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OVERVIEW

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Dry landscapes and parched economies: A review of how drought impacts nonagricultural socioeconomic sectors in the US Intermountain West

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Abstract

From hampering the ability of water utilities to fill their reservoirs to leaving forests parched and ready to burn, drought is a unique natural hazard that impacts many human and natural systems. A great deal of research and synthesis to date has been devoted to understanding how drought conditions harm agricultural operations, leaving other drought-vulnerable sectors relatively under-served. This review aims to fill in such gaps by synthesizing literature from a diverse array of scientific fields to detail how drought impacts nonagricultural sectors of the economy: public water supply, recreation and tourism, forest resources, and public health. We focus on the Intermountain West region of the United States, where the decadal scale recurrence of severe drought provides a basis for understanding the causal linkages between drought conditions and impacts.

This article is categorized under:

Human Water > Value of Water

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KEYWORDS

drought, economic impact, public health, US Intermountain West

1 | MOTIVATION

Drought is often described as an *insidious* natural hazard—proceeding gradually and subtly with harmful effects (Weghorst, 1996; D. A. Wilhite & Buchanan-Smith, 2005). Even though this very same complexity makes accounting difficult, drought is one of the costliest natural disasters, affecting tens of millions of people per large event and often causing damages in the tens of billions of dollars (Riebsame et al., 1991; A. B. Smith & Matthews, 2015; D. Wilhite, 2000). These impacts transcend economic sectors and scientific disciplines, necessitating a deep understanding of how drought conditions affect human and natural systems (Van Loon, Gleeson, et al., 2016).

To date, agriculture has seen the vast majority of work relating drought conditions to impacts, compared to other sectors. This litany of agricultural drought research performed over the previous decades yields real-world benefits. For example, the U.S agricultural community benefits from research-driven adaptation strategies, such as genetically modified, drought-tolerant crop varieties (Blum & Jordan, 1985; Marshall, 2014) and moisture-conserving land use practices (Hatfield et al., 2001). Moreover, well-established mitigation programs, such as drought insurance and indemnity payments (Reyes & Elias, 2019), help to alleviate the expected financial consequences of drought on U.S producers. However, agriculture is far from the only drought-vulnerable economic sector in need of research that connects drought conditions to impacts.

Throughout the western United States, quality of life and economic stability depend on water availability (Bales et al., 2006; Mankin et al., 2015). Without snow, mountain communities will not attract winter tourists and spring runoff volumes will be meager. Without abundant spring runoff, rivers will not attract boaters and anglers, and municipal water supply reservoirs will not fill. Without sufficient moisture, forests will be vulnerable to wildfire and downwind communities will grapple with degraded air quality. Despite the clear dependence of life in the western U.S. on water availability, the causal chains between drought indicators (i.e., hydrometeorological metrics that quantify drought conditions) and impacts are poorly understood and poorly quantified for nonagricultural sectors. This single-sector focus limits understanding and adaptive capacity for other key industries, even when they are as economically and societally important as agriculture. In the state of Colorado, for example, the outdoor recreation industry employs over 300,000 more people and produces $15.8 billion more in economic impact annually than agriculture (Colorado Department of Agriculture, 2020; Colorado Parks and Wildlife, 2018). When examined in the US Drought Impact Reporter, agriculture is mentioned in 33.5% of all reports, compared to only 5.7% for recreation in the Intermountain West (IMW) region of the United States. Similarly, a Google Scholar search for "drought impacts agriculture" returns 1.42 million results, compared to 96,000 for "drought impacts recreation." In a review of previous literature, the most dominant category relating drought indicators to impacts was agriculture (Sophie Bachmair et al., 2016).

To address this knowledge gap, we review literature documenting the state of the science and practice of drought impacts for four nonagricultural, drought-vulnerable economic sectors in the IMW: public water supply, recreation and tourism, forest resources, and public health. Although a diverse set of fields has produced this work, wherever possible we will use common terminology to highlight the interconnectedness of these sectors and to reveal gaps or missed opportunities. For each sector we ask:

- How does drought impact sector-specific operations and functions?
- What are the causal linkages, interactions, and feedbacks relating drought conditions and impacts?
- How are drought impacts assessed, quantified, and defined for the sector?

We begin by defining drought in the context of this work along with various indices that quantify drought severity (Section 2). Next, we introduce our study region, the IMW, and its past and projected future droughts (Section 3). We then give a sector-by-sector review of drought impact literature (Section 4).

2 | DEFINING DROUGHT

By nature of its complex impacts, drought definitions come in multiple forms that aim to properly communicate a given drought's characteristics (Mishra & Singh, 2010). In some cases, drought by one definition may not be a drought by another. For example, while below-average precipitation is a key component of many droughts, it is not always accompanied by marked declines in streamflow. Conversely, because of changes in snowmelt patterns or anthropogenic drivers on terrestrial hydrologic systems, streamflow may be below normal while precipitation is near average (Van Loon, Stahl, et al., 2016). This seeming paradox has led to previous researchers defining four major drought types: meteorological, hydrologic, agricultural, and socioeconomic (D. A. Wilhite & Glantz, 1985).

Meteorological droughts occur during periods of below-average precipitation, which may be accompanied by warmer-than-average air temperature and/or elevated atmospheric moisture demand (Palmer, 1965b). Oftentimes meteorologic drought propagates into hydrologic drought, a state marked by low streamflow, reservoir, lake, snowpack, and groundwater levels (Van Loon, 2015). In some cases, hydrologic drought can persist even when precipitation has returned to near-normal levels (Hisdal & Tallaksen, 2000). Meteorological and hydrologic drought conditions may also coincide with agricultural drought, a period of below-average crop productivity. Socioeconomic drought occurs when water demand outstrips supply and affects societal uses. Impacts of socioeconomic drought may be felt by one sector, while leaving another relatively unscathed. Finally, ecological drought occurs when water deficits push ecosystems over vulnerability thresholds and affect valuable ecosystem services (Crausbay et al., 2017; Raheem et al., 2019). The literature we review in this paper deals with drought in its meteorological, hydrologic, ecological, and socioeconomic forms. In short, we treat drought as a shortage of water in any form that adversely affects our studied sectors.

Within these broader definitions are two epistemological categories used by researchers to evaluate drought, one based on indicators and another based on impacts (Redmond, 2002). Indicator-based definitions rely on objective hydrological or meteorological metrics to indicate the severity, extent, and duration of drought relative to a baseline period. For example, the commonly used Palmer Drought Severity Index is computed as a function of air temperature and precipitation, thus representing the magnitude of meteorological droughts (Alley, 1984; Palmer, 1965a; Wells et al., 2004). Impact-driven drought definitions rely on agricultural, ecological, or socioeconomic impacts realized as the consequence of a sustained water shortage. For example, drought conditions may be described as crop or primary productivity losses, mandatory water use restrictions, declines in revenue, or increased incidences of heat stroke hospitalization.

This split in drought definition, between indicators and impacts, poses a challenge to groups, communities, and researchers grappling with how best to respond and adapt to drought (S. Bachmair et al., 2015; Noel et al., 2020). Purely indicator-based definitions lack the context necessary to anticipate if, how, and when water deficits will impact critical operations. Purely impact-based drought definitions lack the information necessary to understand why observable impacts have emerged and the foresight necessary to learn how the same impacts may arise in the future. One objective of this review is to connect drought indicators to drought impacts to develop a deeper understanding of the causal linkages between hydrometeorological processes and their quantifiable consequences.

3 | DROUGHT IN THE IMW

While we include relevant literature from other regions, we focus our review on the IMW states of Colorado, New Mexico, Arizona, Utah, and Wyoming (National Integrated Drought Information System (NIDIS) (Figure 1). This hydroclimatically diverse region spans a wide elevation range, from near sea level on the Colorado River in Arizona to 4401 m at the summit of Mt. Elbert in the Rocky Mountains of Colorado. According to meteorological data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM), patterns of annual precipitation are similarly varied, with mean annual totals ranging from 77 mm in the Arizona desert to over 2000 mm in Wyoming's Teton Range

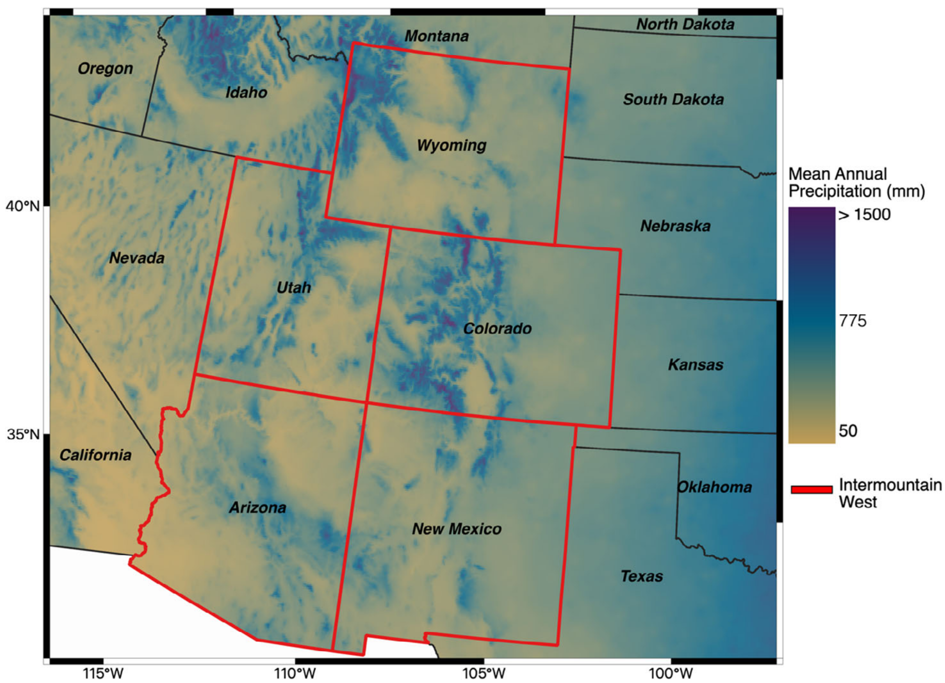

FIGURE 1 Map showing the five states of the IMW (outlined in red) along with surrounding states in the western US. Shading corresponds to 1981–2010 mean annual precipitation from PRISM (Daly et al., 2008; PRISM Climate Group, 2012). The highest annual totals are found in the various mountain ranges of the IMW

(Daly et al., 2008; PRISM Climate Group, 2012). However, high annual precipitation is relatively rare with most areas classified as arid or semi-arid (Huang et al., 2016; Wise, 2012). Mean annual air temperatures below freezing can be found across the high mountains of most states, while the warmest values, above 20°C, are in the Arizona desert near the US-Mexico border (Daly et al., 2008; PRISM Climate Group, 2012). Because the greatest precipitation values tend to occur in the highest, coldest locations, regional hydrology is snow-dominated (Bales et al., 2006). In some river basins, more than 80% of annual streamflow is derived from snowmelt (D. Li et al., 2017).

A defining feature of this region is that major population centers tend to be located downslope and downstream of the high-elevation headwater basins, the so-called "water tower" effect (Messerli et al., 2004; Viviroli et al., 2007). Much of the IMW citizenry and industry are found in arid and semi-arid climate areas, thereby relying on water deliveries from the mountains (Mankin et al., 2015). This combination of geographic positioning and climatic regimes means the IMW is highly exposed and sensitive to drought. Periods of markedly below average precipitation and streamflow are recurrent phenomena in the IMW with wide swings between water feasts and famines (E. B. Allen et al., 2013; S.-Y. Wang et al., 2009). Plotted over time, the maximum extent of extreme and exceptional drought conditions in the five IMW states, according to the US Drought Monitor, shows pronounced multi-year droughts (Figure 2a). Prominent droughts can be seen during the 1930's Dust Bowl period, the protracted 1950's drought, and the major 21st century droughts of 2001–2003 and 2011–2013. During these periods, annual flow in the Colorado River at Lee's Ferry, a bell-wether of western water supply, was well below average (Figure 2b). Notably, the federal government allocated flows from the Colorado River based on the anomalously wet period of the early 1900s.

4 | SECTOR-SPECIFIC DROUGHT IMPACTS

4.1 | Public water utilities

Summer rainfall is insufficient to meet water resources needs over much of the IMW region (Mankin et al., 2015), making the timing and volume of snowmelt deliveries key to municipal water supply (Dziegielewki & Kiefer, 2007; Garfin

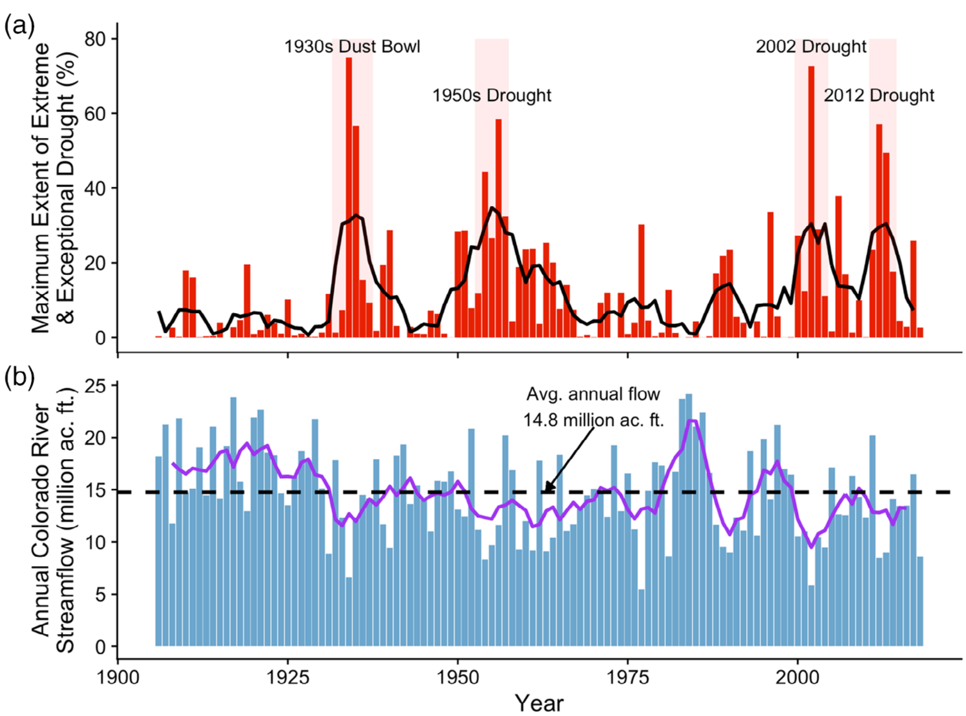

FIGURE 2 Annual maximum extent of extreme and exceptional drought in the five states of the IMW (a) and annual natural Colorado River streamflow at Lee's Ferry (b). Drought values in (a) were computed using Palmer Drought Severity Index data from the Westwide Drought Tracker. As in the US Drought Monitor, extreme and exceptional drought correspond to PDSI values of −4.0 to −4.9 and less than or equal to −5.0, respectively. Streamflow values in (b) come from the US Bureau of Reclamation's Colorado River Natural Flow and Salt Dataset. The solid line in each plot represents the 5-year moving average of the respective drought categorization and streamflow data

et al., 2013). By storing water through the winter and spring, mountain snowpacks act as natural water towers that release meltwater as human and ecosystem demands increase (Immerzeel et al., 2020; Viviroli et al., 2007). However, despite the natural overlap between water availability and demand, utilities must still account for late-summer water needs and multi-year droughts. Changes in streamflow timing due to climate change will exacerbate a growing mismatch between supply and demand (because peak flows are occurring earlier in the spring, while demand is highest in mid-summer) and will present challenges for the management of reservoirs, aquifers, and other water infrastructure (Rajagopalan et al., 2009). Utilities therefore engineer complex systems that satisfy water demands over seasonal and interannual dry spells. Fundamentally, drought impacts these municipal water utilities by lowering supplies, raising water demands, and threatening system reliability. Consequential impacts to infrastructure, water quality, and utility finances make drought one of the most damaging natural hazards for municipal water utilities.

4.1.1 | Water supply

Hydrologic drought conditions affect snow-dependent water utilities by decreasing the total snow water storage, altering the timing and rate of melt, and decreasing catchment water yields (Harpold et al., 2017; Saft et al., 2016). Many utilities use reservoirs to capture snowmelt and store water for release during seasonal and interannual periods of high demand and low supply. In the Colorado River basin, for example, reservoir storage is approximately four times the annual flow, giving some buffering capacity for supply declines during drought years (Christensen & Lettenmaier, 2007; Rajagopalan et al., 2009). Despite this, sustained drought conditions still affect the timing and magnitude of reservoir inflows and bolster evaporation rates, thereby driving reservoir storage volumes to critically low levels (Barnett et al., 2008; Georgakakos et al., 2014; D. Wilhite & Pulwarty, 2005).

The importance of storage was highlighted during the severe prolonged drought in the Colorado River basin that began in 2000. The decreased precipitation, coupled with historically high temperatures and continuing population and economic growth, contributed to reservoirs across the region hitting historic low levels (Rajagopalan et al., 2009; Udall & Overpeck, 2017). Inflow into Lake Powell in 2002 was the lowest on record, amounting to only 25% of average (Fulp, 2005). Impacts of this drought at local municipal reservoirs had direct consequences on public drinking water supply, prompting mandatory water use restrictions across the region (Doesken & Pielke, 2004; Pielke et al., 2005).

The resilience of water supplies in the Colorado River Basin is in question, with climate models projecting a decline in Colorado River flow as a result of increases in hydroclimatic and demand stresses (Barnett et al., 2008; Christensen & Lettenmaier, 2007b; Milly et al., 2005; Udall & Overpeck, 2017; Wu et al., 2008). Although the magnitude of reduction is uncertain given the complexity of physical processes and climate model representations of temperature and precipitation, one model projected runoff decreasing 10%–20% in the next 50 years (Brekke et al., 2009; Cayan et al., 2010). The impacts of expanding aridity is likely to disproportionately affect Upper Basin states (Colorado, Utah, Wyoming, New Mexico, and northern Arizona), with reservoirs declining to dead storage levels and unmet consumptive use requests more likely (Harding et al., 1995; Seager et al., 2012).

As the Upper Basin states continue to develop their allocated share of the Colorado River, water delivery shortages and mandatory cutbacks will be required from some Lower Basin states (Arizona, California, Nevada). For example, Arizona's Central Arizona Project, a 530 km canal that is a water source for 4.7 million people, could theoretically lose its water allocation if continued low flows of the Colorado River persist. Per the prior appropriations framework of western U.S. water law, water deliveries to junior rights holders are fulfilled only when water is first available to supply more senior rights. Looking forward, as drought conditions worsen and competition for Colorado River water increases, collaborative water management strategies will have to be implemented in order to meet the water needs of both senior and junior rights holders the region (Sullivan et al., 2019).

Aside from surface water resources, groundwater resources are an essential component of water supply portfolios for many IMW utilities. Reduced deliveries from surface water sources during drought often lead to excess groundwater withdrawals to minimize impacts on public water supply (Castle et al., 2014; Famiglietti & Rodell, 2013; Kenny et al., 2009). Long-term drought reduces groundwater availability by reducing aquifer recharge rates (Ajami et al., 2011; Dwivedi et al., 2018; Georgakakos et al., 2014). Drought conditions also exacerbate groundwater pumping demands, potentially driving unsustainable negative water balances on water supply aquifers. Such negative balances can reduce aquifer storage capacity, increase pump power requirements, degrade water quality, and contribute to land subsidence (Blue et al., 2015; Brislawn et al., 2013). The impacts of drought on groundwater supplies often exhibit multi-year lags, whereby the most severe impacts are felt years after drought conditions have subsided (Leblanc et al., 2009; Van Loon, 2015).

4.1.2 | Water demand

Coupled with dwindling supply, elevated water demand during drought can strain water supply systems to the limits of reliability. Water utilities, particularly in the IMW, experience a sharp increase in water demand in the summer months, driven by outdoor water use to irrigate lawns, parks, agricultural fields, and other landscapes (AMEC, 2018). In Salt Lake City, Utah, customer demand can be more than four times higher in the summer than in the winter (Duer, 2020). In Colorado, lawn watering during the spring and summer can account for well over half of total annual residential water use (Kenney et al., 2004). Several studies have found that climate change and drought conditions increase plant irrigation requirements, (Cook et al., 2014; Döll, 2002; Fischer et al., 2007) thereby exacerbating peak water demands (Kenny et al., 2009). Some of the highest water demand increases under climate change are projected in Southwest regions where groundwater aquifers are the main water supply source (Georgakakos et al., 2014).

To manage demands during periods of low supply, most water utilities along Colorado's Front Range implemented at least some type of water restriction (voluntary or mandatory) during the droughts of 2002 and 2012. A study done in 2002 showed that, for several cities in Colorado's Front Range, during periods of mandatory restrictions, savings of 18%–56% were seen, while voluntary restrictions saw only 4%–12% savings (Kenney et al., 2004). Utilities imposing the strictest restrictions during the 2002 drought accordingly achieved the greatest savings.

4.1.3 | Utility finances

Water utilities generate revenue by selling water. When nonessential water demand is restricted during drought, revenue streams are impacted (Dilling et al., 2019; H. B. Zeff et al., 2014). For example, drought response water restrictions during the summer of 2013 decreased Denver Water's operating revenue by 13% ($37 million) relative to original fiscal year projections (Denver Water, 2016). Reduced revenue during droughts affects a utility's ability to recover its mostly fixed costs, potentially leading to lower credit ratings and higher bond financing rates (H. Zeff et al., 2020). In turn, this increases the cost of capital required for routine maintenance and infrastructure improvements (Dilling et al., 2019). Additionally, implementing a drought response program is cost intensive. There are significant overhead costs associated with public awareness campaigns and enforcement of mandatory water restrictions (E.P.A., 2018).

Drought-induced low water levels in streams and reservoirs can have adverse impacts on water infrastructure, requiring large capital investments for repairs and upgrades. If reservoirs get too low, intake and pumping stations may not be operational, and hydroelectric power generation capacity is decreased (Fulp, 2005). Low water levels in reservoirs can threaten the structural integrity of earthen dams by facilitating the development of cracks (Z. Li et al., 2018). Excessive sediment flux into reservoirs, often associated with runoff from areas ravaged by drought-induced wildfire, can damage water intake pumps and clog treatment plant filtration systems (Rhoades et al., 2019).

Drought exacerbates land subsidence when groundwater is withdrawn and not recharged at normal rates, and is particularly noticeable in California, Texas, Arizona, and Florida (Brislawn et al., 2013; Zektser et al., 2005). Collapsing ground and changes in soil structure due to drought can damage infrastructure such as road and water mains (Brislawn et al., 2013; Georgakakos et al., 2014). During a 2011 drought in Austin, Texas, 10–15, or more, water main breaks occurred each week because of shifting and shrinking soils (Blue et al., 2015).

Droughts can lead to water quality implications for drinking water supplies, including turbidity, taste and color, lower dissolved oxygen levels, and the altering of nutrient cycling and biota within both watersheds and reservoirs that can influence water quality for months or years after the event (Governor's Drought Task Force, 2004; Wright et al., 2014; Yusa et al., 2015). The decreased volume of water in lakes and reservoirs increases the concentration of pollutants, such as municipal waste water and thermoelectric power plant return flows (Bates et al., 2008; Wright et al., 2014). Drought-related wildfires can also damage water infrastructure and cause chemical and physical damage in rivers and streams, resulting in short-term water quality issues and long-term watershed complications (NRCS, 2016; Ranalli, 2004; Rhoades et al., 2019; Rust et al., 2018). In 2002, Denver Water spent $26 million to restore water quality and remove the large volume of sediment in its reservoirs, due to the Hayman Fire (Blue et al., 2015). In 2012, the Hewlett Fire and the High Park Fire burned 10% of Fort Collins' watershed, causing increased sedimentation in rivers and stress on water treatment plants (Water Shortage Action Plan, 2020).

4.2 | Forest resources

Forests and woodlands are a major source of raw materials for food, fuel, and shelter for the global economy (Oswalt et al., 2019). Forested lands also provide valuable ecosystem services including carbon storage, nutrient cycling, hydrologic cycling, soil preservation, and recreational opportunities (Krieger, 2001). Drought conditions impact the natural capital of forested lands (Crausbay et al., 2017) by pushing trees and shrubs to their physiological limits, increasing pest and pathogen vulnerability, facilitating widespread tree mortality events, decreasing fuel moisture levels, and increasing wildfire risk (Vose et al., 2019).

4.2.1 | Tree health

Drought impacts forest ecosystems by limiting the availability of water to trees and shrubs, which drives hydraulic stress and failure (Adams et al., 2017; W. R. L. Anderegg et al., 2016; McDowell et al., 2008). Hydraulic stress can decrease primary productivity, increase susceptibility to pests and pathogens, and in extreme cases, cause tree mortality (W. R. L. Anderegg, 2012; Bentz et al., 2010; Kolb et al., 2016; McDowell et al., 2008). Because drought is a regularly occurring phenomena in the IMW (Figure 2), forest and grassland ecosystems have evolved natural adaptation strategies to cope with transient water limitation (Bréda et al., 2006; Mariotte et al., 2013). However, "global-change-type" droughts are pushing some forested ecosystems closer to tipping points and altering successional pathways (Breshears et al., 2005).

Drought-induced tree mortality, whether caused directly by hydraulic failure or indirectly by pests and pathogens, affects all biomes and climates across the globe (C. D. Allen et al., 2010). Several tree mortality events are of note in the IMW. A die-off of *Pinus edulis* (pinyon pine) followed a period of severe drought during 2002–2003 and associated bark beetle infestation in forests across Colorado, Utah, New Mexico and Arizona (Breshears et al., 2005, 2009). During this event, over 90% of *Pinus eldus* died across 12,000 km^2 of forested land. Widespread, multi-species tree mortality followed severe drought conditions during 2002 across several forest and climate zones near Flagstaff, Arizona (Gitlin et al., 2006). Elsewhere, severe drought in 2002 prompted a multi-year decline of up to 17% of Colorado's *Populus tremuloides* (quaking aspen) population, a phenomena known as Sudden Aspen Decline (SAD) (L. D. L. Anderegg et al., 2013; Worral et al., 2007; Worrall et al., 2008). Here, drought conditions impacted aspen stands by depleting shallow soil moisture reserves, a critical water source for *Populus tremuloide*, and increasing atmospheric water demand (L. D. L. Anderegg et al., 2013).

As a secondary impact, drought affects forest carbon budgets (Kurz et al., 2008). While forested lands are typically carbon sinks, drought can either decrease carbon uptake rates or transition forests to net carbon sources. Following tree mortality events, reduced photosynthetic carbon uptake and increased microbial respiration (Hicke et al., 2012; Hicke et al., 2013) can cause temporary transitions of forested lands from carbon sinks to sources (W. R. L. Anderegg et al., 2015; Ciais et al., 2005; Doughty et al., 2015). Additionally, earlier snowmelt, one consequence of snow drought, has been shown to reduce carbon uptake during ablation in subalpine forests (Winchell et al., 2016). Available stand-level carbon budget studies show that drought impacts to carbon budgets are temporary, and carbon budgets can recover within 3–5 years following drought or infestation induced mortality events (Amiro et al., 2010; M. G. Brown et al., 2012).

Another secondary impact of drought is long-term shifts in the forest water budget (Adams et al., 2012; Redding et al., 2008). As canopy trees die during mortality events, interception and transpiration rates decrease, allowing more precipitation to reach the forest floor (Ford & Vose, 2007; Spittlehouse, 2007). At the same time, higher radiation and windspeeds at the forest floor increase energy for snowmelt and soil evaporation (Boon, 2007, 2009; Penn et al., 2016; Royer et al., 2011). The consequence is often a higher catchment water yield, larger peak flows, and earlier peak flow timing (Bethlahmy, 1974, 1975; Carver et al., 2009; Jones, 2000; Weiler et al., 2009). However, other site-specific investigations show decreased or unchanged catchment water yields in the wake of mortality events (Biederman et al., 2015; Guardiola-Claramonte et al., 2011; Penn et al., 2016). While the hydrologic impacts of forested land cover changes have been the focus of catchment hydrology studies for decades (e.g., Elliott & Vose, 2011), available literature seems to suggest that net water balance impacts are dependent on site-specific characteristics, such as geology and climate.

Drought, by way of tree mortality, causes tertiary economic impacts by degrading forest aesthetics (Sheppard & Picard, 2006). Surveys of national park visitors in Canada and the United States found that infestation-related tree mortality negatively impact visitor experience and perceptions of forest health (McFarlane & Witson, 2008; Sumner & Lockwood, 2020). These studies suggest carry over impacts of tree mortality to regional recreation-based economies with persistent effects lasting years after a mortality event (Nolte et al., 2018; Peterson et al., 2018). Additionally, tree mortality negatively impacts property values (Holmes et al., 2006). In Grand County Colorado, it is estimated that property values decline by $648, $43 and $17 for every tree killed within a 0.1, 0.5, and 1.0 km radius around the property, respectively (Price et al., 2010).

4.2.2 | Large wildfires

Wildfire is an endemic component of western US ecosystems (Sherriff & Veblen, 2007; Swetnam & Betancourt, 1990) and plays an important role in mediating ecosystem structure, diversity, and function (Debano & Conrad, 1978; Whelan, 1995). Fire geography across the IMW is tightly coupled to climate. Ninety-four percent of fires, accounting for 98% of burned area, burn between May and October, the driest times of the year (Westerling et al., 2003). While drought is not the sole cause of wildfire, drought conditions are a prerequisite for large burns (Abatzoglou et al., 2018; Barbero et al., 2014; Schoennagel et al., 2007; Veblen et al., 2000) that overwhelm suppression capabilities, damage property, and lead to losses of life (Tedim et al., 2018).

Drought conditions deplete water storages in forested lands, including moisture stored in the tissue of live and dead plant matter, also known as fuel moisture (Bessie & Johnson, 1995; Gedalof et al., 2005; Kulakowski & Jarvis, 2011; Turco et al., 2018). Biophysical variables that quantify moisture contents (e.g., snow water equivalent, soil moisture, or fuel moisture) are more strongly correlated with variations in seasonal burned area, compared to strictly weather or climate variables (e.g., air temperature or precipitation; Abatzoglou & Kolden, 2013; Gedalof et al., 2005). For this reason, the frequency and severity of wildfires tend to be greater during drought years than nondrought years (Abatzoglou & Williams, 2016; Gedalof et al., 2005). Looking forward, projected climate change over the coming century is likely to increase the likelihood of extreme fires by facilitating drier fuel moisture conditions and expanding the length of the fire season (Barbero et al., 2015).

Hydrologic conditions prior to the fire season such as snowmelt timing, cumulative precipitation, and cumulative evapotranspiration have been shown to control seasonal fire activity (Littell et al., 2009; Westerling et al., 2003; Westerling et al., 2006). However, the nature of antecedent controls vary by ecoregion (Collins et al., 2006; Westerling et al., 2003). In moisture limited fire systems, such as the Colorado Rockies, interannual variability in burned area is positively correlated with drought conditions preceding the fire season. Here, antecedent drought conditions jump-start the seasonal cycle of fuel desiccation earlier than normal, thereby increasing ignition likelihood. Elsewhere, in fuel-limited fire systems, such as grass and shrublands, annual burned area is positively correlated with wet conditions in spring and early summer (K. J. Brown et al., 2005). In fuel-limited ecosystems, wet antecedent conditions facilitate fuel growth while dry conditions during the fire season lower fuel moisture (Balch et al., 2013).

4.3 | Recreation and tourism

Outdoor recreation is big business across much of the IMW. According to the Bureau of Economic Analysis, the value added from outdoor recreation represents between 2.5% and 4.5% of total state gross domestic product in Arizona, New Mexico, Utah, Colorado, and Wyoming (Awuku-Budu & Franks, 2019). The recreators and tourists coming to these states rely on suitable weather and hydrologic conditions, which are essential for many outdoor recreation pursuits (Scott & Lemieux, 2010). However, this same reliance means that most outdoor activities are uniquely exposed to the effects of drought (Crowley et al., 2019; Thomas et al., 2013; Wilhelmi et al., 2008). Similar to the water utilities sector, drought begins in the mountains with below-average snowfall before propagating downstream. In some cases, drought means an activity cannot take place (e.g., insufficient streamflow for a boat to float), while in other cases drought may reduce visitation or enjoyment as conditions degrade. Interestingly, drought conditions can sometimes increase visitation, particularly in cool, high-elevation areas (Buckley & Foushee, 2012; Fisichelli et al., 2015; Richardson & Loomis, 2005; Scott et al., 2007). However, it is likely that drought and wildfire will negatively disrupt outdoor recreational opportunities over the coming decades (USGCRP, 2018).

4.3.1 | Winter sports

Downhill skiing, snowboarding, snowshoeing, cross-country skiing, and snowmobiling all require the same thing: sufficient snow cover. Drought challenges these industries with reduced snow coverage that either does not support certain activities or reduces consumers' willingness to pay (i.e., the maximum amount a person would pay for a product or experience). In some cases, this sector may experience drought conditions even when meteorological and/or hydrologic drought are not occurring. Warm snow droughts, characterized by increased rain-snow proportions as a result of higher than average air temperatures (Harpold et al., 2017), correspond to poor skiing conditions even if precipitation is near-normal.

The impacts of drought on the winter sports industry can be considerable. Previous reports indicate these activities add $11–12 billion to the US economy, while supporting nearly 200,000 jobs (Burakowski & Magnusson, 2012; Hagenstad et al., 2018). Intuitively, annual user days, the number of single day visits per person, track with snowfall and snow depth, meaning less snow means fewer and less contented participants (Hagenstad et al., 2018). Critically, for the winter sports industry, there is an asymmetry between the profound negative impacts of low-snow years and the slightly positive effects of high snow years, with the former reducing the value added to the US economy by over $1 billion and costing 17,400 jobs (Hagenstad et al., 2018). Compounding matters is the finding that visitation to ski areas can be reduced as a result of snow droughts not only in the resort areas themselves, but also in far-afield population centers from which they derive many of their visitors (Hamilton et al., 2007).

In the western US, the previous decades have challenged the winter sports communities with prolonged droughts not just in the IMW, but also California and the Pacific Northwest. In Washington state, the 2004–2005 drought was particularly difficult on ski resorts. One area extended season passes into the 2005–2006 season for free, another area forewent critical upgrades, and two ski shops closed (Goodman, 2005; Scott & Lemieux, 2010). As such, researchers identify skiing as one of the most vulnerable industries in Washington state to drought (Fontaine & Steinemann, 2009). The 2011–2012 drought was so widespread, it produced the fewest skier visits in the US from 2009 to 2019, nearly 10 million fewer than what would have been typically expected (Vanat, 2020). Record-setting drought in California from 2013 to 2016 saw markedly reduced visitation and early ski area closures (Chang & Bonnette, 2016; Lund et al., 2018). As a result of compounding negative impacts of drought, many ski resort operators fear multiple years of poor snow conditions that may lead to permanent resort closures (Beaudin & Huang, 2014; Even et al., 2020). Ongoing snowfall declines and broader macroeconomic trends have already led to a contraction of the US ski industry, with fewer resorts in operation now than in the 1980s and stagnating annual visitation (Hagenstad et al., 2018; Vanat, 2020).

More than just episodic droughts, the winter sports industry is beholden to the specter of climate change (Scott et al., 2006; Steiger et al., 2019). As a result of its strong relationship to air temperature (Dai, 2008; Jennings et al., 2018) and widespread warming, snowfall is in unequivocal decline across cold and temperate regions (Hock et al., 2019; N. Knowles et al., 2006; Safeeq et al., 2015). As we move toward the future, there is the potential to see the dominant lever affecting snow droughts shift from precipitation to air temperature in some areas. Across the western US, this shift could mean a total annual loss near $1 trillion in ecosystem services that are currently provided by snow (Sturm et al., 2017). For the winter sports industry, future snowfall declines will dramatically shorten season lengths by upward of 50% and 90% by 2050 and 2090, respectively (Wobus et al., 2017). This contraction may produce annualized losses nearing $2 billion, with downhill skiing experiencing markedly larger economic impacts than cross-country skiing and snowmobiling (Wobus et al., 2017).

However, ski resorts have ample opportunities to enhance adaptive capacity (Scott & McBoyle, 2007). The primary adaptation pathway thus far has been expanded reliance on snowmaking to make up for ever-increasing snowfall deficits (Steiger et al., 2019). In Colorado, droughts in 1979 and 1981 are seen as a watershed moment in the adaptation of snowmaking by the state's resorts (Wilhelmi et al., 2008). Improved snowmaking technology will enable many resorts to operate, even as air temperatures warm (Bark et al., 2010; Hennessy et al., 2008; Scott et al., 2006). Despite these positives, the winter sports industry undeniably depends on reliable snowfall. Even with technological advances, there are physical limits to how much snowmaking can make up for changes in climate (Scott et al., 2019). As a result, the Intergovernmental Panel on Climate Change (IPCC) expresses “high confidence” that the ski industry will experience a reduction in financial viability by the end of the 21st century (Hock et al., 2019). Ultimately, the future of many resorts is dependent on their ability to diversity nonsnow dependent business lines (Steiger et al., 2019; Walters & Ruhanen, 2015) and otherwise respond to upcoming challenges in environmental and financial sustainability (N. L. B. Knowles, 2019; McGrady & Cottrell, 2018).

4.3.2 | Rafting, boating, and fishing

In the western US, the majority of streamflow results from snowmelt in high-elevation, headwater basins (D. Li et al., 2017). As such, there is an inextricable link between snow conditions and streamflow volume and timing

(Stewart, 2009), meaning snow accumulation is a useful predictor of the summer boating season (Abramovich, 2007). In drought years, low snow accumulation in the headwaters produces numerous downstream impacts on water-based recreation, including reservoir closures, inaccessible boat ramps, degraded water quality, and fishing restrictions (Chang & Bonnette, 2016). Research indicates that the water recreation industry suffered the greatest economic impact during the 2002 Colorado drought as a result of historically low river and reservoir levels (Wilhelmi et al., 2008). Reductions in streamflow can produce losses of 1000–2000 jobs and millions of dollars in revenue for the Colorado rafting and fishing industries (Loomis, 2008b). During the 2011–2013 drought, the number of fishing license holders decreased relative to expected trends (Colorado Parks and Wildlife, 2020).

Even if a drought is not severe enough to preclude water-based recreation, it can create conditions that are not preferred by participants. In general, those participating in rafting, boating, kayaking, canoeing, fishing, and angling prefer moderate streamflow and lake levels. User preferences decline when streamflow drops below a certain level, which reduces visitation, enjoyment, and consumer surplus (Loomis, 2008a, 2008b; Loomis & McTernan, 2011, 2014; Stafford et al., 2017). On rivers requiring rafting permits, users will actively submit applications with a low probability of succeeding in order to avoid low-flow conditions (Yoder et al., 2014). However, novices may prefer lower streamflow values than experts, making visitation to some river reaches less sensitive than others (Leones et al., 1997). Similarly, some reservoirs express a greater sensitivity to fluctuating water levels than others (Ward et al., 1996). Visitation and expenditures both decline with decreasing water levels and increasing air temperature over a high threshold (Boyer et al., 2017).

Another key concern for waterborne activities is water quality (U.S. Environmental Protection Agency, 2017), declines in which can be linked to drought through warmer-than-average air temperatures, reduced streamflow, and lower lake levels. Previous research indicates that declines in water quality can markedly reduce the willingness to pay for various recreation groups (Roberts et al., 2008; Van Houtven et al., 2007). As climate change exacerbates water quality issues, recreational losses in the US may range between $1.2 and 2.3 billion by 2050 and $2.7–4.8 billion by 2090 (Fant et al., 2017). In Colorado, recreational waters are most commonly impacted by E. coli and harmful algal blooms, with 2% of surveyed streams not meeting water quality standards (Colorado Department of Public Health and Environment, 2020). Whether it is due to reduced streamflow and reservoir levels or degraded water quality, water-based recreation will be challenged by climate change over the coming decades with marked effects on local economies (U.S. Environmental Protection Agency, 2017). However, previous research suggests individuals are willing to pay for stream restoration efforts that enhance water quality, improve fish habitat, and expand recreational opportunities (Loomis et al., 2000).

4.3.3 | Parks and tourism

Similar to other outdoor recreation sectors, droughts can affect parks visitation through changing season lengths, wildfire-related closures, and lake levels. During the 2002–2003 and 2011–2013 droughts, visitation to Colorado State Parks decreased relative to expected trends (Colorado Parks and Wildlife, 2020). As a result of a rapidly spreading wildfire linked to an ongoing drought, Yellowstone National Park closed completely to visitors on September 10th, 1998. Overall, visitation was down by 400,000 people (−15%) relative to 1987 and researchers suggest visits would have declined even without the complete closure due to smoke, temporary road closures, and the constant sounds of firefighting aircraft (Franke, 2000). Heightened wildfire risk during drought can greatly reduce hiking and biking visitation, trail user enjoyment, and consumer surplus (Hesseln et al., 2003; Loomis et al., 2001). All respondents to a survey on the 2002 drought indicated that wildfire was a driving factor in tourism declines in Colorado (Wilhelmi et al., 2008). Similar factors have been ascribed to other US National Parks in the Rocky Mountains, where drier-than-average conditions were indicated in 75% of reduced visitation cases (Jedd et al., 2018). Losses in visitor spending during such years range between $9 and 90 million (Jedd et al., 2018).

However, other research suggests that the hot and dry conditions associated with drought can sometimes increase visitation. Ongoing climate warming is already expanding visitation seasons at cold and temperate US National Parks (Buckley & Foushee, 2012) as trails melt out earlier and stay mud-free for longer (Richardson & Loomis, 2005). Future temperature increases will likely markedly increase shoulder-season visitation with more moderate increases in peak-season visitation as parks reach their capacity (Fisichelli et al., 2015). Notably, an increase in visitation may also be associated with expanded activity substitution as visitors shift toward activities such as hiking and climbing that are less water-dependent (Richardson & Loomis, 2005a). Additionally, visitors may decide to travel to other parks with more favorable conditions (Jedd et al., 2018).

4.4 | Public health

Drought's adverse health effects are mediated through complex environmental, economic and social pathways that can accumulate slowly over time. The lack of highly visible structural impacts of droughts makes seeing and understanding health impacts challenging (Stanke et al., 2013; Vins et al., 2015). Recent comprehensive reviews of the health impacts of drought highlight the mostly indirect risks (Ariza et al., 2016; Centers for Disease Control and Prevention, 2010; Stanke et al., 2013; Yusa et al., 2015). The causal processes that link public health to drought are still being studied and examined, but it is clear that droughts impact water and air quality, mental and physical health, and public safety.

4.4.1 | Water quality and water-related diseases

While decreased water quantity is a defining feature of drought, water quality can be simultaneously affected (Bell et al., 2016; Centers for Disease Control and Prevention et al., 2010; Yusa et al., 2015). Reduced groundwater levels and streamflow during drought can heighten the potential for increased levels of harmful chemicals, as the system's dilution capacity is diminished. This can lead to increased salinity and reduced oxygen levels within the water, threatening aquatic species (Bond et al., 2008). Water temperature increases and nutrient loading can enhance algal production and promote toxic cyanobacterial blooms (Mosley, 2015; Wall & Hayes, 2016).

These drought-induced declines in water quality have adverse consequences on human health. Harmful algal blooms make water unsafe for swimming (Liu et al., 2020). Afflictions such as skin rashes, blisters, vomiting, diarrhea, and even deaths of dogs have been reported and linked to cyanobacteria in lakes in the United States (Centers for Disease Control and Prevention et al., 2010). Degradation of water quality also has economic implications, as increases in contaminant levels in source waters can increase treatment costs and hamper the ability to meet drinking water standards (Yusa et al., 2015). Elevated levels of nutrients in groundwater or saltwater intrusion can contaminate private wells, threatening the quality of drinking water (Centers for Disease Control and Prevention et al., 2010; Wall & Hayes, 2016; Yusa et al., 2015).

Resultant stagnation from diminished water bodies provides optimal conditions for certain vector-borne diseases. Increased outbreaks of waterborne diseases including Escherichia coli (*E. coli*), leptospirosis and other viruses have been linked to periods of drought (Stanke et al., 2013; Yusa et al., 2015). The prevalence of vector insects and pathogens that thrive in shallow, warm waters, such as the mosquito-borne West Nile Virus, has also been linked to drought (Centers for Disease Control and Prevention et al., 2010; K. H. Smith et al., 2020). In the 2002 drought, when more than 50 percent of coterminous United States was experiencing moderate to severe drought conditions, West Nile Virus total cases and deaths spiked (Liu et al., 2020). Shaman et al. (2010) examined the relationship between hydrological variability and the incidence of West Nile Virus in Colorado from 2002 to 2007 and found that dry spring and summer conditions appear to increase the risk of human West Nile Virus infection.

4.4.2 | Air quality and dust-related diseases

Droughts can contribute to airborne dust, which can have a significant effect on public health, particularly among people with chronic health conditions (Garfin et al., 2013; Liu et al., 2020). Dry soil can increase the number of particulates that are suspended in the air, thereby exacerbating chronic respiratory illnesses (e.g., asthma), cardiovascular diseases, and possibly increasing the risk for acute respiratory infection (Ariza et al., 2016; Centers for Disease Control and Prevention, 2010; L. T. Smith et al., 2014). Particle size less than or equal to 2.5 μm, commonly referred to as PM2.5, is positively related to all-cause daily mortality, particularly in the elderly population, and can cause asthma, respiratory inflammation, diminished lung function, and can even promote cancers (Brunekreef & Holgate, 2002; Ostro et al., 2006; Samoli et al., 2005; Schwartz et al., 1996; Xing et al., 2016). The "Dust Bowl" of the 1930's was perhaps the greatest example of this phenomenon with thousands of people dying from "dust pneumonia" (Stanke et al., 2013). Achakulwisut et al. (2018) found that premature deaths in the Southwest U.S. could rise by 20–130%, and annual hospitalizations due to cardiovascular and respiratory illness could grow by 60–300% by 2100. Wang et al. (2017) estimated that, due to changes in local drought severity alone, spring and summer levels of particulate matter could increase by 1%–16% in the US by 2100 relative to the 2000s.

Like dust, smoke from wildfires can cause significant respiratory problems. Wildfires produce an average of 25 percent of PM2.5 across the U.S. and sometimes more than 50% in the western U.S. (Burke et al., 2020). Burke et al. (2020) show that a one microgram increase in PM2.5 was associated with an increase in mortality of approximately one individual per million during the August and September 2020 wildfire season. The authors conclude that hundreds of elderly individuals likely died from smoke exposure in each major West Coast population center from the 2020 wildfire season. Wildfire induced morbidity is also a major concern. In the San Luis Valley in south central Colorado, elevated levels of particulate matter are associated with a rise in respiratory-related visits to the emergency room (James et al., 2018). Other projects from Colorado similarly noted that increases in particulate matter caused by wildfire smoke lead to more hospitalizations for respiratory illnesses (Alman et al., 2016), particularly in children (Stowell et al., 2019).

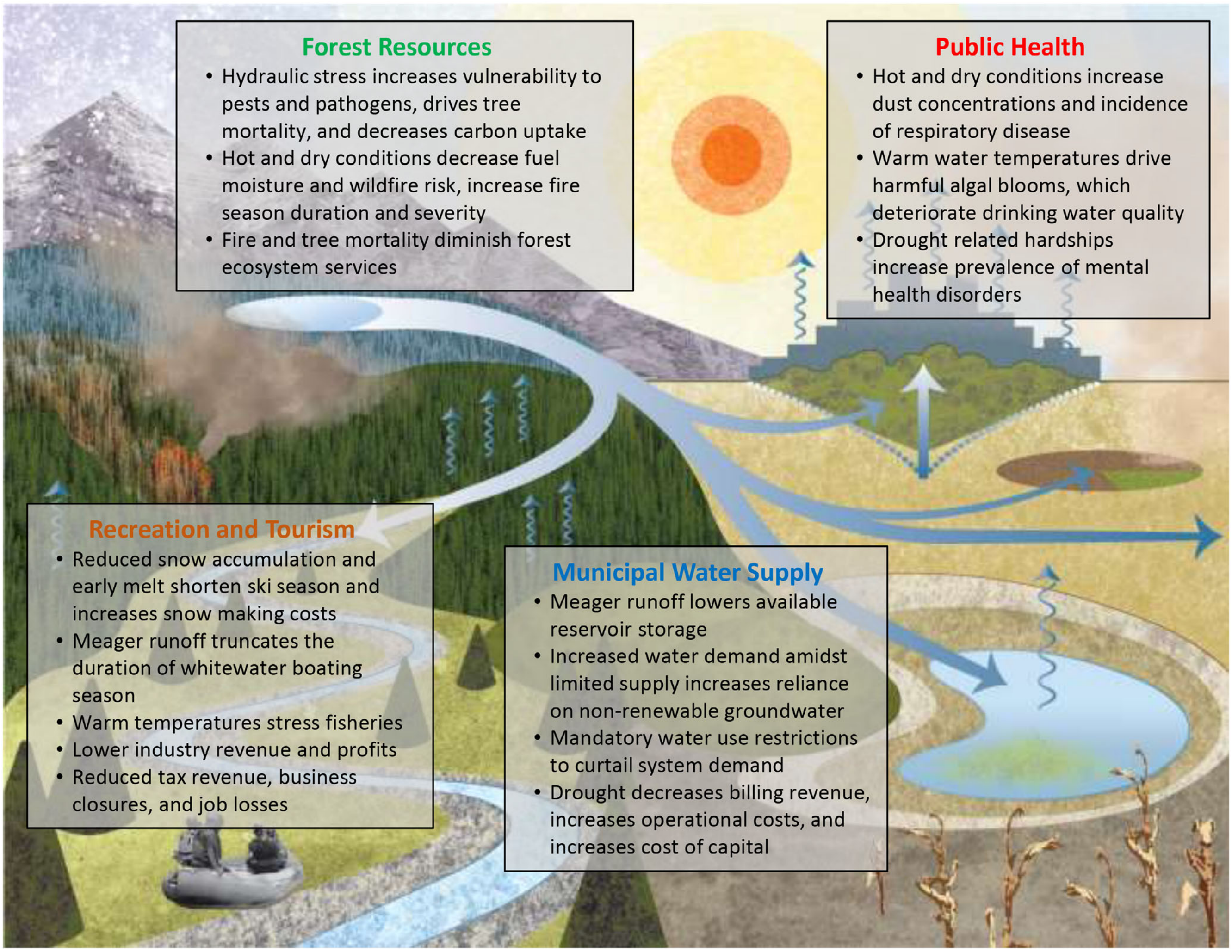

FIGURE 3 Drought in the IMW typically begins during the winter in high elevation mountain basins with reduced snow accumulation and earlier than normal melt. Drought conditions proceed downstream to lower elevations in the form of diminished streamflow, lower reservoir storage, higher plant water demand, increased reliance on groundwater, and desiccated forests. Drought conditions affect the recreation and tourism industry by truncating the winter ski and summer boating seasons. Drought impacts municipal water suppliers by increasing demand amidst lower-than-average supply, which in turn stresses utility finances. Drought impacts forest resources by way of tree mortality, wildfire, and diminished ecosystem services. Hot and dry conditions trigger myriad public health impacts, including increased incidences of respiratory disease, mental health issues, and adverse water quality conditions. While this review focuses on drought impacts to tourism and recreation, municipal water supply, forest resources, and public health, drought impacts also extend beyond these sectors

Drought conditions can also increase exposure to pathogens such as coccidioidomycosis, or valley fever (Centers for Disease Control and Prevention, 2010; Wall & Hayes, 2016). In this case, drought followed by heavy rain releases fungus spores from the soil (Stanke et al., 2013), a process that may have caused outbreaks of valley fever in California in the early 1990s (Stanke et al., 2013). Likewise, in 2016, hospitalization charges for Arizona residents with a primary diagnosis of valley fever totaled $55 million, with a median of $47,212 in total charges per hospitalization (Liu et al., 2020). During the 2010–2012 drought, when nearly two-thirds of the contiguous U.S. was in drought (NDMC, n. d.), the number of reported valley fever cases spiked, with 22,641 total cases in 2011 alone (Liu et al., 2020).

4.4.3 | Mental health

The attribution of mental health outcomes to specific drought related events is challenging (Berry et al., 2010; Hayes et al., 2018). Mental health consequences of drought are indirect and can occur as a result of associated financial impacts, the damage to landscape and agriculture, impacts on food supply, physical health effects, and/or housing displacement (Berry et al., 2010; Hayes et al., 2018; OBrien et al., 2014; Vins et al., 2015). Mental health challenges include increased stress, depression, anxiety, trouble sleeping, decreased quality of life, and suicide (Ariza et al., 2016; Cuthbertson et al., 2016; Liu et al., 2020; Vins et al., 2015; Wall & Hayes, 2016; Yusa et al., 2015). Post-traumatic stress disorder has been linked to acute effects of drought such as wildfire (Finlay et al., 2012).

Agricultural workers and others who rely on water and/or precipitation for their livelihoods are at greater risk of experiencing the mental health impacts of drought (Centers for Disease Control and Prevention, 2010; OBrien et al., 2014; Polain et al., 2011; Yusa et al., 2015). For instance, farmers and their families report increased stress due to drought (Berry et al., 2011; OBrien et al., 2014). The 2011–2013 drought resulted in at least $633 million worth of damage to Colorado agricultural producers (CWCB, 2020) causing significant financial anxiety for Colorado farmers and ranchers (Kohler, 2018). In the 1980s, male farmers and ranchers in the northern U.S. demonstrated rates of suicide that were twice the national rate (Gunderson et al., 1993). Other related factors, such as reduced access to health services and the culture of independence among farmers, can exacerbate the impact of drought in agricultural communities (Berry et al., 2011).

5 | CONCLUSION

In the IMW region of the United States, drought is an insidious problem that leaves few economic sectors untouched. Despite drought's wide-reaching impacts, much of the research and operational focus to date has been on agriculture, with the result that drought impacts on other sectors have been comparatively understudied. In our review, we synthesized papers and reports from a variety of disciplines to evaluate how drought impacts water utilities, recreation and tourism, forest resources, and public health. This work indicated that drought in the IMW typically begins as anomalously low winter snowfall that propagates into below-average mountain snow accumulation. Drought conditions then move from the high-elevation headwaters to downstream communities as a result of below average streamflow. Along the way, reservoirs remain unfilled, recreation and tourism opportunities dry up, forest mortality increases along with wildfire risk, and human health is threatened by dust, wildfire smoke, and harmful algal blooms (Figure 3).

These impacts are defined and quantified in a variety of ways. Water utilities experience both reduced revenue and increased operational costs as they struggle to fulfill water allocations. Recreation and tourism user days decline, which is associated with reduced visitor expenditures and increased costs as resorts try to adapt to drought conditions. At the same time, consumer surplus drops as recreation takes place during suboptimal conditions. Drought conditions also lead to declines in forest health, which then turns into tree mortality, increased incidence of wildfires, and a loss of ecosystem services. Similarly, drought can lead to degraded air quality, an increase in waterborne pathogens, and mental health issues. As a result, hospitalizations and human mortality may rise as drought envelops the IMW. All of these effects produce impacts that reverberate through the economic system, leading to declines in tax revenue, business closures, and job losses.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Adam Wlostowski: Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (equal); resources (equal); software (equal); supervision (equal); validation (equal); visualization (equal). **Keith S Jennings:** Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (equal); resources (equal); software (equal); supervision (equal); validation (equal); visualization (equal). **Rachel E Bash:** Conceptualization (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (equal). **Jesse Burkhardt:** Conceptualization (equal); funding acquisition (equal). **Cameron W Wobus:** Supervision (equal). **Graeme Aggett:** Supervision (equal).

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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