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Lessons Learned from the 2017 Flash Drought Across the U.S. Northern Great Plains and Canadian Prairies

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Essay

Lessons Learned from the 2017 Flash Drought across the U.S. Northern Great Plains and Canadian Prairies

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ABSTRACT: The 2017 flash drought arrived without early warning and devastated the U.S. northern Great Plains region comprising Montana, North Dakota, and South Dakota and the adjacent Canadian Prairies. The drought led to agricultural production losses exceeding $2.6 billion in the United States, widespread wildfires, poor air quality, damaged ecosystems, and degraded mental health. These effects motivated a multiagency collaboration among academic, tribal, state, and federal partners to evaluate drought early warning systems, coordination efforts, communication, and management practices with the goal of improving resilience and response to future droughts. This essay provides an overview on the causes, predictability, and historical context of the drought, the impacts of the drought, opportunities for drought early warning, and an inventory of lessons learned. Key lessons learned include the following: 1) building partnerships during nondrought periods helps ensure that proper relationships are in place for a coordinated and effective drought response; 2) drought information providers must improve their understanding of the annual decision cycles of all relevant sectors, including, and beyond, direct impacts in agricultural sectors; and 3) ongoing monitoring of environmental conditions is vital to drought early warning, given that seasonal forecasts lack skill over the northern Great Plains.

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A familiar saying among agricultural producers of the U.S. northern Great Plains region comprising Montana, North Dakota, and South Dakota (Fig. 1) and the adjacent Canadian Prairies is, “We’re always in a drought. It just depends on how bad it is in a given year.” The year 2017 was a bad year. The 2017 northern Great Plains flash drought began in the spring, evolved rapidly through the summer (Fig. 1), and became the most destructive drought in decades (Fortin 2017; Puckett 2018). The drought led to reduced agricultural production, wildfires, infrastructure damage, and financial, physical, and emotional hardship to those affected. Agricultural losses related to the drought exceeded $2.6 billion in the United States alone (NCEI 2017). Note that these impact estimates do not include the secondary and tertiary costs that filter through the economy.

As a recently emphasized type of drought defined by its rapid onset (e.g., Otkin et al. 2018; Pendergrass et al. 2020), the 2017 northern Great Plains flash drought, and the devastation it caused, motivated us to examine the behavior and predictability of drought in the region and to evaluate how drought-related coordination, communication, and management may be improved for future events. The National Integrated Drought Information System (NIDIS) assembled a multi-institutional team of academic, tribal, state, and federal partners to 1) probe the causes, predictability, and historical context of the drought (Hoell et al. 2019a); 2) describe the impacts of the drought; 3) identify opportunities for drought early warning; and 4) develop an inventory of lessons drawn (Jencso et al. 2019). This essay describes the key findings of these reports.

Chronology, historical context, and predictability

Daily soil moisture, precipitation, and maximum temperature from Glasgow in northeastern Montana illustrate the rapid onset of drought and its persistence during the spring and summer of 2017 (Fig. 1; see also Hoell et al. 2019a). Given the wetness of the land surface state during early May, the sudden onset and continued severity of the drought was even more remarkable. In early May, soil moisture at Glasgow ranked in the 80th percentile. In the absence of any meaningful precipitation, soil moisture declined to the 15th percentile by early June. Limited precipitation during May and June, on average the wettest time of year, was a principal driver of drought onset while above-normal daytime temperatures contributed to the rapid land surface drying (Figs. 1 and 2).

Low soil moisture continued during June and July. Persistent high pressure disrupted the normal weather patterns and deflected storms away from the region, preventing above-average

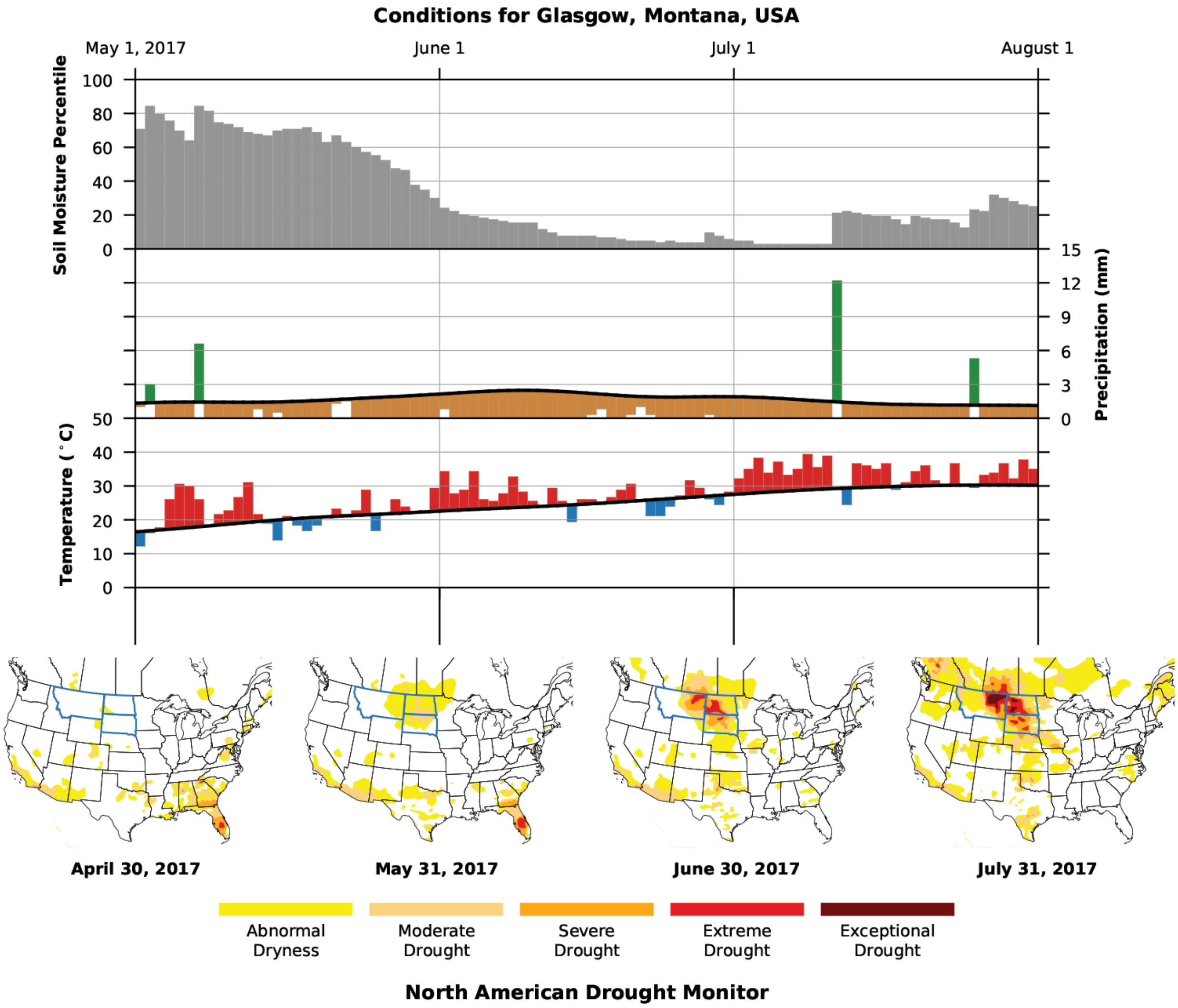

Fig. 1. (top to bottom) Time series of daily soil moisture, precipitation, and maximum temperature at Glasgow, Montana, and the monthly North American Drought Monitor. The time series are adapted from Hoell et al. (2019a). The U.S. northern Great Plains states of Montana, North Dakota, and South Dakota are outlined in blue in the bottom row. Soil moisture percentiles are based on a simulation of the Variable Infiltration Capacity land surface model forced by the observed meteorology obtained from the University of California, Los Angeles (UCLA), Surface Water Monitor (Wood 2008; www.hydro.ucla.edu/SurfaceWaterGroup/forecast/monitor/index.shtml). Precipitation and maximum temperature are based on the Global Historical Climate Network Daily (Menne et al. 2012). The black line in the daily precipitation and temperature time series shows the 1950–2016 average and the bars show the deviation from the daily average.

precipitation on all but two days during June and July. Meanwhile, above-normal daytime temperatures prevailed (Fig. 1).

Drought conditions were not confined to Glasgow as extreme and exceptional drought spread across Montana, the Dakotas, and the Canadian Prairies during late spring and summer 2017. According to the North American Drought Monitor (Fig. 1; Svoboda et al. 2002; Lawrimore et al. 2002), the region was free of drought in early May 2017, with an isolated area of abnormal dryness straddling the border of the Dakotas, a remnant from the prior year. Abnormal dryness spread across eastern Montana, the Dakotas, and the southern Canadian Prairies during May, with the first signs of drought appearing along the border of central North Dakota and South Dakota. During June 2017, drought intensified and expanded with vigor (Otkin et al. 2018; Hoell et al. 2019b; Wang et al. 2019; L. G. Chen et al. 2019). Extreme drought overspread northeastern Montana and southwestern North Dakota amid severe drought elsewhere across the region. Drought continued to intensify throughout the region during July.

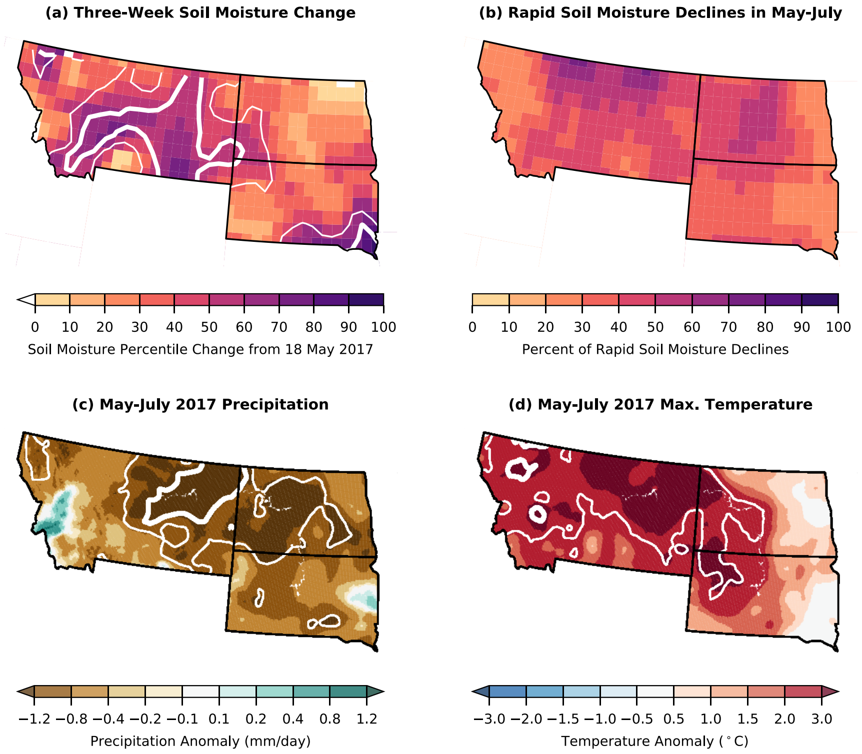

Fig. 2. (a) The 3-week soil moisture percentile decline from 18 May 2017 (shaded) and percentile rank of the decline (contours). (b) Percentage of top 3-week soil moisture percentile declines occurring in May–July for 1916–2017. (c) May–July 2017 precipitation anomaly (shaded; mm day^{-1}) and percentile rank (contours). (d) May–July 2017 maximum temperature anomaly (°C) and percentile rank (contours). The thick and thin contours in (a), (c), and (d) indicate the top percentile and quintile, respectively. Soil moisture is based on the UCLA Surface Water Monitor. Precipitation and temperature are based on nClimGrid/CLIMGRID (Vose et al. 2014). Precipitation and temperature ranks are adapted from Hoell et al. (2019a).

A more complete understanding of the severity of the 2017 northern Great Plains flash drought requires a comparison to historical conditions in the region. Notably, the speed of land surface drying, an up-to-80th-percentile soil moisture decline for the 3-week period beginning on 18 May 2017, was among the quickest such standardized decreases since at least 1916 (Fig. 2a). Rapid soil moisture declines over the U.S. northern Great Plains have a distinct seasonality, as approximately 50%–80% of the top percentile of 3-week soil moisture decreases occur in May–July (Fig. 2b). The seasonality of flash soil moisture declines aligns with the critical growing-season rains (Fig. 1), the failure of which leads to rapid land surface drying.

During May–July 2017, precipitation and daily maximum temperatures ranked among the driest and hottest, respectively, over portions of the U.S. northern Great Plains dating back to at least 1895 (Figs. 2c,d). Areas in eastern Montana that endured historically intense dryness included Fort Belknap, Fort Peck, and Glasgow. Over much of the western Dakotas, precipitation and temperature also ranked in the dry and hot quintiles, respectively, dating back to the late nineteenth century.

Though quick to materialize and briefly intense, the 2017 drought did not exceed many noteworthy droughts in terms of longevity and spatial extent over Montana, North Dakota, and South Dakota (Fig. 3). The drought is hardly noticeable on a time series showing percent of the three-state region covered by simulated soil moisture percentiles. At the pinnacle of the 2017 drought, in July, soil moisture across 65% of the region was in the lower 20th percentile, with much smaller areas falling into the lower 10th and 5th percentiles. By contrast, during the Dust Bowl in the 1930s, most of the U.S. northern Great Plains experienced soil moisture in the lower 20th percentile for many consecutive years. Drought activity based on soil moisture has been relatively quiescent since the late 1980s, the last of the region's protracted droughts. Aside from the short droughts at the turn of the millennium, in 2006, 2012, and 2017, the U.S. northern Great Plains has been largely free of widespread and extended periods of low soil moisture percentiles.

Was early warning of the 2017 northern Great Plains drought possible? The answer is no, given the favorable land surface conditions at the beginning of May (Fig. 1) and inaccurate

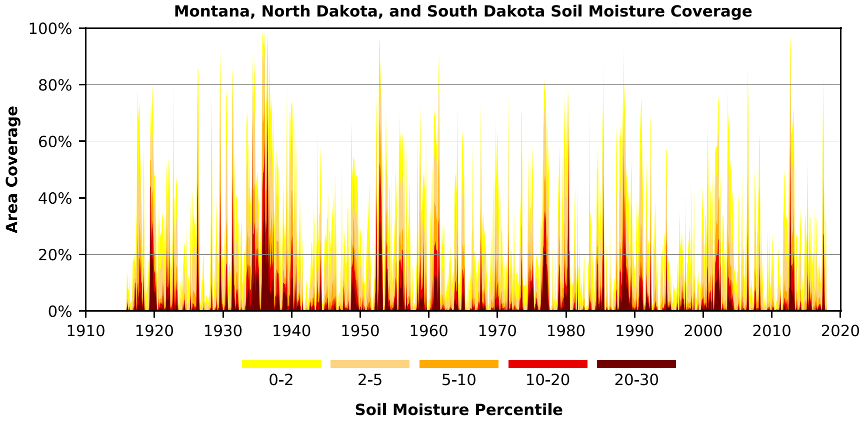

Fig. 3. Percentage of North Dakota, South Dakota, and Montana covered by soil moisture percentiles based on the UCLA Surface Water Monitor. This figure is adapted from Hoell et al. (2019a).

precipitation forecasts for May–July made the preceding April (Fig. 4 as well as Fig. S1 in the online supplemental material; https://doi.org/10.1175/BAMS-D-19-0272.2). These forecasts were based on the most widely used and sophisticated multimodel initialized prediction systems available at the time of the drought: the North American Multimodel Ensemble (NMME; Kirtman et al. 2014), the World Meteorological Organization (WMO) Lead Centre for Long-Range Forecast Multi-Model Ensemble, and the Copernicus Climate Change Service multimodel ensemble. In April 2017, all three forecast ensembles failed to indicate that below-average precipitation during May–July 2017 was a likely outcome, though they did indicate an elevated likelihood of above-average temperatures (Fig. 4 and Fig. S1).

Given the lack of early warning of the 2017 drought, we now ask whether the evolution of the event could have been tracked in sequences of shorter lead NMME forecasts. The answer to this question is also no, as 1-month lead forecasts of June and July 2017 did not indicate that below-average precipitation was a favored outcome in the U.S. northern Great Plains (Fig. 4). The forecast for June 2017 made the preceding month was particularly poor, as NMME forecast above-average precipitation and near-average temperatures over almost the entire region despite this month being among the driest and warmest on record. Despite the continued development, forecasts of July 2017 at 1-month lead also did not indicate that widespread drought was a favored outcome in the region.

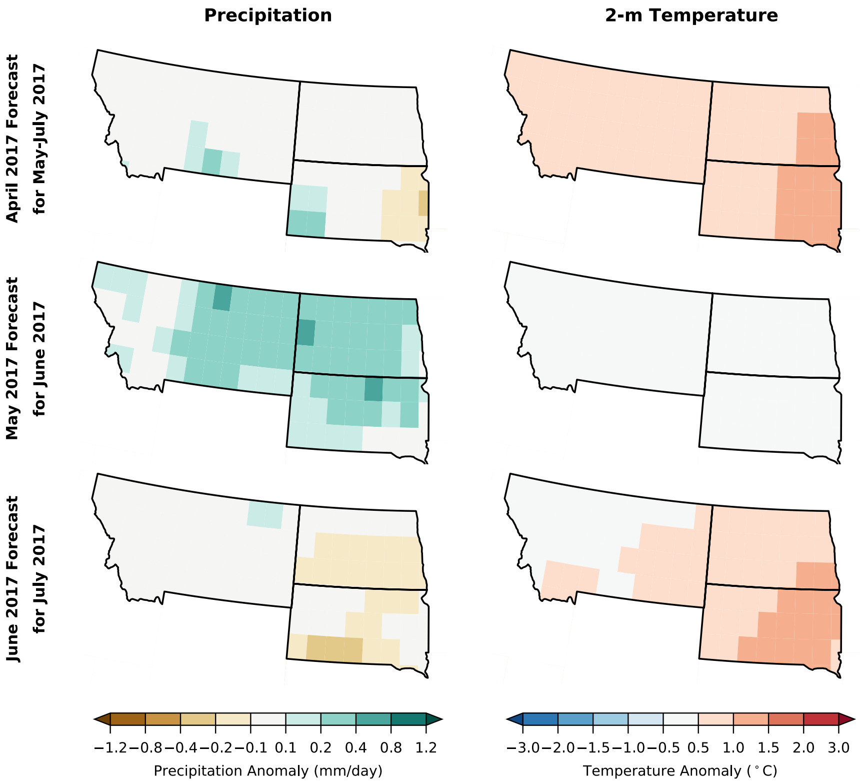

Fig. 4. NMME-forecast (left) precipitation anomaly (mm day^{-1}) and (right) 2-m temperature anomaly (°C) for (top) May–July 2017 made the preceding April, (middle) June 2017 made the preceding May, and (bottom) July 2017 made the preceding June. Forecasts were accessed from the NOAA Climate Prediction Center (at ftp://ftp.cpc.ncep.noaa.gov/NMME/realtime_anom/ENSMEAN/).

Impacts

Impacts of the 2017 flash drought on the U.S. northern Great Plains and the Canadian Prairies were varied and costly. Here, we outline drought impacts on agriculture, human health, fire, ecosystems, water quality, tourism, and infrastructure (Jencso et al. 2019). We recognize that the impacts of a disaster broadly include both market-based and nonmarket effects (National Research Council 1999). The temporal and spatial complexity of drought events makes it one of the most difficult natural hazards on which to fully assess impacts, as these effects filter through the economy, communities, and the environment long after the immediate event (Pulwarty and Verdin 2013).

Agriculture. In April 2017, half of summer pasture was rated as good to excellent in Montana and the Dakotas, but the rapid deterioration of conditions in May and June led to a host of costly impacts on agriculture and livestock production (USDA 2017a). This led to poor grazing conditions, which prompted cattle producers to begin selling cow–calf pairs by June 2017. This response appeared in sharp contrast to the more typical practice of selling calves and a small number of old or less-productive cows in the fall. The severity of conditions, as estimated by the U.S. Drought Monitor, triggered payments through the USDA's Livestock Forage Disaster Program for native or improved pasturelands, which exceeded $206 million in 2017 for Montana, North Dakota, and South Dakota combined (USDA 2017b,c).

Perhaps most striking, the resulting losses of winter and spring wheat, oats, and forages such as alfalfa and pasture grass exceeded $2.6 billion (NCEI 2017). The full cost of these losses is not reflected in this figure because the maximum allowable claims for crop insurance were exceeded in some areas.

Mental health. Farmers and ranchers face higher levels of several risk factors known to affect mental health, such as stress, financial or legal pressures, previous physical injuries, and other forms of trauma (Reed and Claunch 2020; Edwards et al. 2015). Farmers often work long hours, under isolated conditions, exposed to circumstances beyond their control like volatile global markets, declining output prices, rising input costs, labor shortages, and weather and climate extremes (Simes 2019; Stephenson 2018; Jones-Bitton 2018).

Drought can worsen the mental health of farmers, who are already vulnerable to chronic stress, depression, and risk of suicide (Jones-Bitton 2018; Edwards et al. 2015). In Australia, a survey of 8,000 people found that drought has a larger negative mental health impact on farmers and farm workers than on their rural nonfarming counterparts (Edwards et al. 2015). In Canada, a study of over 1,100 farmers showed that nearly half the participants felt highly stressed, ineffective, overextended, or emotionally exhausted (Jones-Bitton et al. 2020). In the aftermath of the 2017 drought, calls to the Saskatchewan Farm Stress Helpline rose from 320 (before the drought) to 757 (after the drought in 2018) (Bernacki 2019).

To combat the growing stress on mental health due to the 2017 drought, South Dakota State University Extension developed a Farm Stress website[1] and provided informational leaflets on mental health to help farmers recognize symptoms of stress and depression. North Dakota State University Extension updated their Farm and Ranch Stress website[2] and hosted behavioral health trainings, such as, "Life Beyond Breaking Event: Farm Stress and Economic Summit." Montana State University Extension also gave metal health presentations at various farm organizations' annual conferences.[3]

Fire and smoke. Fires are larger, longer, and more intense during drought. Even during brief droughts like 2017, short-term precipitation deficits and above-normal summertime temperatures dry fine fuels that encourage fire ignition and expansion. Record-breaking wildfires broke out in 2017, as 1.4 million acres burned in Montana, the largest area burned since at least 1910 (Puckett 2018). In South Dakota, the third largest wildland fire in history began on 11 December 2017. This fire, the Legion Lake Fire, burned 54,000 acres in the Black Hills, near Custer State Park and Wind Cave National Park (Gabbert 2018).

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[1] https://extension.sdstate.edu/tags/farm-stress

[2] www.ag.ndsu.edu/farmranchstress

[3] https://mfbf.org/Article/Montana-Agriculture-Listen-Learn-Lead-119281

Smoke from wildfires in the western United States and Canada also led to poor air quality, especially in the mountain valleys of Montana and southern Alberta where air inversions created pools of dense smoke. In August 2017, there was not a single day in which all monitoring stations in Montana reported good air quality. Tribal members on Indian reservations across the region also reported health impacts because of excessive smoke from wildland fires from late July through early October 2017. Poor air quality also affected cattle and other livestock, causing stress and weight loss.

Ecosystems and cultural resources. The 2017 drought impacted wildlife health and populations by degrading their habitats. In South Dakota, much of the pheasant habitat and cover was cut and used for hay, which made them more susceptible to predation. As a result, pheasant population density was 45% below the previous year and 65% below the 10-yr average. Brood sizes were also 18% lower than the 10-yr average (Runia 2017).

On tribal lands, reduced wildlife populations impacted both subsistence hunting and tribal-guided hunting opportunities. Tribal land managers were also concerned that increased competition from nonnative and invasive plant species during the drought detrimentally affected culturally significant plants. In western Montana, wet conditions in the fall of 2016 and above-normal snowpack in the winter of 2017 benefited the production of berries and medicinal plants. However, the dry and hot conditions in the central and eastern parts of the state greatly diminished yields. Above-normal temperatures in the late summer and fall resulted in a longer-than-normal growing season and affected some tribal cultural activities by delaying the harvest of berries and medicinal plants.

Water quality and supply. Low precipitation in 2017 reduced freshwater inflows to surface water bodies and elevated the relative concentrations of salts, minerals, bacteria, algae, and total dissolved solids. The high temperatures and low humidity also promoted toxic cyanobacteria algal blooms in stagnant ponds. Livestock suffered from reduced water quality and were exposed to higher risks of sulfate, nitrate, salt, and bacteria poisoning. As one example, on 7 July more than 200 cows and calves were found dead in a pasture in southwestern Saskatchewan due to salt poisoning, heat stress, and dehydration (Pasiuk 2017).

Given the brevity of the 2017 drought, storage in the Missouri River reservoirs generally remained stable and the impacts of the drought on irrigation and domestic water supply only appeared locally. Some rural and tribal communities enacted restrictions on lawn watering, vehicle washing, and other activities to reduce domestic consumption and demand in some areas of the Dakotas and Montana, namely, at the Rosebud and Fort Belknap Indian Reservations. Water shortage advisories and outdoor water bans were also issued in Southern Alberta and Saskatchewan.

Tourism. The tourism industry was impacted in Montana and the Dakotas. During the 2017 drought, Montana lost roughly 800,000 visitors and $240 million in visitor spending, leading to a 6.8% loss in expected annual spending (Sage and Nickerson 2017). Studies by the University of Montana Institute for Tourism and Recreation Research found that 7% of nonresident visitors in July, August, and September shortened their stay in Montana due to smoke or fires, and 10% were not able to participate in their desired activities. In South Dakota, fewer pheasants led to reduced tourism and lost revenue during the fall hunting season.

Infrastructure. Low precipitation in 2017 led to depleted groundwater in Regina and Winnipeg, Canada, which resulted in the contraction and shifting of clay-rich soils. Shifting soils in Regina damaged the wiring to power meters, which cost $15 million to repair (Giesbrecht 2018), and broke 125 water mains, up from just 28 breaks in the preceding year. In Regina and Winnipeg, shifting soils also damaged the foundations of dozens of homes (Baxter 2017). These limited examples illustrate that the idea of drought affecting infrastructure is relatively new in the research literature and needs to be further quantified.

Monitoring and response

Due to the rapid development of drought in 2017 (Fig. 1), and uncertain precipitation forecasts leading up to its onset (Fig. 4), drought detection relied on the monitoring of local atmospheric, hydrologic, and terrestrial conditions. Simply put, local, state, and national drought monitoring infrastructures and partnerships prevented significant delays in the detection of the 2017 drought. Authorities in Montana, North Dakota, South Dakota, and the Canadian provinces all monitored (Table 1) and responded to the drought (Table 2) differently, but they shared common practices, which included the use of drought indices and indicators, national drought monitors, drought impact reports, and expert interpretation. The states and Canadian provinces mobilized their drought task forces and enacted their drought management plans, and governors in the United States issued executive orders on drought-related emergency and disaster declarations based on monitoring and response activities.

Though ongoing, drought monitoring oftentimes cannot paint a complete picture of the current drought situation, let alone what may lie in store for the future. The high variability of local weather and climate conditions across the northern Great Plains makes it difficult to distinguish the signals that are meaningful to drought development from those that are not. Furthermore, a complete assessment of the conditions related to drought requires the simultaneous consideration of many atmospheric, hydrologic, vegetative, and human factors, all of which are challenging to monitor consistently, accurately, and broadly. A variety of indicators, or metrics designed to gauge specific drought behaviors, shown in Table 3, are used to evaluate drought conditions. Precipitation, snow cover, evapotranspiration,

Table 1. Summary of state- and province-specific monitoring and assessment activities during the 2017 flash drought.

State/province	Agency	Monitoring and assessment activities
Montana	Governor's Drought and Water Supply Advisory Committee	A technical subcommittee consisting of local, state, tribal, federal, and private partners performed weekly assessments of drought based on the U.S. Drought Monitor, tools developed by federal science agencies, and on-the-ground updates from individuals. Assessments were published regularly on the Drought Management website, public monthly meetings were held, and key drought information was disseminated via local media.
South Dakota	South Dakota Drought Task Force	Drought assessment was led each week by the state climatologist, including a team of weather, water, agriculture, fire, and natural resource experts. The Drought Task Force activation followed the state's drought plan and the Drought Incident Annex. The Drought Task Force met weekly or biweekly and discussed weather and climate conditions, drought impacts, and drought-related activities.
North Dakota	North Dakota Department of Emergency Services	A technical group consisting of extension offices in each county, the Department of Agriculture, and the state climatologist office performed weekly assessments of drought based on current drought conditions, historical perspectives, and range and pasture conditions. These assessments were published on the North Dakota State website. The Department of Emergency Services also hosted periodic meetings on drought and wildfire.
Canadian provinces	National Agroclimate Information Service	Drought assessment was based on the Canadian Drought Monitor. The Canadian Drought Monitor is created from observed and satellite-derived conditions, drought indicators and forecasts, and feedback from regional and local authorities. The drought assessment is published on the website Drought Watch along with supporting information that includes interactive mapping tools and agricultural statistics. Additionally, agriculturally specific assessments are performed biweekly by representatives from across the country.

Table 2. Summary of state- and province-specific response activities during the 2017 flash drought.

State/province	Executive orders	Response activities
Montana	8	Agriculture: The Montana Department of Agriculture established a hay hotline, conducted hay lotteries, and helped producers secure federal assistance. The Montana Stockgrowers Association coordinated cash donations. Several federal programs aided (e.g., USDA's Livestock Forage Disaster Assistance Program, Emergency Haying and Grazing Program, Emergency Assistance for Livestock Program, Emergency Conservation Program, and Emergency Watershed Protection Program). Wildfire: The Montana Department of Natural Resources and Conservation Forestry Division, in close consultation with federal, tribal, and local partners, coordinated fire suppression activities on all state- and privately owned lands. Air quality: The Montana Department of Air Quality maintained a website called Today's Air, which provided smoke updates and offered guidance on how to minimize exposure to smoke.
South Dakota	2	Agriculture: South Dakota State University Extension held many listening sessions in partnership with USDA's Farm Service Agency and Natural Resources Conservation Service. One outcome was the development of a Farm Stress website to link affected producers with mental health resources. Wildfire: South Dakota has worked with partners to incorporate more drought indicators into fire risk products to be better prepared for wildfire during future droughts.
North Dakota	9	Agriculture: The North Dakota Department of Agriculture provided drought information for crop and livestock producers on its drought resources website. The Department of Agriculture also opened a hay hotline and conducted a hay lottery. The Emergency Hay Transportation Assistance Program provided $1.5 million in aid to 500 selected applicants. The USDA Farm Services Agency in North Dakota provided mental health resources for farmers and ranchers feeling stress related to drought. Wildfire: The State Fire Marshal provided fire management planning and outreach. The North Dakota National Guard, Department of Game and Fish, and Department of Parks and Recreation maintained readiness to provide fire response assistance to local and tribal authorities. The North Dakota Forest Service supported local and federal response efforts.
Canadian provinces	—	Livestock: The Federal Livestock Tax Deferral allowed farmers to defer a portion of sale proceeds to the following year in rural Alberta and Saskatchewan. Surface water: Outdoor water bans were issued in Alberta and Saskatchewan. Wildfire: Fire bans began in July 2017. The Alberta government allocated $133 million for wildfire relief. The Department of National Defense made compensation available for a wildfire that started on a military base in Alberta. The Saskatchewan Stock Growers Association launched a wildfire relief fund for affected producers and the Saskatchewan government matched up to $100,000 cash donations to this fund.

potential evapotranspiration, vegetation health, soil moisture, groundwater, and streamflow are just a few key variables considered in drought monitoring and assessment. Despite the development of numerous drought indicators, no single drought index applies to conditions across the entire region and across all seasons. Moreover, it is unclear which indicators, or combination of indicators, are best suited for drought monitoring and decision-making (Purdy et al. 2019).

The coordination of local, state, tribal, and federal government monitoring and response presented unique challenges. Ensuring that farmers and ranchers were aware of, could access, and then meet the requirements of federal assistance programs challenged both producers and service providers. Because of gaps in observation networks, characterizing drought remains an ongoing problem. In many respects, the 2017 drought created an opportunity to strengthen both partnerships and modes of communication with and between those affected. This drought also provided evidence of the need to continue federal, regional, and state efforts to maintain and build out observation networks. One such effort is the National Soil Moisture Network that is being developed by NOAA, USDA, and other partners.

Table 3. Common indicators used for drought assessment in the northern Great Plains.

Indicators	Description
Standardized precipitation index (SPI)	The SPI quantifies observed precipitation data as a standardized departure from the climatological mean. It shows the number of standard deviations by which the observed anomaly deviates from the climatological mean. This flexibility allows the SPI to be useful in various time scales from short-term meteorological to long-term hydrological applications.
Palmer drought severity index (PDSI)	The PDSI is based on actual rainfall, temperature, and soil information compared with their climatological averages. Therefore, PDSI values can be computed back to the beginning of the historical record. However, the PDSI values are not useful for detecting fast-emerging droughts because the index contains an inherent lag and it resets itself annually. The PDSI is produced on a monthly time scale, and was used exclusively in the United States before the U.S. Drought Monitor.
Palmer hydrological drought index (PHDI)	The main input value is the original PDSI with an added algorithm to consider longer-term dryness than the period that PDSI considers. It is useful for detecting water storage, streamflow, and groundwater shortages for water resources management.
Evaporative demand drought index (EDDI)	The EDDI values indicate atmospheric evaporative demand anomalies across a time scale of interest relative to their climatological averages. The index is produced experimentally to indicate the spatial extent and severity of the drought. It usually responds to fast-emerging droughts.
Drought severity and coverage index (DSCI)	The DSCI is an experimental index that converts drought levels from the U.S. Drought Monitor map to a single composite value that considers duration and magnitude of the drought for an area. These weekly values can be accumulated throughout a drought period for a given location for comparison with other drought periods (Akyuz 2017).
Soil moisture data	Observed and modeled soil moisture data can be used to detect agricultural drought, meteorological drought, ecological drought, and flash drought. It indicates how much moisture the soil contains compared to the moisture capacity of the soil. If anomalies are used, the magnitude of the soil moisture deficit indicates the longevity and intensity of the ongoing drought and potential impact on plant development.
Crop moisture index (CMI)	The CMI is calculated based on the Palmer drought severity index. It reflects whether quickly changing soil moisture conditions can supply the water that the crops need for development. However, its use may be limited to a period when plants have developed roots that are long enough to contact water from deeper layers of the soil. These data are produced weekly.
Vegetation drought response index (VegDRI)	The VegDRI was developed to monitor drought-induced vegetation stress using a combination of remote sensing, climate-based indicators, and other biophysical information and land-use data.
Drought Impact Reporter (DIR)	The Drought Impact Reporter, which began in 2005, is an online database of drought impacts sorted by location, drought type, drought impact category, and time. It is also a digital database where media and other reports are archived. As a citizen science effort, the public can submit local drought impacts.
Streamflow data	The USGS provides streamflow data and compares them with long-term average streamflow values. It displays actual streamflow and their comparison with the long-term average. The values are based on conditions measured at USGS gauging stations. The data are useful for detecting hydrological drought.

Lessons learned, needs, and gaps

The effectiveness of federal, state, tribal, and local responses to drought in 2017 and beyond is contingent upon thorough monitoring, skillful forecasts, effective communication, proactive planning, and the response to lessons learned through applied research, as outlined by the five pillars of a drought early warning system (Fig. 5). Based on experiences during the 2017 flash drought over the U.S. northern Great Plains and Canadian Prairies, needs and gaps for each of these five pillars are as follows (Jencso et al. 2019).

Observations and monitoring. As the 2017 flash drought emerged, it became apparent that many areas in the U.S. northern Great Plains and Canadian Prairies are poorly or infrequently measured for in situ weather and climate information. This gap in information led to challenges in making county-level or local assessments of drought conditions. A more systematic network of automated observation sites could provide high-quality information on temperature, wind, rainfall, and soil conditions in sparsely populated areas that currently lack adequate monitoring infrastructure. Investments must be made in sustaining existing monitoring networks, including state-level weather station networks, or mesonets, Remote Automated Weather Station (RAWS) networks, the NOAA Cooperative Observer Program (COOP), U.S. Geological Survey (USGS) stream gauge and groundwater monitoring, and the USDA Natural Resources Conservation Service (NRCS) snow survey and soil moisture monitoring. Efforts are currently underway to create new soil moisture monitoring stations and to establish best practices and consistent protocols.

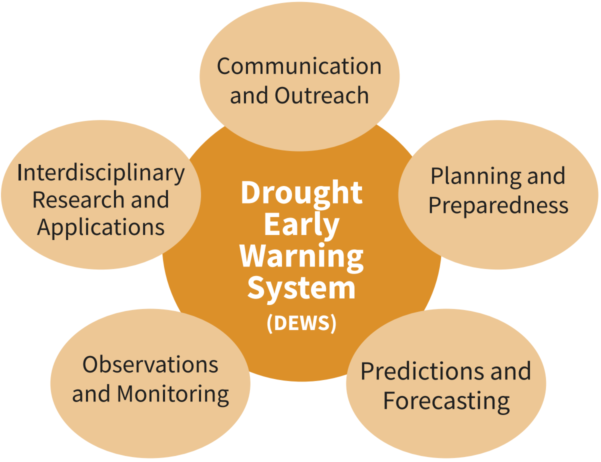

Fig. 5. Schematic of the five pillars that make up a drought early warning system based on the NIDIS Implementation Plan Update of 2016 (National Integrated Drought Information System 2016).

Several state drought task forces highlighted the need for a more detailed evaluation of which drought indicators are best for monitoring rapid onset drought (Table 3). These more detailed evaluations must consider location, time of year, and sector of concern. There is also a need to investigate whether integrated indicators, or indicators that consider more than one phenomenon, are most reliable. To help address these needs, the University of Montana and the Montana State Climate Office are leading an effort to study the applicability and value of drought indicators, including those in Table 3, in quantifying drought variability in the Upper Missouri River basin.

Drought impact reporting within states has relied on university extension staff as local reporters of agricultural drought impacts and nationally through media reports collected by the National Drought Mitigation Center's Drought Impact Reporter. There is a growing interest, however, in drought impacts to other economic sectors like tourism, recreation, and infrastructure, in addition to impacts on ecosystems. National and state entities are working to address the absence of a standardized approach to the evaluation of drought impacts across sectors. The absence of such an approach increases the risk of ad hoc or anecdotal observations that are less representative of conditions at the landscape or watershed scale. States are working with academic partners to standardize protocols for the observation and reporting of drought impacts at the local, regional, and state levels, to explore ways to link state and national databases of impact reports and strengthen and expand impact monitoring and analysis to inform decision-making.

In combination with expanded in situ observation networks, remotely sensed data can also enhance our drought detection abilities. There are numerous satellite-derived drought indices available that provide detailed information about vegetation greenness, solar-induced fluorescence, evapotranspiration, soil moisture, and other drought-relevant measures with high spatial resolution. But these satellite-derived products, on their own, might not provide comprehensive or directly comprehendible measures of socioeconomically relevant outcomes. Furthermore, while remotely sensed datasets have been evaluated at global and large regional extents, their performance within specific smaller regions and landscapes has not been widely tested. An example consequence of satellite-derived data's potential shortcomings is a vegetation index insurance product offered to agricultural producers by the USDA Risk Management Agency for pasture, range, and forage, which relied solely on normalized difference vegetation index (NDVI) as a measure of the impacts of drought on forage production (USDA 2015). This NDVI-based insurance product (known as VI-PRF) was replaced in 2016 with a rainfall index product (known as RI-PRF) because many agricultural producers were frustrated that NDVI did not correlate well with forage measures they considered most relevant to their operations (USDA 2015). This is because vegetation greenness, as measured by NDVI, does not directly predict forage growth (Ceccato et al. 2008). It must be combined, instead, with local information about precipitation, soil moisture, evapotranspiration, soil type, and plant community composition (M. Chen et al. 2019). This example illustrates the importance of leveraging the strengths and weaknesses of satellite-derived and in situ data to effectively monitor drought and its effects on many important socioeconomic and ecological outcomes.

Predictions and forecasting. The 2017 flash drought was not anticipated by operational forecasts,[4] because below-normal precipitation in May–July was an unlikely outcome in initialized prediction systems (Fig. 4). Temperature and precipitation forecasts are most accurate up to lead times of 1 month and 2 weeks, respectively (Lavers et al. 2009; Yuan et al. 2011). However, in terms of drought, Yuan and Wood (2013) state that, “This raises the question of whether seasonal forecasting of global drought onset is essentially a stochastic forecasting problem.” Though improvements in drought forecasts have been reported,[5] recent flash droughts that led to billions of dollars in losses over the Great Plains like 2012 (e.g., Hoerling et al. 2014) and 2017 were not predicted. We encourage the forecasting and model development communities to continue the upward trajectory of drought prediction skill. Continued improvements in drought forecasts may provide local and state managers in the U.S. northern Great Plains the early warning that is necessary to implement proactive drought response strategies.

Communication and outreach. Communication is an essential component of effective drought planning, preparedness, and response activities. During the 2017 drought, state drought task forces, agriculture extension professionals, state climatologists, and local USDA Service Center staff played key roles in communicating across the state drought task forces and with the public. The Missouri River basin Drought Early Warning System (see sidebar) helped to facilitate better communication by building stronger links between relevant federal, state, and tribal partners. However, there remains a need to better understand and capitalize on these pathways of communication in preparing for and responding to drought. The growth and development of new modes and methods of communication, along with the growth of new digital platforms, provides opportunities for improvement in this arena.

Planning and preparedness. Proactive drought and hazard mitigation plans, in addition to the exchange of timely and accurate drought information, are essential to the process of drought preparedness and response. The state drought plans worked as designed in 2017, but in most cases, these plans are intended to provide an emergency response rather than proactive policy direction. They are not as effective in getting services out to the public before conditions reach peak drought severity. It is difficult to plan for drought during a drought, and while short-term response plans provide support during the event, states and municipalities can benefit from longer-term planning that includes identification and implementation of mitigation and adaptation strategies. Effective early warning depends on multisectoral and interdisciplinary collaboration among all concerned actors at each stage in the warming process, especially if the intent is to improve response to impending events, managing through even intensification, and to provide guidance for longer-term resilience (Pulwarty and Verdin 2013). Many states have recognized the need to plan holistically across sectors and apply an ecosystem-based approach, which allows for consideration of building soil and plant health into

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[4] https://origin.cpc.ncep.noaa.gov/products/expert_assessment/SDO/sdo_archive/2017/05/seasonal_drought.png; https://origin.cpc.ncep.noaa.gov/products/expert_assessment/SDO/sdo_archive/2017/07/seasonal_drought.png

[5] www.cpc.ncep.noaa.gov/products/expert_assessment/sdo_verification/raw-persist.png

water management strategies. The importance of proactive drought planning and preparedness will only increase as the likelihood of drought in some regions increases in the future (Hoell et al. 2019b; Wehner et al. 2017; Yuan et al. 2019).

Another facet of planning includes a better understanding of the triggers used for decision making by individuals on the ground, as well as establishing triggers in state drought plans. During the genesis of the 2017 flash drought, agricultural producers recognized and responded to the developing drought before it was suggested by most drought indicators (Table 3). For example, since stock ponds did not fill in May because of the sparse precipitation, ranchers sold cattle and adjusted grazing plans to accommodate forage shortfalls. These actions can provide a form of "early warning" of an ensuing drought, or other weather stressors, for those who provide drought information and related assistance. This example provides an opportunity to retrospectively examine sector-specific indicators and indices that can help improve early warning in the future.

Acting to meet gaps and needs identified through the 2017 drought

The U.S. northern Great Plains is part of the Missouri River basin Drought Early Warning System (DEWS), one of nine regional DEWS that are part of the National Oceanic and Atmospheric Administration's interagency NIDIS. NIDIS was authorized by Congress in 2006 (Public Law 109-430) and reauthorized in 2014 (Public Law 113-86) and 2018 (Public Law 115-423) with a mandate to coordinate and integrate drought research. Each of the nine DEWS builds on existing federal, tribal, state, and local partnerships and is based on five key components (Fig. 5), which are adapted to regional drought-related impacts and information needs.

The lessons learned, needs, and gaps identified through experiences in the 2017 flash drought are being used to inform many initiatives in the Missouri River basin DEWS region. A National Soil Moisture Monitoring Network and Strategy is under development with a pilot in the northern Great Plains led by the U.S. Army Corps of Engineers. The states in that region have used the experience to improve their processes to monitor and respond to drought and consider updating their drought-related plans. The University of Montana is leading research to better understand which drought indicators are best suited temporally, seasonally, and spatially, and for which sectors, to improve drought monitoring. The experience of the 2017 drought and its impacts informed the development of a NIDIS Tribal Engagement Strategy for the Missouri River basin and Midwest DEWS.

The recently released Missouri River basin DEWS Regional Implementation Plan, which will guide investment in the region for the next 3–5 years, will continue to address the needs of the region, focusing on four priorities:

1) Characterize drought indicators and indices for the Missouri River basin DEWS to validate use temporally and spatially considering their uncertainties, appropriateness, and limitations for application to multiple sectors in the region.
2) Understand drought impacts and relate these to indicators to improve drought early warning, better quantify drought impacts across sectors and communities, and inform communication that resonates with target audiences.
3) Identify and communicate proactive steps that can be taken to build drought resilience before drought and inform response during drought to empower those coping with drought impacts to effect change.
4) Enhance collaboration and coordination across national, tribal, state, and local partners and across regions to strengthen drought early warning, preparedness, and resilience across the Missouri River basin.

Research and applications. Although our understanding of droughts, and the ways in which we can prepare for and respond to droughts, has improved over time, the 2017 flash drought underscored many questions that remain unanswered. Can soil moisture observations better characterize and provide early warning for flash droughts? What indicators are best suited to identify flash droughts? What is the potential predictability of flash drought, and can it ever be realized in current and future forecast systems? What are the dominant physical mechanisms of flash drought? The complexities of estimating drought impact beyond immediate agricultural losses remains challenging (e.g., Smith 2020), even more so than for other hazards such as floods and storms. How do we provide better estimates of drought impacts, given the cascading nature of risks across economic sectors? These questions are being addressed through various research and grant programs.

Concluding remarks

A pressing question remains following the 2017 flash drought, given changes in drought characteristics and risk in the northern Great Plains (Wehner et al. 2017; Hoell et al. 2019b). *Is the region prepared for future droughts since the frequency and intensity of future droughts may fall outside the context of our historical experience?* The challenges are large and involve uncertainties (e.g., predictions, forecasts, human behavior, institutional coordination), temporal and spatial scales of impacts, trade-offs between different interests, and scarce resources and capacity, but the 2017 drought provided an opportunity to identify a path forward to a more resilient future for the region.

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References

Akyuz, A., 2017: Drought severity and coverage index. U.S. Drought Monitor, https://droughtmonitor.unl.edu/About/AbouttheData/DSCI.aspx.

Baxter, D., 2017: Regina's drought causes an increase in basement sinking. *Global News*, https://globalnews.ca/news/3786243/reginas-drought-causes-an-increase-in-basement-sinking/.

Bernacki, J., 2019: Mental health services in Sask. see more calls from farmers. *CTV News*, https://saskatoon.ctvnews.ca/mental-health-services-in-sask-see-more-calls-from-farmers-1.4631989.

Ceccato, P., M. Brown, C. Funk, C. Small, E. Holthaus, A. Siebert, and N. Ward, 2008: Remote sensing—Vegetation. *Workshop on Technical Issues in Index Insurance*, New York, New York, Columbia University, https://iri.columbia.edu/~deo/insurance_class_reading/Remote%20Sensing%20-%20Vegetation.pdf.

Chen, L. G., J. Gottschalck, A. Hartman, D. Miskus, R. Tinker, and A. Artusa, 2019: Flash drought characteristics based on U.S. Drought Monitor. *Atmosphere*, **10**, 498, https://doi.org/10.3390/atmos10090498.

Chen, M., and Coauthors, 2019: Assessing precipitation, evapotranspiration, and NDVI as controls of U.S. Great Plains plant production. *Ecosphere*, **10**, e02889, https://doi.org/10.1002/ecs2.2889.

Edwards, B., M. Gray, and B. Hunter, 2015: The impact of drought on mental health in rural and regional Australia. *Soc. Indic. Res.*, **121**, 177–194, https://doi.org/10.1007/s11205-014-0638-2.

Fortin, J., 2017: Montana battles wildfires amid a severe drought. *New York Times*, 7 September, www.nytimes.com/2017/09/07/us/montana-wildfire-drought.html.

Gabbert, B., 2018: Telephone company says Legion Lake Fire was caused by "act of God." *Wildfire Today*, 30 December, https://wildfiretoday.com/tag/legion-lake-fire/.

Giesbrecht, L., 2018: SaskPower meter inspections cost $15 million. *Regina Leader-Post*, 29 May, https://leaderpost.com/news/local-news/saskpower-meter-inspections-cost-15-million.

Hoell, A., J. Perlwitz, and J. Eischeid, 2019a: Drought assessment report: The causes, predictability, and historical context of the 2017 U.S. northern Great Plains drought. National Integrated Drought Information System Rep., 27 pp., www.drought.gov/drought/sites/drought.gov.drought/files/2017-NGP-drought-assessment.pdf.

——, ——, C. Dewes, K. Wolter, I. Rangwala, X.-W. Quan, and J. Eischeid, 2019b: Anthropogenic contributions to the intensity of the 2017 United States northern Great Plains drought. *Bull. Amer. Meteor. Soc.*, **100** (1), S19–S24, https://doi.org/10.1175/BAMS-D-18-0127.1.

Hoerling, M., J. Eischeid, A. Kumar, R. Leung, A. Mariotti, K. Mo, S. Schubert, and R. Seager, 2014: Causes and predictability of the 2012 Great Plains drought. *Bull. Amer. Meteor. Soc.*, **95**, 269–282. https://doi.org/10.1175/BAMS-D-13-00055.1.

Jencso, K., and Coauthors, 2019: Flash drought: Lessons learned from the 2017 drought across the U.S. Northern Plains and Canadian Prairies. NOAA National Integrated Drought Information System Rep., 76 pp., www.drought.gov/drought/sites/drought.gov.drought/files/NIDIS_LL_FlashDrought_2017_high-res_Final_6.6.2019.pdf.

Jones-Bitton, A., 2018: Dr. Andria Jones-Bitton (Associate Professor, Ontario Veterinary College, University of Guelph) at the Agriculture and Agri-Food Committee. Open Parliament, https://openparliament.ca/committees/agriculture/42-1/107/dr-andria-jones-bitton-1/only/.

——, C. Best, J. MacTavish, S. Fleming, and S. Hoy, 2020: Stress, anxiety, depression, and resilience in Canadian farmers. *Soc. Psychiatry Psychiatr. Epidemiol.*, **55**, 229–236, https://doi.org/10.1007/s00127-019-01738-2.

Kirtman, B. P., D. Min, and J. M. Infanti, 2014: The North American Multimodel Ensemble: Phase-1 seasonal-to-interannual prediction; phase-2 toward developing intraseasonal prediction. *Bull. Amer. Meteor. Soc.*, **95**, 585–601, https://doi.org/10.1175/BAMS-D-12-00050.1.

Lavers, D., L. Luo, and E. F. Wood, 2009: A multiple model assessment of seasonal climate forecast skill for applications. *Geophys. Res. Lett.*, **36**, L23711, https://doi.org/10.1029/2009GL041365.

Lawrimore, J., R. R. Heim, M. Svoboda, V. Swail, and P. J. Englehart, 2002: Beginning a new era of drought monitoring across North America. *Bull. Amer. Meteor. Soc.*, **83**, 1191–1192, https://doi.org/10.1175/1520-0477-83.8.1191.

Menne, M. J., I. Durre, R. S. Vose, B. E. Gleason, and T. G. Houston, 2012: An overview of the Global Historical Climatology Network-Daily database. *J. Atmos. Oceanic Technol.*, **29**, 897–910, https://doi.org/10.1175/JTECH-D-11-00103.1.

National Integrated Drought Information System, 2016: NIDIS implementation plan update 2016. NIDIS Rep., 17 pp., www.drought.gov/drought/nidis-implementation-plan-2016-update.

National Research Council, 1999: *The Impacts of Natural Disasters: A Framework for Loss Estimation*. National Academies of Science, 80 pp.

NCEI, 2017: U.S. billion-dollar weather and climate disasters (2017). NOAA, www.ncdc.noaa.gov/billions/.

Otkin, J. A., M. Svoboda, E. D. Hunt, T. W. Ford, M. C. Anderson, C. Hain, and J. B. Basara, 2018: Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bull. Amer. Meteor. Soc.*, **99**, 911–919, https://doi.org/10.1175/BAMS-D-17-0149.1.

Pasiuk, E., 2017: Mass cattle deaths caused by poor water quality. *Global News*, https://globalnews.ca/news/3596732/mass-cattle-deaths-caused-by-poor-water-quality/.

Pendergrass, A. G., and Coauthors, 2020: Flash droughts present a new challenge for subseasonal-to-seasonal prediction. *Nat. Climate Change*, **10**, 191–199, https://doi.org/10.1038/s41558-020-0709-0.

Puckett, K., 2018: 2017 was state's worst fire season since 1910. *Great Falls Tribune*, 8 February, www.greatfallstribune.com/story/news/2018/02/08/2017-fire-season-no-1-produced-largest-fire-states-history/319952002/.

Pulwarty, R., and J. Verdin, 2013: Crafting early warning information systems: The case of drought. *Measuring Vulnerability to Natural Hazards: Disaster Resilient Societies*, J. Birkmann, Ed., UNU Press, 124–147.

Purdy, A. J., J. Kawata, and J. B. Fisher, 2019: Designing drought indicators. *Bull. Amer. Meteor. Soc.*, **100**, 2327–2341, https://doi.org/10.1175/BAMS-D-18-0146.1.

Reed, D. B., and D. T. Claunch, 2020: Risk for depressive symptoms and suicide among U.S. primary farmers and family members: A systematic literature review. *Workplace Health Saf.*, **68**, 236–248, https://doi.org/10.1177/2165079919888940.

Runia, T. J., 2017: Pheasant brood survey report—2017. South Dakota Department of Game, Fish and Parks Rep., 11 pp., https://gfp.sd.gov/userdocs/docs/PBR2017.pdf.

Sage, J. L., and N. P. Nickerson, 2017: The Montana expression 2017: 2017's costly fire season. Institute for Tourism and Recreation Research Publ. 363, 19 pp., https://scholarworks.umt.edu/itrr_pubs/363.

Simes, J., 2019: Study finds burnout a real risk for producers. *Western Producer*, 7 November, www.producer.com/2019/11/study-finds-burnout-a-real-risk-for-producers/.

Smith, A., 2020: 2010-2019 A landmark decade of billion-dollar disasters. NOAA National Centers for Environmental Information, accessed 9 February 2020, www.climate.gov/news-features/blogs/beyond-data/2010-2019-landmark-decade-us-billion-dollar-weather-and-climate.

Stephenson, A., 2018: Depressed on the farm: 'Horrible crop' takes its toll on mental health. *Calgary Herald*, 14 September, https://calgaryherald.com/business/local-business/depressed-on-the-farm-horrible-crop-takes-its-toll-on-mental-health.

Svoboda, M., and Coauthors, 2002: The Drought Monitor. *Bull. Amer. Meteor. Soc.*, **83**, 1181–1190, https://doi.org/10.1175/1520-0477-83.8.1181.

USDA, 2015: Frequently asked questions: Pasture, rangeland, forage. USDA, https://legacy.rma.usda.gov/help/faq/faq-prf2016.html.

——, 2017a: 2017 crop progress and conditions. National Agricultural Statistics Service, www.nass.usda.gov/Charts_and_Maps/Crop_Progress_&_Condition/2017/index.php.

——, 2017b: Livestock forage program, native pasture—2017 program year. Farm Service Agency, 1 p., www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/Disaster-Assist/LFP-Maps/2017/native_pasture_2017.pdf.

——, 2017c: Livestock forage program state summary. Livestock Forage Program, www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/Disaster-Assist/lfp-lip/xls/LFP%20State%20Summary.xlsx.

Vose, R. S., and Coauthors, 2014: Improved historical temperature and precipitation time series for U.S. climate divisions. *J. Appl. Meteor. Climatol.*, **53**, 1232–1251, https://doi.org/10.1175/JAMC-D-13-0248.1.

Wang, H., S. D. Schubert, R. D. Koster, and Y. Chang, 2019: Attribution of the 2017 northern High Plains drought. *Bull. Amer. Meteor. Soc.*, **100** (1), S25–S29, https://doi.org/10.1175/BAMS-D-18-0115.1.

Wehner, M. F., J. R. Arnold, T. Knutson, K. E. Kunkel, and A. N. LeGrande, 2017: Droughts, floods, and wildfires. *Climate Science Special Report: Fourth National Climate Assessment*, D. J. Wuebbles, Ed., Vol. I, U.S. Global Change Research Program, 231–256, https://doi.org/10.7930/J0CJ8BNN.

Wood, A., 2008: The University of Washington surface water monitor: An experimental platform for national hydrologic assessment and prediction. *22nd Conf. on Hydrology*, New Orleans, LA, Amer. Meteor. Soc., 5.2, https://ams.confex.com/ams/88Annual/webprogram/Paper134844.html.

Yuan, X., and E. F. Wood, 2013: Multimodel seasonal forecasting of global drought onset. *Geophys. Res. Lett.*, **40**, 4900–4905, https://doi.org/10.1002/grl.50949.

——, ——, L. Luo, and M. Pan, 2011: A first look at Climate Forecast System version 2 (CFSv2) for hydrological seasonal prediction. *Geophys. Res. Lett.*, **38**, L13402, https://doi.org/10.1029/2011GL047792.

——, L. Wang, P. Wu, P. Ji, J. Sheffield, and M. Zhang, 2019: Anthropogenic shift towards higher risk of flash drought over China. *Nat. Commun.*, **10**, 4661, https://doi.org/10.1038/s41467-019-12692-7.