Current Climate Change Reports
https://doi.org/10.1007/s40641-018-0109-y

ECOLOGICAL IMPACTS OF CLIMATE CHANGE (A BAKER, SECTION EDITOR)

Drought and Fire in the Western USA: Is Climate Attribution Enough?

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Abstract

Purpose of Review I sought to review the contributions of recent literature and prior foundational papers to our understanding of drought and fire. In this review, I summarize recent literature on drought and fire in the western USA and discuss research directions that may increase the utility of that body of work for twenty-first century application. I then describe gaps in the synthetic knowledge of drought-driven fire in managed ecosystems and use concepts from use-inspired research to describe potentially useful extensions of current work.

Recent Findings Fire responses to climate, and specifically various kinds of drought, are clear, but vary widely with fuel responses to surplus water and drought at different timescales. Ecological and physical factors interact with human management and ignitions to create fire regime and landscape trajectories that challenge prediction.

Summary The mechanisms by which the climate system affects regional droughts and how they translate to fire in the western USA need more attention to accelerate both forecasting and adaptation. However, projections of future fire activity under climate change will require integrated advances on both fronts to achieve decision-relevant modeling. Concepts from transdisciplinary research and coupled human-natural systems can help frame strategic work to address fire in a changing world.

Keywords Fire · Wildfire · Drought · Climatic water deficit · Water balance deficit · Resilience · Climate change

Introduction

Knowledge of the relationships between drought and fire and how they vary across landscapes and through time is important because wildland fire is a threat to human safety, infrastructure, and ecosystem services. That knowledge can also be useful; resource management agencies' mandates often require planning for fire events and fire management [1•, 2, 3]. Yet, in many landscapes, the very ecosystem services we depend on are themselves predicated on fire-adapted and fire-prone landscapes—these systems cannot provide for us the characteristic ecosystems goods and services on which we depend without some role of wildfire in them [2, 4]. Substantial research has focused on the role of the climate system, including drought, in driving wildfire. But wildfire is as much an ecohydrological and human-driven event as climatic, and we know less about the complexity of fire in the Earth system than we should if we want to minimize human vulnerability to fire in the future.

The combination of climate change, disturbance, and landscape responses will present novel fire regimes [5, 6••] that will likely affect people and resources in novel ways [7••]. In the western USA, projected climate change effects also include expansion of arid, semiarid, and dry sub-humid drylands [8]. Knowledge of how ecosystems and landscapes will respond is critical for predicting the likely trajectories of landscapes and anticipating management challenges in the future, and wildfire will be an important contributor to landscape change. But historical and future approaches to ecosystem management, management responses to fires that occur, and land use choices complicate prediction of fire regimes by changing the amount and arrangement of fuels, the sources of ignitions, and ultimately the landscapes on which our current understanding of fire is fundamentally based. In some fire-dependent systems, people are therefore part of a wicked problem [9] that includes all aspects of fire, from hemispheric climatic controls to local impacts of fire events on

This article is part of the Topical Collection on *Ecological Impacts of Climate Change*

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Published online: 09 August 2018

communities to the governance institutions that define and determine responses to the problem [10, 11•, 12]. Adaptation to fire impacts in the coming decades therefore depends both on understanding and transforming the coupled human-natural system in which fire occurs [7••, 10, 11•, 12, 13•]. Anticipating the likely differences between historical and future droughts and their implications for fire regimes is a key element of adaptation, but only addresses future exposure given climate. It may be time to turn more of our collective research capacity to the adaptive potential of coupled human-natural systems, which requires less emphasis on reductionist scientific work and more emphasis on solving transdisciplinary problems.

Pohl and Hirsch Hadorn [14, 15] suggest a useful framework for transdisciplinary research that characterizes research questions into those focused on how systems work and how that knowledge can be applied. They describe these as "systems", "target", and "transformation" knowledge. For example, much of the existing research on the role of drought in fire is systems research that emphasizes the relative importance of fire drivers, how ecosystems and landscapes respond to fires, and how fire regimes might respond to climate change, all other things being equal. However, the current and future approach to the role of fire in the Earth system necessarily requires considering people as drivers (of fuels, climate, ignitions) and as agents capable of changing the nature of and solutions to the problem [10, 12]. Target and transformation knowledge extend the problem development toward solutions driven by the need for change in existing practices and introducing new ones more likely to result in the desired outcome. For example, we now know there are unintended effects of persistent fire suppression in ecosystems [16], so a more flexible spectrum of approaches to suppressing and using fire may be warranted depending on the desired future conditions [17]. But in order to deliberately apply that knowledge, more information is required to understand how various fire management strategies affect fire behavior, consequences, and subsequent fire regimes (target knowledge). On longer timescales, there is a need for collective knowledge on how the human role(s) in fire regimes and the management strategies and policies governing them can eventually address fire problems (transformation knowledge). Finally, our approach to fire in the Earth system must be cognizant of the fact that it will be applied in climatic and ecological contexts that are different—perhaps very different—from those that resulted in the ecosystems with which we have historical experience [6••, 18•]. Drought, therefore, is but one agent to be considered in the complex set of fire regime drivers, and both its mechanisms and relative importance vary with ecosystems and their management across the continuum of fire-climate relationships in North America.

In this paper, I review the fire research community's recent contribution to our collective systems knowledge of drought and fire in the western USA and discuss some limitations of that knowledge. I also argue that, to be maximally useful, we should re-focus at least some of our research to bridge our systems knowledge of climate, drought, and fire to existing target knowledge and the relatively small amount of transformational knowledge that focuses on drought and fire applications. The response of fire to and its role in ecological drought, which recognizes drought as a mechanism within more complex coupled human-natural systems, should be a fruitful area of research [19••].

What Kind of Drought?

The literature on fire responses to climatic factors characterizes drought in many ways from short timescale indices integrating fire weather variables used in fire hazard or fire behavior work to longer timescale seasonal to multi-annual variables related to vegetation response [20•]. The most obvious is a lack of precipitation, defined as meteorological drought, but there is a range from indices expressing a lack of soil or atmospheric moisture (e.g., relative humidity) to more complex variables including the Palmer drought severity index (PDSI, a standardized index incorporating both temperature and precipitation, see Dai [21] for a review), which is correlated with fire in the western USA [22]. Various forms of water deficits expressed as relationships between demand for water (potential evapotranspiration driven by solar radiation, wind, stomatal resistance, albedo) and water availability (actual evapotranspiration, precipitation) are often well correlated with fire and capture mechanisms driving both fuel flammability and fuel availability [6••, 23–26]. Sherwood and Fu [27] distinguish between climate change-driven changes in precipitation rate and aridity, defined as the difference between evaporative demand and water availability to meet that demand. Fu and Feng [8] show that the ratio of precipitation to potential evapotranspiration (PET) will decrease over the western USA under mid-twenty-first century climate even though precipitation is expected to increase over much of the region, consistent with increasing likelihood of water balance deficit levels associated with wildfire in the western USA [6••, 23–25].

Increasing attention has also focused on more complicated mechanisms resulting from different manifestations of drought. The additive influence of increasing temperature associated with climate change exacerbates meteorological droughts of historical magnitude. Breshears et al. [28] termed these "global-change-type" droughts, wherein higher temperatures associated with a given precipitation deficit increase drought severity. On shorter timescales, a similar distinction has been made [29] between anomalously low precipitation and anomalously high temperature as mechanisms of rapidly developing "flash droughts." These have varied implications for fire response in different regions because they affect both live and dead fuel moisture, but the mechanims vary with fuel and vegetation structure which vary in their responses to evapotranspiration and depletion of plant-available soil moisture. However, heat wave flash droughts are more likely in the Midwest and Pacific northwest, where as precipitation deficit flash droughts are more likely in the Great Plains and Southwest [29]. Williams et al. showed that combined record low atmospheric moisture and warm temperatures contributed to the 2011 extreme fire season in the Southwest [30]. Marlier et al. concluded that the 2015 wildfires in Washington State were the result in part of seasonal weather anomalies exceeding historical and comparable with mid-twenty-first century projections expected under climate change [31]. They further noted that historical droughts in the region were driven by precipitation deficits, but that 2015 represents a year with near-normal winter precipitation, but by fire season, drought nevertheless occurred, driven by warmer winter temperatures and lower spring snowpack. This essentially describes one form of snow drought [32•], where precipitation alone would not lead to drought but lack of snow accumulation or early snowmelt lead to anomalously low water availability in summer. Early snowmelt and subsequently longer fire seasons are a recognized driver of anomalous regional fire years, generally in forested systems [18•, 33–35]. And fires have been related [36] to hydrologic drought, defined as a lack of runoff. Generally, meteorological, hydrological, snow, and other drought indices or variables all correlate with fire responses, but the variability in land use history, fire suppression, and the data available on fire regime components all affect the interpretation of the responses. However, analyses of correlations between drought and fire serve primarily to describe the plausible relationships between the climate system, hydrology, vegetation, and disturbance. They may be useful in advancing forecasting and systems knowledge, but new approaches putting fire regime responses to climate and management actions into context are needed. Ecological drought [19••] has been defined as "an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems," and as such incorporates the human dimensions of fire drivers and impacts in a more integrated framework than quantifying the relative explanatory power of various drought metrics. The next section explores the literature on the mechanisms implied by these relationships in the literature.

Drought Mechanisms and Fire in the Western USA

The scientific literature is clear that components of fire regimes respond to drought see reviews [20•, 37], but the variations on the simple "drought means more fire" theme are worth considering [6••, 20•]. Globally, significant variation exists in the relative importance of drought as a control on fire [5, 38]. While drought preconditions fuel flammability, the availability and flammability of fuels and fire weather determine the probability of ignition and spread (fire hazard). The ways drought influences wildfire therefore vary not only with the spatial and temporal scale of the drivers of drought, but also with vegetation characteristics that develop over long periods of time (years to millennia) and the processes (natural or human) that provide ignitions. Understanding what constitutes fire-relevant "drought" includes a continuum of related processes from persistent global and hemispheric drivers to their regional and local manifestations as weather anomalies relative to mean climate [20•], Table 1. As a result, much of the fire-drought literature has focused on relating anomalous fire responses to weather and climatic drivers. These include short-term synoptic drivers and responses (e.g., associations with atmospheric anomalies and weather), seasonal climate anomalies (e.g., associations with anomalous precipitation, temperature, or related variables), and persistent interannual to interdecadal ocean-atmosphere anomalies (e.g., the El Niño Southern Oscillation (ENSO) or Pacific Decadal Oscillation (PDO)).

At timescales of hours to seasons, drought and fire weather (low precipitation or humidity, high temperature, wind, and their interactions) driven by synoptic regional patterns affect fire behavior for individual or regionally coherent fire events [39, 40]. For example, several studies have characterized synoptic patterns associated with regional extreme fire years or fire behavior across North America, including Canada [41, 42], the Pacific Northwest (PNW) [43], southwestern USA [44], and northern California/Oregon [45], and the entire West [46].

The synoptic and meteorological drivers of the 1910 fires in the PNW and Northern Rockies (NR) demonstrate mechanistic linkages that, along with other contributing factors such as fuel loads and ignitions associated with settlement, resulted in one of the largest fire events in recorded US history [47]. Collectively, this work indicates that persistent atmospheric anomalies (pressure ridging associated with waves in the westerlies over the North Pacific) are important mechanisms leading to lower moisture, fuel flammability, and higher fire hazard. Hostetler et al. [46] further distinguish between pressure height anomalies that influence different mechanisms important during the fire season. They note the role of ridges (positive 500-hPa height anomalies) in blocking precipitation associated with Pacific storms in the cool season and also sinking air masses in summer, which are, in turn, associated with warmer and drier conditions. Seasonally persistent anomalies therefore can provide the antecedent drier conditions favoring fire as well as warmer, drier conditions during the fire season. They also note that the interaction between ridges and troughs produces summertime instability and increased potential for convective storms with lightning, increasing ignition potential. Finally, surface pressure gradients between

Table 1 Temporal scale and mechanisms of fire-related drought

Temporal scale	Drought indicator/variable	Physical mechanism	Fire response mechanism(s)
Days	Synoptic meteorology	Atmospheric pressure: blocking ridges	Increased PET, VPD: decreased foliar and dead fuel moisture, increased fuel flammability
		Atmospheric pressure: ridge-trough interactions	Lightning, ignition potential; Foehn winds
	Flash drought	Low precipitation	Decreased soil moisture: decreased foliar and dead fuel moisture, increased fuel flammability
		High temperature	Increased PET, VPD: decreased foliar and dead fuel moisture, increased fuel flammability
	Fire weather	High surface winds	Increased PET: decreased foliar and dead fuel moisture, increased fuel flammability
			Increased fire spread
		Low relative humidity	Increased PET, VPD: decreased foliar and dead fuel moisture, increased fuel flammability
	Meteorological drought	Low precipitation	Decreased soil moisture: decreased foliar and dead fuel moisture, Increased fuel flammability
	Hydrological drought	Low runoff	Correlation with decreased soil moisture: decreased foliar and dead fuel moisture, increased fuel flammability
Seasons	Snow drought	Low winter precipitation as snow	Longer snow-free season, decreased soil moisture: decreased foliar and dead fuel moisture, increased fuel flammability
		Early snow melt	Longer snow-free season, decreased soil moisture: decreased foliar and dead fuel moisture, increased fuel flammability
	Global-change-type drought	High temperature for given low precipitation anomaly	Decreased soil moisture: decreased foliar and dead fuel moisture, increased fuel flammability
			Increased PET, VPD: decreased foliar and dead fuel moisture, increased fuel flammability
Years	Ecological drought	Water availability deficit	Drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems
Decades to centuries	Persistent or frequent seasonal and interannual droughts	Atmosphere/ocean interactions: ENSO, PDO, etc.	Increased (drier) or decreased (wetter) frequency of above events; long term changes in fuel availability and distribution

high interior and low marine pressure are associated with Foehn winds, a notable driver of extreme fire behavior on the western slopes of West coast mountain ranges. Short-term drought during the fire season is clearly associated with large fire occurrence, and short-term anomalies are sufficient in some cases to override previous seasonal positive moisture anomalies, leading to increased fire potential [48]. The atmosphere-ocean connections between short- and longer-term patterns of variability are important [46], and these studies demonstrate the potential to incorporate persistence into decision-relevant forecasting, but interannual to decadal drought forecasts are still experimental.

At timescales of weeks to seasons and even years, persistent weather patterns affect fire via droughts. The relationship between drought and fire is well documented in the literature and includes both modern for example, [22, 26, 33, 43, 46, 48–51, 52•] and paleoecological studies for example, [53–64]. Modern studies typically focus on monthly to seasonal climate driving variables while fire histories based on proxy records use seasonally to decadally resolved reconstructed. These studies conclude that years with increased fire occurrence or area burned are associated with drought in one or more seasons leading up to and during those fire seasons. Along a gradient from fuel-limited to flammability-limited ecosystems, however, there are differences in the magnitude, seasonality, and drought mechanisms implicated, and whether fire responses to drought are contingent on antecedent conditions [6••, 22, 26, 51, 54, 55]. In less productive, water-limited systems where fuel is at least partially limiting, anomalous moisture in the year or years prior to fire combined with drought in the year of fire is associated with more regional fire activity [54] and area burned [22, 51, 52•, 55]. In flammability-limited systems, anomalously low precipitation and high temperature, or increased water deficit, in the year of and years prior to fire are associated with increased fire [22, 26, 51, 55]. The climatic mechanisms that influence fire, however, are often inferred based on statistical relationships. The literature, especially that which focuses on modern drought and fire, is inconsistent in how it treats drought, but there are generally two approaches. First, the statistical interactions of temperature and precipitation, including snowpack, are assumed to adequately model the role of climatic variables driving fire e.g., [18•, 51]. Alternatively, some studies use indices that integrate temperature and precipitation. For example, PDSI [22, 51], standardized precipitation index (SPI) [48], and various water balance deficit or aridity metrics (such as PET-AET, actual evapotranspiration, or precipitation-PET) [6••, 23, 24] all attempt to quantify energy-water interactions, sometimes with other variables that influence the effects of drought on fuels (such as wind, plant stomatal resistance, or soil field capacity). In direct comparisons of these approaches, a few studies [24, 26, 51] have concluded that using the latter approach or both results in improved ability to statistically explain observed variation in area burned. Both approaches have been successful for documenting associations between fire responses and climate in modern, and with reconstructed climate variables, paleoecological records. It may well prove true that for projection purposes, assuming statistical interactions capture appropriate dynamics is a strategy more prone to stationarity problems than integrated variables due to changing climate-fire relationships and sub-regional vegetation changes [6••], but as yet, there is no clear superiority of any one formulation of drought. For future changes, however, improved simulation of the physical, as opposed to statistical, interaction between atmospheric demand for water (e.g., PET or vapor pressure deficit) and fuel and foliar moisture should result in more capable simulation of the timing and magnitude of future fire hazard and fire regime responses.

At longer timescales, interannual to multi-decadal ocean-atmosphere circulation anomalies affect the likelihood of precipitation [65] and drought conditions [66] that, in turn, affect the probability of wildfire occurrence [49, 53–57, 59, 61, 65–67]. Heyerdahl et al. [59] and Kitzberger et al. [66] use multi-centennial fire history data to show teleconnections and drought have characteristic regional patterns. However, in the longer paleoproxy record, these are not necessarily consistent through time—for example, Pacific Northwest fire history records indicate that sometimes the characteristic regional dipole of contrasting Southwest/Pacific Northwest precipitation anomalies [65] is evident [58], while other times, west-wide droughts or wet periods occur [59]. Crimmins [68] demonstrated that for the southwestern USA, PDO (negative) ENSO (La Niña) were associated with synoptic patterns that favored extreme fire weather. Mason et al. [69] suggest that the effect of ENSO on fire is possibly more related to relative humidity than other indicators of drought. Schubert et al. [70] note that the connections between interannual to decadal sea-surface temperatures and drought are well mapped, but that “better understanding of the physical basis for the leading modes of climate variability” is still needed. For fire purposes, the predictive potential of these indices is often suggested, but rarely realized, perhaps because the conditions indexed are only partially deterministic for fire events. The extra-regional structure of the indexed physical phenomena allows estimation of coarse changes in likelihood of regional conditions favoring drought, but forecasts are challenged by the complex, multi-scale climatic controls on fire. Both paleoecological and modern fire studies indicate a kind of top-down causal chain from hemispheric ocean-atmosphere processes to regional variation in climatic controls on area burned. However, the relationships between fire activity and circulation indices based on ENSO or PDO may be transient, especially in the future due to the potential for global and regional dynamics to dominate teleconnection-driven patterns [71•, 72]. This reinforces the need to evaluate the physical global-to-local controls on fire mechanistically with an eye toward prediction rather than diagnostically.

In recent years, studies evaluating the differences between historical climate variability and current anthropogenic climate change in their contributions to extreme anomalies and their impacts (including wildfire) have emerged. Recent analysis of global fire weather indicates that the length of the fire weather season increased over the past four decades due both to warming and the number of rain-free days [73]. More than half the fuel moisture (termed “fuel aridity” [74]) changes from 1970s to recent were driven by anthropogenically forced increases in warming and drying, and total area burned was twice what would be expected under historical climate.

Collectively, the literature attributing fire responses to climate and drought implicates mechanisms that vary from planetary to local, and from drivers of weather and climate variability to fuel responses [20•, 67]. Both live and dead fuels affect fire behavior, and they have different hydrologic responses to moisture anomalies because live fuels are actively connected to field capacity in soils, moderating their responses when sufficient soil moisture is available. Aridity makes fuels available differentially across fuel classes (e.g., by definition, 1-h and 10-h fuels respond faster than, e.g., 100-h and 1000-h fuels), and therefore, the same magnitude and duration of drought can affect ecosystems very differently depending on what kinds of vegetation and dead fuels predominate. The effect of anomalously high precipitation also varies across fuel classes, because fine fuels are generally produced comparatively quickly. The complexity of these global-to-local patterns indicates knowledge of the characteristic patterns and stationarity of hemispheric controls on climatic variability is required, but so is knowledge of how closely coupled regional-to-local drought and fuel responses track the hemispheric controls. Finally, potential fire hazard driven by climate and weather necessarily interacts with management, suppression, and human ignitions, underscoring the idea that drought is one component of a complicated fire system.

In summary, of the above literature and references therein, a considerable fraction of the research on climate and wildfire responses in the western USA focuses on the role of drought in governing wildfire, especially on drought and forests where the responses are statistically stronger and easier to detect. The literature cited above includes substantive work sharpening our understanding of which drought indices have the best statistical correlations with fire occurrence and area burned. Comparatively, there has been a moderate amount of work on the role of teleconnections between ocean/atmosphere variation and fire, most of which focuses more on correlation with indices rather than on the mechanistic drivers and their variation. This simplifies attribution, but it risks collapsing relevant variation into indices representing one or a few dominant modes of behavior and therefore potentially misses the variation in actual dynamics required for prediction. Hostetler et al. [45, 75] provide a thorough treatment integrating western US responses of fire to meteorological drought (precipitation and standardized precipitation index) and atmospheric anomalies in the late twentieth century. But there has been comparatively less work on how the full weather-to-climate continuum affects the components of fire regimes, especially how regionally and temporally variable such relationships may be and how they will change with climate change.

Thorough diagnostic analyses that span the spatial and temporal dimensions of weather and climate drivers of fuel and fire responses are needed to bridge between our understanding of the role of drought in fire and the ability to use that information in the more complex contexts of risk assessment, planning, fire use, and deliberate changes in the way we address fire problems [11•]. Planning for increasing area burned in forests [18•, 74••] and increased impacts in the wildland-urban interface [7••] can use general projections to assess future likelihood of impacts. But more specific uses, such as deciding whether an expanded range of conditions suitable for fire use, may require more precise information. For example, persistence in atmospheric drivers and soil moisture conditions may allow at least 5 months' lead in predicting drought anomalies [76]. For future fire projections given climate change, such systems knowledge of the continuum of drivers of drought [76, 77] may help better describe the mechanisms causing and the uncertainty associated with—and variation in—future fire projections. Ultimately, it is the risk associated with a fire event in a particular place and time that must be gaged. To achieve this, however, requires consciously shifting analysis from correlative exercises and statistical projections to simulating the multi-scale and contingent causal drivers, with an emphasis on the drivers and responses of fuel availability and flammability.

Discussion

The progression of meteorological drought over years and seasons prior to a fire season sets the stage on which shorter-term anomalies (e.g., "flash droughts" and extreme fire weather) determine the magnitude, timing, and contribute to the effects of fire events [20•, 66]. Regional preparedness for fire suppression and containment is affected both by the rapidity of the onset of fire events and the size of the region over which they are coherent—years with more and/or larger fires over wider regions stretch management resources thinner. Anomalously large fire years are products of meteorological, hydrological, and snow droughts in the seasons leading up to each fire season coupled with flash droughts that can exacerbate existing conditions closer to normal; these are, however, contingent on ignition, weather, and fuels, and absence of these can result in no fire response. Land management agencies are used to considering the long-term lead up to each fire season in their planning for specific fire hazard as the fire season develops [78]. At intermediate timescales, some forecasting efforts consider persistent ocean/atmosphere indices as proxies for the probability of specific weather patterns associated with fire and anticipate the likelihood of anomalous fire seasons. Similarly, fire management agencies issue forecasts based on physical and ecological variables for fire behavior during fires. Current systems knowledge is therefore useful.

But from resource adaptation perspectives, it is an open question whether our "systems knowledge" is sufficient by itself. The exposure associated with climate change would imply the answer is "no," because the ecological and human contexts in which fires burn ultimately determine the impacts (consequences) of fires [9, 11•, 19••]. Given the observed [79] and expected future non-stationarity [6••] of fire-climate relationships, research efforts focused narrowly on comparing drought indices' statistical skill in explaining observed fire season outcomes provide only a fraction of the system knowledge needed to plan for and adapt to climate change. Instead, emphasis might be better placed on research that focuses effort on predicting ecological and ecosystem service responses to projected fire severity and extent, and more usefully, management actions likely to confer resilience of those services.

Perhaps a useful extension of current drought and fire research should explore the high priority target knowledge that could assess vulnerability and trial adaptation options. For example, statistical drought-fire relationships calibrated on historical data e.g., [51] would eventually fail to describe evolving landscapes because the interaction of disturbance, land use, and management (including suppression) will be sufficient that underlying assumptions about fuels are invalid [6••]. But as climate changes the probability and nature of droughts, anticipated fire frequencies, severities, and areas burned will respond. The combined changes will in some cases resemble impacts familiar to managers and in other cases will likely have no analogs. To be most useful, our systems knowledge of fire and its responses to drought must change with those landscapes, and the scientific community is well prepared to do that work. However, it is an open question whether better forecasting the likely landscape scenarios given current conditions and probable changes is sufficient to solve the wicked problems faced by resource managers and residents of the fire-prone West [9, 11•].

A better understanding of drought and fire alone is useful, but by itself is likely an insufficient preparation for a no-analog future. Instead, desired target knowledge might include better understanding of the types and timing of, as well as tradeoffs associated with, land use and management actions designed to increase resilience given relatively certain future drought and fire events. Such work requires a foundation of projected future scenarios of likely drought and fire responses and their ecohydrological consequences, but of equal or greater importance are well-defined actions to trial, or at least simulate. To be useful, such experiments need to go well beyond model frameworks that contrast suppression and let-it-burn model simulations and incorporate human interventions in drivers and responses. Schoennagel et al. [7••] propose actively conferring resilience to future fire regimes by planning for inevitable fires, actively managing both fuels and fire where they can be most effective, and planning for fire in development. Such approaches employ transformational knowledge to simultaneously increase adaptive capacity and reduce exposure of human systems in fire-prone and fire-adapted ecosystems, thereby decreasing vulnerability under a stationary climate, and possibly even under no-analog climates with fundamentally different probabilities of drought. The target and transformation knowledge required to succeed, however, is not likely universal—regional differences in coupled human-natural systems (including climate-fire relationships, fuels and fire management, and policy instruments) suggest important regional texture, and climate-fire and drought research would do well to shift some attention toward such questions.

Holling and Gunderson [80] suggested fire as one example of an abrupt system release the provides the catalyst for rapid ecosystem change, and drought represents one "trigger" that marks the transition from phases of growth (vegetation development) and conservation (in which resilience to disturbance decreases). Fath et al. [81] speculated that, "While ecosystems are complex, human agency adds a less understood and therefore less predictable component, but also adds potential responsive dynamic preparedness and management that is otherwise not found in ecological systems." Fire in most ecosystems in the modern era is driven in part by exogenous hemispheric-to-regional climate and drought, but also at least in part by regional to local human action and decisions. Systems, target, and transformation knowledge thus provide

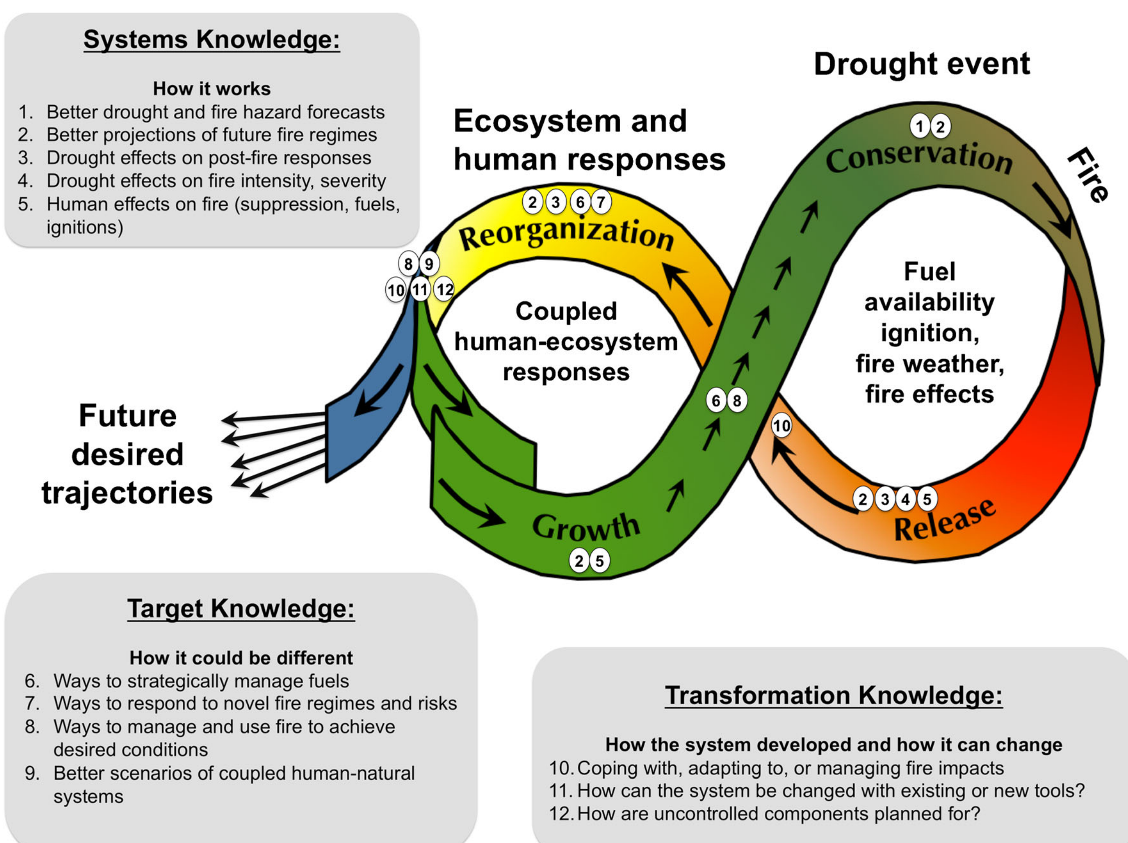

Fig. 1 Adaptive cycle with systems, target, and transformation knowledge leverage points. Four-phase adaptive cycle after Holling and Gunderson [80]. Transdisciplinary knowledge classification after Pohl and Hirsch-Hadorn [14, 15]

a classification for the understanding required for preparedness and management actions that potentially change the complex, adaptive system driven in part by drought and fire. Figure 1 illustrates several hypothetical outcomes of this three-part transdisciplinary classification of knowledge and where in the complex adaptive cycle [80] they might provide leverage on the larger fire problem. Drought is clearly an important part of the whole system, but better predictions and understanding of the drought-fire dynamic [6••] are only one part of the knowledge required to exit the current cycle of wildfire impacts.

For example, the transition from the release to reorganization phase is an optimal time to affect the trajectory of post-fire vegetation response. Adaptation options identified in a case-study of two US National Forests included treating large-scale disturbances as a management opportunity [82]. Such complex systems often have multiple preferred states [83], and large interventions are often required to move from one regime to another. Future desired trajectories may be possible, but adaptive transition requires change. For wildfire in the western USA, the reorganization phase to growth phase transition is also critical because the bifurcation in trajectories that results from prior choices and actions represents either continuing in the historical regime subject to changing drivers or applying knowledge of system behavior differently to transition. Here, different roles for fire use and better understanding of system responses to fuel treatments, fire suppression and prescribed fire, and unpredicted disturbances could at least aid preparation and might allow deliberate transition toward a differently structured system. On the other hand, there exist barriers to novel approaches to wildland fire use [84] that do not lend themselves to easy systems knowledge solutions; instead, they are more likely to come from transformation knowledge. Emphasizing research that targets these transitions and the role of drought in them may provide knowledge and information for navigating drought and fire issues in the late twenty-first century.

Conclusion

The climate-fire effects on landscapes and resources we face in the rest of the twenty-first century are the consequences both of a long-term fire deficit [64] and a quickly evolving, fire-driven future landscape [6••] that will require significant adaptation [7••]. Just as the target knowledge required to adapt to climate change is in part our experience with and understanding of systems past, we would do well to recognize the limits of short-term systems knowledge and do everything possible to bring new techniques to existing data so that it becomes more useful. Such studies clearly indicate that the twentieth century fire history we have experience with and the longer history we understand from the paleofire record are insufficient to prepare for future variability. Increasingly, accurate prediction of future fire and its impacts requires approaches that simultaneously consider the climatically determined exposure to drought, the vegetation and landscape context for response of fuels and fire, and the human constraints, including management actions, applied to the landscape before and after fire.

Increased collaboration will be required to meet the challenges of further understanding climate and fire relationships as they will likely unfold in the future under climate change [11•]. The transformational knowledge required to change the expected outcomes of fire and impacts on the landscapes and resources of the western USA over the next several decades depends not only on the relationships between drought and fire, but on human responses prior to and after fire. I am unaware of any comprehensive synthesis of the trajectories of landscapes in the West after early twentieth century regional fire years evident in the fire history record, nor of what the human land use decisions in response to them might have been. The lessons to potentially learn from those responses, and the responses to years in the recent fire record, like 2012 and 2015, would require a human historical approach to fire and ecosystem management that may teach us as much as, or more than, investigating the physical drivers of drought and fire.

Acknowledgements I thank three anonymous reviewers for constructive comments on earlier drafts of the manuscript.

Funding Information This work was funded by the Department of Interior Alaska Climate Adaptation Science Center. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

Compliance with Ethical Standards

Conflict of Interest Corresponding author states there is no conflict of interest.

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Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major Importance

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