects from other environmental factors remains complex. Finally, defining drought exposures pertinent to specific health outcomes remains one of the largest challenges.

Drought and vector-borne illness provide a useful example highlighting the importance of selecting a drought exposure based on the health outcome of interest. Studies have found that drought conditions amplify mosquito-borne encephalitis and West Nile virus [74–76]. The proposed mechanism is that reduced rainfall shrinks surface water, forcing avian hosts and mosquito vectors into a converged environment ideal for epizootic amplification. There is also evidence that drought can lead to dehydration in mosquitoes, which increases their feeding [77]. After a drought ends, the infected mosquitoes and birds will rapidly disperse and escalate disease transmission to humans [76, 78, 79]. Therefore, an investigation of drought and West Nile virus would choose a drought definition that captures surface water availability. A long-term hydrological drought index might be preferred, as it would best reference the availability of standing water (e.g., ponds, marshes) necessary for avian hosts. Had an agricultural or meteorological drought measure been selected, our exposure index would emphasize soil moisture and plant growth, which are not as useful for understanding mosquito populations. A second consideration is to select an index that effectively measures drought duration. With West Nile virus, it is the post-drought dispersal of birds that influences human infection [79, 80], so accurately assessing the lagged response means effectively capturing the time period of drought exposure. When considering the tradeoffs of choosing a drought index, one would give higher priority to capturing temporality, as opposed to characteristics like spatial extent or severity that might be less important to dispersing birds.

Conversely, consider another vector-related outcome of drought and tick populations. Ticks are the known vectors for multiple human diseases, including Lyme disease, babesiosis, and ehrlichiosis. Unlike mosquitoes, which benefit from drought conditions, dry conditions will negatively influence ticks. Tick ecology is driven by microclimates, including a preference for high relative humidity, drainage, and vegetation height [81, 82] with poor survival under low humidity and high-temperature conditions [47]. Increased desiccation from drought will directly harm tick populations [83]. Therefore, the ideal drought index for tick-borne disease would emphasize short-term drought conditions that focus on soil moisture, vegetation, or evaporative demand. The co-occurrence of rapid drought with heat waves (e.g., flash droughts) might also be a strong consideration.

While acknowledging that the type of drought impacting ticks would likely be quite different from conditions impacting mosquitoes, it is not clear how the authors selected their drought measures in published West Nile virus and tick studies. Shaman et al. and Paull et al. both utilized the Palmer Drought Severity Index, while Johnson and Sukhdeo incorporated weather station data and compared this to long-term trends. The studies did not discuss alternate drought exposure metrics or different drought definitions in their evaluations. It has been found that inconsistent exposure definitions for other environmental hazards, such as heat waves, may substantially influence health effects estimation and hinder the development of early warning systems [56, 84]. Failure to properly consider the drought definition may result in incorrect health effect estimates or at worst a false association with disease. But how to identify the "best" drought definition is an active and complex question. Cycling through different drought definitions using the over 100 existing drought indices and testing their association with multiple health outcomes would be impractical, yet no alternative solution has been apparent. Identifying the most accessible, globally reproducible, and public health–appropriate drought indices should be a priority of future work.

Knowing the At-Risk Populations

Drought events are geographically large and impact broad populations, but the vulnerability of those affected varies substantially by subgroup. Sociodemographic and occupational factors are especially critical for community susceptibility and resilience. Populations reliant on agriculture for livelihoods or sustenance are vulnerable to food insecurity, malnutrition, and the accompanying psychosocial stress when drought causes economic loss [85, 86]. Those in farming occupations already have higher rates of suicide, and the impacts of drought have been shown to increase their mental health threats [40•, 87]. In general, rural individuals show greater mental health–related stress from drought events compared to urban counterparts with this divide increasing for populations that are already disadvantaged, including remote, aboriginal, and indigenous communities [88–90]. However, urban communities may experience their own crises and disparities resulting from drought. From 2015 to 2018, the City of Cape Town, South Africa, experienced an extended drought and increasingly dire water shortage that included the threat of "Day Zero," a period when water reservoirs would be completely exhausted [91]. While Day Zero was avoided, the city's household water restrictions and rationing disproportionately harmed its most disadvantaged residents. In Cape Town, predominantly black and lower-income households often reside in multifamily or extended homes. These larger households with more individuals per property experienced greater hardship to reduce water consumption, as all individuals have basic water needs [92]. In wealthier households, a smaller number of people and the prevalence of water-reliant luxuries, such as landscaping or pools, often meant that water cuts could be instituted with relatively little impact on individual water demands [92].

Among age groups, children and elderly are both vulnerable to various drought-related health outcomes, such as respiratory and waterborne diseases [61, 63, 65, 93, 94•, 39, 42, 90]. These studies hypothesize that older adults may better cope with the psychosocial stress of natural disasters having experienced them before [39]. Reliance on small or inadequately maintained water systems puts populations at risk for drinking water contamination during drought or limited water resources for hygiene and food washing [93, 95]. Lastly, lowered surface water volumes put recreational water users at risk of waterborne disease and injury from aquatic accidents [85].

Following a natural disaster, the displacement of populations presents a challenge for both identifying vulnerable groups, evaluating overall health effects, and reducing disparities [7]. For some disasters, such as hurricanes, people that are displaced or temporarily housed are tracked by government agencies, such as the Federal Emergency Management Agency in the United States. Researchers can partner with these groups and identify affected individuals to evaluate their health burdens resulting from natural disasters. But, as a slow-moving environmental hazard, drought rarely results in rapid and federally supported relocations. As families trickle away from stricken areas, it becomes difficult to follow up on the health impacts of drought, adding potential misclassification to health effect evaluation [96].

Is It Drought Alone? Or Exacerbation of Other Extreme Events?

Estimating the health effects of drought is complex because drought exposures rarely occur in isolation. Droughts are part of interrelated environmental phenomenon that may trigger or exacerbate the occurrences of multiple extreme weather events, such as dust storms, wildfires, or heat waves [30••, 96]. To accurately evaluate the impacts of drought, investigators must consider if the drought should be investigated alone or jointly with other simultaneous exposures, a phenomenon known as compound risks [54•, 97, 98]. For example, it is known that dry soil produces less evaporative cooling, which makes surface temperatures hotter during dry periods [99]. Therefore, the probability and severity of a heat wave increase during drought compared to non-drought conditions [100, 101], and the simultaneous occurrence of drought and heat waves is called a "flash drought" [102, 103]. Heat waves have killed at least 4275 people during the 30 droughts that have been designated as billion-dollar disasters since 1980 [104]. While many heat wave and health investigations have investigated how exposure definitions and geographic variability in trends influence effect estimates [56, 84, 105], few have examined whether estimated heat wave health risks are mediated by drought conditions.

Drought conditions have also been associated with worsening air quality attributable to more frequent or severe emissions from wildfires and dust storms [15, 28] and can exacerbate air pollution disparities [68, 106]. Drought will intensify wildfire seasons by increasing the availability of fuel and decreasing surface soil moisture [34]. Models predict that by 2050, increasing temperature and drought from climate change will double wildfire-related aerosols and increase overall carbon aerosols by 40% in the Western United States [107]. Fine dust concentrations will similarly increase during drought conditions and are estimated to increase premature mortality by 24% and 130% under increasingly severe climate change scenarios [28]. Air quality issues from wildfires and dust storms are known to transfer across large distances and impact populations far from a source location.

Contrary to what is expected, droughts produce conditions that can lead to flooding. Decreased soil moisture and changes to the landscape during drought cause a reduction in precipitation soil absorption capacity and lead to flash flood conditions. In addition to impacting physical hazards, the occurrence of a drought is likely to increase stress on both individuals and communities. If a drought is high severity or persists for extended periods of time, the continued exposure will likely lower the populations' baseline susceptibility to other extreme events. If a flood, wildfire, or other natural disaster event takes place following a drought, the community may be at greater vulnerability to this second exposure, particularly if there is inadequate time to regain their resilience [108]. Future research should consider the synergy between drought and other extreme weather events and identify whether the risks from natural disasters are modified during drought conditions. This has important consequences from a health preparedness standpoint. Risk mitigation should consider not just an emergency response to drought, but a response to the increased likelihood of related natural disasters. Since drought is slow to develop, comprehensive risk strategies can be instituted prior to a drought reaching a severe point and proactively protect against these multiple effects.

Conclusions

Droughts are a constant threat to the United States and other parts of the world. While the impacts of drought are sometimes less apparent, their consequences can be as severe and long-lasting as any other disaster. Over the last 40 years, droughts are the third costliest weather-related disaster in the United States in dollars and the second costliest in human lives [104]. However, droughts do not garner as much attention from the public health, healthcare, and emergency preparedness sectors. Most of the time, droughts are perceived as threats to agriculture and water resources, but not threats to our communities or health. For sectors that work on health security to perceive drought as a public health concern, the scientific community must first identify the health issues that are connected to drought and the populations that are more susceptible. Determining these relationships will help with mitigation efforts necessary for reducing the health risks that occur during droughts. Because droughts are likely to continue to increase in intensity and frequency in the future with anthropogenic climate change, it is crucial that the relationships between drought and health are better understood today before the risks increase in magnitude.

Evaluation of multiple drought definitions will help drought early warning systems capture health risks, and applying this information to seasonal drought forecasts can provide time for health professionals to prepare for upcoming health threats. As mentioned above, no current definition of drought or individual drought index is designed to capture health effects. Because of the variety of health impacts that can manifest from drought events, a single drought index is unlikely to capture the complexity of all possible health outcomes. Utilizing best practices for selecting drought indices enables a better evaluation of health threats and allows us to use already operational products, thus eliminating the need to create another drought index to populate the list of numerous existing metrics. Instead, careful consideration is warranted to identify the appropriate drought metric, and understanding the environmental triggers leading to a health threat will assist in selecting the appropriate drought measure. Matching drought indices with health outcomes will provide more accurate and reliable early warnings. In the prescribed methods listed in this paper, there is an opportunity to acknowledge the health threats from droughts, better evaluate them, and reduce the negative health outcomes through more informed mitigation strategies.

Author contributions JDB, AMA, and JEB conceptualized the topic. JDB drafted the manuscript text and prepared the figures. All authors reviewed and edited the manuscript.

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Declarations

Competing interests The authors declare no competing interests.

Conflict of Interest The authors declare that they have no actual or competing financial interests.

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- •• Of major importance

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