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On the Ground

- Because fire activity fluctuates with short- and long-term term weather and climate trends, understanding trends relative to climate forecasts is critical to mitigating the loss of life and property and rapid vegetation state changes.
- Through the analysis of charcoal and trees scars, historical droughts and fire patterns can be quantified retrospectively for hundreds of years. This evidence suggests that generally fire was most frequent during warm-dry periods as opposed to cool-moist periods. However, arid regions may see an increase of fire activity with an increase of moisture due to inherent fuel load limitations.
- Using federal wildfire and weather data from 2002 to 2015 for New Mexico, Nevada, Oklahoma, and Wyoming, we demonstrate that the worst wildfire activity occurred after average or above average precipitation years followed by drought in Oklahoma and Wyoming. Nevada wildfire activity was correlated with precipitation the preceding year, and New Mexico wildfire activity was not correlated with annual precipitation or preceding year precipitation.
- The effects of future drought on fire intensity and severity are projected to be highly variable because they are both a function of fuel load. However, the potential for very large wildfires is predicted to increase; fire weather is expected to create hotter and drier conditions that start earlier and last longer; and the relative changes may be most noticeable in cooler regions that are of higher latitude and elevation.

Keywords: climate cycles, disturbance, fire, forest, rangeland, weather variability.

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Wildfire size, extent, seasonality, and severity seems to have accelerated in the western United States over the last several decades, with 2006 and 2011/2012 being some of the most active wildfire years on record. Although fire is a disturbance that has regulated plant communities in North America for millennia, the recent escalation and potential correlation with a changing climate and drought, in particular, is a major social and ecological concern. While frequent fires structuring grasslands and park-like ponderosa forests is a regulating ecological process, catastrophic events causing rapid vegetation state change are less understood. Examples from Wyoming of rapid state changes include wildfires in 2003 that eliminated all sagebrush with no apparent recovery to date (Fig. 1A) and wildfires in 2012 that caused over 99% mortality of mature ponderosa pine (Fig. 1B). In fact, both 2003 and 2012 were years with below average precipitation and negative Palmer Drought Severity Index values. This suggests that the regulatory role of fire does not act independently of drought, but rather interacts with short-term weather and long-term climatic patterns that change over time. This interaction is evident in the formation and physiography of characteristic vegetation structure found in the grassland biome, a process hypothesized to have been a function of occasional arid periods restricting woody plants and increasing drought leading to frequent fires.

Because fire activity fluctuates with short- and long-term term climatic trends such as drought and precipitation deluges, understanding current trends relative to future climate projections is critical not only ecologically but also socially. The droughts and wildfires of 2011 and 2012 were some of the worst on record and caused substantial property losses and threats to human lives (Fig. 2). As the financial costs of wildfire management escalate, the socio-ecological consequences of drought–wildfire interactions must be understood.[1] The goals of this paper are to 1) review the historical interaction between drought and wildfire in western US rangelands, 2) summarize the societal impacts of this interaction, 3) use recent weather and state-level wildfire data from four case studies (Southwest: New Mexico; Great Basin: Nevada; Southern Great Plains:

Figure 1. Examples of rapid vegetation state changes from wildfires in drought years. **A,** Burn scar of the Lake Creek Wildfire in the Thunder Basin of Wyoming that burned in August of 2003. The year this fire burned was a below average precipitation year and above average wildfire year. Mortality of sagebrush is estimated at > 90% (note the lack of sagebrush in this picture that was taken in 2015 or 12 years after the wildfire). **B,** Ponderosa pine stand in the Laramie Mountain range of Wyoming three years after the Arapaho wildfire that burned > 100,000 acres in 2012one of the worst drought and wildfire years in the state. Mature tree mortality was estimated at ~ 99%. Photo courtesy of J.D. Scasta.

Oklahoma; and Rocky Mountains: Wyoming) to understand the variability of this interaction at a meaningful social scale, and 4) synthesize what we can expect in the future relative to climate projections and wildfire risk.

Figure 2. Wildfire damage in north-central Oklahoma in 2012. Note the proximity of eastern red cedars to the destroyed property. Photo credit: J.R. Weir.

Historical Fire and Drought

Historically fires did not occur regularly or uniformly through space or time. This spatio-temporal variability is largely a function of fuels, topography, weather/climate patterns, and ignitions. During dry or prolonged drought conditions, if fine fuel cover is adequately contiguous then fire activity often increases. Through the analysis of charcoal and trees scars, historical droughts and fire patterns can be quantified retrospectively for hundreds of years (Fig. 3). In the cooler, northern Great Plains, fire was most frequent over the last 750 years during warm dry periods, especially from 1770 to 1820 and from 1870 to 1920, as opposed to less frequent fire in the moist and cool time from 1820 to 1870.[2] The opposite effect can occur in drier regions that are fuel-limited where century-long and longer moist periods can correspond with increased fire activity.[3] This is important because long-term, decadal to multidecadal droughts have been relatively common in the Great Plains.[4] However, over time these prolonged droughts can reduce biomass production, resulting in increased bare soil and drought-tolerant forbs, which can also lead to a loss of fine fuels and eventually decreased fire occurrence.[5]

The frequency and size of wildfires is also dependent on fuel production and ability of fires to spread. For example, in the central Great Plains of the United States, aboveground net primary production varied greatly from 1975 to 1993 due to irregularity in precipitation resulting in fuel loads being driven largely by precipitation patterns.[6] This fuel load : fire frequency relationship is broadly demonstrated across the Great Plains of the United States where fire frequency generally increases from west to east due to precipitation and north to south due to temperature.[5]

Figure 3. Cross section of a dead ponderosa pine tree collected from Scotts Bluff, Nebraska. Tree-rings cover the years 1527 to 1762. Historical droughts can be determined based on patterns of narrow rings. Historical fire years can be dated from the tree rings where fire injuries occur (white arrows). Photo courtesy of M. Stambaugh.

In the southern Great Plains, specifically southwestern Oklahoma, historically, more fire events occurred in drier conditions than wetter conditions. Fire activity increased during the prolonged Civil War drought (1856–1865) when fire frequency was 1.7 years.[7] Fire history work in the Cross Timbers on the edge of tallgrass prairies of northeast Oklahoma found no significant relationship between fire events and drought for a 250-year period[8]; however, the authors did conclude that several moderate to severe drought years had spatially widespread fires.[8] Thus, variability in fire activity during droughts appears to be spatially complex, but why?

This complexity is attributed to inter- and intra-annual precipitation patterns that can confound the drought–wildfire interaction through the timing of precipitation. If adequate precipitation occurs during the growing season and the dormant season is dry, increased fire events may occur due to increased fuel accumulation and promotion of fuel curing and combustion rates. However, if the growing season is dry but the dormant season has average or above average precipitation, fire activity can be low due to the lack of fuel accumulation and moist dormant season conditions reducing ignition and fire spread potential. Such reasoning suggests that, to understand fire activity, it is important to consider the timing of precipitation, regardless of drought conditions.

Certainly, fire occurrence does not solely hinge on drought conditions, but also presence of ignition sources. Droughts can occur without fire when an ignition source is absent. Ignition sources include humans, lightning, or fires burning into a region from distant ignitions. Frequent fire during droughts or infrequent fires during wet periods reflect strong climate control of fire regimes, while infrequent fire during droughts and frequent fire during wet periods may reflect strong human controls.

Societal Impacts of Fire and Drought

Fires and droughts have impacts on society through agricultural damage, loss of property, and threat to lives. In

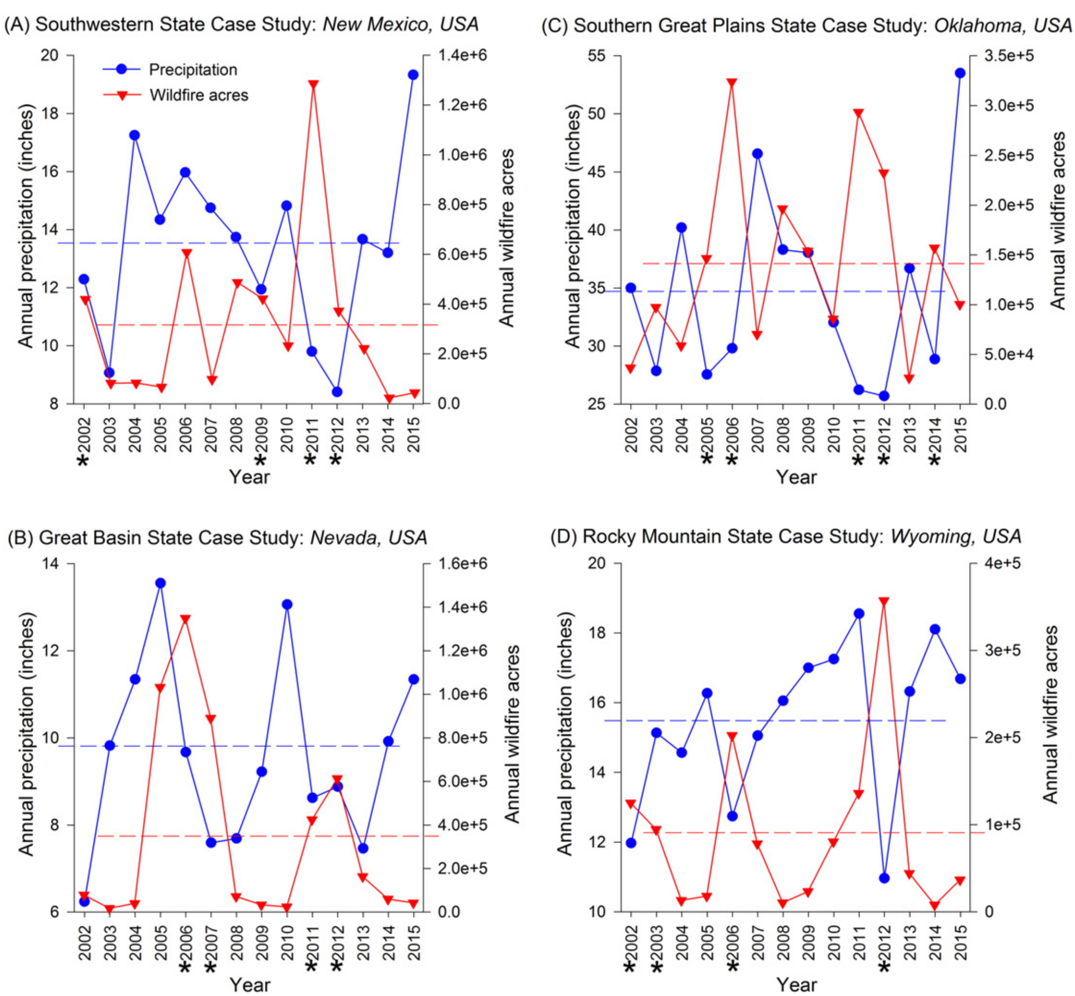

Figure 4. Annual wildfire acres and precipitation relative to 14-year means for four state-level case studies including **A,** New Mexico, droughts occurred in 2002, 2009, 2011, and 2012 with more than 1.6 million acres burning in the 2011/212 drought combined; **B,** Nevada, droughts occurred in 2006, 2007, 2011, and 2012 with more than 2.2 million acres burning during the 2006/2007 drought combined; **C,** Oklahoma, droughts occurred in 2005, 2006, 2011, and 2012 with more than 0.5 million acres burning in 2006 and 2012 combined; and **D,** Wyoming, (which includes dry forest, northern mixed grass prairie and sagebrush steppe) droughts occurred in 2002, 2003, 2006, and 2012 with more than 300,000 acres burning in 2012, the most for this period of record. Asterisks (*) indicate years with above average wildfire activity and below average precipitation. Wildfire data are from the National Interagency Fire Center[18] and precipitation data are from National Oceanic and Atmospheric Administration.[19]

Oklahoma and Texas, losses to agricultural production due to the drought and wildfires of 2011 to 2012 were estimated at $7.2 billion.[9,10] During 2009, property damaged from wildfires in Oklahoma was estimated at nearly $30 million (Fig. 2).[11] In Texas, the 2011 drought and affiliated wildfires cost $500 million in insured losses and $48 million in suppression costs.[12] In recent decades, fire sizes and suppression costs are both increasing, particularly associated with western US fires[1]. More recently, these costs are associated with fires in the central United States. For example, it was estimated that the cost to extinguish a single wildfire that burned around 40,000 acres in southwestern Oklahoma in 2011 was approximately $5 million.[13] More recently in 2016, a single fire burning in Oklahoma and Kansas was markedly larger, reaching over 400,000 acres in size.

Recent Weather and Climate Trends

Over the last several decades, wildfire incidents and extent have increased, in part due to changing climate.[1] As relative humidity decreases and fire activity escalates, the number of high fire danger days is predicted to increase.[14] Moreover, fire seasons may be getting longer due to warming and the earlier onset of the spring fire season.[15] Trends of increasing drought severity, frequency, and duration have also been correlated with an increase in the number of large wildfires and the total area burned per year.[16,17] From 1997 to present, there have been over 156 wildfires throughout the entire United States that burned more than 100,000 acres, many of which burned during years with below average precipitation.[18] For example, the 2006 East Amarillo Complex Fire in Texas burned > 900,000 acres.

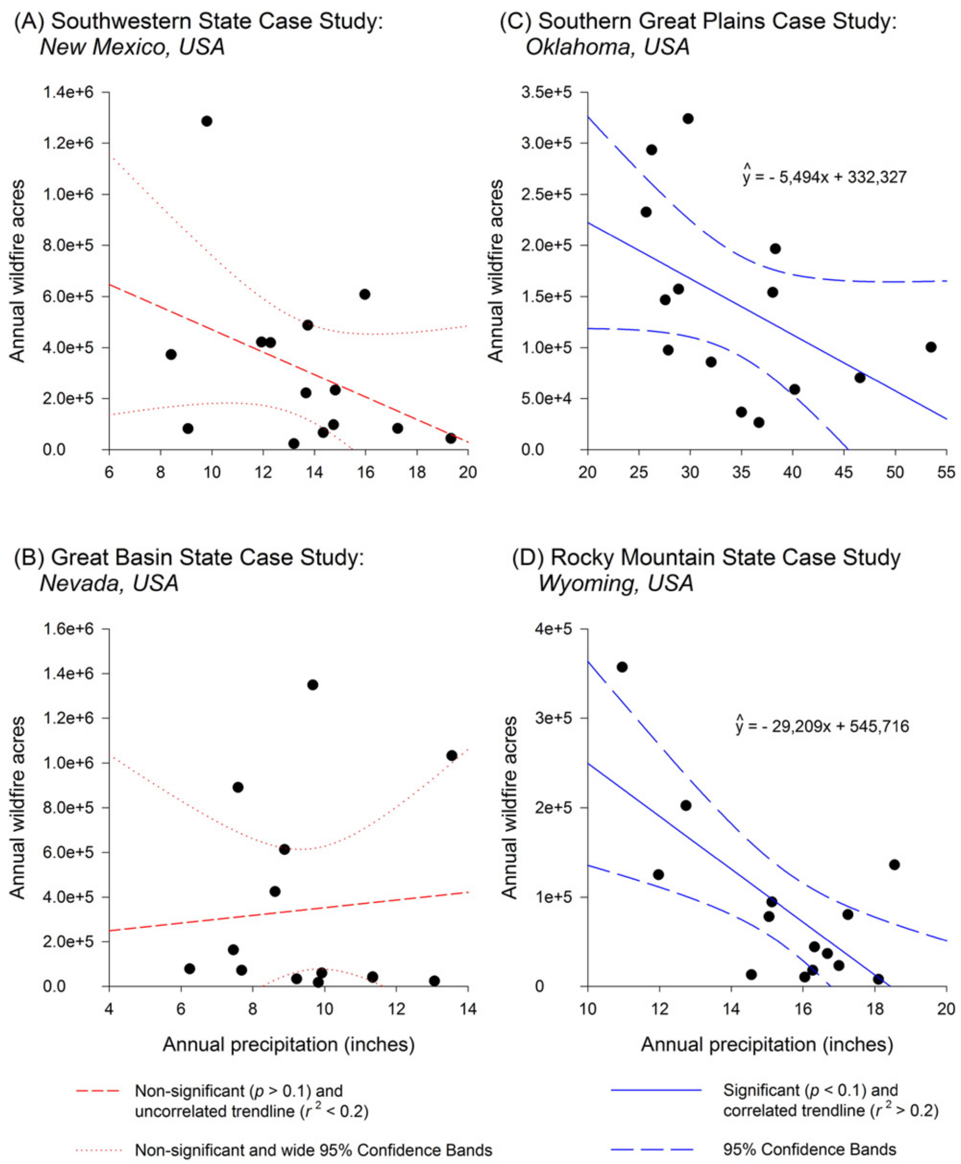

Figure 5. Linear least squares regression of annual precipitation (x-axis) and annual acres burned by wildfire (y-axis) for four state-level case studies including **A,** Southwest: New Mexico; **B,** Great Basin: Nevada; **C,** Southern Great Plains: Oklahoma; and **D,** Rocky Mountains: Wyoming, from 2002 to 2015. Wildfire data are from the National Interagency Fire Center[18] and precipitation data are from National Oceanic and Atmospheric Administration.[19]

Case studies from four states demonstrate recent drought–wildfire interactions (Fig. 4). In each of these cases since 2002, states experienced 4 to 5 years with below average precipitation and above average total area burned by wildfire (Figs. 4A–D).[18,19] In these state-level scenarios, the worst wildfire activity occurred almost exclusively in drought years following average or above average precipitation years (Figs. 4A–D). In cases in which fires were of high severity, the effects could be long term, especially where vegetation state changes occurred. For example, the 2012 Arapaho Fire in central Wyoming burned > 100,000 acres of ponderosa pine rangeland with mature tree mortality exceeding 99% with little regeneration documented to date (Fig. 1B). These long-term effects are also apparent in shrubland/grassland matrices like the sagebrush steppe and northern mixed-grass prairie ecotone of eastern Wyoming where the Lake Creek Fire in the Thunder Basin burned in 2003 with no apparent sagebrush recruitment 12 years post-fire (Fig.1A).

Since 2002, New Mexico and Nevada annual wildfires are not correlated with annual precipitation (Figs. 5A and B), but Oklahoma and Wyoming are (Figs. 5C and D). In Oklahoma and Wyoming, total area burned increases from 5,494 acres to 29,209 acres for every 1-inch precipitation reduction (Figs. 5C and D). Based on the lack of correlation in this analysis of New Mexico and Nevada and a 1-year lag relationship observed for Nevada (Fig. 4), we then used regression to determine if the amount of precipitation in the preceding year was correlated with the following year total area burned for New Mexico and Nevada. Only total area burned by wildfire in Nevada was significantly correlated with precipitation the preceding year (Fig. 6) with an estimated increase of 148,931 acres for every additional inch of precipitation received the preceding year. Thus, in our driest state case study, the wildfire response to drought is different than in our wettest state case study both in timing and direction.

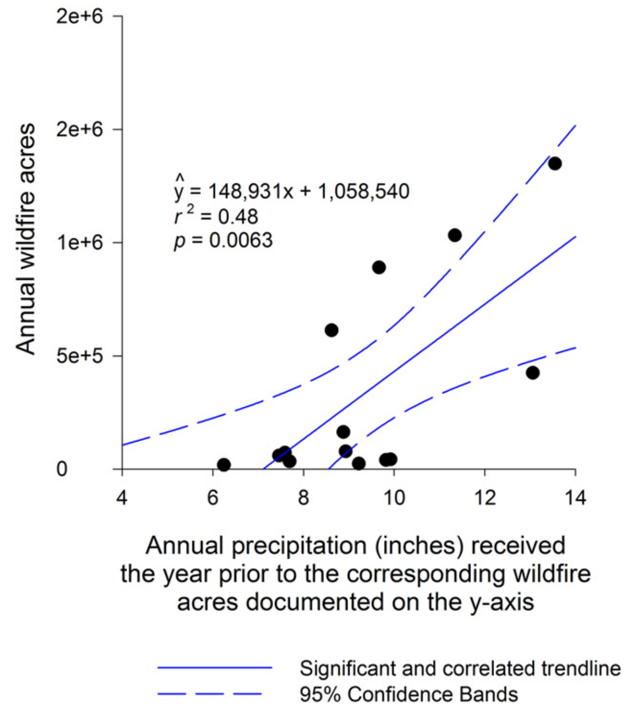

Figure 6. Linear least squares regression of the Great Basin state-level case study of Nevada, annual acres burned by wildfire (y-axis) and total annual precipitation from the preceding year (x-axis) from 2002 to 2015. Wildfire data are from the National Interagency Fire Center[18] and precipitation data are from National Oceanic and Atmospheric Administration[19].

What Can We Expect for Future Drought-Wildfire Interactions in Western U.S. Rangelands?

Regional climate change is expected to increase wildfire frequency and severity and make applying prescribed fire more difficult.[20] However, the effects of climate change on fire intensity and severity are projected to be highly variable because they are both a function of fuel load and regional variation.[21] This is in agreement with our state-level case studies because drought is often regional and the state-level is a meaningful social scale where resource allocation and response decisions are often made.

In rangeland, an important factor contributing to increased fuel accumulation is the reduction of grazing livestock. Cattle numbers have declined from 96.7 million in 2002 to 88.5 million in 2014.[22] The largest period of decline (4 million) was from 2010 to 2013 during the peak of the severe drought in the Great Plains and Rocky Mountain cattle-producing states (Figs. 4B–D). Widespread reduction in cattle numbers limits the total area grazed and thus increases fuel loads that may increase wildfire ignitions and spread or make suppression less manageable for fire crews.

Adding to the complexity of predicting climate-induced fire patterns, the effects of regional temperature and precipitation variation and change make generalizations difficult. Two global climate models and the Physical Chemistry Fire Frequency Model demonstrate the potential for greater fire probability in cooler northern latitudes and high-elevation regions but lower fire probability for some hotter and drier regions of the southwestern United States.[5] It is generally agreed upon that the seasonality of very large wildfires in the United States is predicted to expand in terms of wildfire season and more areas becoming fire-prone over the 21st century in response to forecasted climate change (Table 1).[23,24] Furthermore, the complex and interactive influence of temperature and precipitation can be difficult to untangle, as demonstrated by our four state-level case studies that have different vegetation types and precipitation patterns. These drivers of fire are further influenced by external forces such as policy and anthropogenic ignitions—both of which are subject to rapid changes as well. It is important to note that projections for the influence of climate on current and future fire regimes are not uniformly agreed upon, particularly due to underlying model assumptions (Table 1).[25] Despite this, multiple studies suggest that the Northern Rockies, Great Basin, and portions of the Southwest may be the most at risk in regional climate change–driven fire patterns.[5,14,15,24] Some researchers also predict increases in very large wildfires[26] and suggest these conflagrations are not outside of the historical variability of western dry forests—a claim that has been disputed (Table 1).[25] This alternative hypothesis is important because it runs counter to the current rhetoric about wildfires in the United

Table 1. Summary of key scientific studies documenting and/or modeling drought-wildfire interactions and patterns on US rangelands with forecasts for future wildfire activity

Study	Conclusions regarding drought, climatic variability, and wildfires
Barbero et al. 2015[24]	The potential for very large wildfires was projected through modeling for the intermountain west and northern California. Atmospheric conditions conducive for large wildfires are anticipated to begin earlier in the southern United States and remain in place longer in the northern regions (i.e., earlier and longer wildfire seasons).
Brown et al. 2004[14]	Drying patterns will alter relative humidity and increase the number of high fire danger days generally across the west. Regions of high susceptibility are the Northern Rockies, Great Basin, and Southwest. Regions of low susceptibility are the front range of the Rockies and High Plains.
Dennison et al. 2014[17]	From 1984 to 2011, the trend in the western United States was a significant increase the number of large fires and total area burned. These trends were the most significant in the southern and mountain ecoregions and were related with increasing drought severity trends. The rate of annual increase was +7 fires and +87,722 acres per year.
Flannigan et al. 2009[21]	A general increase can be expected in the total area that burns and the number of wildfire occurrences. However, these trends will likely be spatially variable. Fire seasons are anticipated to continue to lengthen in temperate and boreal regions. Fire severity and intensity forecasts are difficult to make.
Guyette et al. 2014[5]	Probability for future fires is generally increasing throughout the United States but is decreasing in the semi-arid hot/dry southwestern United States where fuels become limited due to desertification.
Stavros et al. 2014[23]	Climate models suggest the probability of very large wildfires will continue to increase in the next century. The greatest changes may occur in flammability-limited areas such as the Pacific Northwest. Other areas of anticipated escalation are the eastern Great Basin, Rocky Mountains, and Southwest.
Williams and Baker 2012[26]	Current catastrophic and large wildfire trends in dry forests are within the historical range of variation based on tree-ring constructions across > 2.2 million acres. Dry forests had a history of large and severe wildfires. Attempting to reduce fuels and fire severity may move the fire disturbance of these forests out of their historic range of variation (*Note the response by Fulé et al. 2014 disagreeing with these conclusions*).
Westerling et al. 2003[16]	Modeling indicates that the seasonality of wildfires is correlated with climate variation. Drought and prior precipitation patterns jointly explain future wildfire season severity. Understanding the moisture conditions in the previous year is a good way to forecast future fire season severity up to 1 year in advance.
Westerling et al. 2006[15]	The mid 1980s were a time of greater large-wildfire frequency, longer wildfire durations, and longer wildfire seasons. The drivers of these changes were increased spring and summer temperatures and earlier snowmelt, particularly in mid-elevation forests of the Northern Rockies.

States but could indicate that these conflagrations are not unprecedented. Moreover, high-severity fire regimes are characteristic of some forest types (e.g., subalpine) and should be expected.[27]

In the last 14 years, the droughts in our state case studies have only lasted 1 to 3 years, but they were extreme to exceptional and followed average or well above average precipitation years (Fig. 4A–D). This type of climate cycle was the "perfect storm" for increasing drought-induced wildfires, especially in locations where wildfire risk is elevated due to 20th-century fire suppression and its effects on altering fuel types and loading.[27] Throughout the United States, the effects of fire suppression have also altered stand structure and density along with increasing the potential for surface to crown fire transitions, creating higher levels of canopy tree mortality (Fig. 1B).[28,29] As we continue to refine drought prediction capabilities, we will be better able to anticipate exceptional wildfire events in some areas and may utilize strategic grazing, fire breaks, and fuels management to reduce risks to sensitive plant communities, structures, and lives.

It is important to realize drought influences on wildfire activity are variable and may increase total area burned in some rangelands (Rockies and Southern Great Plains), may decrease total area burned in other areas (Great Basin: Nevada), and may be unrelated in others (Southwest: New Mexico). Moreover, the literature shows variable effects of climate on fire frequency, size, and season, making an overall generalization unclear. However, it does appear that as drought escalates and fire weather conditions deteriorate (higher wind speed, lower relative humidity, hotter ambient temperatures), the probability and severity of fires increases and wildfire season is lengthened.

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