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A scoping review of drought impacts on health and society in North America

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Abstract

Drought is a highly destructive natural hazard with wide-ranging impacts on water security, agriculture, energy, and human health. Unlike most natural hazards, droughts can develop anywhere, evolve rapidly within a month or slowly over a season, and span months to decades without a clear beginning or end. Few studies investigate the direct link between drought and drought-related impacts on health and society, and little research has identified critical science gaps in the field of drought-society. This scoping review aims to explore the societal implications of drought and identify knowledge gaps for future drought-society studies. We performed a PRISMA scoping review with a four-element search model on articles published since 2010. We extracted drought impacts data from 74 articles. Results were synthesized into three main topical areas examining public health impacts, water quality impacts, and water quantity impacts. While studies were heterogeneous in terms of objectives and methods, they illustrated the full breadth of drought impacts. The current body of evidence lacks a standard set of drought indices that can be readily applied to evaluate and monitor societal impacts due to drought. The challenge of defining drought limits a holistic understanding of drought effects and recovery time. More interdisciplinary collaborations are needed to establishes community-wide consensus on the identification of relevant hydrological indicators that best describe an adverse outcome is an understudied research priority.

Keywords Drought impacts · North America · Scoping Review

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1 Introduction

As vulnerability to drought increases because of mounting pressure on water availability and climatic changes, the scientific community faces a significant challenge producing comprehensive, timely, and accurate assessments of drought-induced impacts (Wilhite et al. 2017). Globally, the drought impacts from climate change are still uncertain due to the large uncertainties in projected water availability (Greve and Seneviratne 2015) and the lack of direct observations (e.g., Africa, South America), the methodological uncertainties, and the geographical inconsistencies in the precipitation trends (IPCC 2013). The potential for drought impacts is heightened by population growth, urban expansion, aging or deteriorating water infrastructure, and environmental protection, all of which exacerbate ongoing water competition and quality issues. Water security is increasingly becoming a central resilience issue in North America, especially given that water is foundational for the health of humans and ecosystems, as well as an integral component of the agriculture, energy, urban, and industrial sectors. Observed changes in the frequency and intensity of climate extremes, particularly drought, are important to understand regional geographic vulnerabilities in water quality and quantity (Hayhoe et al. 2018).

Recent droughts since the 1980s have taken large economic and human tolls on the USA with estimated losses exceeding $236 (CPI-adjusted) billion and 3865 deaths (Smith 2020). Studies exploring the impacts of drought on society are challenged by the complexity of this phenomenon where moisture deficits accumulate irregularly across the hydrological cycle as they evolve (Otkin et al. 2018). As a result, there is no standard definition for drought, despite being a climatological characteristic of most locations (Maybank et al. 1995). Instead, drought is often categorized into four classifications based on the portion of the hydrological cycle of interest. These classifications include *meteorological drought*, *agricultural drought*, *hydrological drought*, and *socioeconomic drought.* Within each grouping, drought indices can range with varying complexity. For instance, meteorological drought indices can vary from considering only precipitation (Gibbs and Maher 1967) to more complex measures that incorporate evapotranspiration (water transfer from land to the atmosphere by evaporation from soil or plants), antecedent soil moisture (water content of the upper soil layer), and surface run-off conditions. These drought types and a plethora of corresponding indices, over 60 unique indicators compiled by Heim (2002) and Zargar et al. (2011) in their drought indices reviews, complicate efforts to evaluate drought impacts and associated risks (Below et al. 2007; Lloyd-Hughes 2014). Since it may not always be clear which type of measure (lack of precipitation, soil moisture, or streamflow) or combination of measures should be applied to evaluate an adverse outcome (Lloyd-Hughes 2014), this complication is particularly true for human health, where underlying economic and social disparities and associated access to water are highly regionalized.

While the National Drought Mitigation Center (NDMC) has identified a variety of economic, environmental, and societal based drought impacts (NDMC 2020), most studies have primarily focused on agriculture (Yu and Babcock 2010) and economic (Ding et al. 2011) impacts. Of equal importance are the adverse effects of drought on human health and other societal impacts (i.e., access to quality water and fire risks). Drought negatively impacts human health by increasing the risk of water-borne, vector-borne, and respiratory diseases. Water quantity and quality decrease during periods of drought and can cause shifts in water-borne diseases, human consumption behavior, and sanitation (Yusa et al. 2015). Moreover, water quality can affect soil, agriculture, and water consumption, whereas water quantity can have important implications for water resource managers and electricity. Prolonged drought can also

negatively impact psychosocial health and well-being and has been associated with an increase in suicide and mental distress, particularly for rural populations who depend on water for their livelihood (Nicholls et al. 2006; Polain et al. 2011).

This scoping review examined the societal impacts of drought on (1) public health, (2) water quality, and (3) water quantity in North America. A scoping review is a literature synthesis method that merges a diverse knowledge base in multiple topical areas (Pham et al. 2014, Arskey and O'Malley 2005). To date, the scoping review methodology has been underutilized in the disciplines outside of medicine and public health. Results from our study identified critical gaps and highlighted future research directions to advance the cross-disciplinary science on drought.

2 Methods

2.1 Databases, search terms, and inclusion/exclusion criteria

A systematic search was conducted in 5 electronic bibliographic databases to identify relevant peer-reviewed studies following the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) protocol guidelines for scoping review (Moher et al. 2009). Different databases that range in specialty from medicine (PubMed™©), psychology (PsycINFO™©), science/medicine (ScienceDirect™©), and broad scholarly literature (Google Scholar™©) were selected to ensure a comprehensive and diverse search on drought impacts was conducted (Table 1)

Search terms were adapted from preliminary informal scoping of the literature, and the final keywords were agreed upon by all authors (Table 1). Search criteria were classified thematically based on preliminary results into three subcategories: (1) water quality, (2) water quantity, and (3) health impacts. For each subcategory, abstracts were screened and assessed for eligibility by at least one author and reviewed by a separate author. In the instance of discrepancies, the entire author team met and reached a consensus. Inclusion criteria were the following: (1) research where an explicit link is made between drought and a drought-related impact; (2) geographic location restricted to North America (which was expanded for public health topics to the entire globe due to small sample sizes); and (3) studies published from 2010 to the present to examine recent and emerging trends in the field. The exclusion criteria were the following: (1) no gray literature (e.g., thesis, dissertation, and government report) and (2) articles only in the English language (Supplemental Figures 1–3). We found a total of 50 studies that met our inclusion criteria and expanded the public health search to include studies outside of North America, which resulted in a total of 74 articles used in our scoping review.

2.2 Data extraction and synthesis

From eligible studies, data were extracted to summarize, collate, appraise the quality, and make a narrative account of the findings. A data extraction form was developed and pilot-tested by all authors on a sample of 3 papers. Data were extracted by one reviewer and verified by another for quality control, and discrepancies were discussed by all co-authors where they met and reached a consensus. The data were compiled into a single excel spreadsheet and imported into R statistical software for analysis. It included the packages wordcloud, ggplot2, and dplyr (R core team 2019, Fellows 2018, Wickham 2016, Wickham et al. 2019)

Table 1 Search terms for each database

Database	Search strategy syntax
PubMed	"drought" [Title]) AND "mental health" [Title/Abstract] (16 citations) OR "depression" [Title/Abstract] (16) OR "suicide" [Title/Abstract] OR "suicide" [All Fields] (4) OR "anxiety" [Title/Abstract] OR "anxiety" [All Fields] (0) OR "food security" [Title/Abstract] (77) OR "food insecurity" [Title/Abstract] (8) OR "nutrition" [Title/Abstract] (62) OR "malnutrition" [Title/Abstract] (9) OR "disease" [Title/Abstract] (93) OR "infect*" [Title/Abstract] (113) OR "mosquito" [Title/Abstract] (5) OR "vector" [Title/Abstract] (56) OR "pathogen" [Title/Abstract] (93) OR "respiratory" [Title/Abstract] (35) OR "cholera" [Title/Abstract] (1) OR "e. coli" [Title/Abstract] (22) OR "hepatitis" [Title/Abstract] (0) OR "malaria" [All Fields] (2) OR "scabies" [All Fields] (2) OR "asthma" [Title/Abstract] (1) OR "dengue" [Title/Abstract] (3) OR "west nile" [Title/Abstract] (4)
PsycINFO	"drought" [Title] AND "mental health" [Title/Abstract] (7) OR "depression" [Title/Abstract] (0) OR "suicide" [Title/Abstract] (0) OR "suicide" [All Fields] (2) OR "anxiety" [Title/Abstract] (0) OR "anxiety" [All Fields] (0)
Google Scholar	"drought" [Title] AND "food security" [Title] (160) OR "food insecurity" [Title] (36) OR "nutrition" [Title] (3) OR "malnutrition" [Title]) (0) OR "mosquito" [Title/Abstract] (3) OR "vector" [Title/Abstract] (28) OR "pathogen" [Title/Abstract] (41) OR "e. coli" [Title/Abstract] (2) OR "hepatitis" [Title/Abstract] (0) OR "malaria" [All Fields] (1) OR "scabies" [All Fields] (1) OR "west nile" [Title/Abstract] (2)
Science Direct	(Drought) [Title] AND (Migration) [Title] (6) OR (Electricity) [Title] (3) OR (Crop Yield) [Title] (3) OR (Water Quantity) [Title] (1) OR (Built Environment) [Title] (0) OR (Farmers) [Title] (8) OR (Water Resource Management) (4) [Title] OR (Urban Planning) [Title] (2) OR (Planning) [Title] (5) "drought" [Title] AND "food security" [Title] (308) OR "food insecurity" [Title] (59) OR "nutrition" [Title] (285) OR "malnutrition" [Title] (26) ("drought" (3264) [Title] AND "water quality" (34 citations) [All Fields] OR "turbidity" (49) OR "sedimentation" (35) [All Fields] OR "erosion" (155) [All Fields] OR "acidification (21) [All Fields] OR "salinity" (162) [All Fields] OR "algal blooms" (15) [All Fields] OR "cyanobacteria" (43) [All Fields] OR "cyanobacterial bloom" (43) [All Fields] OR "microcystis" (6) [All Fields])

3 Results

The search was conducted from January to February 2020 and yielded 74 relevant citations from 5 electronic databases (Supplemental Figures 1–3). These citations primarily focused on both rural and urban locations ($n = 33$, 44.6%) or rural only locations ($n = 31$, 41.9%) rather than urban only locations ($n = 10$, 13.5%). Drought-related research focused on either drought event that occurred at a time scale within 1 year ($n = 17$, 23%), between 1 and 3 years ($n = 33$, 45%), between 4 and 10 years ($n = 18$, 24%), or greater than 10 years ($n = 6$, 8%). Spatially, study areas were more common on the local level ($n = 15$, 20.2%) or state/province level ($n = 27$, 36%).

Defining drought A word cloud and corresponding code frequency table were produced to identify commonly used terms for drought definitions (Fig. 1). Commonly referenced terms were presented in black and red letters. Drought definitions varied across each article; however, most definitions incorporated precipitation ($n = 12$), rainfall ($n = 13$), water ($n =$

16), agricultural ($n = 10$), meteorological ($n = 10$), hydrological ($n = 6$), or socioeconomic ($n = 5$) variables. Commonly used drought indices, such as the Palmer Drought Severity Index ($n = 3$), Standardized Precipitation Index ($n = 2$), and Standardized Precipitation-Evapotranspiration Index ($n = 2$) were referenced less than broader drought definitions and case studies on specific drought events.

Causal process diagram The following framework highlights major pathways identified in the scoping review involving the examination of drought-impacts on society and health (Fig. 2).

3.1 Public health

Unlike other search terms in this review, public health articles were limited in North America; therefore, we expanded our scope to consider articles from regions outside North America (Fig. 3). Public health studies mainly focused on rural locations ($n = 16$) rather than urban locations ($n = 3$). These impacts were further subdivided into disease and illness, malnutrition and food insecurity, and mental health and stressors based on results.

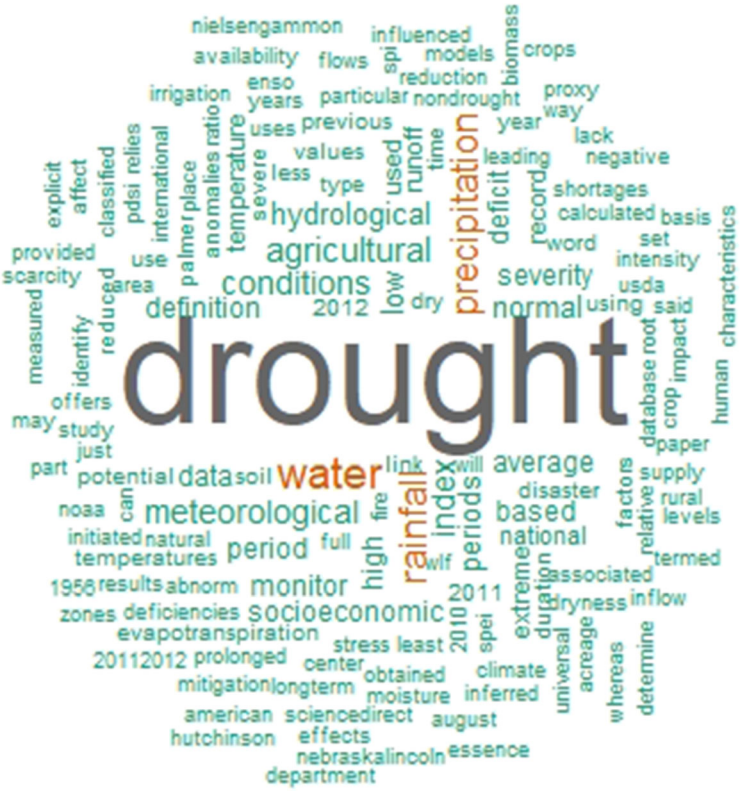

Fig. 1 Word cloud of drought definitions from all search criteria

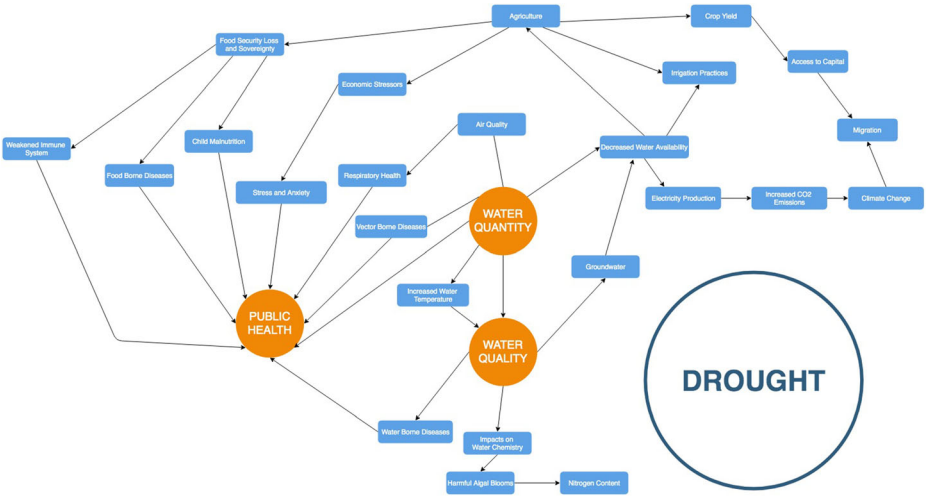

Fig. 2 Causal diagram of drought and drought-related impacts from scoping review

3.1.1 Disease and illness

Drought negatively impacts human health by increasing the risk of water-borne, vector-borne, and respiratory diseases. Scabies, a skin infestation, have been positively associated with drought in Ethiopia due to shortages of safe water for drinking and personal hygiene (Enbiale and Ayalew 2018). Diarrheal diseases, especially in children, have also been found to increase in drought-affected areas due to the limited availability of clean drinking water and low levels of water in storage tanks, increasing the risk for pathogens to develop (Emont et al. 2017). Overall, the studies included found that the health of children, the elderly, and low-income areas was the most vulnerable to drought (Emont et al. 2017; Enbiale and Ayalew 2018; Trewin et al. 2013; Berman et al. 2017; Smith et al. 2014; Yusa et al. 2015).

Communities that rely on stagnant water storage during drought periods and are characterized by populations of concern with low immunity or high vulnerability are more susceptible to vector-borne viruses, such as the West Nile Virus (Trewin et al. 2013). An Australian study showed that mosquito-borne diseases, such as West Nile Virus (WNV), exhibit a higher risk of transmission during drought as a result of increased availability of water storage containers for breeding that are near to human development (Trewin et al. 2013). In New Jersey, drought conditions during the 2010 season were associated with an increase in WNV infection rates in mosquitoes than wetter and milder 2011 (Johnson and Sukhdeo 2013).

Cardiovascular and respiratory diseases are associated with periods of drought, especially among the elderly and locations with fewer experiences with drought events (Berman et al. 2017). Drought conditions exacerbate the risk of respiratory diseases through reduced air quality during dry seasons due to increased erosion, wildfires, and human inhalation of particulate matter (Yusa et al. 2015). In the Amazon, peak hospitalizations for respiratory diseases in children occurred during the fire season within a 100-year drought event, exacerbated by the direct effect of increased

inhalation of smoke and particulates during this more significant drought (Smith et al. 2014). In 2019, Figgs identified an increase in the emergency department for asthma during a drought period in 2012 as compared with a nondrought period in 2011 in Douglas County, NE (Figgs 2019). Overall, the risk for respiratory and cardiovascular diseases will increase with environmental change and be most prominent among vulnerable communities lacking previous experience with severe droughts (Berman et al. 2017).

3.1.2 Malnutrition and food insecurity

Malnutrition and food insecurity in populations are heightened during drought periods, especially in rural communities (Abenet et al. 2016; Delbiso et al. 2017; Iqbal et al. 2018; Keshavarz et al. 2013). In rural agricultural areas, drought can be devastating to a family's food security (Abenet et al. 2016; Delbiso et al. 2017; Iqbal et al. 2018; Keshavarz et al. 2013). Malnutrition is intensified in times of drought (Abenet et al. 2016; Mason et al. 2010; Somketta Emmanuel et al. 2011). In certain countries, such as Ethiopia and Burkina Faso, child malnutrition is the leading cause of child morbidity and mortality. Girls tend to be slightly better fed than boys because they are typically involved in the family's food preparation (Bauer and Mburu 2017). Young children often rely on one or two key cereals. When these vital cereal crops fail, the children suffer greatly (Abenet et al. 2016).

Women's food security is also more affected by drought. For example, in Iran, it is traditional for the men to eat first, and often, nothing of substance is left for the women (Keshavarz et al. 2013). Drought-related impacts on food insecurity often have a cascading effect and lead to inflation in food prices in core and periphery countries (Delbiso et al. 2017; Friel et al. 2014). Farmers may be forced to sell their land or migrate to provide for their families' immediate nutritional needs (Delbiso et al. 2017; Iqbal et al. 2018). Another common coping mechanism is seeking out cheaper, less nutritious food options (Friel et al. 2014; Keshavarz et al. 2013).

3.1.3 Mental health and stressors

Drought-related stressors, including economic stress, often lead to mental health issues such as depression, anxiety, and eventually to extreme outcomes like suicide. Several studies focused on drought and mental health in Australia ($n = 7$). Many of the studies completed were in rural communities ($n = 8$), specifically focusing on the effects of drought on farmers ($n = 6$), with a couple of outlying studies considering the impact of drought on women and adolescents ($n = 2$).

Farmers are significantly impacted by drought and demonstrated a lower level of resilience (Edwards et al. 2015; Viswanathan et al. 2019). Farmers who experienced stressful situations, such as financial issues due to drought affecting their food and crops, also had increased anxiety (Vins et al. 2015). Young and less experienced farmers, particularly in rural areas, young women, and adolescents experienced higher levels of stress during drought than older populations (Austin et al. 2018; Dean and Stain 2010; Gunn et al. 2012; Hanigan et al. 2018, Viswanathan et al. 2019). A similar study conducted in Victoria, Australia, during the 2001–2007 drought, concluded that suicide risk did not increase during this prolonged drought (O'Brien et al. 2014).

3.2 Water quality

Over 20 studies met the inclusion criteria and represent the following domains: water quality ($n = 7$), acidification ($n = 0$), salinity ($n = 5$), turbidity ($n = 2$), sedimentation ($n = 2$), erosion ($n = 1$), algal blooms ($n = 4$), and cyanobacteria ($n = 1$). The water quality impacts from drought were further subdivided into impacts from harmful algal blooms, groundwater, and other impacts based on results.

3.2.1 Harmful algal blooms

Water quality deterioration as a result of prolonged drought conditions is diverse, and the severity of decay is dependent on local activity, including agricultural/pastoral, industrial, and urbanization (Vincent-Serrano et al. 2020). Higher water temperatures were linked with *Microcystis* blooms (i.e., most common type of Cyanobacteria that cause Harmful algal blooms), in addition to elevated concentrations of certain nutrients such as nitrogen, phosphorus, and chlorophyll-a (Lehman et al. 2017; Lehman et al. 2019; Vincent-Serrano et al. 2020).

3.2.2 Groundwater

Groundwater is more sensitive to surface water quality during and following drought events. Within the first month of wet conditions following a drought event, spring water and groundwater were composed mainly of surface water (Wong et al. 2012). Surface water infiltration and influence in aquifers and groundwater is applicable for various terrains, but with differing infiltration rates and lag times (Wong et al. 2012; Vose et al. 2016; Saber et al. 2020).

3.2.3 Other drought-water quality impacts

Aquatic vegetation stress brought on by drought can induce complex ecosystem responses, including changes in species composition and productivity (Xuan and Chang 2014). Submerged aquatic vegetation (SAV) is extremely vulnerable to the impacts of drought. The ebb and flow of SAV populations have a direct effect on phytoplankton and fish populations (Xuan and Chang 2014). Since SAV serves to stabilize sediment when SAV populations decrease, there is a drastic increase in erosion and turbidity. Aquatic systems are sensitive to changes in their environment. The responses are dependent upon several local factors such as type of water body, regional climate and land use, and antecedent conditions before the onset of drought (Vincent-Serrano et al. 2020).

3.3 Water quantity

Water quantity studies mainly focused on rural locations ($n = 16$) rather than urban locations ($n = 3$), while the remaining studies were either undefined or encompassed both urban and rural impacts ($n = 16$). The study areas were predominately at the state or province spatial scale ($n = 12$), rather than the regional ($n = 8$), global ($n = 2$), or city levels ($n = 1$). The water quantity impacts from drought were subdivided into electricity, water quantity, agriculture, and migration.

3.3.1 Electricity

Studies of drought impacts on the electrical grid focused on water availability from dams in British Columbia and Texas for hydroelectric generation ($n = 1$) and cooling capacity for coal-fired power plants ($n = 3$).

Regardless of energy source (e.g., hydropower, nuclear, or coal-fired power plants), drought stresses the electricity system by both reducing water availability through weaker streamflow (Miller and Fox 2017) and increasing water temperatures, which not only reduces access to water but also makes the cooling process less efficient (Scorah et al. 2012; Pacsi et al. 2013; Mu et al. 2020; Miller and Fox 2017). In the USA, cooling for power plants accounts for 40% of freshwater withdrawals and is necessary for electricity generation (Pacsi et al. 2013). For instance, suppose the volume of cooling water drops below a certain threshold. In that case, plants can no longer meet demand and or operate at reduced capacity, requiring electricity to be imported from other regions with increased potential for more CO_2 emissions (Scorah et al. 2012). The strain of drought on the electrical grid could be mitigated by placing future power plants further downstream (Pacsi et al. 2013) and integrating other renewable energy sources into the electrical grid such as wind power (Scorah et al. 2012).

3.3.2 Water resource management

The main topics for these articles were water resource management ($n = 4$), planning for future droughts ($n = 5$), and drought mitigation techniques ($n = 3$). The long-term planning and crisis management of drought focused on arid locations like Texas and the southwestern USA. They found that urban growth could be supported with expanded conversation efforts, rationing, and water reuse (Gober et al. 2016, Ickert et al. 2013). For specific sectors, such as agriculture, water response techniques such as farmers' willingness to pay for water rather than fixed rationing may be more efficient and cost-effective (Forni et al. 2016). Urban growth requires long-term planning and management to deal with drought and extreme drought, particularly in locations with semi-arid and arid climates. These locations need to consider emergency water options and responses that are not solely reactive to extreme drought situations (Gober et al. 2016; Fu et al. 2013).

3.3.3 Agriculture

Common themes looked at modeling techniques for drought effects on agricultural yields and economic impacts. Higher than usual temperatures resulting from drought had a significant impact on crop yield (Matiu et al. 2017). Crop yields were reduced for maize, soybeans, and wheat when drought occurred during growing seasons. Rice was found to be the least affected by drought (Matiu et al. 2017). One estimate suggests that the economic impacts of drought on agriculture may be as high as $100 million for small areas like the southern tier of Colorado, USA (Bauman et al. 2013). Model-based research found that drought-monitoring indices based upon meteorological data alone, such as the standardized precipitation index (SPI), may miss substantial variability in vegetative production (Zhang et al. 2010). Researchers should consider multiple indices that focus on agricultural drought (i.e., soil moisture deficits) when examining agriculture impacts.

3.4 Migration

Migration articles focused on recent drought events and the migrants from Mexico into the USA ($n = 2$) or historical events in the 1930s in Canadian provinces ($n = 2$). The migration of people from drought-stricken regions has high economic and social costs and is not necessarily a lack of adaptation but more of a last resort for families (Gilbert and McLeman 2010). Over the more extended periods, migrants successfully adapted to the destination region. They were a very disruptive process in the short term, entailing high economic costs through the abandonment of land and resources and high social costs when family and community ties were broken (Gilbert and McLeman 2010).

4 Discussion

There is a growing need to understand the impacts of drought across multiple sectors like emergency management, water resources, and public health. This need is exacerbated in the context of ongoing climatic changes, where future drought may become more frequent or severe (Wehner et al. 2017). Our study aimed to map the evidence of drought impacts on health using a scoping review framework. Our review focused on studies that examined the direct impacts of drought-specific outcomes since 2010 on public health, water quantity, and water quality.

Our review illustrated the overall complexity of identifying a universal drought definition, which makes comparisons among studies and quantifiying the associated drought impacts difficult. Previous studies have discussed the complications of using drought definitions and how different interpretations of similar drought indices can result in disparate scientific findings (Trenberth et al. 2013). The articles in our study were focused on drought impacts. They, therefore, were often not conducted by climatologists or meteorologists and failed to use standard drought definitions like the Palmer Drought Severity Index or the Standardized Precipitation-Evapotranspiration Index. Instead, these studies focused on case study drought events (e.g., Somketta Emmanuel et al. 2015), employed drought simulations (e.g., Gober et al. 2016), or did not specifically define a drought period (e.g., Xuan et al. 2014). The inconsistency and lack of drought definitions presented in existing drought-impact research

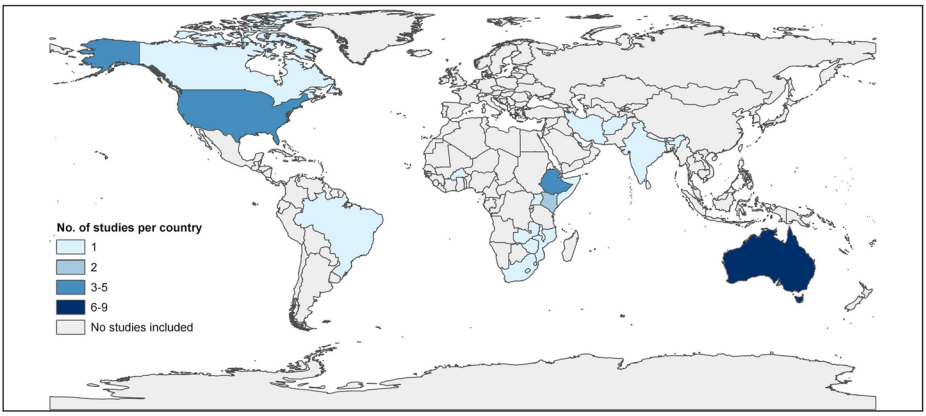

Fig. 3 Map of health-drought study locations in the scoping review

base highlight the need for more cross-disciplinary perspectives with input from geographers, climatologists, and meteorologists. Additionally, the integration of multiple drought indices into drought-impact research would allow for more comparison of drought impacts regionally and across different sectors. We also found that research integrating a trans-disciplinary approach is absent. In many ways, the evaluation of drought-induced damage is not easily identifiable as a societal stressor mainly due to the many indirect ways drought disrupts water supply and quality, energy costs, food production, the health of communities, and beyond. Despite these limitations, our findings provide an overview of the current evidence base and identify significant key findings and research gaps.

4.1 Key findings and research needs for public health

In general, the young are most vulnerable to health impacts (e.g., respiratory illness, diarrheal illnesses, and malnutrition). Low-income communities are also more susceptible to mental and physical health effects, particularly agricultural communities. Elderly populations are more at risk for physical ailments from drought, including heat stress, respiratory impairments, and vector-borne, water-borne, and food-borne diseases; however, this group tends to be more resilient to mental health stressors (Berman et al. 2017; Hanigan et al. 2018; Stanke et al. 2013; Yusa et al. 2015).

A critical gap in the literature involves the unknown disease burden of drought on population health, particularly on the mental health consequences of drought and associated stigma in at-risk groups (e.g., farmers) in seeking out mental health resources. There is a need for more interventions to increase mental health literacy in these groups. Retrospective studies employing latent class analysis are warranted to examine patterns in multi-morbidity changes associated with drought onset, duration, and severity. These studies will shed light on the effect of drought on chronic disease trajectories and the associated role of social determinants of health that can be used in targeted local and regional intervention programs. Another area that needs further exploration involves the latency effects of drought exposure over shorter- and longer-term windows, particularly around examining the impacts of cumulative drought exposure on mental health.

Moreover, to fully understand the impacts of drought on human health across at-risk demographics, public health surveillance systems at the local, state, and regional levels are needed to capture drought-related health impacts and their changes over time. With information on the drought-health implications across local, state, and regional scales, public health practitioners can evaluate the effectiveness of current adaptation strategies to ensure communities frequently or severely impacted by drought can reduce the socioeconomic, physical, and mental health risks. Future drought-health studies should examine drought-related impacts on air, food, and water-related illness with a particular focus on health inequities in urban areas.

4.2 Key findings and research needs for water quality

Water availability estimates largely exclude water quality despite water quality's impact on altering estimates and expenses needed for water treatment (Saber et al. 2020). Drought events result in increased water temperatures, decreased flow rates, reduced soil moisture content, reduced soil respiration, and limited productivity of microbial activity resulting in less productive soil and more sediment in waterways (Hinojosa-Huerta et al. 2013; Mosley

2015; Aronson et al. 2019; Vincent-Serrano et al. 2020; Allen et al. 2011). Understanding the interrelationships between surface water, groundwater, vegetation, water depth, and flow rates allows for a better understanding of water quality effects during drought events as water quality can change throughout a drought period (e.g., nitrogen increases due to expanding roots as they look for water sources and then increases if roots die) (Vose et al. 2016). Furthermore, reductions in water quantity result in increases in water temperature, salinity, contamination, and toxic algal blooms (Vincent-Serrano et al. 2020). Expansion of water quality monitoring efforts in regions that lack sufficient data is needed, as well as regions that are not typically considered vulnerable to drought (i.e., water-rich areas).

Fortunately, most ecosystems are resilient to drought, and lasting impacts are more likely to occur in areas that are already vulnerable due to increases in human activities or species on the periphery of their distribution range (Vincent-Serrano et al. 2020). Drought resiliency in diverse ecosystems and climate zones is needed to understand how quickly water and soil quality recovers after drought events in humid, arid, and developed areas. Specific indicators like submerged aquatic vegetation (SAV) should be considered an ecological indicator for understanding drought resiliency in an ecosystem setting. The decrease in SAV indicates reductions in water quantity/quality and servers as a soil stabilizer reducing semination in waterways (Xuan and Chang 2014).

A more in-depth analysis is needed on the effects of wet conditions following drought periods and the proliferation of HABs beyond surface water and into other parts of the water column. Mainly since it is unclear whether the cause of bacterial growth in water is attributed to favorable conditions propagated by drought or by the presence of contaminants that came from some anthropogenic source. Still, the conditions conducive to their proliferation are not well understood. More research on less common (rare) cyanobacteria is warranted as drought conditions become more common.

4.3 Key findings and research needs for water quantity

Water quantity impacts from drought can affect many different aspects of society. Specific examples from our review on migration and agriculture highlight the underlying risk for specific populations who are already vulnerable (e.g., migrants, urban communities living in a semi-arid climate, farmers) and how drought will be a threat multiplier for these underlying vulnerabilities. These populations of concern are highly vulnerable to drought, and future research should identify the impacts on these populations and ecosystems.

Given that there is no universal definition of drought, the inclusion of multiple drought indices is needed to accurately assess regional vulnerability (Hao et al. 2014). City and regional planners should consider drought as a regular climatological occurrence and integrate drought planning into all aspects of their current work plan and planning and preparedness efforts (Fu et al. 2013). More investigation is required to address the gap between local drought management planning and water quality preservation, as well as the spatial dimensions and vulnerabilities of multi-sectoral planning, preparedness, and adaptation plans across different levels of governments. Further drought monitoring and research should employ geospatial analysis to understand intra-urban inequities in urban water access, water delivery, household location, and impacts of urban growth. Research is also needed to examine other geographic areas in North America, including the Eastern USA, Mexico, and Latin American countries.

4.4 Drought data and relevant statistical modeling techniques

Several drought-related data products can be leveraged in research examining the societal impacts of drought. Table 2 shows a subset of the available drought indices for North America.

There is no current consensus concerning the appropriate statistical methodology for population health studies examining prolonged drought exposure and human health end points. An emerging method, the distributed lag nonlinear model (DLNM), is uniquely poised to explore the delayed and nonlinear effects of drought exposure on human health response over time. These models can be used to examine the influence of multiple climate hazards and their interactions, as well as aid hypothesis generation about the association between the many indirect effects of drought exposure and associated health response. More spatial multi-level analysis examining a variety of drought indicators on geographic disparities in emergency department visits and hospitalizations about population morbidity will help understand drought impacts on the local scale. In addition to observational studies, more research is needed to expand predictive modeling capability to regional and local levels for drought early warning systems.

Future directions to address current gaps in the literature include the following: (1) Develop hybrid modeling strategies that simultaneously account for drought in the context of other climate hazards over time (e.g., generalized linear models); (2) integrate epidemiologic approaches (e.g., latent class analysis) to assess geographic, sociodemographics, and medical resources in drought-affected areas over time; (3) conduct local and regional studies that compare multiple drought indices or exposure metrics to enhance understanding on which drought characteristics over what time scales have the most detrimental effects on human health.

5 Future research and limitations

In the context of ongoing climatic changes, drought is expected to occur more frequently and be more severe across the globe. Climatic change in North America is expected to result in reductions in the frequency of lighter precipitation events in favor of more extremes with little to no variation in mean rainfall (Trenberth 2011, Dai 2013). However, discerning recent trends in US droughts are complicated by increases in long-term precipitation patterns and the absence of reporting like reductions in snowpack and snow-water equivalent that also influence surface moisture deficits (Wehner et al. 2017). Despite these limitations, the current evidence base has not fully explored or adequately measured the full range of drought-related impacts.

Given that drought affects North America and increasing concern over the association between climate change and drought, the linkages between drought and societal impacts are increasingly important. Our knowledge mapping and preliminary review highlights the need for a full systematic review to understand the multi-faceted implications of drought on society. The use of meta-analysis, scoping reviews, and systematic reviews is promising but underutilized in applied climatology and more research is needed that focuses on the intersection of climate extremes and society.

There are several limitations to consider. One limitation is the restriction of our analysis to studies that directly investigate the link between drought and drought-related impacts. We were unable to address all impacts and excluded important topics such as wildfires and air

Table 2 Drought-related data products relevant for drought impact studies in North America

Data	Temporal/spatial extent	Variables	Examples of applications	Caveats
North American Drought Monitor (NADM)/US Drought Monitor (USDM)	Map output based on a five-category system that is updated weekly to reflect location and intensity of drought across the country.	Qualitative scoring based on expert assessment using the following categories: D0—abnormally dry D1—moderate D2—severe D3—extreme D4—exceptional drought	Mallya et al. (2013)	Limitations: lacks predictive capacity and does not incorporate climate forecasts
Standardized Precipitation Index (SPI)/Standardized Precipitation and Evapotranspiration Index (SPEI)	Globally available where precipitation is observed. Calculated from monthly (often 1 to 12 months) accumulations that can be evaluated at monthly to daily timescales.	Precipitation is fitting to a normal distribution to generate a *z*-score or measure of standard deviations from normal. Negative values represent dryer than normal conditions.	Hayes et al. (1999); Vicente-Serrano et al. (2010)	SPI: Based solely on precipitation. Choice of monthly accumulation length is not always clear and impacts index results.
Self Calibrated Palmer Drought Severity Index (SC-PDSI)	Based on precipitation and temperature, the index can be evaluated globally where these measures are available. Computed at monthly timescales.	Temperature and precipitation observations are used to run a simple water balance model with negative *z*-scores indicating dryer conditions.	Wells et al. (2004)	Developed for the US Great Plains and needs to be regionally calibrated. Not well suited for mountainous regions with snowpack or frozen soils.
EDDI	A measure of evaporative demand derived over the contiguous USA at ~12 km resolution. This multiscalar index can be aggregated from weekly to 12-month periods computed at daily to monthly timescales	Based on temperature, wind, humidity, and solar radiation, the measure is evaluated as a percentage (0 to 100%) with 100% representing the driest conditions.	Hobbins et al. (2016)	The index has a higher degree of temporal variability than other measures as it changes with prevailing weather conditions.
Evaporative Stress Index (ESI)	Evaluated globally at weekly timescales the index is available as either a 4- or 12-week composite.	Land surface temperature, precipitation, wind, and solar radiation are used to estimate actual and potential evapotranspiration and evaluated as a *z*-score.	Anderson et al. (2011)	Remotely sensed data obscured by cloud cover.

For a more comprehensive list of drought indices, visit: https://www.drought.gov/drought/search/data

quality. PRISMA guidelines were used to minimize bias in our inclusion and exclusion criteria and to ensure transparency in our scoping review methodology. The lack of studies identified by our review among certain subjects was because either they did not directly examine drought impacts or no studies had been conducted since 2010 within North America. It is possible that researchers framed their study as a hydrologic extreme or included a primary objective that did not directly address drought impacts. Nevertheless, studies that focus on the indirect pathways of drought should be considered in future research and reviews.

6 Conclusions

Comprehensive and multi-sectoral plans for adaptation and resilience are needed in the face of expected climate-related changes in drought frequency and severity. Across agencies, sectors, and scales, the challenge of defining drought limits a holistic understanding of its wide-ranging effects on society and recovery time across regions and different time periods. This is a problem that can be overcome through interdisciplinary collaboration that builds a community-wide consensus on the identification of those hydrological indicators that best describe the multi-faceted challenges that drought poses to society.

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