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SPECIAL FEATURE

A review of the relationships between drought and forest fire in the United States

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Abstract

The historical and presettlement relationships between drought and wildfire are well documented in North America, with forest fire occurrence and area clearly increasing in response to drought. There is also evidence that drought interacts with other controls (forest productivity, topography, fire weather, management activities) to affect fire intensity, severity, extent, and frequency. Fire regime characteristics arise across many individual fires at a variety of spatial and temporal scales, so both weather and climate – including short- and long-term droughts – are important and influence several, but not all, aspects of fire regimes. We review relationships between drought and fire regimes in United States forests, fire-related drought metrics and expected changes in fire risk, and implications for fire management under climate change. Collectively, this points to a conceptual model of fire on real landscapes: fire regimes, and how they change through time, are products of fuels and how other factors affect their availability (abundance, arrangement, continuity) and flammability (moisture, chemical composition). Climate, management, and land use all affect availability, flammability, and probability of ignition differently in different parts of North America. From a fire ecology perspective, the concept of drought varies with scale, application, scientific or management objective, and ecosystem.

Keywords: climate change, climate variability, drought, ecological drought, fire, water balance

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Introduction: drought and fire

The paleoecological record indicates that on time scales of centuries to millennia, climatic controls on fuel availability and fuel flammability influence aspects of the fire regime, with fire responding to the limits of available fuels (vegetation) and vegetation responding to frequency of fire (e.g., Prichard *et al.*, 2009; Whitlock *et al.*, 2010). Historical and pre-European settlement relationships between drought and wildfire have been well-documented in much of North America: forest fire occurrence and area burned clearly increase in response to drought. Drought interacts with other controls (forest productivity, topography, and fire weather) to affect fire intensity and severity. Fire regime characteristics (including area, frequency, and severity) arise across many individual fires, so both weather and climate – including short- and long-term droughts – are important.

Fire history evidence from diverse climates and forest ecosystems suggests that components of North American forest fire regimes were moderately to strongly controlled by climate prior to Euro-American settlement and subsequent fire exclusion (Swetnam 1993; Swetnam & Betancourt, 1998; Heyerdahl *et al.*, 2002; Hessl *et al.*, 2004; Guyette *et al.*, 2006; Heyerdahl *et al.*, 2008; Flatley *et al.*, 2013). These presettlement fire histories indicate a relationship between low precipitation anomalies and widespread fire activity, especially in forests of the western United States. This is consistent with a regional depletion of soil and atmospheric moisture, leading to low moisture in foliage and surface fuels, and ultimately the potential for widespread fire (Swetnam & Betancourt, 1998). Some fire histories derived from fire-scarred trees in the American Southwest demonstrate a lagged relationship with above-average antecedent precipitation (Swetnam & Betancourt, 1998) and/or cooler temperatures (Veblen *et al.*, 2000) in the year(s) prior to years of widespread fire. Most of these records are derived from fire-scarred trees that survived fire events in low- or mixed-severity

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fire regimes, but some work has also focused on high-severity fire regimes (e.g., Heyerdahl *et al.*, 2001).

In the mid to late 20th century, relationships between area burned and climate parallel those in the fire history record. From at least 1980 forward, area burned on Federal lands was related to monthly Palmer Drought Severity Index (PDSI), and the sign and magnitude of the relationships were consistent with reconstructed fire histories (Westerling *et al.*, 2003). Littell *et al.* (2009) documented ecologically and geographically variable responses of area burned to year-of-fire climate, with area burned increasing with increased temperature, decreased precipitation, or anomalously low (negative) PDSI in most forests. Over seasonal and longer time scales, these conditions also influence productivity, although the relationship between antecedent moisture and fire is statistically strongest in 'fuel limited' systems (Littell *et al.*, 2009). Fuel limitation is high in grasslands and shrublands and low to moderate in forest and woodland ecosystems (Littell & Gwozdz, 2011; Pausas & Ribeiro, 2014), so both drought and anomalously high moisture are controls on fire regimes, and drought alone is insufficient to predict fire dynamics across all ecosystems. Relationships between fire occurrence or area burned and drought are well-documented, whereas the relationship between drought and fire severity is still emerging. Although clear relationships between years with extensive fires and fractional area burned with high severity do not exist (Dillon *et al.*, 2011; Holden *et al.*, 2012), years with more widespread fires show less distinction for landscape and topographic controls on severity (Dillon *et al.*, 2011). For example, north-facing slopes that retain moisture (Northern Hemisphere) might offer some degree of local protection during mild droughts, but even they become dry under extreme conditions, reducing fine-scale heterogeneity in fire effects.

The conditions that affect fires after ignition, from initial spread to eventual extinguishment, exert the strongest control over fire behavior (e.g., Rothermel, 1972) and thus the ultimate outcomes in terms of area burned and severity. Drought influences the likelihood of ignition and fuel availability at multiple time scales, and shorter term weather affects fuel moisture and propagation, but intensity and severity are also determined by other local factors that interact with drought. At long time scales (seasons to centuries), moisture availability and drought affect fuel availability via controls on ecosystem characteristics and productivity, and at short time scales (seasons to years) via controls on fuel structure and flammability (e.g., Loehman *et al.*, 2014). In the modern era, however, other factors have become more prominent – human management of landscapes and fuels, fire suppression, and use of fire – in tandem with climate (e.g., Moritz *et al.*, 2005). Drought therefore acts with a complex set of other variables, including climatic facilitation of fuels, by making those fuels more available (flammable) than normal. For research on forest fires and drought to be most useful in risk assessment, climate change vulnerability assessments, and adaptation, a review and assessment of the current literature are needed. Here, we synthesize scientific evidence on the nature of fire-drought relationships as one mechanism in broader climate-related changes in United States forests.

Quantifying and projecting drought effects on wildfire: biological and physical factors

Tree-ring evidence of North American 'megadroughts' indicates that droughts of severity and duration not yet encountered by modern societies occurred on a widespread basis in the past (Cook *et al.*, 2007). The effect of climate change on drought occurrence is not certain (Maloney *et al.*, 2014); confidence exists for projected temperature increases across most of the planet in future decades, whereas altered precipitation, relative humidity, and climate variability are less certain (e.g. Blöschl & Montanari, 2010).

As temperatures continue to warm, all else being equal, droughts of given magnitude and low fuel moistures may become more likely in summer-dry climates even if precipitation increases, because potential evapotranspiration will also increase (Cook *et al.*, 2014). Seasonal timing of increases or decreases in precipitation would have important effects on fire occurrence, with geographic heterogeneity driven by historical fire regimes, ecological responses to climate change, and management. Regardless of specific climatic mechanisms, fire occurrence may change, with the magnitude of change depending on the temporal scale associated with changes in factors influencing probability and consequences of fires. Fire occurrence could be affected through fuel production (climatically driven productivity in the near term, species assemblages and thus fuels in the long term) or flammability (fire frequency drives changes in species assemblages). Leaf area of some forests may decrease in response to prolonged drought, which could increase water available for understory plants. In this case, understory plants could contribute to the intensity of surface fires. We suggest that projections of future system response incorporate the physical drivers, ecological responses, and complex feedbacks between them to adequately describe the potential for nonanalog conditions.

Characterizing drought – metrics of fire risk

Indicators: drought metrics and fire risk

Drought can be defined in meteorological terms, or in relative terms with respect to hydrology or ecosystems. Meteorological drought is not a necessary or sufficient condition for fire, because fires burn during conditions of normal seasonal aridity (e.g., dry summers that occur annually in California), and drought occurs without wildfires in the absence of ignitions. However, when drought occurs, both live and dead fuels can dry out and become more flammable, and probability of ignition increases along with rate of fire spread (Andrews *et al.*, 2003; Scott & Burgan, 2005). If drought continues, the number of days with elevated fuel flammability and fire spread increases, increasing the risk of widespread burning. Long droughts are not necessary to increase risk of large wildfires; anomalous aridity of 30 days or more is sufficient to dry both dead (Cohen & Deeming, 1985; Riley *et al.*, 2013) and live fuels.

Possibly because drought influences fire both directly via fuel moisture and indirectly through biological effects on vegetation, both drought indices and fire behavior metrics have been used in the literature to model fire occurrence, spread, and area burned. Interpretation of these metrics is complicated by the fact that fuel availability and flammability in different vegetation types respond differently to the same meteorological conditions, but the probability of ignition increases in most fuels when fuel moisture is low. However, even short-term drought generally increases wildfire occurrence through effects on fuel moisture.

Palmer drought severity index (PDSI). Palmer drought severity index (Palmer, 1965) is commonly used in fire occurrence research in the United States (Balling *et al.*, 1992; Westerling *et al.*, 2003; Collins *et al.*, 2006; Littell *et al.*, 2009; Miller *et al.*, 2012). PDSI was designed to capture agricultural drought, using a water balance method to add precipitation to the top two layers of soil, and a temperature-driven evapotranspiration algorithm to remove moisture (Thornthwaite, 1948). PDSI assumes all precipitation falls as rain, making its application less reliable where snow comprises a significant proportion of annual precipitation. Because the algorithm does not include some of the important drivers of evapotranspiration (relative humidity, solar radiation, wind speed), its correlation with soil moisture is weak (r = 0.5–0.7; Dai *et al.*, 2004). Correlation between PDSI and soil moisture peaks during late summer and autumn, corresponding with fire season in much of the western United States. PDSI does not have an inherent time scale, but its 'memory' varies from 2 to 9 months depending on location (Guttman, 1998).

During the past century, PDSI was weakly to moderately associated with fire occurrence in many parts of the western United States. In Yellowstone National Park (Wyoming and Montana), year-of-fire summer PDSI calculated for two adjacent climate divisions had a Spearman's rank correlation of −0.55 to −0.60 (1895–1990), with the correlation decreasing to −0.23 to −0.27 during the previous winter and −0.2 for the previous year (Balling *et al.*, 1992). Regional PDSIs for groups of Western States using the average of the PDSI value for each state were r^2 = 0.27–0.43 (1926–2002) for current-year PDSI and area burned (Collins *et al.*, 2006). Including PDSI from the two antecedent years increased correlations with area burned to r^2 = 0.44–0.67, indicating that multiyear droughts may increase fire occurrence. PDSI was a significant predictor, along with precipitation and sometimes temperature, in modeling area burned in 12 of 16 ecoregions in the western United States for 1916–2003 (Littell *et al.*, 2009). Summer PDSI explained 37% of area burned and number of fires in national forests of northwestern California during the period 1910–1959; PDSI was not a significant predictor during 1987–2008, but total summer precipitation was (Miller *et al.*, 2012). Among an array of possible drought indices, PDSI values from the previous October showed the strongest correlation with nonforested area burned in the western Great Basin (r^2 = 0.54 for 1984–2010), indicating that wet conditions during the previous autumn promoted area burned during the next fire season, but the index did not perform well in other regions (Abatzoglou & Kolden, 2013).

Precipitation totals (monthly, seasonal). Precipitation totals and anomalies are a measure of meteorological drought. In addition to the study by Miller *et al.* (2012) referenced above, monthly and seasonal precipitation anomalies have been used in several studies linking drought to fire occurrence (Balling *et al.*, 1992; Morgan *et al.*, 2008; Littell *et al.*, 2009). Littell *et al.* (2009) demonstrated that seasonal precipitation was a significant factor in multivariate models predicting area burned in most ecoregions in the western United States. However, the magnitude and sign of the precipitation term varied; in mountain and forest ecoregions, summer precipitation was generally negatively correlated with burned area, whereas in nonforested ecoregions, antecedent (usually winter) precipitation was positively correlated with area burned. In Yellowstone National Park, total annual precipitation had a Spearman's rank correlation of −0.52 to −0.54 with area burned, stronger than was demonstrated in the same study using PDSI (Balling *et al.*, 1992). Riley *et al.* (2013) found that precipitation had a strong correlation with area burned and number of large fires in the western United States ($r^2 = 0.89$). Summer precipitation had the strongest relationship among drought indices with area burned in nonforested areas of the Pacific Northwest ($r^2 = 0.48$) and eastern Great Basin ($r^2 = 0.31$) (Abatzoglou & Kolden, 2013).

Standardized Precipitation Index (SPI) is a measure of meteorological drought, calculated as the difference of precipitation from the mean for a specified time period divided by the standard deviation (McKee *et al.*, 1993). Because the distribution of precipitation amounts is generally right-skewed (Riley *et al.*, 2013), it must be normalized before this equation is applied (Lloyd-Hughes & Saunders, 2002). Riley *et al.* (2013) found that 3-month SPI explained 70% of the variability in area burned and 83% of variability in number of large fires at the level of the western United States. (Riley *et al.*, 2013), but correlations decreased until 24-month SPI explained essentially none of the variability.

Energy release component (ERC). Energy release component is a National Fire Danger Rating System fire danger metric for the United States and a proxy for both fuel moisture and fuel availability. ERC is based on recent weather (temperature, solar radiation, precipitation duration, and relative humidity). ERC is most commonly used to estimate fire occurrence for fuel models with a heavy weighting of larger fuels (7.5–20 cm diameter) (Bradshaw *et al.*, 1983; Andrews *et al.*, 2003). ERC approximates fuel dryness based on weather during the previous 1.5 months, the amount of time required for fuels 7.5–20 cm diameter (i.e., 1000-h fuels) to equilibrate to atmospheric conditions (Fosberg *et al.*, 1981). ERC varies by ecosystem so percentiles are used to indicate anomalies (Riley *et al.*, 2013).

Energy release component has been shown to correlate with area burned in southern Oregon and northern California (Trouet *et al.*, 2009) and the U.S. Northern Rockies (Abatzoglou & Kolden, 2013). Over the population of large, individual wildfires, ERC percentile during the first week of burning is highly correlated with fire occurrence at the scale of the western United States, explaining over 90% of the variability in area burned and number of large fires for the period 1984–2008 (Riley *et al.*, 2013). Probability of a large fire ignition can be predicted from ERC (Andrews *et al.*, 2003), although fires are likely to ignite at different ERCs depending on local fuels and weather. Because of its strong association with fire occurrence, ERC can indicate heightened fire risk (e.g., Calkin *et al.*, 2011). Abatzoglou & Brown (2012) demonstrate ERC as a product of downscaled climate projections, facilitating its use in modeling under climate change.

Keetch–Byram drought index (KBDI). Keetch–Byram drought index is a soil moisture deficit indicator (Keetch & Byram, 1968). Soil water transfer to the atmosphere through evapotranspiration is determined by temperature and annual precipitation, which is used as a surrogate for vegetation cover (areas with higher annual rainfall are assumed to support more vegetation). KBDI was developed and evaluated for the southeastern United States, and has been used to estimate expected fire conditions and potential suppression problems for this region (Melton, 1989). KBDI has been useful beyond the southeastern United States but with possible limitations (Xanthopoulos *et al.*, 2006; Liu *et al.*, 2010), especially lack of radiation and soil parameters, and the fact that it relies on latitude instead of dynamical inputs.

Wildfire potential is divided into four levels based on KBDI values (National Interagency Fire Center 1995): (i) low (KBDI = 0–200) – soil moisture and fuel moistures for large fuels are high and contribute little to fire intensity; (ii) moderate (200–400) – lower litter and duff layers are drying and beginning to contribute to fire intensity; (iii) high (400–600) – lower litter and duff layers contribute to fire intensity and will actively burn; and (iv) extreme (600–800) – intense, deep burning fires with significant downwind spotting can be expected. The four KBDI levels are typical of (i) spring dormant season following winter precipitation, (ii) late spring and early in the growing season, (iii) late summer and early autumn, and (iv) severe drought and increased wildfire occurrence respectively. The fire hazard measured by KBDI shows large spatial, seasonal, and interannual variability across the continental United States (Liu *et al.*, 2013a), but multiple-year trends of KBDI show a positive sign in all seasons and regions except three seasons in the Pacific Northwest and two seasons in the Southeast.

Fosberg fire weather index (FFWI). The Fosberg fire weather index (Fosberg, 1978) measures fire potential and hazard. It is dependent on temperature, relative humidity, and wind speed, assuming constant grass fuel and equilibrium moisture content (Preisler *et al.*, 2008). To gauge fire-weather conditions, FFWI combines the equilibrium moisture content (Simard, 1968) with Rothermel's (1972) rate of spread calculation (Crimmins, 2006). FFWI demonstrated significant skill in explaining monthly fire occurrence in the western United States (Preisler *et al.*, 2008). To further include the effect of precipitation, a modified version of FFWI (mFFWI) was developed by adding KBDI as a factor (Goodrick, 2002). The mFFWI can be regarded as a refinement of KBDI by adding the effects of relative humidity and winds.

Evapotranspiration. Evapotranspiration, the combined evaporation from the surface and transpiration from plant tissues, is affected by meteorological conditions near the surface, plant physiology, and soil characteristics. Among drought indices, summer evapotranspiration had the highest correlations with forested area burned in the Southwest and southern California, and with nonforested area burned in the U.S. Northern Rockies and Southwest (r^2 = 0.44–0.83) (Abatzoglou & Kolden, 2013). June through September values of potential evapotranspiration (evapotranspiration that could occur if plants did not limit water loss through stomata) was a significant predictor (r^2 range of 0.19–0.61) of area burned in forested Pacific Northwest ecoregions during recent decades (1980–2009, Littell *et al.*, 2010; Littell and Gwozdz, 2011).

Ecological water deficits: water balance deficit, climatic water deficit. Various algorithms are used to define water deficit, but all approach deficit as the evaporative demand not met by available water. Deficit is the difference between atmospheric demand for water from plants and the land surface and how much water is available to meet that demand through evaporation and transpiration. Like PDSI, water deficit attempts to integrate energy and water balance to describe water availability. Stephenson (1990, 1998) defined water balance deficit as the difference between potential evapotranspiration (PET) and actual evapotranspiration (AET) and related it to the coarse distribution of biomes. Littell *et al.* (2010) showed that PET, AET, and water balance deficit (PET-AET) were related (range of R^2 = 0.25–0.78) to area burned in the Pacific Northwest. Among drought indices, summer water balance deficit had the highest correlation with area burned in forested areas of the region (r^2 = 0.66) (Abatzoglou & Kolden, 2013). Others have used a version closer to Thornthwaite's approximation and defined deficit as PET minus precipitation.

Relationship to hydrologic drought

Many of the same factors affecting moisture in vegetation also affect moisture available for streamflow as evidenced by tree-ring flow reconstructions (e.g., Woodhouse *et al.*, 2006; Lutz *et al.*, 2012), and both fire and hydrologic drought occur with some lag after meteorological drought begins. Such relationships could be useful, because fire forecasts based on the same mechanisms could be built from the substantial infrastructure and capacity for forecasting hydrologic drought. Recent trends in snowpack, streamflow timing, and streamflow volume have been noted in various parts of the western United States (Mote *et al.*, 2005; Regonda *et al.*, 2005; Luce & Holden, 2009; Stewart, 2009; Luce *et al.*, 2012), as have recent trends in fire occurrence related to climatic forcings (Dennison *et al.*, 2014).

Analysis of wildfire occurrence across the western United States with streamflow records showed negative correlation between the dominant signal of streamflow center of timing (the point in the water year when half the total runoff has passed) and burned area in forests (Westerling *et al.*, 2006). Other work found similar relationship strength between burned area and annual streamflow volumes, and between burned area and streamflow timing (Holden *et al.*, 2012). In the Pacific Northwest, streamflow and precipitation declines, particularly during drought years, suggest that much of the trend in fire in the historic record may be related to precipitation trends (Luce & Holden, 2009; Luce *et al.*, 2013).

Synthesis of index relationships

The time window over which drought indices are calculated affects inferences about mechanistic relationships with fire and skill in predicting different aspects of fire regimes (Fig. 1). As the time window for the index increases to longer lags, the correlation with fire *occurrence* decreases, although the correlation with *area burned* may increase to a point (Higuera *et al.*, 2015) where seasonal predictors have stronger statistical relationships than shorter time frames. At finer scales, drought-fire relationships differ across ecosystems. For example, above-normal precipitation in the year(s) prior to fire is associated with higher area burned in the southwestern United States (Swetnam & Betancourt, 1998; Westerling *et al.*, 2003; Littell *et al.*, 2009) and Great Basin (Westerling *et al.*, 2003; Littell *et al.*, 2009). Long-term drought (>4 months) is not necessarily a prerequisite for extensive area burned, and seasonal climate can override the effect of antecedent climate (Abatzoglou & Kolden, 2013). However, the index used to define drought may at least partially determine the ability to detect mechanisms by which climate affects wildfire. Indices or variables that capture the interactions of the soil-to-atmosphere continuum at multiple temporal scales (PET-AET, Littell & Gwozdz, 2011; or vapor pressure deficit, Williams *et al.*, 2014) may help clarify the mechanisms and increase confidence in projections of future fire responses compared to approximations like ERC or PDSI. These variables also have the advantage of integrating multiple ecological and disturbance mechanisms, and provide a more direct approach to simulating local-to-regional responses to

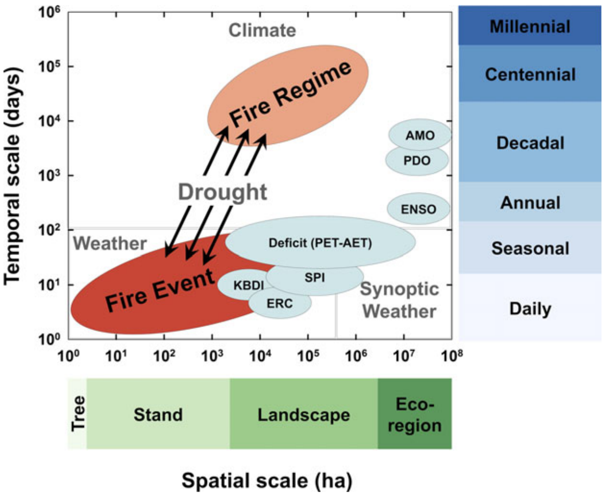

Fig. 1 Scaling of climatic controls on fire events, fire regimes (top, after climatic scaling of Clark, 1985), drought metrics, and climatic drivers related to their variation. Drought metrics are generally temporally coincident with fire events. The correlation between drought metrics and components of the fire regime in some location varies with time and spatial scales. Climatic factors that affect probability of ignitions, spread, area burned, and severity in a location in a given year are the product of multiscale influences of the climate system (top down) on fuel flammability and historical controls on fuel availability. AMO, Atlantic Multidecadal Oscillation; ENSO, El Niño Southern Oscillation; PDO, Pacific Decadal Oscillation refer to modes of climatic variability. AET, PET, ERC, KBDI, and SPI are described in the text.

climatic variability and change. On the other hand, metrics like ERC, Keetch–Byram, and the Fosberg index have current uses in fire prediction and management, and are operationally useful for management decisions prior to and during the fire season because they consider finer time scales associated with fire hazard and fire behavior. In summary, the continuum of climate-fire relationships across scales from macroscale ecoclimatology to fire behavior demonstrates a strong role of climate and weather, including drought. The most appropriate index depends on the intended application. Metrics that consider (i) both the supply of and demand for water, and (ii) the role of vegetation and fuels in and responses to those processes are likely to outperform approximations that do not adequately account for variation in either.

Expected changes in drought and consequences for wildfire

Translating projected climate into future fire risk must account for physical, hydrological, ecological, and human dimensions. In the near term (first half of the 21st century), it can be argued that changes in fire risk will occur on landscapes and within management strategies we already recognize. We present projections of two fire-related drought indicators: an ecohydrological indicator (water balance deficit, Fig. 2) and the hydrologic indicator 7q10 (the lowest 7-day average flow that occurs on average once every 10 years) (Fig. 3). A composite of 10 global climate models shows that summer (June to August) water balance deficit is projected to increase in much of the West except in portions of the Southwest that have significant monsoon precipitation and in some areas in the Pacific Northwest. Four climate models that bracket the range of projected changes in temperature and precipitation suggest that historical extreme low streamflows would be more frequently exceeded in the Cascades than in other areas of the West. Model output suggests that the Columbia Basin, upper Snake River, southeastern California, and southwestern Oregon may exceed extreme low flows less frequently than they did historically. Given the historical relationships between fire occurrence and drought indicators such as water balance deficit and streamflow, climate change can be expected to have significant effects on fire risk.

Similarly, future fire hazards as measured by KBDI are projected to increase in most seasons and regions of the continental United States in the 21st century (Liu *et al.*, 2013a). The largest increases in fire hazard are in the Southwest, Rocky Mountains, northern Great Plains, Southeast, and Pacific coasts, mainly caused by future temperature increase. The most pronounced increases occur in summer and autumn, including an extended fire season in several regions.

Interactions between drought and other stressors

Drought increases probability of fire occurrence in forest ecosystems, but other biotic and abiotic disturbances and stressors interact with drought and fire in stress complexes that affect the vigor of forest ecosystems (McKenzie *et al.*, 2009; Fig. 4). Although some of these interactions are predictable, they are generally poorly quantified. In addition, equilibrium rarely occurs even in relatively constant climate, punctuated by disturbance episodes that may or may not be associated with climatic variability. In turn, this allows succession to proceed along multiple pathways (Frelich & Reich, 1995) and creates vegetation dynamics that are difficult to project. These dynamics and their consequences reflect natural processes in many forest ecosystems. However, climate change will likely increase the probability of drought and associated effects of climate on forest processes that modify disturbance, in some cases resulting in faster change than from drought alone.

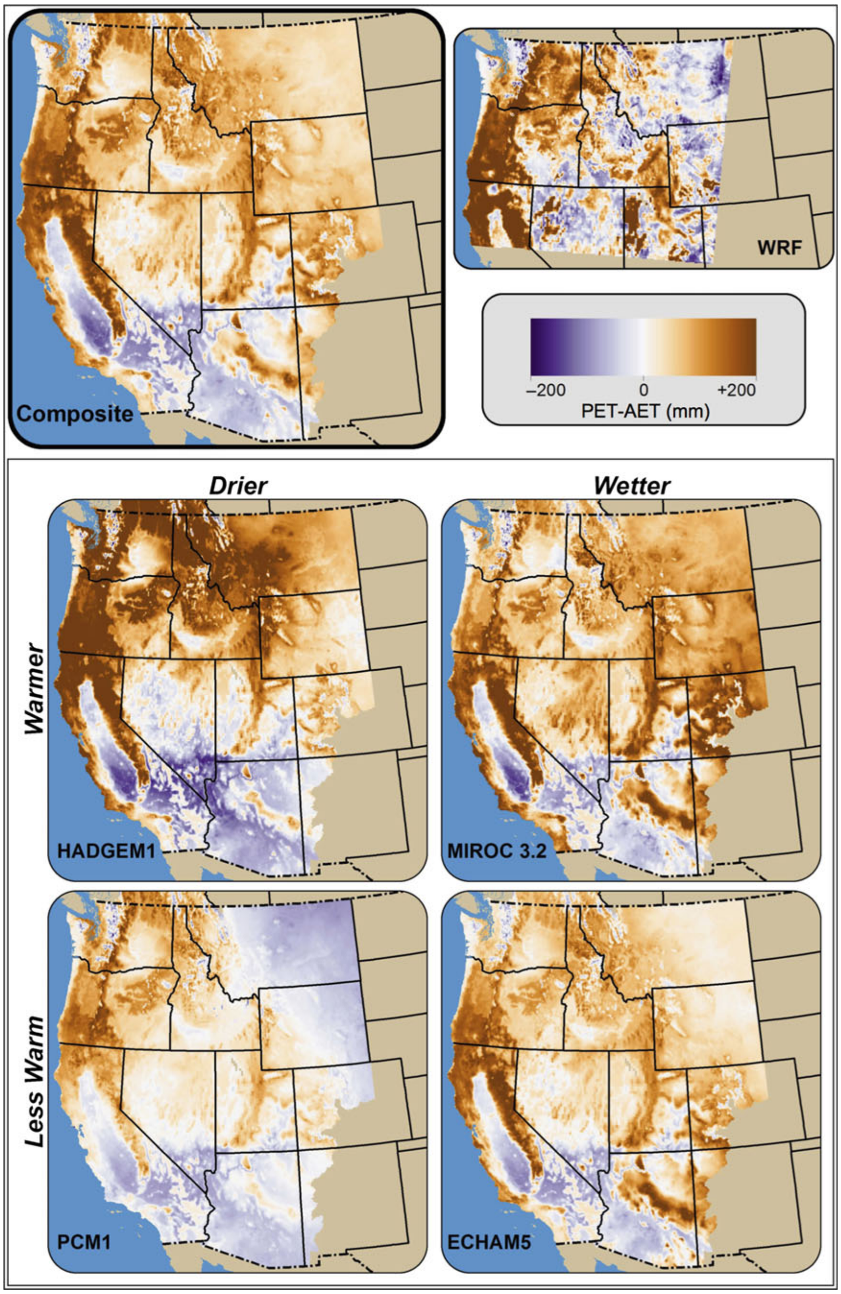

Fig. 2 Downscaled change (2030–2059) in summer (JJA) water balance deficit (potential evapotranspiration – actual evapotranspiration) from historical (1916–2006), measured in total mm water. Water balance deficit is well correlated with many climate effects on vegetation. In this representation, positive responses reflect an increase in deficit (less water availability), while negative responses reflect a decrease (more water availability). Ten-model composite (upper left) and output from the Weather Research and Forecasting (WRF) model (upper right), followed by four bracketing GCM scenarios (CMIP3/AR4, after Littell *et al.*, 2011; Elsner *et al.*, 2010).

Increasing air temperatures are expected to change the frequency, severity, and extent of wildfires (McKenzie *et al.*, 2004; Littell, 2006; Moritz *et al.*, 2012). Large wildfires that have occurred during a warmer climatic period during the past two decades portend a future in which wildfire is an increasingly dominant feature of Western landscapes. Similarly, bark beetles, whose life cycles are accelerated by increased temperatures, are causing extensive mortality across the West (Veblen *et al.*, 1991; Swetnam & Betancourt, 1998; Logan & Powell, 2001; Bentz *et al.*, 2010).

Fire and insect disturbance interact, often synergistically, compounding rates of change in forest ecosystems (Veblen *et al.*, 1994). For example, mountain pine

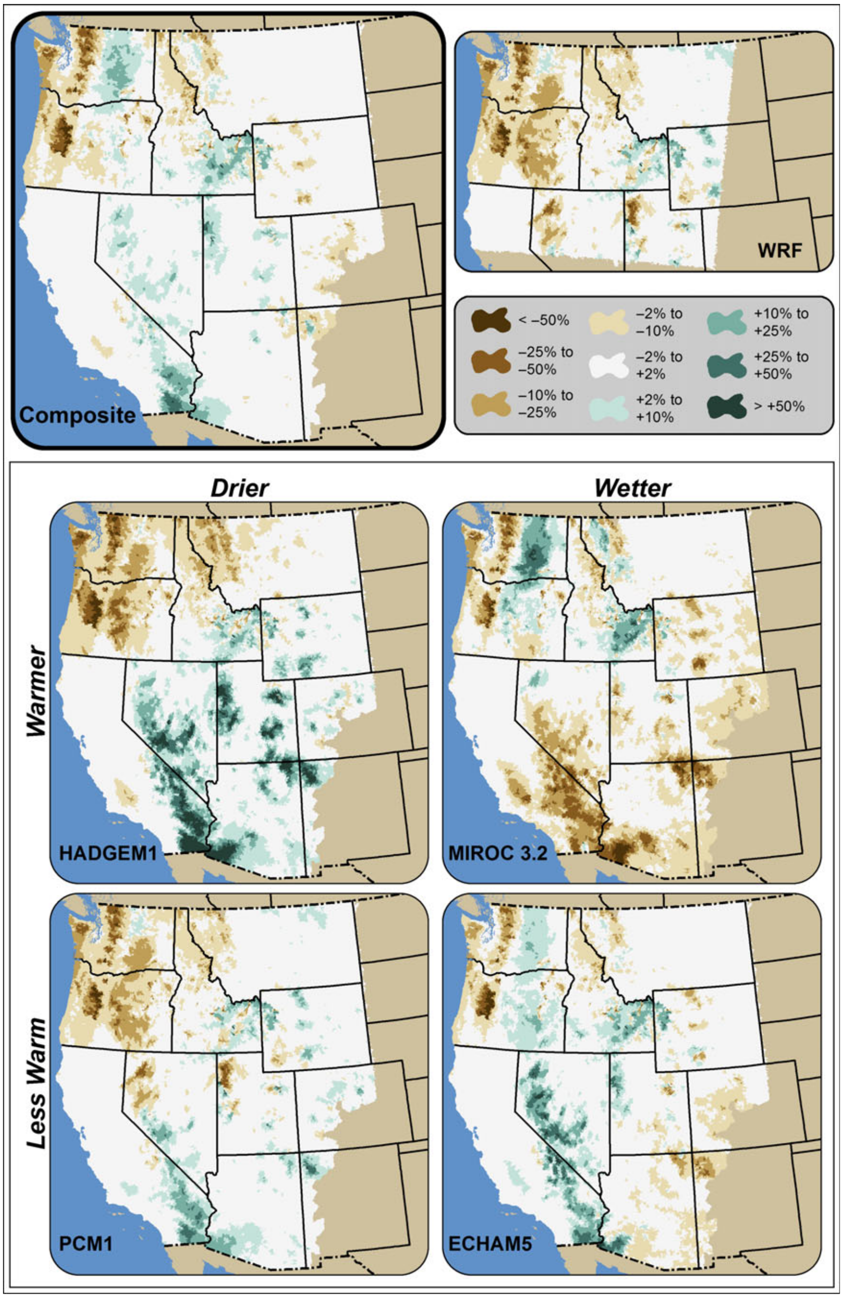

Fig. 3 Changes (2030–2059) from historical (1916–2006) in 7Q10 (the lowest weekly average flow that occurs on average once every 10 years), a measure of extreme low flow periods in streams. The climate change driven change in low flows depends on characteristics unique to watersheds, regions, and future climate.

beetles (*Dendroctonus ponderosae*), which have caused high mortality, mostly in lodgepole pine (*Pinus contorta* var. *latifolia*) forest across 20 million ha in western North America, may significantly increase fine fuels and fire hazard for several years following outbreaks (Hicke *et al*., 2012).

To explore the consequences of these interactions for different ecosystems, we extend a pathological model of cumulative stress in trees (Manion, 1991, 2003) to forest ecosystems by describing interacting disturbances and stresses as stress complexes that have potentially far-reaching effects. Temperature increases are a predisposing factor causing often lethal stresses on forest ecosystems (Williams *et al*., 2013), acting both directly through increasingly negative water balances (Stephenson, 1998; Milne *et al*., 2002; Littell, 2006) and indirectly

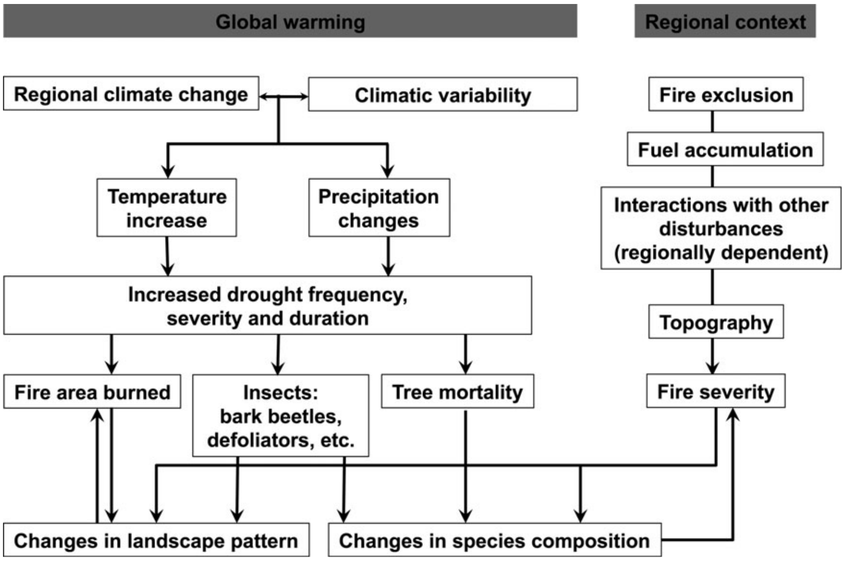

Fig. 4 General stress complex in forests of North America. The effects of disturbance regimes (insects and fire) will be exacerbated by global warming, but also interact with regionally specific disturbances or mechanisms (such as hurricanes and coastal change in the Southeast or permafrost in Alaska). Stand-replacing fires and drought-induced mortality both contribute to species changes and non-native plant invasions. Warmer and drier climate leads to longer and possibly more frequent periods with flammable fuels. Changes in fire and hydrologic regimes, and responses to them, may lead to species change and altered carbon dynamics.

through increased frequency, severity, and extent of disturbances, chiefly fire and insect outbreaks (Logan & Powell, 2001, 2009; McKenzie *et al*., 2004). Increased disturbance can in turn cause rapid changes in forest structure and function, and will likely be more important than temperature increase or drought variability alone in altering ecosystems.

Pinyon-juniper woodlands of the American Southwest

Pinyon pine (*Pinus edulis*) and various juniper species (*Juniperus* spp.) are among the most drought-tolerant trees in western North America, and characterize lower treelines across much of the West. Although pinyon-juniper woodlands may be expanding in some areas (Samuels & Betancourt, 1982), they are clearly water-limited systems. At fine scales, pinyon-juniper ecotones are affected by local topography and existing canopy structure that may buffer trees against drought to some degree (Milne *et al*., 1996), although multiyear droughts periodically cause dieback of pinyon pines. Dieback of both ponderosa pine (*Pinus ponderosa*) and pinyon pine occurred during and before the 20th century (Allen & Breshears 1998; Breshears *et al*., 2005), and the recent (since the early 2000s) dieback is associated with low precipitation, high temperatures, and the insect pinyon ips (Breshears *et al*., 2005; Meddens *et al*., 2015). Ecosystem change comes also from large-scale, severe fires that can compromise the ability of pines to regenerate, although severe fires were historically characteristic of many pinyon pine systems (Floyd *et al*., 2004).

Mixed conifer forests of the Sierra Nevada and Southern California

Dominated by various combinations of ponderosa pine, Jeffrey pine (*Pinus jeffreyi*), sugar pine (*Pinus lambertiana*), Douglas-fir (*Pseudotsuga menziesii*), incense cedar (*Libocedrus decurrens*), and white fir (*Abies concolor*), these forests experience a Mediterranean climate with long, dry summers. Increasing temperatures were not correlated with fire frequency and extent in the mid-to late 20th century (McKelvey *et al*., 1996); rather, 20th century fire frequency and likely area were at lower levels than those present over the rest of the last 2000 years (Swetnam, 1993; Swetnam & Baisan, 2003). Fire exclusion has led to increased fuel loadings and competitive stresses on individual trees as stand densities have increased (Ferrell, 1996; van Mantgem *et al*., 2004). Elevated levels of ambient ozone, derived from vehicular and industrial sources in urban environments upwind, are phytotoxic and reduce net photosynthesis and growth of ponderosa pine, Jeffrey pine, and possibly other species in the Sierra Nevada and the mountains of southern California (Peterson & Arbaugh, 1988; Peterson *et al*., 1991; Byternowicz & Grulke, 1992; Miller, 1992). Sierra Nevada forests support endemic levels of insect defoliators and bark beetles (typically

Dendroctonus spp.), but bark beetles in particular have reached outbreak levels in recent years facilitated by protracted droughts. Dense stands, fire suppression, and non-native pathogens such as white pine blister rust (*Cronartium ribicola*) can exacerbate both biotic interactions (van Mantgem *et al.*, 2004) and drought stress.

Interior lodgepole pine forests

Lodgepole pine is widely distributed across western North America, and is the dominant species over much of its range, forming nearly monospecific stands that are maintained either because poor soils preclude other species or through adapting to stand-replacing fires via cone serotiny (Burns & Honkala, 1990). Lodgepole pine is the principal host of the mountain pine beetle, and older, low-vigor stands are vulnerable to extensive mortality during beetle outbreaks. Recent beetle outbreaks have caused mortality across large portions of western North America, with mature forest cohorts (age 70–80 year) contributing to vulnerability. Warmer temperatures facilitate insect outbreaks by drought stress, making trees more vulnerable to attack and speeding up the reproductive cycles of some insect species (Logan & Bentz, 1999; Logan & Powell, 2001; Régnière *et al.* 2012). Warming temperatures would be expected to exacerbate these outbreaks northward and to higher elevations (Logan & Powell, 2009; Bentz *et al.* 2012; but see Hicke *et al.*, 2006), but lodgepole pine ecosystems are poised for significant changes even at current levels of mortality. In the stress complex for lodgepole pine forests, warmer temperatures in combination with the higher flammability of dead biomass associated with beetle mortality exacerbates the natural potential for severe crown fires for roughly 3 years – and surface fire for longer – until fine fuels decompose and become compressed (e.g., Hicke *et al.*, 2012; Jolly *et al.*, 2012). Despite increased risk factors for fire ignition and spread, burned area does not seem to have increased as a result of the recent large outbreaks (Simard *et al.*, 2011; Hart *et al.*, 2015).

South-central and interior Alaskan forests

A combination of large crown fires and outbreaks of spruce bark beetle (*Dendroctonus rufipennis*) in south-central Alaska has affected millions of hectares of boreal forest during the past 20 years (Berg *et al.*, 2006). The recent outbreaks are unprecedented in extent and percentage mortality (over 90% in many places) (Ross *et al.*, 2001; Berg *et al.*, 2006). Summer temperatures in the Arctic have risen 0.3–0.4 °C per decade since 1961 (Chapin *et al.*, 2005), and wildfire and beetle outbreaks are both likely associated with this temperature increase (Duffy *et al.*, 2005; Berg *et al.*, 2006; Werner *et al.*, 2006). Although fire-season length in interior Alaska is associated with the timing of late-summer precipitation, the principal driver of annual area burned is early summer temperature (Duffy *et al.*, 2005). White spruce (*Picea glauca*) and black spruce (*Picea mariana*) are more flammable than co-occurring deciduous species [chiefly paper birch (*Betula papyrifera*)]. Similarly, conifers are a target of bark beetles, so spruce is disadvantaged compared to deciduous species, most of which respond to fire by sprouting. The stress complex for Alaskan boreal forest projects a significant transition to deciduous species via more frequent and extensive disturbance associated with warmer temperatures. This transition would be unlikely without changes in disturbance regimes, because warmer temperatures alone will not favor a life-form transition (Johnstone *et al.*, 2004; Bachelet *et al.*, 2005; Boucher & Mead, 2006).

Southern pine forests

Much of the forested landscape in the southeastern United States is adapted to frequent fire, and prescribed fire is a mainstay of ecosystem-based management. Fire-adapted inland forests overlap geographically with coastal areas affected by hurricanes and potentially by sea-level rise (Ross *et al.*, 2009), such that interactions between wildfires and hurricanes are synergistic. For example, dry-season (prescribed) fires may have actually been more severe than wet-season (lightning) fires in some areas, causing structural damage via cambium kill and subsequent increased vulnerability to hurricane damage (Platt *et al.*, 2002). Increasing frequency and magnitude of drought are expected to increase the flammability of live and dead fine fuels in upland forests and pine plantations (Mitchell *et al.*, 2014). This may increase the frequency and intensity of some wildfires, and may reduce opportunities for safe implementation of prescribed burning. Both drought and increased fire may lead to greater dominance by invasive species [e.g., cogongrass (*Imperata cylindrica*)], which can in turn alter the flammability of fuels (Mitchell *et al.*, 2014). Assertive fuel reduction through prescribed burning may be even more important in a warmer climate.

Eastern mesic deciduous forests

Evidence suggests that disturbance in eastern deciduous forests was common (e.g., Foster *et al.*, 2002; Guyette *et al.*, 2006) and related to drought (Pederson *et al.*, 2014), but since the arrival of Euro-Americans, land use and associated disturbances have been stronger controls than climate-driven fire (Abrams & Nowacki, 2015; Nowacki and Abrams, 2015). Both fire (Guyette *et al*., 2006; Brose *et al*., 2014) and drought-induced canopy mortality (Pederson *et al*., 2014) affect these forests, but spatial continuity is less and scale of disturbances smaller than in Western forests. Pederson *et al*. (2014) concluded that a stress complex of drought combined with elevated air pollution, non-native insects, and pathogens could drive widespread tree mortality and subsequent canopy turnover. Extreme winds, a periodic disturbance in space and time, can cause large areas of windthrow that may interact with other stressors.

Effects of drought and stress complexes on ecosystems

Rapid climate change and accompanying changes in disturbance regimes may send ecosystems across thresholds into dominance by different life forms and cause significant changes in productivity and capacity for carbon storage. For example, in the Southwest, stand-replacing fires are becoming common in what were historically low- or mixed-severity fire regimes (Allen *et al*., 2002). If these trends continue, ponderosa pine may be lost from some of its current range in the Southwest, and productivity of these systems will decline. In contrast, if warming temperatures accelerate mountain pine beetle reproductive cycles (Logan & Powell, 2001) such that outbreaks are more frequent and more prolonged, lodgepole pine might be replaced by a more productive species such as Douglas-fir, at least on mesic sites where conditions for establishment are favorable.

As the climate warms, we expect that more ecosystems will become water limited (after Milne *et al*., 2002; Littell, 2006; Albright & Peterson, 2013), more sensitive to variability in temperature (due to its controls on both phenology and ecophysiological processes), and prone to more frequent disturbance. Consequently, productivity may decline across much of the West (Hicke *et al*., 2002), and long-term carbon sequestration may be limited by a continuous mosaic of disturbances of various severities. Species and ecosystems will be affected in various ways, and not all undesirable changes will be preventable by management intervention (McKenzie *et al*., 2004).

There is no historical or current analog for the combination of climate, disturbance regimes, and land-use changes expected by the end of the 21st century. For example, tempering the idea of ‘desired future conditions’ with ‘achievable future conditions’ may facilitate more effective adaptive management and more efficient allocation of resources to maintain forest resilience. Conceptual models of stress complexes improve our understanding of disturbance interactions in forest ecosystems affected by climate change. We suggest that quantitative models of stress complexes that incorporate direct impacts of climate on mortality and changes in fuel, and their interactions, may be needed to characterize alternative future states for a broad range of forest ecosystems across North America.

Fire feedbacks to drought

Drought is caused by changes in one or more of three atmospheric properties: thermal stability, water vapor supply, and dynamic weather systems creating subsidence in the atmosphere. Wildfires can contribute to these properties from local to global scales by emitting particles and gases that affect atmospheric dynamics and by modifying land cover, feedbacks that were not systematically investigated until recently (Fig. 5, Liu *et al*., 2013b).

Smoke particles

Fires emit particles including organic carbon (OC), which is bound in various compounds derived from plant tissue, and black carbon (BC), which is a pure carbon component of fine particulate matter (<2.5 μm) formed through incomplete combustion as soot. BC emissions from biomass (forest and savanna) burning account for 5–10% of fire smoke particles and about 40% of total global BC emissions (Bond *et al*., 2004). These smoke particles can affect atmospheric radiative budgets by scattering and absorbing solar radiation (direct radiative forcing). This can further affect cloud cover and precipitation at regional scales. Koren *et al*. (2004) analyzed MODIS satellite measurements during biomass burning in the Amazon region and found that cloud cover was reduced from 38% in clean conditions to nearly 0% for heavy smoke.

The radiative forcing of smoke can affect regional precipitation in many ways, but especially by modifying atmospheric thermal stability. The land surface and the atmosphere below the smoke layer are cooled by scattering and absorption of solar radiation by smoke particles. During a wildfire near Boulder, Colorado in 2010, the surface under the smoke plume was cooled 2–5 °C (Stone *et al*., 2011). Meanwhile, the upper air with smoke particles was warmed by solar radiation absorption. These changes in the vertical temperature profile stabilize the atmosphere and suppress cloud development.

Relative humidity of the smoke layer is reduced from the warming effect of solar radiation absorption by BC, and cloud formation is inhibited. Relatively low cloud cover over the ocean has been documented due to the

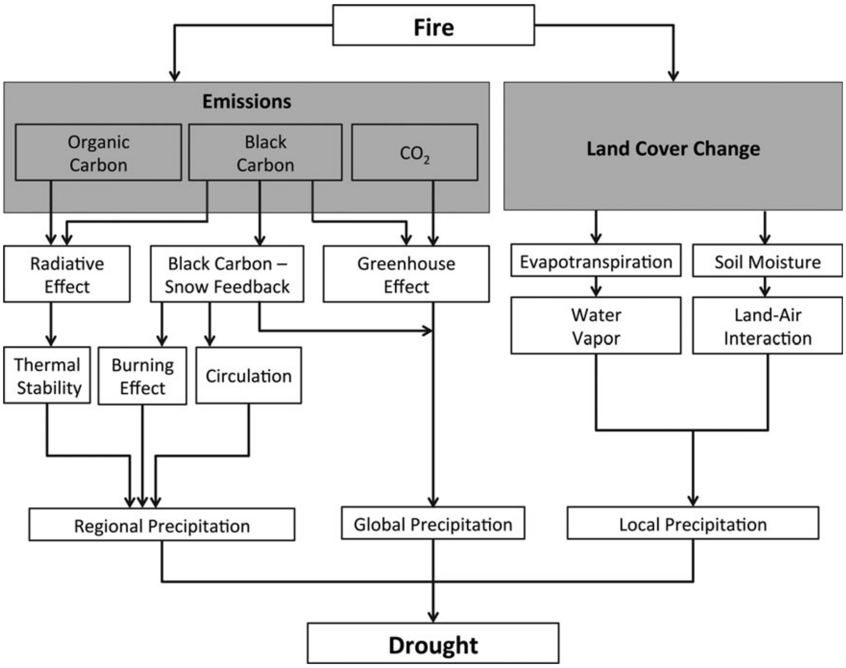

Fig. 5 Physical processes for feedbacks of wildfires to drought.

large concentration of soot aerosols, which leads to higher air temperature and lower relative humidity that help to 'burn out' clouds (Ackerman *et al.*, 2000). Clouds and precipitation are reduced during the burning season over the Amazon because water vapor transport from the ground is low, and the planetary boundary layer to clouds is weakened from lower turbulent activity (Liu, 2005a).

Atmospheric horizontal airflow convergence and vertical ascending in the lower troposphere favor cloud and precipitation formation. The radiative forcing of smoke particles leads to cooling on the ground and in the lower troposphere, despite possible warming at some elevations due to solar radiation absorption by BC. In a simulation study of the 1988 Yellowstone National Park wildfires that occurred during a drought (Liu, 2005b), absorption of solar radiation by smoke particles over the fire area released heat in the upper smoke layer. This phenomenon altered westerly airflows, transporting warmer air downwind and converging in the trough area over the Midwest. The trough weakened, reducing clouds and rainfall, which suggests that feedbacks from wildfires may enhance drought.

The impacts of smoke particles on the three atmospheric properties essential for cloud and precipitation formulation occur at different time scales. Wildfires can impact individual weather events at daily and weekly scales, such as an intense wildfire during the 2004 Alaska fire season examined by Grell *et al.* (2011). Large wildfires that occur during a fire episode can enhance or prolong (not cause) monthly, seasonal, or even multiyear drought events, as indicated in the case of the Yellowstone example above.

Greenhouse gases

Carbon dioxide is the largest fire emission component, accounting for 87–92% of total carbon burned (Urbanski *et al.*, 2008). Average annual global fire carbon emissions were about 2 Pg in the recent decade, about one-third of total carbon emissions. BC emissions enhance the greenhouse effect in the atmosphere, and deposition of BC emissions on snow and ice at high latitudes reduces albedo and increases solar radiation absorbed by the surface, which in turn accelerates snow melting (Hansen & Nazarenko, 2004). Boreal fires contribute more BC to the Arctic than human sources in summer based on multiyear averages (Stohl *et al.*, 2006). As a major source of atmospheric carbon dioxide and BC, wildfire emissions contribute significantly to atmospheric carbon dynamics and radiation absorption. Analyses of the Coupled Model Intercomparison Program phase 3 and 5 (CMIP3 and CMIP5) indicate that future drought occurrence, duration, and severity will likely increase in response to the greenhouse effect globally and in many mid-latitude areas including the United States (Maloney *et al.*, 2014). Increasing drought amplifies the warming effect over decades to centuries.

Land cover change

Water transfer from the land surface, a local water vapor source for precipitation, is much higher on vegetated landscapes through evapotranspiration than unvegetated landscapes through evaporation (Wang *et al.*, 2014). Leaf area after stand-replacing fires decreases greatly from prefire conditions, and evapotranspiration is temporarily reduced, leading to reduced water transfer through transpiration. The Bowen ratio (a ratio of sensible to latent heat flux) increases after burning, meaning that more solar energy absorbed on the surface is converted to sensible heat instead of being used as latent energy for water-phase change. Following fire, the capacity of soil to store water is reduced, canopy and understory interception is decreased, and evapotranspiration from live vegetation is decreased, with a net effect of increased runoff and reduced soil water available for transfer to the atmosphere despite the reduction in evapotranspiration.

During the 2004 Alaska fire season, wildfires altered land cover over large areas, leading to a change in dynamic, radiative, vegetative, thermal, and hydrological surface characteristics (Möldersa & Kramma, 2007). A simulation to quantify the effects of fire-caused land-cover changes indicated that sensible heat fluxes into the atmosphere increased by up to 225 W m^{-2} over burned areas (Möldersa & Kramma, 2007). There was enough enhanced lifting in the areas during large burns to produce areas of increased clouds followed by an area of decreased clouds downwind of them. Precipitation increased significantly in the lee of burned areas, but decreased slightly a few days after large fires.

Management and social implications

Risk is often defined as the product of the probability of an event and its consequences. Wildfire risk can be calculated as the probability of fire of a given intensity times the effect on resource values (Bratten, 1982; Mills & Bratten, 1982; Calkin *et al.*, 2011). Wildfire probability increases as the moisture stored in fuels (live and dead vegetation) declines. Wildfire risk therefore responds to meteorological drought, and fire occurrence and area are correlated with metrics that measure precipitation delivery, relative humidity, and/or fuel moisture, reflecting both supply of water and demand for it (Littell *et al.*, 2009, 2010; Abatzoglou & Kolden, 2013; Riley *et al.*, 2013).

Wildfire risk differs across the continental United States (Radeloff *et al.*, 2005; Preisler & Westerling, 2007; Finney *et al.*, 2011) as a function of probability of burning and values at risk (buildings, municipal watersheds, endangered species habitat, etc.). Fire probability is numerically related to the inverse of fire return interval, with longer fire return intervals having a lower annual probability of burning. For example, annual probability of burning in forests that burn less frequently (return intervals more than a decade and possibly centuries) is lower than that of chaparral, which can have return intervals of less than a decade (Agee, 1993; Frost, 1998; Finney *et al.*, 2011). Climatically and ecologically, however, fire probability is contingent on fuel availability and flammability. Because many ecosystems in the United States were structured by fire until effective fire exclusion, some consider wildfire to be a regulating ecosystem service through periodic reduction of fuels. Cessation of Native American burning combined with fire suppression may have reduced area burned annually in the United States by an order of magnitude (Leenhouts, 1998; Marlon *et al.*, 2012). If modern burning takes place preferentially under extreme drought conditions when it cannot be suppressed, it is more likely to be of uncharacteristically high severity than if it took place under more moderate conditions. The probability of high-severity events may therefore be increasing in many forests due to fire suppression effects on fuels as well as climate, and the exposure to risk increasing.

In regions where area burned has historically been higher with high temperature anomalies and low precipitation anomalies (most of the western United States), area burned will likely increase with temperature and possibly the frequency of drought (Committee on Stabilization Targets for Atmospheric Greenhouse Gas Concentrations, National Research Council 2011). Fire severity and frequency may also increase, but will be strongly affected by local conditions – severity is also influenced by topography, extreme weather (such as wind), and the ecological context in which fire occurs. However, larger fires and higher area burned will continue to challenge fire suppression efforts and budgets, and may require rethinking historical approaches to fire management. If annual area burned increases over 200% in most of the western United States as projected for the mid 21st century (Peterson & Littell, 2014), the fraction of landscapes recently burned would also increase. Combined with the effects of increasing temperature on climatic suitability for regeneration, ecosystem function and structure may change rapidly (Littell *et al.*, 2010), thus altering the vegetation and hydrology in landscapes for which land management agencies have responsibility.

In some regions of the United States, a longer season during which fuels are highly flammable may affect management activities intended to reduce the quantity of those fuels.

Even if there is minimal change in probability of historically extreme droughts, effective or 'ecological' drought caused by increased water demand may decrease favorable conditions for prescribed fire. However, periods when burning can be conducted (relative to fuel conditions, regulatory compliance, and social acceptance) could shift to other times of year. If drought-caused wildfire activity increases, wildland-urban interface areas may face increased fire risk, thus increasing suppression costs and potentially altering social perceptions of management and risk in fire-prone human communities.

Synthesis

Although drought is clearly a contributing factor to wildfire occurrence and effects, the relationships between drought and wildfire in forests of the United States are more complex than the general statement 'with drought comes fire.' Regional-to-local variation in forest management (e.g., Keeley & Syphard, 2015), surface and canopy fuels, and ignitions affect how much anomalous fuel moisture conditions contribute to area burned anomalies in forest and woodland environments and ultimately determine the trajectory of fire regimes. Although ocean-atmosphere circulation anomalies affect the likelihood of drought conditions that in turn affect the probability of wildfire occurrence and spread (Swetnam & Betancourt, 1998; Collins *et al*., 2006; Kitzberger *et al*., 2007), the effect of teleconnections on seasonal climate and therefore wildfire may be transient at longer time scales (Barbero *et al*., 2015). For example, relationships between climate and wildfire have changed in the U.S. Pacific Northwest (Higuera *et al*., 2015) over a century of climate and fire observations. These contingencies represent some, though by no means all, of the factors that may modulate the relationship between drought and fire in forests. The validity of statistical projections of the effects of climate change on fire regime components depends on incorporating transience both in the expected climate dynamics that lead to drought as well as the relationships between drought and forest fire, which are contingent on more local factors such as surface and canopy fuels.

The role of regional drought in local fire regimes and how they will change given climate change scenarios is still not as well understood as necessary to justify some adaptation actions. The multiscale drivers and responses that comprise the fire regime for an individual location are clearly transient in time and evolve according to their internal and external feedbacks. The mechanisms that either accelerate or buffer ecosystem change after fire are themselves regulated by climate and other regionally-specific contingencies, but scientific understanding of these processes is minimal. Including ecohydrologic variables that capture mechanisms by which drought affects forest species and disturbance would likely produce more accurate projections for scientific assessment and management applications.

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