

Fire–Climate Interactions in the Southwest: Literature Review and Annotated Bibliography

Stephanie Mueller, Martha Sample, Alexander Evans, William Flatley, Andrea Thode, Megan Friggens



Abstract

Climate-induced changes to fire regimes have cascading effects on ecosystem characteristics. Evidence from forested ecosystems in the western United States suggests that interactions between climate and fire will have lasting effects that alter the ecosystem services and values historically provisioned by these landscapes, especially in the Southwest. A diverse science–management partnership, Southwest Fire-Climate Interactions in Montane Ecosystems (Southwest FireCLIME), was formed to evaluate how fire regimes, fuels, and fire effects will shift across landscapes in the Southwest as climate changes. Here we present the first phase of work by the team and collaborators: an extensive literature search of climate, fire, and vegetation (fuel) dynamics, and the resulting Southwest FireCLIME annotated bibliography. The bibliography contains 200 of the most contemporary and foundational papers related to climate change effects on fire regimes, fuels, and ecosystems from or encompassing the southwestern United States. Most papers focus on forested ecosystems at local and regional scales and a smaller number of articles cover multiple ecosystem types, including nonforested (desert, grassland, scrub, or shrubland) ecosystems, at a global, regional, or local scale. The unique element of this bibliography is that every entry is tagged with 1 or more of 48 “linkages” between climate, fire regime, and ecosystem effects variables identified by the Southwest FireCLIME team. Most studies dealing specifically with climate–fire interactions consider the impacts of drought; others consider changing temperature, relative humidity, or vapor pressure deficit. Collectively, this information can fulfill managers’ and researchers’ needs for a comprehensive reference on changing conditions.

Keywords: drought, fire season length, Energy Release Component (ERC), relative humidity (RH), vapor pressure deficit (VPD), fire regime, vegetation survival or mortality, regeneration, fuels conditions, community composition and structure

Cover: Mixed-conifer stand that has burned multiple times. Located on the North Rim, Grand Canyon National Park. Courtesy photo by William Flatley, University of Central Arkansas, used with permission.

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BACKGROUND

In 2012, a science–management partnership, the Southwest Fire-Climate-Landscape Interactions in Montane Ecosystems (Southwest FireCLIME; for more information, visit: <https://swfireclime.org/>), was formed to address the critical need to provide the best available science to fire managers in the southwestern United States. Southwest FireCLIME strives to evaluate how fire regimes, fuels, and fire effects will shift across landscapes in the Southwest as climate changes, and assesses the implications of anticipated changes for resource managers. Southwest FireCLIME’s team of researchers and managers representing universities, Federal land management agencies, and nongovernmental organizations (NGOs) has sought to interpret the diverse and rich body of information on southwestern climate–fire dynamics, develop and test new climate–management scenarios, and provide strategies for managing regional resources under changing climate and fire regimes. The first phase of work by the team and collaborators included an extensive literature search of climate, fire, and vegetation (fuel) dynamics. The annotated bibliography summarizes results from this literature search in the hope that it will be useful for managers and researchers working to respond to the changing climate in the Southwest.

The Southwest FireCLIME annotated bibliography contains a selection of the most contemporary and foundational literature related to climate change effects on fire regimes, fuels, and ecosystems from or encompassing the Southwest. Each entry contains a general summary and specific publication findings that have been written with an eye toward the themes of climate, fire regime, and ecosystem effects. The unique element of this bibliography is that every entry is tagged with 1 or more of 48 “linkages” between climate, fire regime, and ecosystem effects variables identified by the Southwest FireCLIME team (fig. 1). The end product provides insight into the synergies that we might expect from interactions between these variables in the coming years, and also fulfills management needs for a comprehensive reference on changing conditions. This report is a companion to an online, interactive version of the annotated bibliography, which is a living “document” (please visit: <https://www.frames.gov/swfireclime/bibliography>) that allows for interested parties to survey the current status of the literature and update the bibliography as new publications become available (fig. 2).

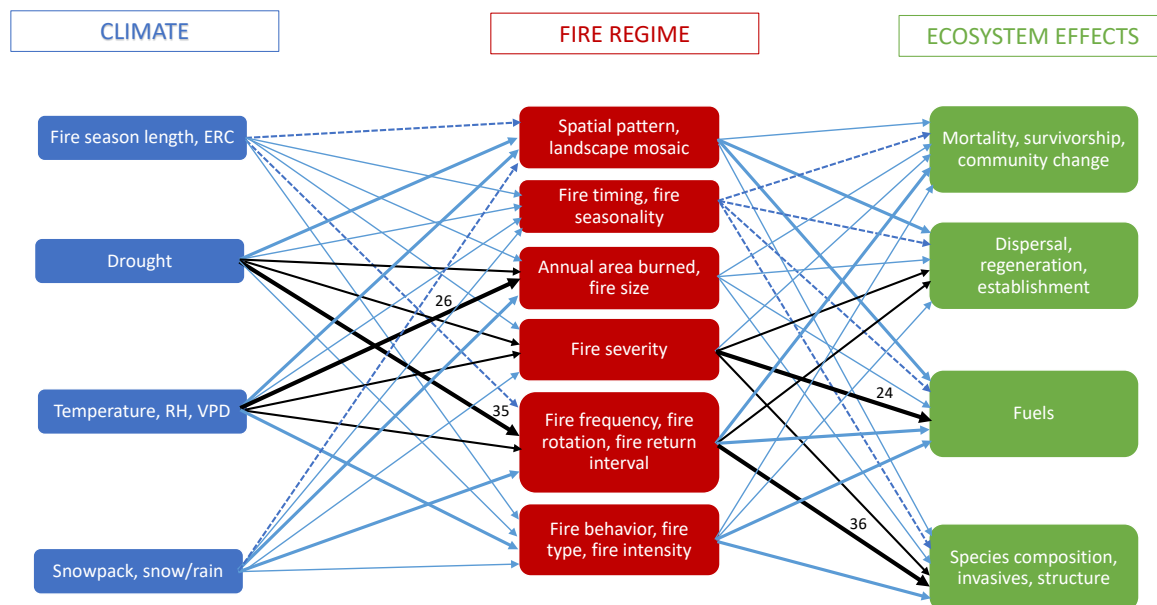
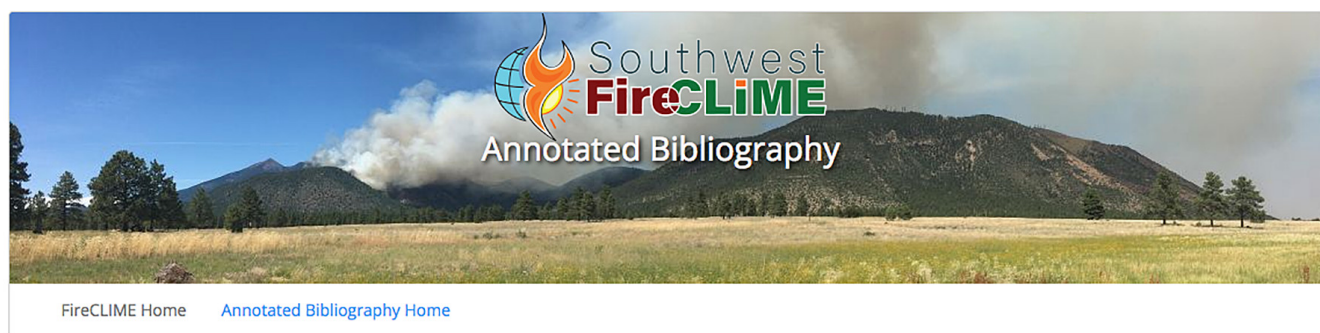


Figure 1—Linkage diagram of the major pathways of climate–fire–ecosystem interactions demonstrating concentration of studies included in annotated bibliography. Our literature search concentrated on studies that relate to or focus on southwestern U.S. plant communities and, in particular, forested ecosystems. Climate variables consider factors related to the duration of changing conditions (fire season length, Energy Release Component [ERC], drought), moisture conditions (temperature, relative humidity [RH], vapor pressure deficit [VPD]), and antecedent conditions (snowpack, snow and rain). Color and line thickness correspond to the number of studies that consider different linkages. The number of papers is included next to the linkage arrow for the four most numerous linkages considered in the literature.



Annotated Bibliography

The Southwest FireCLIME document library is an annotated bibliography of published research related to the interactions between climate change, wildfire, and subsequent ecosystem effects in the southwestern U.S. The 190 publications contained in the library were identified through a comprehensive literature review, and have each been summarized to distill the outcomes as they pertain to fire and climate.

Each publication has been categorized using a set of 48 'linkages' between climate & fire and/or fire & ecosystem variables. Publication findings specific to each tagged linkage are also summarized in every document record in the annotated bibliography to facilitate targeted searching.

Climate + Fire Interactions

View all results from the annotated bibliography that answer one of 24 questions generated from combinations of one climate variable (4 options) and one fire variable (6 options). Link from the results list to the full entry for each publication.

Fire + Ecosystem Interactions

View all results from the annotated bibliography that answer questions generated from combinations of one fire variable (6 options) and one ecosystem effects variable (4 options). Link from the results list to the full entry for each publication.

Search

Search the Southwest FireCLIME document library for:

- Author
- Ecosystem
- Keywords
- Title / Description

Climate Variable

View and search publications related to one of the following climate change variables:

- Drought
- Fire season length
- Snowpack & precipitation (snow/rain) balance
- Temperature, relative humidity (RH), & vapor pressure deficit (VPD)

Fire Variable

View and search publications related to one of the following fire variables:

- Annual area burned & fire size
- Fire behavior, type, & intensity
- Fire frequency, rotation, & return interval
- Fire severity
- Fire timing & seasonality
- Spatial & landscape patterns of fire

Ecosystem Effects Variable

View and search publications related to one of the following ecosystem effects variables:

- Tree mortality, survivorship, & turnover
- Tree dispersal, regeneration, & establishment
- Fuels
- Species composition, non-natives, & structure

Figure 2—Screenshot of the search options on the homepage of the Southwest FireCLIME annotated bibliography website.

INTRODUCTION

The Southwest FireCLIME team conceptualized dynamic fire, climate, and vegetation interactions into a diagram that forms the theoretical basis which ties together several aspects of the Southwest FireCLIME project, including the FireCLIME Vulnerability Assessment tool (Friggens et al. 2019), the Fire Climate adaptation menu (Sample et al. 2022), and this bibliography (fig. 1). The conceptual diagram links climate drivers to fire regime and fire regime to ecosystem impact. Fire ecologists and managers rely on models, assessment tools, and decision support exercises to help translate projections of future conditions into effective management strategies to prevent undesirable change. However, there is a limit to which models and tools can emulate real-world interactions, and there is a tradeoff between product complexity and interpretability. For our literature search and the resulting bibliography presented in later sections, we employ this simplified, top-down vision of climate–fire–ecosystem interactions that allows us to examine the current literature in the context of recognized interaction pathways. Specifically, to visualize and organize information related to climate impacts we view these relationships in an ordered and hierarchical manner with climate driving change in fire regime and consequently change in ecosystem characteristics (fig. 1). However, climate also drives changes in ecosystem characteristics that alter future fire regimes and accelerate microclimate changes. Wildfires can influence climate through the release of greenhouse gases and aerosols. Similarly, vegetation determines albedo, evapotranspiration rates, methane production, carbon sequestration and advection or convection processes that influence local and regional climate conditions (Brown et al. 2004). Though we recognize that climate–fire–ecosystem interactions are more complex than those displayed in the conceptual diagram, we use this representation as an organizational tool to simplify this complex system and focus on the dominant interactions.

Each climate driver has the potential to influence each fire regime component and in turn, each fire regime component can be tied to each ecosystem effect. Not represented in this diagram are the potential feedbacks of vegetation change on fire regime components and the role of ecosystem and fire change in mitigating or accelerating local consequences of climate change though these are inherent in studies of climate-driven fire regime change. To conceptualize the basic relationship between climate, fire, and ecosystems, we recognize four primary climate impacts. Fire season length and the Energy Release Component (ERC) form the first group and are presented together as they both relate to aspects of prolonged climate warming. Second, drought has both direct and indirect impacts for fire regimes. Third, temperature, relative humidity (RH), and vapor pressure deficit (VPD) represent climate-driven changes to moisture-related drivers of fire behavior. Last, snowpack, and snow and rain equivalencies represent antecedent drivers of fire behavior. Fire regime components form six categories representing various spatial and temporal characteristics, and characteristics associated with fire behavior: (1) spatial pattern, landscape mosaic; (2) fire timing, fire seasonality; (3) annual area burned, fire size; (4) fire severity; (5) fire frequency, fire return interval; and (6) fire behavior, fire type, fire intensity. Finally, ecosystem components are represented by four categories dealing with (1) vegetation community survival or

mortality, (2) regeneration, (3) fuel conditions, and (4) community composition and structure. Though knowledge gaps exist for some of these linkages (fig. 1; “Results and Management Implications” section), we do know how some of these components relate.

Perhaps most important in terms of wildfire regimes is the influence of climate conditions on fuels, specifically via fuel moisture conditions known to influence fire behavior (Abatzoglou and Williams 2016; Parks et al. 2014b; Williams et al. 2015). Tellingly, all of the four climate drivers selected in our diagram (fig. 1) are used as proxies for fuel combustibility in various studies. Further, ERC, an index representing available heat per unit area (kilojoules m⁻²), itself relies on moisture values of dead fuels and, in turn, relates to temperature and RH (Brown et al. 2004; Goss et al. 2018). However, these climate drivers have subtly different influences on fire regimes apparent at different temporal and geographic scales. In turn, these drivers lead research and fire management to focus on the individual linkages between climate, fire, and ecosystem response. In the case of complex systems, where simultaneous study is impossible, an approach that focuses on individual linkages is reasonable and even necessary. Using our linkages diagram, we consider the climate–fire–ecosystem literature to identify the current concentration of research for the western United States.

Climate Change Influence on Fire Regimes

Climate change may impact fire regimes in multiple, interacting ways (Hessl 2011). Though uncertainty increases at finer scales, general climate trends have direct implications for key fire regime characteristics including frequency (rotation, return interval), severity, size (annual area burned), behavior (type, intensity), timing (seasonality), and spatial pattern of fires (Littell et al. 2009; Miller et al. 2009; Singleton et al. 2019; Swetnam et al. 2016; van Mantgem et al. 2013). These impacts are large. Broad-scale climate patterns lead to regionally synchronized fire occurrence, and climate variability often mutes any fuel treatment effects (Brown et al. 2004). Fire regime disruptions impact ecosystems with both predictable and unexpected results (Flannigan et al. 2009; Hessl 2011). In the western United States, climate variability can be tied to over half of the area burned in the past half-century, though the effects vary across vegetation types (fig. 3). We next provide a brief review of the specific climate variable categories presented in figure 1 and their influence on fire regimes.

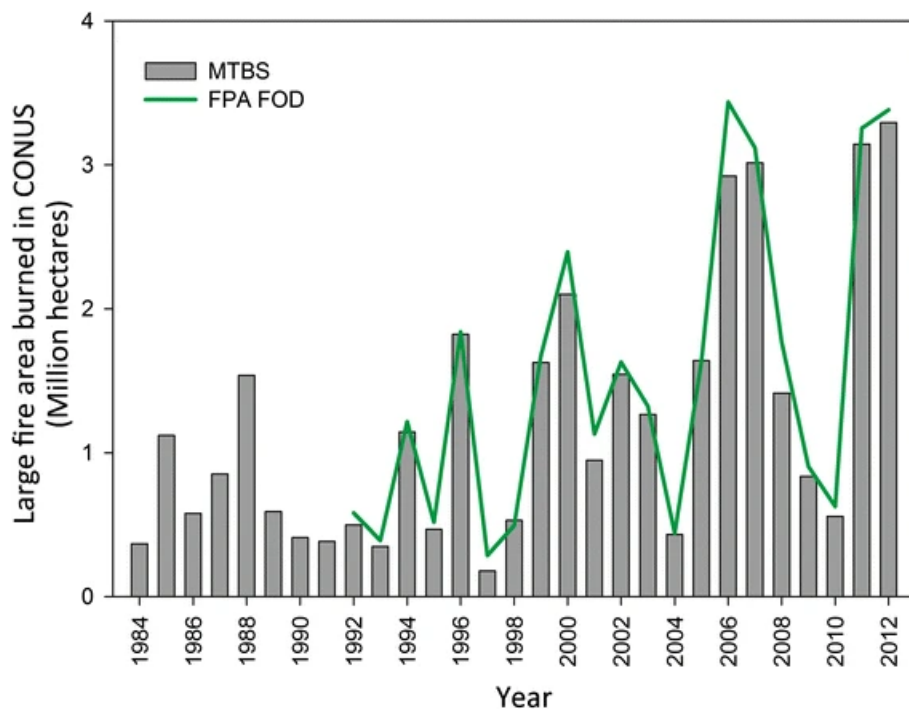


Figure 3—Estimates of area burned by large wildfires in the contiguous United States (CONUS), 1984–2012. A large wildfire is defined here as ≥ 405 ha in the western United States and ≥ 203 ha in the eastern United States. Estimates for 1984–2012 (bars) are based on large perimeters mapped as part of the Monitoring Trends in Burn Severity (MTBS) project (Eidenshink et al. 2007). An additional set of estimates for 1992–2012 (line) is based on records of wildfires > 405 ha included in the Fire Program Analysis Fire-Occurrence Database (Short 2014). [Figure and caption reprinted from Calkin et al. (2015) with permission via Creative Commons (<https://creativecommons.org/licenses/by/4.0/>).]

Fire Season Length and the Energy Release Component

Longer fire seasons and increased fire danger as measured by the Energy Release Component (ERC) are projected changes that will influence fire regimes, and are direct results of changes in temperature, humidity, and precipitation (Jolly et al. 2015). Warm temperatures earlier in the spring leading to warmer, drier, and longer seasons of favorable fire weather can increase ignition, spread, and annual area burned (Barbero et al. 2015; Riley and Loehman 2016; Westerling et al. 2006). Across various climate models, the number of days with high fire danger is projected to increase across the United States (Brown et al. 2005; Tang et al. 2015). Fire season length has already increased significantly world-wide, leading to a doubling of burned area (Holden et al. 2007; Jolly et al. 2015). In the western United States, fire season length increased significantly over the last half century, and annual area burned has increased as well during this period (Abatzoglou and Williams 2016; Westerling et al. 2006). Similarly, ERC is significantly correlated to annual area burned in western U.S. forests (Abatzoglou and Williams 2016), where large fires tend to occur when ERC is above the 80th percentile, and total number of fires and area burned increase exponentially with ERC percentile (Riley et al. 2013).

Temperature, Relative Humidity, and Vapor Pressure Deficit

Historically, wildfire activity has been tied to years of warm and dry conditions in the western United States (Diaz and Swetnam 2013). Higher temperatures and increased risk of drought are projected across the West (Hayhoe et al. 2018; Williams et al. 2014). In western forests, models project increased fire frequency, annual area burned, and fire season length due to warmer and drier conditions (Barbero et al. 2015; Flannigan et al. 2000; Loehman et al. 2018; McKenzie et al. 2004; Pechony and Shindell 2010; Westerling et al. 2006), and empirical studies have already documented these changes (Abatzoglou and Williams 2016; Dennison et al. 2014; Littell et al. 2009; Singleton et al. 2019; fig. 3). Especially in systems that are not fuel-limited, increasing temperatures are expected to drive large fire occurrence and size (Dennison et al. 2014; Stavros et al. 2014). High vapor pressure deficit (VPD) and subsequently low fuel moisture are significantly correlated to annual area burned and burn severity in western forests (Abatzoglou and Williams 2016; Mueller et al. 2020; Parks et al. 2014a; Williams et al. 2015). Growing season VPD is also related to forest drought stress and subsequent tree mortality, which can contribute to fuel accumulation (Diggins et al. 2010).

Drought and Snowpack

Climate change is likely to affect variables tied to moisture availability, including increased drought, decreased precipitation, less snowpack, and lower snow-to-rain ratios (Hayhoe et al. 2018), though precipitation projections vary among climate models. Drought is a known driver of large fire occurrence and size (Dennison et al. 2014), and historical drought years have been linked to fire occurrence and severity (Margolis and Swetnam 2013; Schoennagel et al. 2007; Yocom et al. 2015). In the forests of the western United States, drought severity and corresponding fuel aridity are significantly correlated to annual area burned (Abatzoglou and Williams 2016; Westerling et al. 2003), and precipitation influences size, severity, and synchrony of fires (Holden et al. 2007; Liu and Wimberly 2015). In the Southwest, decreased winter and spring precipitation is projected to shift the timing of the fire season earlier in the year (Barbero et al. 2015). At higher elevations and latitudes, decreased snowpack can lead to increase in fire activity, especially early in the year (Haire et al. 2013; Lutz et al. 2009), and earlier snowmelt contributes to the occurrence of large fires (Westerling et al. 2006). Littell et al. (2009) found winter climate variables to be important predictors of annual area burned across several ecoprovinces.

Consequences of Fire Regime Change: Ecosystem Effects

Climate-induced changes to fire regimes, as previously outlined, have cascading effects on ecosystem characteristics. Where systems are already experiencing high levels of baseline stress due to climate change and other anthropogenic impacts, disruptions to fire regimes may prove to be resilience “tipping points” (Adams 2013). Additionally, reciprocal relationships between variables and positive feedbacks can amplify ecosystem effects (Holden et al. 2010; Jia et al. 2019). Evidence from western U.S. forested ecosystems suggests that interactions between climate and fire will have lasting effects that alter the ecosystem services and values historically provisioned by

these landscapes. This is especially true in the Southwest, where the adaptive capacity of ecotone regions has already been overwhelmed in multiple instances (e.g., Haffey et al. 2018). We consider four categories of ecosystem effects (fig. 1) tied to climate-induced changes in fire regimes: mortality, survivorship and community change; dispersal, regeneration, and establishment; species composition and structure; and fuels.

Plant Mortality, Survivorship, and Community Change

Ecosystems undergoing changes to fire regimes will be subject to altered rates of tree and other plant mortality, survivorship, and turnover (Barton 1999; Baumgartner and Fulé 2007). In historically fire-adapted vegetation communities, wildfire has been a key driver of mortality and survivorship and has strongly influenced turnover events (Abella and Fulé 2008; Brown and Wu 2005; Coop et al. 2015; Iniguez et al. 2016). Importantly, proximate impacts of climate change such as warming temperatures and declining moisture directly affect tree mortality in the western United States (van Mantgem et al. 2009), in addition to the effects of climate via changes to fire regimes. Direct effects of climate change and indirect effects of fire regime change often interact to increase tree mortality. For example, trees already under climatic stress due to high temperatures and low moisture are more susceptible to mortality due to fire damage (Allen et al. 2010; van Mantgem et al. 2013). In some areas of the Southwest, extreme climate change scenarios could result in substantial loss of certain species (e.g., high elevation spruce and fir in northern Arizona and New Mexico) (Flatley and Fulé 2016; Loehman et al. 2018; Tarancón et al. 2014). Expansion of fire into nonfire-adapted ecosystems, such as invasive grasses facilitating fire in desert ecosystems, is an additional scenario which often results in high plant mortality followed by slow or no regeneration (Abella 2009; Parmenter 2008).

Plant Dispersal, Regeneration, and Establishment

Climate-induced fire regime change will impact tree and other plant dispersal, regeneration, and establishment. For example, regeneration of some key western species, such as ponderosa pine, is dependent on nearby surviving trees; thus, regeneration may be hindered following larger and more severe fires (Haire and McGarigal 2010; Owen et al. 2017). While increased fire frequency and severity may correspond to higher incidence of regeneration failure of prefire tree species (e.g., ponderosa pine), it is also likely to favor establishment of other species (e.g., Gambel oak) (Abella and Fulé 2008; Baumgartner and Fulé 2007; Loehman et al. 2018). As demonstrated over the past few decades, large patches of high severity fire have been followed by low regeneration success and could be susceptible to postfire vegetation type conversion (e.g., Coop et al. 2020; Haffey et al. 2018). Regardless of species, fire severity and landscape pattern can affect the size and distribution of surviving fire refugia, which are important sources of postfire regeneration (Blomdahl et al. 2019). Even with nearby sources, seed germination and seedling establishment may be challenged by harsh postfire soil conditions including low water availability and high temperatures (Feddema et al. 2013) and by vegetation competition and xeric topographic features (Singleton et al. 2021).

Plant Species Composition and Structure

Climate- and fire-induced changes to plant species' demography directly influence community composition, structure, and the role of invasive plant species (Iniguez et al. 2016). Shifts in vegetation types are expected to continue (Lawler et al. 2006; Rehfeldt et al. 2012) even in the absence of disturbance, but increased wildfire activity has the potential to transform ecosystems rapidly (Adams 2013; Coop et al. 2020; Overpeck et al. 1990). Increased frequency and severity of wildfire may cause shifts in forest structure and composition, including transitions from forested sites to alternative vegetation communities (Coop et al. 2015; Flatley and Fulé 2016; Loehman et al. 2018). Change in vegetation community composition is more likely to occur following higher severity fire, and those changes may persist (Abella et al. 2015). Nonnative opportunistic or invasive species can also respond positively to higher severity fire, potentially displacing native species (Abella and Fornwalt 2015; Hunter et al. 2006; Shive et al. 2013). Particularly problematic, especially in desert systems, are nonnative invasive species with positive fire-feedback, such that they benefit from the increased fire activity which they promote (Abatzoglou and Kolden 2011).

Fuels

Fire activity is generally limited by fuel availability or fuel moisture (Krawchuck and Moritz 2011), both of which interact with climate directly and indirectly through climate-related fire regime change (Abatzoglou and Kolden 2011; Barbero et al. 2015). Climate-based changes to fire activity are expected to alter fuels in different ways. Higher severity of an initial fire can alter fuel loads in a manner that affects the likelihood of future fire activity (Passovoy and Fulé 2006), or even high severity reburn (Hoff et al. 2014; Lydersen et al. 2017; Parks et al. 2014a). On the other hand, lower severity fires may lower fuel loads, thereby moderating severity of subsequent fires (Coppoletta et al. 2016; Hoff et al. 2014; Lydersen et al. 2017; Parks et al. 2014a). In drier southwestern forests, the regulating effect of previous low severity burns appears to taper off as time since fire increases and during years with extreme weather conditions (Parks et al. 2015). Nonnative invasive species (e.g., annual grasses) favored by changing climate and fire regimes are also an important consideration as they can drastically alter fuels and increase fire activity (Abatzoglou and Kolden 2011).

METHODS

A network of expert scientists and managers with decades of experience working with fire ecology and forest management in the Southwest identified the documents included in the Southwest FireCLIME annotated bibliography. The literature search took place from 2016 to 2018. The search was initiated with an email request to the Southwest FireCLIME team (17 co-principal investigators; Co-PIs), which was then extended to a broader group of collaborators. Co-PIs and collaborators were asked to recommend sources covering the broad topics of fire, climate, and vegetation in the Southwest, including peer-reviewed articles (empirical studies, modeling studies, climate change modeling, meta-analysis, literature reviews, and editorials or opinions) and nonpeer-reviewed sources (General Technical Reports, abstracts, project reports, incident

reports, dissertations or theses, interviews). Publications recommended by this network were supplemented with additional sources located through targeted, topical searches of the literature using Web of Science and Google Scholar. We focused on studies and information applicable to forested ecosystems of the Southwest (specifically Arizona and New Mexico), but also considered larger regional studies that pertained to the Southwest (e.g., western United States, North America), and examined climate–fire–vegetation dynamics affecting the Southwest or similar to those found in the Southwest.

Each paper was coded using Nvivo Pro v. 11 (QSR International, Melbourne, Australia) software and important findings in each paper were assigned codes or “nodes” (exhibit 1). These fell under six main topic areas: climate, disturbance, ecosystem response, environment, fire, and vegetation. For the purpose of the annotated bibliography, the classified papers were then each reviewed for findings related to climate, fire, and ecosystem response variables (fig. 1) using the information compiled under each node.

Exhibit 1—“Nodes” used for coding specific segments within publications included in the literature review. Nodes fall within six topic areas.

Topic area	Nodes
Climate	20th century, carbon fertilization, circulation/wind, condition, current, drought, extreme change, fire weather, general change, historical, moderate change, precipitation, seasonality, snow, teleconnections, temperature
Disturbance	Fire exclusion, fuel treatments, grazing, insects, interactions, logging, other fuels, planting, prescribed fire, restoration, thinning, wind
Ecosystem response	Carbon, composition, demography, diversity, endangered species, fecundity, genes, hydrology, migration, nutrients, productivity, resilience, soil, spatial pattern, structure, succession, tree regeneration, tree survivorship/mortality, type change, understory, wildlife
Environment	Elevation, latitude, topography, wildland-urban interface (WUI)
Fire	Annual area burned, behavior, cost/resources, frequency, general, growth (spread rate), hazard, historical regime, ignitions, intensity, management, regime, season length, seasonality, severity, size, spatial complexity, suppression, type
Vegetation	Aspen, desert, dry mixed conifer, exotic species, generic forest, generic nonforest, grassland, interior chaparral, invasive species, lodgepole, oak, piñon-juniper, ponderosa pine, shrubland, spruce-fir, wet mixed conifer, woodlands

For each piece of literature reviewed, we recorded the study location and ecosystem type(s) and summarized main objectives and methodology. Ecosystems defined in this literature cover a gradient of scope from specific vegetation types (e.g., ponderosa pine forest or aspen stands) to generic (e.g., woodlands or forested ecosystems). Papers that discussed large regional or global effects do not necessarily define specific ecosystem types (table 1). The spatial scale of each paper was classified according to five categories. Local papers examined fires, bogs, national forests and parks, wilderness areas, valleys, mesas, hills, lakes, watersheds, mountains, or canyons within

a single state boundary. Papers within the “state” category reviewed multiple sites within a single state. Studies in two or more states were placed within the multistate scale. Regional papers covered broad locations including the Southwest, western United States, contiguous United States, and plateaus, deserts, basins, and mountains across state lines. Global papers investigated more than one country. Ecosystems covered by each paper were identified and summarized into six broader ecotypes: desert, grasslands, and shrublands (collectively nonforested); forested; forested and nonforested; forested, nonforested, and desert (desert, shrubland, woodland, and montane); multiple (not specified but covering a geography that contains both forest and nonforest types), and oak. The appendix summarizes the ecosystem or assigned ecotype, temporal and spatial scale, primary interacting agents, and research location for each of the annotated publications.

Table 1—Numerical summary of papers reviewed according to their ecosystem and spatial scale as determined by the methods described in each paper. Nonforested types include deserts, grasslands, meadows, and shrublands. “Forested” includes ponderosa pine, mixed conifer, forested, piñon-juniper woodland, chaparral, fir, oak, aspen, and spruce. “Multiple” refers to large-scale studies of a geographic area which did not outline specific ecosystems (e.g., the Southwest, Interior West, United States, Canada). See the Appendix for specific ecosystem types, locations, and scales.

Ecosystem type	Local	State	Multistate, regional	Continental, global	Total
Nonforested: Desert, grasslands, shrubland	4	--	3	--	7
Forested	90	4	45	6	145
Forested + nonforested	6	--	2	--	8
Forested + nonforested + desert	--	--	2	2	4
Multiple	--	1	18	17	36
Total	100	5	70	25	200

-- Indicates no data.

Within the annotated bibliography, the description of each paper included three sections. The “Summary: What the authors did and why” section covers the purpose of the study, relevant topics (climate, fire, ecosystem response), and typically references methods or analyses. Next, the “Publication findings” section highlights important results and findings specific to the effects of climate on fire regimes or fire regime effects on ecosystem responses. Finally, the section titled “Linkages” summarizes these findings according to the 48 “linkages” between climate and fire or fire and ecosystem response components (or a combination thereof) (fig. 1). Papers are listed by authors in alphabetical order with the linkage summaries below each citation.

Our bibliography focuses only on literature that demonstrates or associates the effects of climate on fire regimes or the effects of fire regimes on ecosystem responses. We do not review papers that discuss only the effect of climate on ecosystem responses (i.e., those that did not include information on fire regimes or their effects). Finally, literature

reviews or articles that synthesized findings from the literature are also not included in the bibliography.

RESULTS AND MANAGEMENT IMPLICATIONS

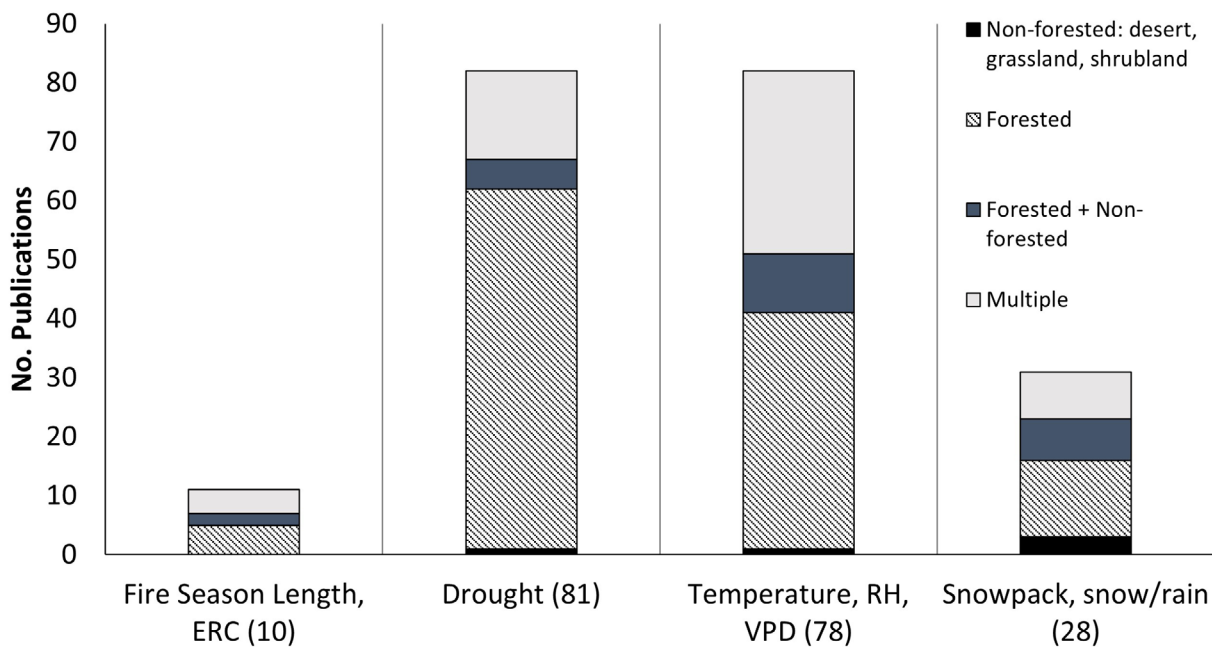
Concentration of Studies

The Southwest FireCLIME bibliography covers 200 papers representing a range of ecosystems and scales (table 1). The breakdown of articles by their topic emphasis shows that most of the papers covered in this bibliography focus on forested ecosystems (72 percent) at local and regional scales (60 percent and 30 percent of forest papers, respectively). Thirty-six articles cover multiple ecosystem types at global, regional, and local scales. A minority (7) focus solely on nonforested (desert, grassland, scrub, or shrubland) ecosystems.

Most studies that considered climate–fire interactions (197 papers) dealt with the impacts of drought (81 papers, or 41 percent) or changing temperature, relative humidity (RH), or vapor pressure deficit (VPD) (78, or 39 percent; fig. 4). The most common linkage considered by these studies addressed drought impacts on fire frequency, whereas studies of temperature, RH, and VPD impacts were most commonly considered in the context of annual area burned or fire size (fig. 4). Fire frequency (70 papers, or 38 percent) and fire severity (65 papers, or 35 percent) were the primary focus of the 186 studies that considered fire regime impacts for ecosystem effects (fig. 5). The most common fire–ecosystem linkages considered in the literature were fire severity impacts on fuels and fire frequency on species composition, invasive species, or ecosystem structure (fig. 1).

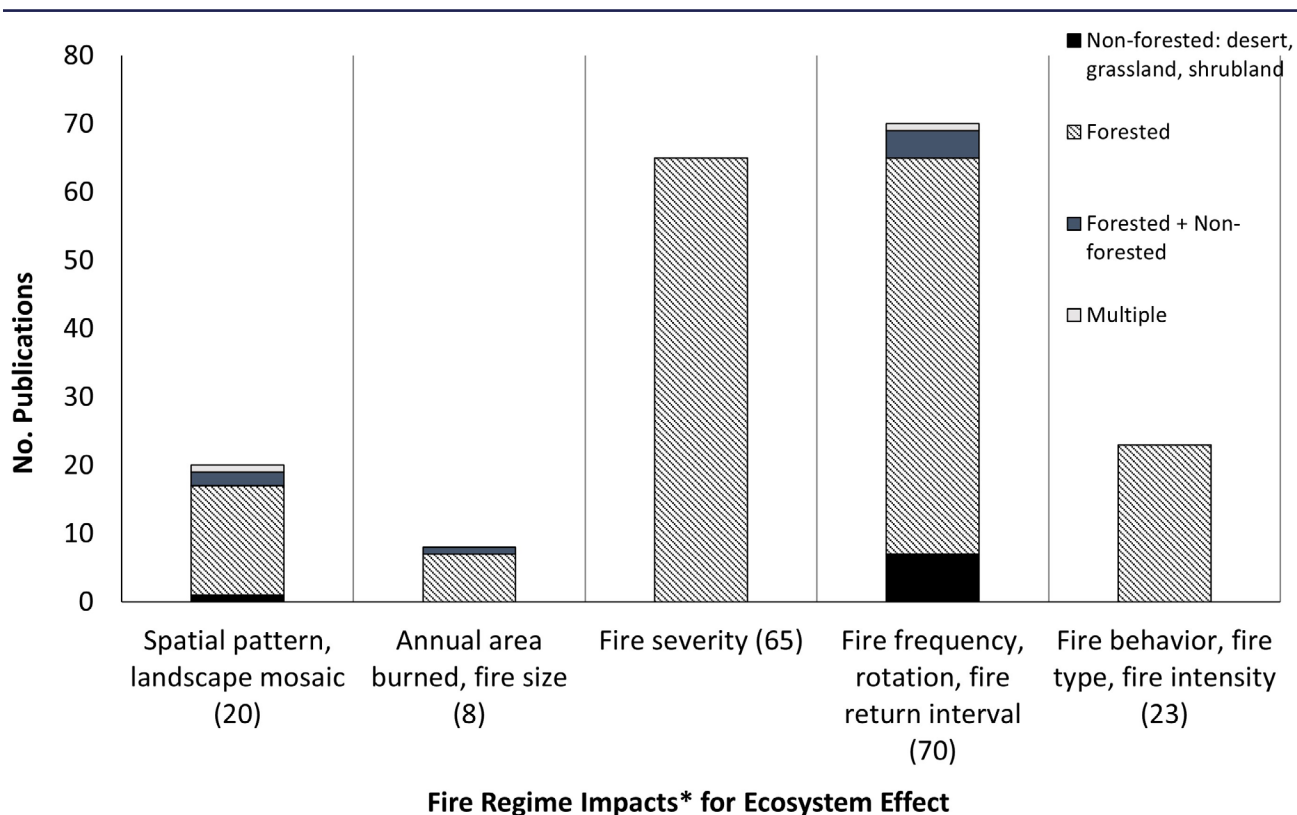
The frequency with which a linkage was considered in the literature can be predicted in part by its inherent temporal and geographic scale and the mechanism by which each is studied. Fire season length and ERC, which relate to the likelihood and severity, respectively, of fire events within a year were considered in studies of annual measures of fire regimes, including fire timing and seasonality, annual area burned, fire size, and fire severity, and were notably absent from studies that considered longer time periods like fire frequency (fire return interval) (fig. 5; Appendix 2). Drought, which acts at regional, multiyear time scales, was related to spatial patterns (landscape mosaic) and fire frequency (fire return interval), which are based on tree ring data and to a much lesser degree (fewer studies) other fire regime characteristics that use alternative methods of measurement. Impacts of drought vary according to the type of forest studied, where increased fire size and severity are associated with periods of persistent or frequent drought in mesic forest types but have less influence on fire conditions in drier forests (O'Connor et al. 2014; Schoennagel et al. 2004; Trouet et al. 2010). In contrast, temperature, RH, and VPD studies were well represented across all fire regime characteristics with the exception of fire timing and seasonality. Summer temperatures are known to influence the timing of fires at regional scales, including regionally synchronous fires in the northern Rocky Mountains (Heyerdahl et al. 2008; Morgan et al. 2008), that drive seasonal fire trends such as the different peak burn

periods observed for the western (typically during July and August) and southwestern (typically May and June) United States (Westerling et al. 2003). Snowpack and snow or rain equivalencies were primarily considered in studies of annual area burned (or fire size) and fire frequency (or fire return intervals). Snowpack controls runoff and other factors that are important to spring and summer soil moisture (Pederson et al. 2011; Sheffield et al. 2004). Snowcover directly influences the period in which fire ignitions are possible, leading to observed correlations with fire frequency and earlier snowmelt days (Westerling et al. 2006).



Climate Change Impact for Fire Regimes

Figure 4—The number of publications covering each of four climate change impacts broken down by ecosystem type. Parenthetical numbers represent the total number of papers considering that climate impact. ERC: Energy Release Component; RH: relative humidity; VPD: vapor pressure deficit.



* No papers consider fire season timing and seasonality on ecosystem effects

Figure 5—The number of papers considering five fire regime impacts broken down by ecosystem type. Parenthetical numbers represent the total number of papers considering that fire regime characteristic.

Gaps in our Knowledge

Risk management for wildfire must consider uncertainties that arise from incomplete knowledge, model variation, and unknown cofactors (Dunn et al. 2017). Bibliographies and reviews such as this one provide an important first step toward quantifying data availability and coverage in order to identify critical data gaps. A notable gap in the available literature regards the impacts of changing fire timing and seasonality on ecosystem effects (fig. 5); we found no studies for this linkage. Seasonal climate indicators (fire season length and ERC) appear less studied than other climate influences, perhaps because of the existence of and preference for other related climate measures (temperature, RH). Additionally, more cross-scale studies are needed that consider multiple linkages to better gauge the relevant impact of specific mechanisms on annual, decadal, and longer time scales.

This literature review and resulting bibliography focus on ecological impacts, but we recognize that the social and economic burden of wildfires is also significant and in need of review (Burke et al. 2021). A separate complementary effort that addresses this topic would be useful in helping managers adjust current fire management paradigms in order to support social-ecological resilience under rapidly changing conditions

(Dunn et al. 2017). We recognize that a gap remains in our knowledge of how different types of fire management will affect fire outcomes (Dunn et al. 2017) though we do not explicitly review that gap here. Among the key gaps noted by Dunn et al. (2017) is how fire managers assimilate different types of information into decision-making processes. Importantly, information on the effectiveness of fire suppression and other management strategies continues to be a priority need (Hunter et al. 2011). Connecting our understanding of climate–fire–vegetation relationships with management strategies that target specific linkages will be an important next step.

CONCLUSIONS

Fire management needs to adapt to issues posed by climate-related increases in fire activity in the western United States given potentially high ecological and social impacts. Long-term management of forests to reduce wildfire-associated risk must consider the potential impacts of climate change. New fire management strategies and policies will be required to deal with fire suppression and fuel treatment needs that address added climatic risks (Nagel et al. 2017; Sample et al. 2022). Managers will need accessibility to research relatively quickly as climate change impacts increase and change occurs more rapidly. Adaptive management is an iterative process that requires good communication between managers and scientists to understand what is working and where it is working within scientific and management contexts. This bibliography, both in print and online, can help managers assess available information and begin to identify different management strategies under climate change for particular ecosystems. Compiling this information is only a first step. Future efforts could assess the efficacy of studies to address local management needs (box 1). Adaptive management strategies are needed to address observed and projected climate changes.

Box 1—Modeling Treatment Effectiveness

Projecting fire regime response to climate change is one method to help guide fire policies and mitigate costs associated with wildfires (USDA FS 2015). However, even when available, studies can provide varying opinions and outcomes. Diggins et al. (2009, 2010) modeled ponderosa pine landscapes in the Southwest and predicted that climate-related declines in fuel production will counter increased burning expected due to warmer, drier fuels and longer fuel seasons. For example, their models predict a 36 percent decline in growth rates of ponderosa forests as a result of increased drought. Their studies suggest that current management strategies to reduce fuel hazards be adapted to include longer burning intervals (~20 years) and alternative thinning regimes to prevent forest decline. In a different analysis, Loehman et al. (2018) applied a mechanistic ecosystem–fire model in two forested landscapes of the Southwest to simulate climate- and management-driven changes in forests and fire regimes. Of the four management strategies considered (suppression only, a current treatment intensity, and two amplified treatment intensities), none was able to prevent the structural and compositional changes to either ecosystem or changes in fire activity projected for future hotter, drier conditions. These results suggest that novel management approaches will be necessary to counteract the effects of climate change. Littell et al. (2009) do not explicitly consider fuel treatment impacts in their analysis but hypothesize that management strategies to mitigate fire risk may not be very effective in climate-limited ecosystems such as southwestern and western montane ecosystems. Stephens et al. (2012) note that current treatments which include prescribed fire and mechanical thinning are successful for reaching short-term goals related to reducing fire hazard but note that treatment effects are transient. However, to implement longer term benefits different strategies not based on presettlement conditions will be needed to help forest be more resilient and resistant to climate change. Stephens et al. (2020) consider conventional methods, such as prescribed fire and thinning, effective for reducing wildfire severity and thus associated risk, and potentially beneficial to other environmental objectives such as enhancing biodiversity, greater water availability, better carbon storage, and improved forest resilience. They propose that these benefits are best achieved when treatments mimic historical conditions though they suggest a shift away from commodity-focused management toward more active management of wildfire. Dunn et al. (2017) note alternative management paradigms often deemphasize fire exclusion and promote expanded use of prescribed fire and managed wildfire (see also USDOJ and USDA 2014). Regardless of the strategy, fuel management must be effective under the extreme fire weather conditions that drive the largest and most damaging fires (Graham et al. 2004).

Adaptation to changing climate and fire regimes is a question not only of environmental change but also of complex social and political environments (Hayhoe et al. 2018; Nagel et al. 2017). Locally relevant prescriptions and ecosystem-specific climate adaptation strategies are necessary to include in management and silvicultural decision making (Nagel et al. 2017) and these strategies will be best informed by locally relevant research. Our review shows a predominance of studies that consider local scales (table 1), with the potential for more connection from the research to climate adaptation work.

ANNOTATED BIBLIOGRAPHY

Acronyms and other abbreviations that commonly appear in this bibliography are defined in exhibit 2.

Exhibit 2—Commonly appearing abbreviations.

AMO	Atlantic Multidecadal Oscillation
ENSO	El Niño-Southern Oscillation
ERC	Energy Release Component
GCM	general circulation model
KBDI	Keetch–Byram Drought Index (KBDI)
PDO	Pacific Decadal Oscillation
PDSI	Palmer Drought Severity Index
RH	relative humidity
SWE	snow water equivalent
VPD	vapor pressure deficit
WD	water deficit

1. **Abatzoglou, J.; Kolden, C. 2013.** Relationships between climate and macroscale area burned in the western United States. *International Journal of Wildland Fire*. 22(7): 1003–1020. <https://doi.org/10.1071/WF13019>

Location

Across the eight Geographic Area Coordination Centers (GACCs) in the western United States: the Pacific Northwest, Northern Rockies, Northern California, Southern California, Western Great Basin, Eastern Great Basin, Rocky Mountain, and the Southwest

Ecosystem type(s)

Forested and nonforested ecosystems

Summary - What did the authors do and why

The authors looked at the relationships between a diverse set of standard (i.e., temperature and precipitation) and biophysical variables related to water balance and fire danger indices to detect their relationships with the interannual variability of area burned derived from the Monitoring Trends in Burn Severity dataset (1984–2010).

Publication findings

The authors found variation between fire–climate relationships across the different GACCs. For the Southwest GACC specifically, temperature, precipitation, and drought indicators were strongly correlated to forested area burned. Unburned area within a fire perimeter did show a negative correlation to summer (June–August) temperature; however, they conclude that temperature is acting as an indirect proxy for fuel moisture stress and flammability. In general, biophysical variables that include a direct link to fuel moisture conditions performed better than any single individual variable, such as temperature or precipitation. In the Southwest GACC, reference evapotranspiration explained the greatest percentage of variance between climate and area burned for both forested and nonforested

areas. Furthermore, antecedent climate factors were more important for early season wildfire activity whereas fire season conditions were consistently stronger predictors of area burned and fire potential concurrent with the fire season. Specifically, when water-balance or fire danger indices were integrated over longer periods of time, their predictive power increased, meaning they were best at predicting later or end-of-season conditions. Negative relationships with increased SWE were also observed in montane ecosystems where precipitation in late winter through early spring delays the onset of fire season and increases fuel moisture into the fire season.

Linkages

- **Temperature, RH, VPD on Fire timing, fire seasonality**

Antecedent climate factors were more important for early season wildfire activity whereas fire season conditions were consistently stronger predictors of area burned and fire potential concurrent with the fire season. Specifically, when water-balance or fire danger indices were integrated over longer periods of time, their predictive power increased, meaning they were best at predicting later or end-of-season conditions.

- **Temperature, RH, VPD on Annual area burned, fire size**

For the Southwest GACC specifically, temperature, precipitation, and drought indicators were strongly correlated to forested area burned. Unburned area within a fire perimeter did show a negative correlation to summer (June–August) temperature; however, the authors conclude that temperature is acting as an indirect proxy for fuel moisture stress and flammability. In general, biophysical variables that include a direct link to fuel moisture conditions performed better than any single individual variable, such as temperature or precipitation.

- **Snowpack, snow and rain on Annual area burned, fire size**

In the Southwest GACC, reference evapotranspiration explained the greatest percentage of variance between climate and area burned for both forested and nonforested areas. In general, biophysical variables that include a direct link to fuel moisture conditions performed better than any single individual variable, such as temperature or precipitation. Negative relationships with increased SWE were also observed in montane ecosystems where precipitation in late winter through early spring delays the onset of fire season and increases fuel moisture into the fire season.

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2. **Abatzoglou, J.T.; Kolden, C.A. 2011.** Climate change in western US deserts: Potential for increased wildfire and invasive annual grasses. *Rangeland Ecology & Management*. 64(5): 471–478. <https://doi.org/10.2111/REM-D-09-00151.1>

Location

Western United States

Ecosystem type(s)

Arid and semiarid rangeland ecosystems; deserts

Summary: What the authors did and why

The authors looked at the effects of climate change on invasive species establishment in western deserts. Specifically, they examined the effects of the interannual variability of temperature- and precipitation-related indicators associated with the National Fire Danger Rating System (NFDRS). Furthermore, they projected the future influence of large fire potential into the mid-21st century using downscaled general circulation models.

Publication findings

Reduced winter moisture either in the form of reduced snowpack or cool season rain are likely to increase extreme fire activity earlier in the spring (May and June) through impacts to fuel conditions. Longer freeze-free seasons favor cold-intolerant annual grasses, such as cheatgrass (*Bromus tectorum*), red brome (*Bromus rubens*), and buffelgrass (*Pennisetum ciliare*), allowing them to germinate during warmer temperatures and expand their range, thereby creating highly flammable ecosystems.

The authors found that recent declines in cool season precipitation appear to have advanced the timing of the fire season across the Sonoran and Mojave Deserts in the Southwest and on rangelands of Colorado and the Great Basin Desert. General circulation models in this study project continued decreases in winter precipitation across the warm deserts in the study area and an increase in the annual mean temperature by 2.5 to 3 °C by the mid-21st century. This future climate change is likely to increase the potential for megafires across the Southwest by increasing the frequency of weather conditions conducive to extreme fire activity, especially an increase in temperature and decrease in corresponding precipitation and humidity indicators. Along with the predicted changes in temperature and precipitation, periods of extreme fire danger are expected to increase by 1 to 3 weeks across these areas, leading to the occurrence of active fire seasons every fifth year to every other year. Furthermore, in these ecosystems, climate change may result in a fire-invasive feedback loop in deserts, where increases in the amount and continuity of annual grasses lead to more extensive and frequent wildfire, thus increasing the potential for invasive species to proliferate while decreasing the opportunity for slower-regenerating native shrub species to establish.

Linkages

- **Snowpack, snow and rain on Fire timing, fire seasonality**

Reduced winter moisture either in the form of reduced snowpack or cool season rain are likely to increase extreme fire activity earlier in the spring (May and June) through impacts to fuel conditions. Longer freeze-free seasons favor cold-intolerant annual grasses, such as cheatgrass (*Bromus tectorum*), red brome (*Bromus rubens*), and buffelgrass (*Pennisetum ciliare*), allowing them to germinate during warmer temperatures and expand their range, thereby creating highly flammable ecosystems.

The authors found that already declines in cool season precipitation appear to have advanced the timing of the fire season across the Sonoran and Mojave Deserts in the Southwest and on rangelands of Colorado and the Great Basin Desert.

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

General circulation models in this study project continued decreases in winter precipitation across the warm deserts in the study area and an increase in the annual mean temperature by 2.5 to 3 °C by the mid-21st century. This future climate change is likely to increase the potential for megafires across the Southwest by increasing the frequency of weather conditions conducive to extreme fire activity, especially an increase in temperature and decrease in corresponding precipitation and humidity indicators. Along with the predicted changes in temperature and precipitation, periods of extreme fire danger are expected to increase by 1 to 3 weeks across these areas leading to the occurrence of chronic fire seasons every fifth year to every other year.

- **Snowpack, snow and rain on Fire frequency, fire rotation, fire return interval**

General circulation models in this study project continued decreases in winter precipitation across the warm deserts in the study area and an increase in the annual mean temperature by 2.5 to 3 °C by the mid-21st century. This future climate change is likely to increase the potential for megafires across the Southwest by increasing the frequency of weather conditions conducive to extreme fire activity, especially an increase in temperature and decrease in corresponding precipitation and humidity indicators. Along with the predicted changes in temperature and precipitation, periods of extreme fire danger are expected to increase by 1 to 3 weeks across these areas leading to the occurrence of severe fire seasons every fifth year to every other year.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

Longer freeze-free seasons favor cold-intolerant annual grasses, including cheatgrass (*Bromus tectorum*) red brome (*Bromus rubens*) and buffelgrass

(*Pennisetum ciliare*) allowing them to germinate during warmer temperatures and expand their range creating highly flammable ecosystems. In these ecosystems, climate change may result in a fire-invasive feedback loop in deserts where increases in the amount and continuity of annual grasses lead to more extensive and frequent wildfire, thereby increasing the potential for invasive species to proliferate while decreasing the ability of slower-regenerating, native shrub species.

3. **Abatzoglou, J.T.; Williams, P.A. 2016.** Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences*. 113(42): 11770–11775. <https://doi.org/10.1073/pnas.1607171113>

Location

Western United States

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors quantified the contribution of past anthropogenic climate change to increases in area burned based on observed increases in fuel aridity metrics, including temperature and VPD, from 1979 to 2015.

Publication findings

The interannual variability of each of the eight fuel aridity metrics—reference potential evapotranspiration (ET_o), VPD, climatic WD, PDSI, fire weather index (FWI) from the Canadian forest fire danger rating system, ERC from the U.S. national fire danger rating system, McArthur Forest Fire Danger Index (FFDI), and KBDI—were all significantly correlated to annual area burned of forested lands from 1984 to 2015.

Increasing trends toward aridity were found for all eight of the climate metrics used in the study. The authors found that anthropogenic climate change had the strongest signal tied to VPD and evapotranspiration, which are highly dependent on temperature. The anthropogenic climate change signal was weak for PDSI and ERC, whose values are driven primarily by precipitation. When the fuel aridity metrics were averaged, anthropogenic climate change accounted for 55 percent of the increasing trend from 1979 to 2015. Furthermore, the authors observed a 3.3-fold difference in the area burned between 1984 to 1999 and 2000 to 2015. Finally, they found an increase in the fire season length of 17 days of high fire potential since 1979; anthropogenic climate change accounts for approximately 45 percent of that increase. The authors state that the influence of anthropogenic climate change will continue to increase area burned due to projected increases in aridity unless fuels become limiting.

Linkages

- **Fire season length on Fire timing, fire seasonality**

The authors found an increase in the fire season length of 17 days of high fire potential since 1979; anthropogenic climate change accounts for approximately 45 percent of that increase.

- **Drought on Annual area burned, fire size**

The interannual variability of each of the eight fuel aridity metrics—reference potential evapotranspiration (ET_o), VPD, climatic WD, PDSI, fire weather index (FWI) from the Canadian forest fire danger rating system, ERC from the U.S. national fire danger rating system, McArthur Forest Fire Danger Index (FFDI), and KBDI—were all significantly correlated to annual area burned of forested lands from 1984 to 2015. Furthermore, the authors observed a 3.3-fold difference in the area burned between 1984 to 1999 and 2000 to 2015. The authors state that the influence of anthropogenic climate change will continue to increase area burned due to projected increases in aridity unless fuels become limiting.

- **Temperature, RH, VPD on Annual area burned, fire size**

The interannual variability of each of the eight fuel aridity metrics—reference potential evapotranspiration (ET_o), VPD, climatic WD, PDSI, fire weather index (FWI) from the Canadian forest fire danger rating system, ERC from the U.S. national fire danger rating system, McArthur Forest Fire Danger Index (FFDI), KBDI—were all significantly correlated to annual area burned of forested lands from 1984 to 2015. Furthermore, the authors observed a 3.3-fold difference in the area burned between 1984 to 1999 and 2000 to 2015.

4. **Abella, S.R. 2009.** Post-fire plant recovery in the Mojave and Sonoran Deserts of western North America. *Journal of Arid Environments*. 73(8): 699–707.

Location

Mojave Desert and Sonoran Desert in the southwestern United States and Mexico

Ecosystem type(s)

Warm desert ecosystem

Summary: What the authors did and why

This paper is a systematic review of vegetation recovery in warm deserts post-fire. The authors evaluated postfire species composition based on time since fire and each desert, postfire sprouting frequency, and perennial plant cover establishment.

Publication findings

Perennial vegetation in burned areas was able to reestablish to prefire levels after approximately 40 years post-fire; however, community composition was slower to recover. Specifically, several species in the Cactaceae family were slowest to recover or absent 40 years after fire and may require centuries to recolonize

burned areas. Invasive species colonization or climate change may interfere with plant community development in the future, and a better understanding of postfire recovery of arid lands is needed.

Linkages

- **Spatial pattern, landscape mosaic on Dispersal, regeneration, establishment**

Perennial vegetation in burned areas was able to reestablish to prefire levels after approximately 40 years post-fire; however, community composition was slower to recover. Specifically, several species in the Cactaceae family were slowest to recover or absent 40 years after fire and may require centuries to recolonize burned areas. Invasive species colonization or climate change may interfere with plant community development in the future, and a better understanding of post-fire recovery of arid lands is needed.

5. **Abella, S.R.; Fornwalt, P.J. 2015.** Ten years of vegetation assembly after a North American mega fire. *Global Change Biology*. 21(2): 789–802.

Location

Hayman Fire, Colorado, USA

Ecosystem type(s)

Ponderosa pine ecosystem

Summary: What the authors did and why

The authors examined the postfire recovery, resistance, and resilience of understory vegetation after a mega-fire along a gradient of fire severities.

Publication findings

Postfire resistance to change in plant community composition decreased with increasing fire severity over a 10-year period. Furthermore, sites that burned at low or moderate severity returned to prefire conditions over time, while high severity sites continued to diverge from prefire conditions throughout the study period. Conversely, species richness persisted after the fire regardless of fire severity and exceeded prefire levels 5 years after the fire. Though the colonizing species were often different species than existed on the site pre-fire, communities remained composed of 89 percent native species. Nonnative species also increased with increasing burn severity, but did not dominate any site in the study area.

The authors suggest that although these mega-fires are often catastrophic for overstory vegetation, they may not always be catastrophic for the understory in dry conifer forests. If managers can ameliorate fire severity through forest management, thereby allowing areas to burn at low or moderate severities, ponderosa pine ecosystems may mimic historical fire regimes, which could increase the resistance and resilience to community composition change post-fire while stimulating understory growth and species richness.

Linkages

- **Fire severity on Species composition, invasives, structure**

Postfire resistance to change in plant community composition decreased with increasing fire severity over a 10-year period. Furthermore, sites that burned at low or moderate severity returned to prefire conditions over time, while high severity sites continued to diverge from prefire conditions throughout the study period. Conversely, species richness persisted after the fire regardless of fire severity and exceeded prefire levels 5 years after the fire. Though the colonizing species were often different species than existed on the site pre-fire, communities remained composed of 89 percent native species. Nonnative species also increased with increasing burn severity, but did not dominate any site in the study area.

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6. **Abella, S.R.; Fulé, P.Z. 2008.** Fire effects on Gambel oak in southwestern ponderosa pine-oak forests. Research Note RMRS-RN-34. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 6 p.

Location

Colorado Plateau, USA

Ecosystem type(s)

Ponderosa pine–oak forests

Summary: What the authors did and why

The authors summarized literature on the fire regime of Gambel oak (*Quercus gambelii*), specifically, the frequency and timing of fire in these ecosystems historically, and the effects of prescribed fire on Gambel oak.

Publication findings

Gambel oak (*Quercus gambelii*) can survive in forests dominated by frequent fire regimes, although top-kill by fire is common. However, it is a prolific resprouter, survives even intense wildfire, and may even become the dominant species if frequent high-severity wildfire eliminates competing vegetation. The frequency and intensity of prescribed fire could be adjusted to alter species composition of pine–oak forests by maintaining a variety of oak growth forms. Several tactics may enhance survival of large oaks during prescribed fire: keeping pine slash away from oak boles, avoiding lighting near oaks or reducing fire intensity near oaks, and raking fuels away from oak boles.

Linkages

- **Fire severity on Mortality, survivorship, community change**

Gambel oak (*Quercus gambelii*) is a prolific resprouter, survives even intense wildfire, and may become the dominant species if frequent high severity wildfire eliminates competing vegetation.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

Gambel oak can survive in forests dominated by frequent fire regimes, although top-kill by fire is common. The frequency and intensity of prescribed fire could be adjusted to alter the species composition of pine–oak forests by maintaining a variety of oak growth forms.

7. **Allen, C.D.; Anderson, R.S.; Jass, R.B.; Toney, J.L.; Baisan, C.H. 2008.** Paired charcoal and tree-ring records of high-frequency Holocene fire from two New Mexico bog sites. *International Journal of Wildland Fire*. 17(1): 115–130.
<https://doi.org/10.1071/WF07165>

Location

Chihuahueros and Alamo Bogs, Jemez Mountains, New Mexico, USA

Ecosystem type(s)

Mixed-conifer ecosystem

Summary: What the authors did and why

The authors aimed to reconstruct historical fire histories and fire–climate relationships extending back approximately 15,000 years by sampling from charcoal cores in medium-elevation bog sites.

Publication findings

Charcoal concentration in the sediment records at both bogs varied considerably over 15,000 years, suggesting that climate affected both vegetation and fire regimes. Around approximately 8,000 years before present, sharp increases in charcoal concentrations indicate increased warming; however, the authors were unable to interpret the fire history due to confounding factors, specifically the low sedimentation rate during these periods. Still, at both bog sites, a departure in superposed epoch analysis PDSI of -2, indicating very dry conditions, coincided with widespread fire years between the 1500s and early 1900s.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

Charcoal concentration in the sediment records at both bogs varied considerably over 15,000 years suggesting that climate affected both vegetation and fire regimes. At the both bog sites, a departure in superposed epoch analysis PDSI of -2,

indicating very dry conditions, coincided with widespread fire years between the 1500s and early 1900s.

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

Charcoal concentration in the sediment records at both bogs varied considerably over 15,000 years suggesting that climate affected both vegetation and fire regimes. Around approximately 8,000 years before present, sharp increases in charcoal concentrations indicate increased warming; however, the authors were unable to interpret the fire history due to confounding factors, specifically the low sedimentation rate during these periods.

8. Allen, C.D.; Macalady, A.K.; Chenchouni, H.; Bachelet, D.; McDowell, N.; Vennetier, M.; Kitzberger, T.; Rigling, A.; Breshears, D.D.; Hogg, E.H.; Gonzalez, P.; Fensham, R.; Zhang, Z.; Castro, J.; Demidova, N.; Lim, J.-H.; Allard, G.; Running, S.W.; Semerci, A.; Cobb, N. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*. 259(4): 660–684.
<https://doi.org/10.1016/j.foreco.2009.09.001>

Location

Global

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors review the literature on tree mortality due to water stress and increased temperatures as a result of climate change in forests around the world.

Publication findings

Climate-induced stress leading to increased tree mortality interacts with disturbance such as fire, further exacerbating mortality. There is uncertainty about how future climate change may affect this feedback loop between physiological stress and fire disturbance.

Linkages

- **Drought on Annual area burned, fire size**

Climate-induced stress leading to increased tree mortality interacts with disturbance such as fire, further exacerbating mortality. There is uncertainty about how future climate change may affect this feedback loop between physiological stress and fire disturbance.

- **Annual area burned, fire size on Mortality, survivorship, community change**

Climate-induced stress leading to increased tree mortality interacts with disturbance such as fire, further exacerbating mortality. There is uncertainty about how future climate change may affect this feedback loop between physiological stress and fire disturbance.

9. **Amato, V.J.; Lightfoot, D.; Stropki, C.; Pease, M. 2013.** Relationships between tree stand density and burn severity as measured by the Composite Burn Index following a ponderosa pine forest wildfire in the American Southwest. *Forest Ecology and Management*. 302: 71–84. <https://doi.org/10.1016/j.foreco.2013.03.015>

Location

Trigo Fire, Manzano Mountains, New Mexico, USA

Ecosystem type(s)

Ponderosa pine ecosystem

Summary: What the authors did and why

The authors assessed the relationship between fire severity and stand density using the composite burn index (CBI).

Publication findings

Using the Spearman's Rank Correlation analysis, the authors found that tree density strongly correlated with CBI scores such that denser stands on ponderosa pine burned at higher severities.

Linkages

- **Fire severity on Fuels**

Using the Spearman's Rank Correlation analysis, the authors found that tree density strongly correlated with CBI scores such that denser stands on ponderosa pine burned at higher severities.

10. **Anderson, R.S.; Allen, C.D.; Toney, J.L.; Jass, R.B.; Bair, A.N. 2008.** Holocene vegetation and fire regimes in subalpine and mixed conifer forests, southern Rocky Mountains, USA. *International Journal of Wildland Fire*. 17(1): 96–114. <https://doi.org/10.1071/WF07028>

Location

Southern Rocky Mountains, Colorado and New Mexico, USA

Ecosystem type(s)

Alpine–subalpine forest; mixed-conifer forest

Summary: What the authors did and why

The authors reconstructed fire history of the Holocene based on pollen and sedimentary records in high elevation forests in New Mexico and analyzed the relationships between climate, vegetation, and fire over the long term.

Publication findings

The paleovegetation record shows a shift from alpine tundra or steppe vegetation to subalpine or mixed-conifer forests, or both, around approximately 12,500 years before present. Drier conditions were likely at these forests in the mid-Holocene, followed by a period of greater winter precipitation and warmer temperatures associated with ENSO. Synchronous fire episode frequency occurred between approximately 12,000 and 9,000 years before present and approximately 2,000 to 1,000 years before present. The authors suggest that the first period was associated with increased biomass and lightning ignitions due to climate change and that during the second period persistent drought with intermittent wetter periods provided conditions for increased fire activity. The fire return interval for these sites historically was likely one fire event every 100 to 200 years, suggesting that the current fire regime is anomalous due to fire suppression.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

Synchronous fire episode frequency occurred between approximately 12,000 and 9,000 years before present and approximately 2,000 to 1,000 years before present. The authors suggest that the first period was associated with increased biomass and lightning ignitions due to climate change and that during the second period persistent drought with intermittent wetter periods provided conditions for increased fire activity.

- **Snowpack, snow and rain on Fire frequency, fire rotation, fire return interval**

Drier conditions were likely at these forests in the mid-Holocene followed by a period of greater winter precipitation and warmer temperatures associated with ENSO. Synchronous fire episode frequency occurred between approximately 12,000 and 9,000 years before present and approximately 2,000 to 1,000 years before present. The authors suggest that the first period was associated with increased biomass and lightning ignitions due to climate change and that during the second period persistent drought with intermittent wetter periods provided conditions for increased fire activity.

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11. **Andrus, R.A.; Veblen, T.T.; Harvey, B.J.; Hart, S.J. 2016.** Fire severity unaffected by spruce beetle outbreak in spruce-fir forests in southwestern Colorado. *Ecological Applications*. 26(3): 700–711. <https://doi.org/10.1890/15-1121>

Location

Colorado Rocky Mountains, Colorado, USA

Ecosystem type(s)

Subalpine forests

Summary: What the authors did and why

The authors examined the effects of spruce beetle (*Dendroctonus rufipennis*) infestation on fire severity during the drought years of 2012 and 2013.

Publication findings

The authors found that spruce beetle infestation (<5 years) did not correlate with fire severity regardless of burning conditions. Instead, topography, preoutbreak basal area, climate, and short-term weather conditions during the fires all had a stronger influence on fire severity.

Linkages

- **Drought on Fire severity**

Topography, preoutbreak basal area, climate, and short-term weather conditions during the fires all had a stronger influence on fire severity than spruce beetle (*Dendroctonus rufipennis*) infestation (<5 years).

- **Fire severity on Fuels**

The authors found that spruce beetle (*Dendroctonus rufipennis*) infestation (<5 years) did not correlate with fire severity regardless of burning conditions. Instead, topography, preoutbreak basal area, climate, and short-term weather conditions during the fires all had a stronger influence on fire severity.

12. **Arkle, R.S.; Pilliod, D.S.; Welty, J.L. 2012.** Pattern and process of prescribed fires influence effectiveness at reducing wildfire severity in dry coniferous forests. *Forest Ecology and Management*. 276: 174–184. <https://doi.org/10.1016/j.foreco.2012.04.002>

Location

Payette National Forest, Idaho, USA

Ecosystem type(s)

Mixed-conifer ecosystem

Summary: What the authors did and why

The authors examined the relationship between vegetation and topography on prescribed fire severity and the effects of prescribed burns on subsequent wildfire.

Publication findings

Prescribed fire reduced the severity of subsequent wildfire compared to untreated areas, suggesting that prescribed fire is an effective treatment to reduce fuel loads and high severity fire in dry mixed-conifer ecosystems. Pretreatment vegetation volume, heat load, and prescribed fire burn severity were all significantly related to the severity of the subsequent wildfire; however, the interactions between these variables were complex. Higher severities in the prescribed fire were more effective at reducing fire severity in the following wildfire.

The authors also found that landscape context of the burn strongly influenced wildfire severities. Fire severity was lower farther inside contiguous patches of burned area and increased with increasing distance from the center of the disturbance. The authors suggest that fire size and burn continuity may be more important in reducing subsequent fire severity than the severity of the prescribed fire.

Linkages

- **Spatial pattern, landscape mosaic on Fuels**

The authors found that landscape context of the burn strongly influenced wildfire severities. Fire severity was lower farther inside contiguous patches of burned area and increased with increasing distance from the center of the disturbance. The authors suggest that fire size and burn continuity may be more important in reducing subsequent fire severity than the severity of the prescribed fire.

- **Annual area burned, fire size on Fuels**

The authors suggest that fire size and burn continuity may be more important in reducing subsequent fire severity than the severity of the prescribed fire.

- **Fire severity on Fuels**

Prescribed fire reduced the severity of subsequent wildfire compared to untreated areas, suggesting that prescribed fire is an effective treatment to reduce fuel loads and high severity fire in dry mixed-conifer ecosystems. Pretreatment vegetation volume, heat load, and prescribed fire burn severity were all significantly related to the severity of the subsequent wildfire; however, the interactions between these variables were complex. Higher severities in the prescribed fire were more effective at reducing fire severity in the following wildfire.

The authors also found that landscape context of the burn strongly influenced wildfire severities. Fire severity was lower farther inside contiguous patches of burned area and increased with increasing distance from the center of the disturbance. The authors suggest that fire size and burn continuity may be more important in reducing subsequent fire severity than the severity of the prescribed fire.

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13. **Baisan, C.H.; Swetnam, T.W. 1990.** Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, U.S.A. *Canadian Journal of Forest Research*. 20(10): 1559–1569. <https://doi.org/10.1139/x90-208>

Location

Rincon Mountain Wilderness, Saguaro National Park Wilderness Area, Arizona, USA

Ecosystem type(s)

Mixed-conifer forest; pine forest

Summary: What the authors did and why

Fire regimes vary both regionally and within a limited geographic area, due to changes in elevation and aspect. Site-specific studies are therefore important to highlight local fire patterns and site ecology. The authors reconstructed the fire history of the montane region of the Rincon Mountains for the 490 years prior to 1990 by combining material from fire records, historical reports, and analysis of fire scars. Most of the analysis focuses on the Mica Mountain above 2,300 m.

Publication findings

While the highest rate of lightning ignition occurred in late July, almost 60 percent of the average yearly total area burned occurred in June because the arid conditions that precede the monsoon allow fires to spread quickly. The fire-scar data specimens cross-dated for the Mica Mountain study are for the period of 1657 through 1893 and indicated a mean fire interval of 6.1 years with a range of 1 to 13 years for larger fires. During this time 41 major fires occurred in the region. Mixed-conifer sites from 1748 through 1886 had a mean fire interval of 9.9 years with a range of 3 to 19 years.

Linkages

- **Fire frequency, fire rotation, fire return interval on Fuels**

The authors indicate that frequent fires may maintain overstory stability by decreasing fuel loading on a regular basis. Improved fuel production on moist sites in combination with decadal or longer fire intervals may result in more intense fires with greater mortality of mature trees.

- **Drought on Fire timing, fire seasonality**

Mean July PDSI for 2 years prior to fires was higher (wetter) than average, while mean fire year PDSI was near average. The authors suggest that the moist conditions prior to the fires may have encouraged the production of fine fuels, priming the area for the subsequent fire season.

Fire activity on a regional scale may reflect a more direct relationship to drought as reflected in the dry years of 1748, 1822, and 1879, which show up in other fire history dates of the southwestern United States.

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14. **Baker, W.L.; Veblen, T.T.; Sherriff, R.L. 2007.** Fire, fuels and restoration of ponderosa pine–Douglas-fir forests in the Rocky Mountains, USA. *Journal of Biogeography*. 34(2): 251–269. <https://doi.org/10.1111/j.1365-2699.2006.01592.x>

Location

Rocky Mountains, USA

Ecosystem type(s)

Mixed-conifer forest; ponderosa pine forest

Summary: What the authors did and why

The authors formulated a model based on mixed or variable fire severity (or combination thereof) and tested its applicability to ponderosa pine and mixed-conifer ecosystems in the U.S. Rocky Mountains.

Publication findings

The authors suggest that fire severity varied greatly across most of these forests, and that high severity fires were common and burned thousands of hectares at a time. High severity fire typically varied along elevational and moisture gradients. Areas with increased dominance of Douglas-fir (*Pseudotsuga menziesii*) typically burned at higher severities, and xeric sites dominated by ponderosa pine (*Pinus ponderosa*) typically burned at low severities. However, periods of drought or wind events can override fuel conditions, leading to higher fire severities and variation from year to year. Furthermore, under a more variable-severity fire regime, fuel loads tend to be more spatially heterogeneous, which is consistent with fuel data from the U.S. Rocky Mountains.

Finally, the authors found that tree regeneration was abundant after, and even enhanced by, high severity fire.

Linkages

- **Drought on Fire severity**

High severity fire typically varied along elevational and moisture gradients. Areas with increased dominance of Douglas-fir (*Pseudotsuga menziesii*) typically burned at higher severities, and xeric sites dominated by ponderosa pine (*Pinus ponderosa*) typically burned at low severities. However, periods of drought or wind events can override fuel conditions, leading to higher fire severities and variation from year to year.

- **Fire severity on Fuels**

Periods of drought or wind events can override fuel conditions, leading to higher fire severities and variation from year to year. Furthermore, under a more variable-severity fire regime, fuel loads tend to be more spatially heterogeneous, which is consistent with fuel data from the U.S. Rocky Mountains.

- **Fire severity on Dispersal, regeneration, establishment**

The authors found that tree regeneration was abundant after, and even enhanced by, high severity fire.

15. **Barbero, R.; Abatzoglou, J.T.; Steel, E.A.; Larkin, N.K. 2014.** Modeling very large-fire occurrences over the continental United States from weather and climate forcing. *Environmental Research Letters*. 9(12): 124009.
<https://doi.org/10.1088/1748-9326/9/12/124009>

Location

Contiguous United States; 13 Omernik Level II ecoregions of the United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors developed models of very large fire occurrence (>5,000 ha) using solely atmospheric climate predictors and compared the models to the observed spatial and temporal variability across ecoregions of the United States to identify the most important climate variables driving large fire occurrence and to understand how large fire occurrence may be changing due to future climate changes.

Publication findings

The authors found that in flammability-limited ecoregions, specifically the Western Cordillera and Appalachian Forests, long-term drought conditions were strong predictors of very large fire occurrence. Prior-year anomalously wet conditions preceded very large fire occurrence in two fuel-limited ecoregions: the Semi-arid Prairies and Sierra Madre Piedmont of southern Arizona.

Linkages

- **Drought on Annual area burned, fire size**

The authors found that in flammability-limited ecoregions, specifically the Western Cordillera and Appalachian Forests, long-term drought conditions were strong predictors of very large fire occurrence. Prior year anomalously wet conditions preceded very large fire occurrence in fuel-limited ecoregions: the Semi-arid Prairies and Sierra Madre Piedmont of southern Arizona.

16. **Barbero, R.; Abatzoglou, J.T.; Larkin, N.K.; Kolden, C.A.; Stocks, B. 2015.** Climate change presents increased potential for very large fires in the contiguous United States. *International Journal of Wildland Fire*. 24(7): 892–899.
<https://doi.org/10.1071/WF15083>

Location

Contiguous United States; 13 Omernik Level II ecoregions of the United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

Very large fire (>5,000 ha) potential was projected from 2041 to 2070 using an ensemble of 17 global climate models. The authors used known empirical relationships between climate and very large fire occurrence in order to identify future potential regional and seasonal fire distributions under future climate change.

Publication findings

The authors found that very large fire potential is projected to increase across much of the United States, with the greatest increases expected across the Intermountain West due to overall warming and diminished moisture. The increase in fire potential results from both an increase in fire frequency and the length of the seasonal window when conditions are conducive to extreme fire activity. For the southwestern warm deserts, they projected a shift in the timing of fire season and very large fire potential to earlier in the year due to increasing temperatures and decreasing precipitation during the winter and spring. The authors note that these projections are dependent on forest and vegetation composition and may not materialize if fuels become a limiting factor.

Linkages

- **Fire season length on Annual area burned, fire size**

The authors found that very large fire potential is projected to increase across much of the United States, with the greatest increases expected across the Intermountain West due to overall warming and diminished moisture. The increase in fire potential results from both an increase in fire frequency and the length of the seasonal window when conditions are conducive to extreme fire activity.

- **Temperature, RH, VPD on Annual area burned, fire size**

The authors found that very large fire potential is projected to increase across much of the United States, with the greatest increases expected across the Intermountain West due to overall warming and diminished moisture. The increase in fire potential results from both an increase in fire frequency and the length of the seasonal window when conditions are conducive to extreme fire activity.

- **Temperature, RH, VPD on Fire timing, fire seasonality**

For the southwestern warm deserts, the authors projected a shift in the timing of fire season and very large fire potential to earlier in the year due to increasing temperatures and decreasing precipitation during the winter and spring.

- **Snowpack, snow and rain on Fire timing, fire seasonality**

For the southwestern warm deserts, the authors projected a shift in the timing of fire season and very large fire potential to earlier in the year due to increasing temperatures and decreasing precipitation during the winter and spring.

17. **Barton, A.M. 1999.** Pines versus oaks: Effects of fire on the composition of Madrean forests in Arizona. *Forest Ecology and Management*. 120(1–3): 143–156.
[https://doi.org/10.1016/S0378-1127\(98\)00531-3](https://doi.org/10.1016/S0378-1127(98)00531-3)

Location

Southeastern Arizona, USA

Ecosystem type(s)

Madrean forests

Summary: What the authors did and why

The authors examined historical fire regimes of Madrean pine–oak communities and the effects of fire on current establishment and survivorship. They also compared the response of pine versus oak to fire (i.e., fire-resistant species versus sprouting species) and their relative abundance and structure post-fire.

Publication findings

Historically, frequent fires led to abundant seedling recruitment of both pine and oak species, but low survival into maturity. Fire suppression starting in the early 1900s led to low levels of seedling recruitment, but allowed young trees to mature without disturbance for long periods of time.

Pine and oak have different strategies for dealing with frequent fire. The pine species in this study (*Pinus engelmannii* and *P. leiophylla*) are fire resistant while the oak species (*Quercus hypoleucoides*) resprouts after top-kill by fire. These differing responses can lead to differences in abundance post-fire, such that immediately after fire, pines dominate through resistance to fire until oaks, which grow rapidly, catch up in abundance through resilience to fire. The authors suggest that continued fire exclusion may favor oak species over pine due to prolific sprouting in the understory while disrupting pine seedling establishment.

Linkages

- **Fire frequency, fire rotation, fire return interval on Mortality, survivorship, community change**

Pine and oak have different strategies for dealing with frequent fire. The pine species in this study (*Pinus engelmannii* and *P. leiophylla*) are fire resistant while the oak species (*Quercus hypoleucoides*) resprouts after top-kill by fire.

Historically, frequent fires led to abundant seedling recruitment of both pine and oak species, but low survival into maturity. Fire suppression starting in the early

1900s led to low levels of seedling recruitment, but allowed young trees to mature without disturbance for long periods of time.

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

Historically, frequent fires led to abundant seedling recruitment of both pine and oak species, but low survival into maturity. Fire suppression starting in the early 1900s led to low levels of seedling recruitment, but allowed young trees to mature without disturbance for long periods of time.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

Differing fire, survival strategies can lead to differences in abundance post-fire. Pines dominate through resistance to fire until oaks, which grow rapidly, catch up in abundance through resilience to fire. The authors suggest that continued fire exclusion may favor oak species over pine due to prolific sprouting in the understory while disrupting pine seedling establishment.

18. **Barton, A.M.; Poulos, H.M. 2018.** Pine vs. oaks revisited: Conversion of Madrean pine-oak forest to oak shrubland after high-severity wildfire in the Sky Islands of Arizona. *Forest Ecology and Management*. 414: 28–40.
<https://doi.org/10.1016/j.foreco.2018.02.011>

Location

Chiricahua Mountains, southeastern Arizona, USA

Ecosystem type(s)

Madrean pine–oak forest

Summary: What the authors did and why

To improve understanding of the fire-driven changes to forest communities, the authors examine the influence of high severity fires in converting Madrean pine-oak forest to a predominantly oak-dominated shrubland using repeat sampling obtained before and after the 1994 Rattlesnake and 2011 Horseshoe Fires.

Publication findings

By 2016 areas where fires had burned at high severity had changed from mixed pine-oak forest to oak shrublands and grasslands. Low pine recruitment was not limited only to areas of high severity fires, suggesting conversion was exacerbated by the extreme drought of the past two decades. Chihuahua pine (*Pinus leiophylla*) resprouted in limited numbers after top-kill, indicating that the species may be retained at low numbers in the region. Topography played an important role, with less exposed plots experiencing lower severity fires and consequently less conversion to oak shrublands.

Linkages

• Fire severity on Fuels

Canopy cover exhibited a significant curvilinear relationship with fire severity; the most open plots occurred at sites with moderate fire severity. Plots were shaded by mature trees after low severity fire, by oak resprouts and other shrubs after high severity fire, and by a mixture of the two after moderate severity fire. Litter depth and percent soil carbon and nitrogen were significantly negatively related to fire severity and elevation and positively related to topographic relative moisture index (TRMI).

• Fire severity on Dispersal, regeneration, establishment

Fire severity in the Horseshoe Two Fire increased from less to more exposed sites. Pine and oak recruitment in 2016 were significantly affected by fire severity and other environmental factors, but these effects differed by species and between seedlings and resprouts. In general, seedling recruitment declined with increasing fire severity and increased with soil moisture. Chihuahua pine (*Pinus leiophylla*) resprout abundance also declined with fire severity, but this pattern was marginally insignificant. Oak resprout recruitment increased with fire severity (and elevation) and decreased from drier to moisture sites.

19. **Baumgartner, K.H.; Fulé, P.Z. 2007.** Survival and sprouting responses of Chihuahua pine after the Rodeo-Chediski fire on the Mogollon Rim, Arizona. *Western North American Naturalist*. 67(1): 51–57.
[https://doi.org/10.3398/1527-0904\(2007\)67\[51:SASROC\]2.0.CO;2](https://doi.org/10.3398/1527-0904(2007)67[51:SASROC]2.0.CO;2)

Location

Mogollon Rim, Arizona, USA

Ecosystem type(s)

Ponderosa pine–evergreen oak community

Summary: What the authors did and why

The authors assessed the ability of Chihuahua pine (*Pinus leiophylla*) to survive fire or resprout after fire based on tree age and fire intensity.

Publication findings

Chihuahua pine is one of the few pine species that can resprout from its base after a disturbance. In the Rodeo-Chediski Fire, Chihuahua pine (*Pinus leiophylla*) resprouted post-fire, but the ability to resprout was negatively influenced by increasing fire intensity. Smaller trees had greater mortality due to fire; however, of the survivors at any age class, these younger trees were more likely to resprout from their base. The authors suggest that repeated higher severity fires may provide a regeneration advantage to sprouting species such as the Chihuahua pine over nonsprouting species such as ponderosa pine.

Linkages

- **Fire severity on Mortality, survivorship, community change**

Chihuahua pine (*Pinus leiophylla*) is one of the few pine species that can resprout from its base after a disturbance. Smaller trees had greater mortality due to fire; however, of the survivors at any age class, these younger trees were more likely to resprout from their base.

- **Fire severity on Dispersal, regeneration, establishment**

Chihuahua pine (*Pinus leiophylla*) is one of the few pine species that can resprout from its base after a disturbance. In the Rodeo-Chediski fire, Chihuahua pine resprouted post-fire, but the ability to resprout was negatively influenced by increasing fire intensity. Smaller trees had greater mortality due to fire; however, of the survivors at any age class, these younger trees were more likely to resprout from their base.

- **Fire severity on Species composition, invasives, structure**

The authors suggest that repeated higher severity fires may confer an advantage to sprouting species such as the Chihuahua pine (*Pinus leiophylla*) over nonsprouting species such as ponderosa pine.

20. **Bessie, W.C.; Johnson, E.A. 1995.** The relative importance of fuels and weather on fire behavior in subalpine forests. *Ecology*. 76(3): 747–762.
<https://doi.org/10.2307/1939341>

Location

Kananaskis Valley, Alberta, Canada; Vermillion Pass area of Banff and Kootenay National Parks, Canada

Ecosystem type(s)

Upland subalpine conifer forest

Summary: What the authors did and why

The authors used the fire models of Rothermel (1972) and Van Wagner (1977) to predict surface fire intensity and crown fire initiation based on fuel data from upland subalpine conifer forest stands using daily weather variables. They used this information to determine the relative importance of fuel components versus weather components on fire behavior.

Publication findings

The authors found that surface fire intensity and crown fire initiation were both strongly related to weather factors (temperature, precipitation, wind speed, and RH), significantly more so than fuel components. Subalpine forests historically burned only during extreme weather events, such as prolonged drought. The authors suggest that during extreme weather events, fuels become increasingly less important in determining fire behavior as forest stands pass a threshold that

permits crown fire initiation. They also found a significant correlation between annual area burned and fire intensity directly related to the weather variable frequency. Years where large area burned were associated with extreme fire weather and subsequent high intensity fire.

Linkages

- **Drought on Annual area burned, fire size**

The authors found a significant correlation between annual area burned and fire intensity directly related to the weather variable frequency. Years where large area burned were associated with extreme fire weather and subsequent high intensity fire.

- **Temperature, RH, VPD on Annual area burned, fire size**

The authors found a significant correlation between annual area burned and fire intensity directly related to the weather variable frequency. Years where large area burned were associated with extreme fire weather and subsequent high intensity fire.

- **Drought on Fire behavior, fire type, fire intensity**

The authors found that surface fire intensity and crown fire initiation were both strongly related to weather factors (temperature, precipitation, wind speed, and RH), significantly more so than fuel components. Subalpine forests historically burned only during extreme weather events, such as prolonged drought. The authors suggest that during extreme weather events, fuels become increasingly less important in determining fire behavior as forest stands pass a threshold that permits crown fire initiation. They also found a significant correlation between annual area burned and fire intensity directly related to the weather variable frequency. Years where large area burned were associated with extreme fire weather and subsequent high intensity fire.

- **Temperature, RH, VPD on Fire behavior, fire type, fire intensity**

The authors found that surface fire intensity and crown fire initiation were both strongly related to weather factors (temperature, precipitation, wind speed, and RH), significantly more so than fuel components. Subalpine forests historically burned only during extreme weather events, such as prolonged drought. The authors suggest that during extreme weather events, fuels become increasingly less important in determining fire behavior as forest stands pass a threshold that permits crown fire initiation. They also found a significant correlation between annual area burned and fire intensity directly related to the weather variable frequency. Years where large area burned were associated with extreme fire weather and subsequent high intensity fire.

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21. **Bigler, C.; Kulakowski, D.; Veblen, T.T. 2005.** Multiple disturbance interactions and drought influence fire severity in Rocky Mountain subalpine forests. *Ecology*. 86(11): 3018–3029. <https://doi.org/10.1890/05-0011>

Location

Flat Tops Wilderness, White River National Forest, Colorado, USA

Ecosystem type(s)

Subalpine forest

Summary: What the authors did and why

The authors studied the effects of past disturbances, specifically beetle outbreak and extreme drought, on the spatial variability of fire severity.

Publication findings

Stands affected by beetle outbreak burned at higher severities and more often than expected, although forest cover type and vegetation were stronger predictors of severity than previous disturbance or elevation. Furthermore, the authors point to other studies in nearby stands that did not see a relationship between fire and beetle outbreaks. They suggest that beetle outbreaks followed by extreme drought, as occurred prior to the fire in the study, or wind is required to increase the flammability of the large, dead fuels, resulting in increased fire severity.

Linkages

- **Drought on Fire severity**

Beetle outbreaks followed by extreme drought, as occurred prior to the fire in the study, or wind is required to increase the flammability of the large, dead fuels, resulting in increased fire severity.

- **Fire severity on Fuels**

Stands affected by beetle outbreak burned at higher severities and more often than expected, although forest cover type and vegetation were stronger predictors of severity than previous disturbance or elevation. Furthermore, the authors point to other studies in nearby stands that did not see a relationship between fire and beetle outbreaks. They suggest that beetle outbreaks followed by extreme drought, as occurred prior to the fire in the study, or wind is required to increase the flammability of the large, dead fuels, resulting in increased fire severity.

22. **Biondi, F.; Jamieson, L.P.; Strachan, S.; Sibold, J. 2011.** Dendroecological testing of the pyroclimatic hypothesis in the central Great Basin, Nevada, USA. *Ecosphere*. 2(1): 1–20. <https://doi.org/10.1890/ES10-00068.1>

Location

Great Basin, Nevada, USA

Ecosystem type(s)

Piñon-juniper woodlands

Summary: What the authors did and why

The authors reconstructed the fire history of a piñon-juniper woodland and identified climate-fire relationships in a case study for an area of the Great Basin in southeastern Nevada.

Publication findings

Fire was common historically in this area; mean fire return intervals were about 4 years until about 1860, coinciding with the arrival of European settlers and the removal of Native Americans who deliberately set fires for hunting and agricultural use.

The authors suggest that long periods of drought may not be necessary to dry fuels enough to burn in the naturally arid climate of the Great Basin. Consequently, fires were more common in wet years, when fuels were more abundant, than dry years.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors suggest that long periods of drought may not be necessary to dry fuels enough to burn in the naturally arid climate of the Great Basin. Consequently, fires were more common in wet years, when fuels were more abundant, than dry years.

23. **Birch, D.S.; Morgan, P.; Kolden, C.A.; Abatzoglou, J.T.; Dillon, G.K.; Hudak, A.T.; Smith, A.M. 2015.** Vegetation, topography and daily weather influenced burn severity in central Idaho and western Montana forests. *Ecosphere*. 6(1): 1–23. <https://doi.org/10.1890/ES14-00213.1>

Location

Idaho and Montana, USA

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors compared the strength or importance value of “bottom-up” controls, such as vegetation and topography, to fire danger indices and daily weather variables on fire severity and daily area burned across 42 large forest fires in central Idaho and western Montana using Random Forest models.

Publication findings

The optimized Random Forest model found that vegetation and topography were stronger predictors of burn severity than daily weather. Temperature and humidity were only marginally important. Wind speed percentile was the strongest climate or weather predictor of fire severity (and third strongest predictor overall) for daily area burned when considering only the largest daily areas burned (99.5 percentile, or >600 ha) while temperature and humidity were not important in this model. The authors suggest that the factors influencing fire severity are not necessarily the same as those that control fire extent.

Linkages

- **Temperature, RH, VPD on Fire severity**

The optimized Random Forest model found that vegetation and topography were stronger predictors of burn severity than daily weather. Temperature and humidity were only marginally important. Wind speed percentile was the strongest climate or weather predictor of fire severity (and third strongest predictor overall) for daily area burned when considering only the largest daily areas burned (99.5 percentile, or >600 ha) while temperature and humidity were not important in this model. The authors suggest that the factors influencing fire severity are not necessarily the same as those that control fire extent.

- **Temperature, RH, VPD on Annual area burned, fire size**

Temperature and humidity were only marginally important. Wind speed percentile was the strongest climate or weather predictor of fire severity (and third strongest predictor overall) for daily area burned when considering only the largest daily areas burned (99.5 percentile, or >600 ha) while temperature and humidity were not important in this model. The authors suggest that the factors influencing fire severity are not necessarily the same as those that control fire extent.

24. **Blondahl, E.M.; Kolden, C.A.; Meddens, A.J.; Lutz, J.A. 2019.** The importance of small fire refugia in the central Sierra Nevada, California, USA. *Forest Ecology and Management*. 432: 1041–1052. <https://doi.org/10.1016/j.foreco.2018.10.038>

Location

Yosemite Rim Fire, California, USA

Ecosystem type(s)

Lower-montane forest zone; mixed-conifer ecosystems; white fir–sugar pine forest

Summary: What the authors did and why

The authors characterized the spatial distribution and size of unburned patches within the study area and examined the relationships between environmental variables and unburned patches to predict the occurrence of small refugia.

Publication findings

Small fire refugia occurred on all landscape positions and within areas burned at all burn severity classes. Individual patches were not significantly related to burn severity, and the authors suggest that refugia may arise within high- or low-severity burned areas for different reasons, such as fuel continuity or changes in weather conditions during the fire. However, the authors found that the amount and distance between refugia decreased with increasing burn severity.

They also found that small fire refugia were more likely 11 to 30 m from a stream, and in areas with low prefire basal area, but the authors suggest that data limitations reduced the predictive power of environmental variables on refugia.

Linkages

- **Spatial pattern, landscape mosaic on Mortality, survivorship, community change**

Small fire refugia occurred on all landscape positions and within areas burned at all burn severity classes. Individual patches were not significantly related to burn severity, and the authors suggest that refugia may arise within high- or low-severity burned areas for different reasons, such as fuel continuity or changes in weather conditions during the fire. However, the authors found that the amount and distance between refugia decreased with increasing burn severity.

- **Fire severity on Mortality, survivorship, community change**

Small fire refugia occurred on all landscape positions and within areas burned at all burn severity classes. Individual patches were not significantly related to burn severity, and the authors suggest that refugia may arise within high or low severity burned areas due to different reasons, such as fuel continuity or changes in weather conditions during the fire. However, the authors found that the amount and distance between refugia decreased with increasing burn severity.

25. **Brooks, M.L.; Matchett, J.R. 2006.** Spatial and temporal patterns of wildfires in the Mojave Desert, 1980–2004. *Journal of Arid Environments*. 67: 148–164.
<https://doi.org/10.1016/j.jaridenv.2006.09.027>

Location

Mojave Desert, USA

Ecosystem type(s)

Desert; shrubland; woodland

Summary: What the authors did and why

The authors described the spatial and temporal patterns and potential trends of wildfire in the Mojave Desert from 1980 to 2004.

Publication findings

Fire size in the lower and middle elevations are related to rainfall in the season previous to the fire season, but at higher elevations, this pattern does not hold. For the mid-elevation and, less so, the lower elevations of the Mojave Desert, the increase in area and continuity of nonnative grasses after wet years increased the average size of fires during those years. However, there was no significant increasing trend in annual area burned in the Mojave Desert even though earlier literature of more limited time periods reported an increasing trend.

Linkages

- **Snowpack, snow and rain on Annual area burned, fire size**

Fire size in the lower and middle elevations are related to rainfall in the season previous to the fire season, but at higher elevations, this pattern does not hold.

- **Annual area burned, fire size on Species composition, invasives, structure**

For the mid-elevation and, less so, the lower elevations of the Mojave Desert, the increase in area and continuity of nonnative grasses after wet years increased the average size of fires during those years. However, there was no significant increasing trend in annual area burned in the Mojave Desert even though earlier literature of more limited time periods reported an increasing trend.

26. **Brown, K.J.; Clark, J.S.; Grimm, E.C.; Donovan, J.J.; Mueller, P.G.; Hansen, B.C.S.; Stefanova, I. 2005.** Fire cycles in North American interior grasslands and their relation to prairie drought. *Proceedings of the National Academy of Sciences*. 102(25): 8865–8870. <https://doi.org/10.1073/pnas.0503621102>

Location

Kettle Lake, North Dakota, USA

Ecosystem type(s)

Grassland prairie

Summary: What the authors did and why

The authors reconstructed the historical fire history and fire–climate relationships throughout the Holocene by sampling fossilized charcoal cores in the grassland prairies of the Northern Great Plains.

Publication findings

The authors found that fire frequency was not consistent during the Holocene, but that fire activity was driven by short-term climatic cycles. Wetter periods were associated with higher fire occurrence due to the increase in available vegetation, whereas dry periods were associated with less dense vegetation and therefore less fire activity.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that fire frequency was not consistent during the Holocene, but that fire activity was driven by short-term climatic cycles. Wetter periods were associated with higher fire occurrence due to the increase in available vegetation, whereas dry periods were associated with less dense vegetation and therefore less fire activity.

- **Snowpack, snow and rain on Fire frequency, fire rotation, fire return interval**

The authors found that fire frequency was not consistent during the Holocene, but that fire activity was driven by short-term climatic cycles. Wetter periods were associated with higher fire occurrence due to the increase in available vegetation, whereas dry periods were associated with less dense vegetation and therefore less fire activity.

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27. **Brown, P.M. 2006.** Climate effects on fire regimes and tree recruitment in Black Hills ponderosa pine forests. *Ecology*. 87(10): 2500–2510.
[https://doi.org/10.1890/0012-9658\(2006\)87\[2500:CEOFRA\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2006)87[2500:CEOFRA]2.0.CO;2)

Location

Black Hills, South Dakota, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors examined long-term, historical fire and postfire recruitment chronologies of ponderosa pine in the Black Hills to evaluate the relationship between climate, fire years, and tree recruitment patterns and their effects on forest structure over time.

Publication findings

The authors found that regional fire years were highly associated with drought with no prior lag years of moisture required. They suggest that because fire return intervals were generally longer in the Black Hills than in ponderosa pine forests of the Southwest, fuels had adequate time to build up between fire years. Fire years in the Black Hills were also related to La Niña years (summer-dry conditions) and cool phases of PDO, which magnifies the effects of the La Niña drought. Finally, episodes of synchronous tree recruitment and growth were highly associated with periods of increased moisture. These pluvial periods limited fire frequency and likely contributed to the increased establishment and survivorship of seedlings. The authors propose that variations in fire frequency and timing were more important in shaping forest structure than variations in fire severity.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that regional fire years were highly associated with drought with no prior lag years of moisture required. They suggest that because fire return intervals were generally longer in the Black Hills than in ponderosa pine forests of the Southwest, fuels had adequate time to build up between fire years. Fire years in the Black Hills were also related to La Niña years (summer-dry conditions) and cool phases of PDO, which magnifies the effects of the La Niña drought.

- **Fire frequency, fire rotation, fire return interval on Mortality, survivorship, community change**

Episodes of synchronous tree recruitment and growth were highly associated with periods of increased moisture. These pluvial periods limited fire frequency and likely contributed to the increased establishment and survivorship of seedlings. The authors propose that variations in fire frequency and timing were more important in shaping forest structure than variations in fire severity.

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

Episodes of synchronous tree recruitment and growth were highly associated with periods of increased moisture. These pluvial periods limited fire frequency and likely contributed to the increased establishment and survivorship of seedlings. The authors propose that variations in fire frequency and timing were more important in shaping forest structure than variations in fire severity.

- **Fire severity on Species composition, invasives, structure**

The authors propose that variations in fire frequency and timing were more important in shaping forest structure than variations in fire severity.

28. **Brown, P.M.; Wu, R. 2005.** Climate and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. *Ecology*. 86(11): 3030–3038. <https://doi.org/10.1890/05-0034>

Location

Archuleta Mesa, Colorado, USA

Ecosystem type(s)

Douglas-fir ecosystem; Gambel oak ecosystem; piñon-juniper woodlands; ponderosa pine ecosystem

Summary: What the authors did and why

The authors used tree-ring chronologies to compare timing of historical ponderosa pine (*Pinus ponderosa*) recruitment to tree-ring based climate reconstruction variables, including annual precipitation, PDSI, Southern Oscillation Index, and Niño3 sea surface temperature (SST) index, and also fire disturbance to understand how both climate and fire have influenced current forest stand structure.

Publication findings

The authors linked a large period of megadrought in the 1580s to high mortality of ponderosa pine (*Pinus ponderosa*) as no trees predated this event, and seedlings nearest the time of the event grew especially slowly. Due to the lack of surviving trees, there is no evidence of fire-caused mortality during this event.

Pulses of regeneration occurred during several periods of increased moisture; however, the authors suggest it was the absence of fire that allowed many trees to survive into adulthood; these trees were then exposed to episodic mortality events caused by fire or other disturbance. Climate change likely affected fuel conditions that were less favorable for burning during these fire-quiescent periods, allowing fuels to build up until drier years when synchronous regional fires occurred. This pattern has been commonly attributed to the ENSO cycle, with wet El Niño years followed by dry La Niña years.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

Climate change likely affected fuel conditions that were less favorable for burning during these fire-quiescent periods, allowing fuels to build up until drier years when synchronous regional fires occurred. This pattern has been commonly attributed to the ENSO cycle, with wet El Niño years followed by dry La Niña years.

- **Snowpack, snow and rain on Fire frequency, fire rotation, fire return interval**

Successful regeneration pulses occurred when conditions were less conducive to fire, such as during periods of increased precipitation or during cycles of El Niño, which are typically wet. Synchronous fire years typically occurred during La Niña years following a 1- to 3-year wet period.

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

Pulses of regeneration occurred during several periods of increased moisture; however, the authors suggest it was the absence of fire that allowed many trees to survive into adulthood; these trees were then exposed to episodic mortality events caused by fire or other disturbance. Climate change likely affected fuel conditions that were less favorable for burning during these fire-quiescent periods allowing fuels to build up until drier years when synchronous regional fires occurred. This pattern has been commonly attributed to the ENSO cycle, with wet El Niño years followed by dry La Niña years.

- **Fire frequency, fire rotation, fire return interval on Mortality, survivorship, community change**

The authors suggest that even-aged cohorts of ponderosa pine are not the result of severe crown fire, but long fire-free intervals that allowed seedlings to survive long enough to resist fire-induced mortality.

29. **Brown, P.M.; Kaufmann, M.R.; Shepperd, W.D. 1999.** Long-term, landscape patterns of past fire events in a montane ponderosa pine forest of central Colorado. *Landscape Ecology*. 14(6): 513–532.

Location

Cheesman Lake watershed, Colorado, USA

Ecosystem type(s)

Montane forest: ponderosa pine forest

Summary: What the authors did and why

The authors reconstructed the fire history of a montane ponderosa pine forest

stand to understand the effects of fire on the current heterogeneity of the forest structure and composition.

Publication findings

The authors found considerable variation in the spatial extent, frequency, seasonality, and severity of fire over the five centuries within the project area. The authors suggest that the extensive variation in the fire regime at the project site has resulted in changes in vegetation spatial patterns at multiple scales over time, leading to greater landscape heterogeneity.

Linkages

- **Spatial pattern, landscape mosaic on Species composition, invasives, structure**

The authors found considerable variation in the spatial extent, frequency, seasonality, and severity of fire over the five centuries within the project area. The authors suggest that the extensive variation in the fire regime at the project site has resulted in changes in vegetation spatial patterns at multiple scales over time leading to greater landscape heterogeneity.

30. **Brown, P.M.; Kaye, M.W.; Huckaby, L.S.; Baisan, C.H. 2001.** Fire history along environmental gradients in the Sacramento Mountains, New Mexico: Influences of local patterns and regional processes. *Ecoscience*. 8(1): 115–126.
<https://doi.org/10.1080/11956860.2001.11682637>

Location

Sacramento Mountains, New Mexico, USA

Ecosystem type(s)

Gradient: mixed-conifer forest; piñon-juniper woodlands; ponderosa pine forest

Summary: What the authors did and why

The authors reconstructed the historical fire regime along a gradient of forest types in the study area to determine the influences of regional climate and local human land use across different spatiotemporal scales.

Publication findings

The authors found synchrony of fire occurrence across the region when dry years were preceded by wet years. Strong El Niño events associated with especially wet years suppressed fire regionally, but also resulted in a pulse of fine fuel growth that became the primary fuels for surface fire during drought years. The authors found that at local scales, however, topography and elevation had a stronger influence on fire frequency and pattern than climate.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found synchrony of fire occurrence across the region when dry years were preceded by wet years. Strong El Niño events associated with especially wet years suppressed fire regionally, but also resulted in a pulse of fine fuel growth that became the primary fuels for surface fire during drought years. The authors found that at local scales, however, topography and elevation had a stronger influence on fire frequency and pattern than climate.

- **Snowpack, snow and rain on Fire frequency, fire rotation, fire return interval**

The authors found synchrony of fire occurrence across the region when dry years were preceded by wet years. Strong El Niño events associated with especially wet years suppressed fire regionally, but also resulted in a pulse of fine fuel growth that became the primary fuels for surface fire during drought years. The authors found that at local scales, however, topography and elevation had a stronger influence on fire frequency and pattern than climate.

31. **Cocke, A.E.; Fulé, P.Z.; Crouse, J.E. 2005.** Forest change on a steep mountain gradient after extended fire exclusion: San Francisco Peaks, Arizona, USA. *Journal of Applied Ecology*. 42(5): 814–823. <https://doi.org/10.1111/j.1365-2664.2005.01077.x>

Location

San Francisco Peaks, Arizona, USA

Ecosystem type(s)

Forested ecosystems: aspen; bristlecone pine; mixed-conifer; ponderosa pine; spruce-fir

Summary: What the authors did and why

The authors compared current forest vegetation structure and composition across an elevational gradient to a dendrochronological reconstruction of vegetation from 1876 to understand the effects of forest management, specifically fire exclusion.

Publication findings

All forest types were significantly less dense in 1876 compared to 2000; however, the changes were less apparent in the higher altitude forests. The authors observed a shift in composition toward more mesic species in lower altitude forests. They suggest that because fire frequency is typically lower in higher altitude forests, the impact of fire exclusion was not as great as low altitude forests, where frequent fire thinned encroaching fire-susceptible mesic species.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

All forest types were significantly less dense in 1876 compared to 2000; however, the changes were less apparent in the higher altitude forests. The authors observed a shift in composition toward more mesic species in lower altitude forests. They suggest that because fire frequency is typically lower in higher altitude forests, the impact of fire exclusion was not as great as low altitude forests, where frequent fire thinned encroaching fire-susceptible mesic species.

32. **Collins, B.M.; Omi, P.N.; Chapman, P.L. 2006.** Regional relationships between climate and wildfire-burned area in the Interior West, USA. *Canadian Journal of Forest Research*. 36(3): 699–709. <https://doi.org/10.1139/x05-264>

Location

Interior West, USA; southwestern United States; Colorado, USA

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors studied the influence of the AMO and PDO on the relationships between interannual climate and area burned across climate regions of the Interior West and climate divisions of Colorado.

Publication findings

The authors found that area burned was strongly related to PDSI across all regions of the Interior West, but that PDSI had a varying relationship with phases of AMO and PDO in the different regions. For example, in Arizona and New Mexico, area burned was most strongly related to PDSI during the warm phase of the AMO (long-term drought conditions typical) or the cool phase of PDO (cooler and wetter winters typical), whereas the relationship was either weak or not significant in the other regions during these same periods.

Linkages

- **Drought on Annual area burned, fire size**

The authors found that area burned was strongly related to PDSI across all regions of the Interior West, but that PDSI had a varying relationship with phases of AMO and PDO in the different regions. For example, in Arizona and New Mexico, area burned was most strongly related to PDSI during the warm phase of the AMO (long-term drought conditions typical) or the cool phase of PDO (cooler and wetter winters typical), whereas the relationship was either weak or not significant in the other regions during these same periods.

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33. **Coop, J.D.; Givnish, T.J. 2007.** Spatial and temporal patterns of recent forest encroachment in montane grasslands of the Valles Caldera, New Mexico, USA. *Journal of Biogeography*. 34(5): 914–927.
<https://doi.org/10.1111/j.1365-2699.2006.01660.x>

Location

Valles Caldera, New Mexico, USA

Ecosystem type(s)

Montane and subalpine grassland

Summary: What the authors did and why

The authors quantitatively assessed the spatial and temporal patterns of tree invasion into montane and subalpine grasslands in the study area. They further assessed the effects of topography, climate, and land use practices on these changes in grassland structure over time.

Publication findings

The authors found that the interruption of frequent fire in the late 19th century was the main cause of tree invasion on upper mountain slopes and mountain tops within the region.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors found that the interruption of frequent fire in the late 19th century was the main cause of tree invasion on upper mountain slopes and mountain tops within the region.

34. **Coop, J.D.; Holsinger, L.; McClernan, S.; Parks, S.A. 2015.** Influences of previous wildfires on change, resistance, and resilience to reburning in a montane southwestern landscape. In: Keane, R.E.; Jolly, M.; Parsons, R.; Riley, K., tech. eds. *Proceedings of the Large Wildland Fires conference*; 2014 May 19–23; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 273–276.

Location

Las Conchas Fire, New Mexico, USA

Ecosystem type(s)

Mixed-conifer forests; ponderosa pine forests

Summary: What the authors did and why

The authors used nonmetric multidimensional scaling to assess how time since fire and burn severity of a previous fire affected the severity of patches on the Las Conchas Fire, and how vegetation patterns changed following the fire.

Publication findings

The authors found that earlier burns were associated with shifts from forested to open savannah, meadow, oak scrub, and ruderal plant community types. Previous shifts toward nonforested states were strongly reinforced by reburning. Furthermore, those fire perimeters that had not been burned recently prior to the Las Conchas Fire exhibited the largest changes in community composition whereas those perimeters that reburned showed reduced impacts of fire on the vegetation communities. Prior to the Las Conchas Fire, the vegetation in the recently burned communities had reduced canopy cover, and higher cover of shrubs and grasses.

The authors suggest that areas converted to nonforest types after wildfire were both more resistant (reduced burn severity) and more resilient (improved vegetation recovery) to subsequent burns than forested sites.

Linkages

- **Fire severity on Fuels**

Prior to the Las Conchas fire, the vegetation in the recently burned communities had reduced canopy cover, and higher cover of shrubs and grasses.

The authors found earlier burns were associated with shifts from forested to open savannah, meadow, oak scrub, and ruderal plant community types.

- **Fire severity on Species composition, invasives, structure**

Fire perimeters that had not been burned recently prior to the Las Conchas fire exhibited the largest changes in community composition whereas those perimeters that reburned showed reduced impacts of fire on the vegetation communities. Prior to the Las Conchas fire, the vegetation in the recently burned communities had reduced canopy cover, and higher cover of shrubs and grasses.

In high frequency and low severity fire-adapted ecosystems, increases in the frequency of high severity fire may lead to changes in vegetation of forested sites to alternative communities. The authors found earlier burns were associated with shifts from forested to open savannah, meadow, oak scrub, and ruderal plant community types.

- **Fire frequency, fire rotation, fire return interval on Fuels**

Prior to the Las Conchas fire, the vegetation in the recently burned communities had reduced canopy cover, and higher cover of shrubs and grasses.

35. **Coppoletta, M.; Merriam, K.E.; Collins, B.M. 2016.** Post-fire vegetation and fuel development influences fire severity patterns in reburns. *Ecological Applications*. 26(3): 686–699. <https://doi.org/10.1890/15-0225>

Location

Sierra Nevada, California, USA

Ecosystem type(s)

Mixed-conifer forest

Summary: What the authors did and why

The authors sampled field plots that reburned to examine how biophysical characteristics, topography, fire weather, time-since-fire, and initial fire severity affected subsequent reburn severity.

Publication findings

The authors found that areas that burned initially as high or moderate severity fire were more likely to reburn at high severity due to the increase in snags and shrub vegetation as a result of the first fire entry. Average daytime temperature was the most important predictor of high severity fire in the reburn. When temperatures exceeded a threshold of 27.3 °C, snag basal area and shrub cover were the strongest variable driving reburn severity patterns. The authors also found that as time between fires increased, severity also increased.

Linkages

- **Temperature, RH, VPD on Fire severity**

Average daytime temperature was the most important predictor of high severity fire in the reburn. When temperatures exceeded a threshold of 27.3°C, snag basal area and shrub cover were the strongest variable driving reburn severity patterns.

- **Fire severity on Fuels**

The authors found that areas that burned initially as high or moderate severity fire were more likely to reburn at high severity due to the increase in snags and shrub vegetation as a result of the first fire entry.

- **Fire frequency, fire rotation, fire return interval on Fuels**

The authors found that areas that burned initially as high or moderate severity fire were more likely to reburn at high severity due to the increase in snags and shrub vegetation as a result of the first fire entry. The authors also found that as time between fires increased, severity also increased.

36. **Covington, W.W.; Moore, M.M. 1994.** Southwestern ponderosa forest structure: Changes since Euro-American settlement. *Journal of Forestry*. 92(1): 39–47.

<https://doi.org/10.1093/jof/92.1.39>

Location

Bar-M Canyon, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors sampled the structure and composition of a ponderosa pine forest

stand along a soil type and topographic gradient to assess changes since Euro-American settlement. The authors also simulated the future trajectory of the stand using ECOSIM through the year 2027.

Publication findings

Since Euro-American settlement, the density of ponderosa pine stands has increased drastically. Prolific regeneration due to fire exclusion, logging, and climate has changed the age structure and density of the forests over the past century. Without management or the reintroduction of fire to increase tree mortality, the authors predict trends in increasing tree density and other changes to forest structure to continue, and an increase in frequency of high-severity crown fire.

Linkages

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

Since Euro-American settlement, the density of ponderosa pine stands has increased drastically. Prolific regeneration due to fire exclusion, logging, and climate has changed the age structure and density of the forests over the past century. Without management or the reintroduction of fire to increase tree mortality, the authors predict trends in increasing tree density and other changes to forest structure to continue, and an increase in frequency of high-severity crown fire.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

Since Euro-American settlement, the density of ponderosa pine stands has increased drastically. Prolific regeneration due to fire exclusion, logging, and climate has changed the age structure and density of the forests over the past century. Without management or the reintroduction of fire to increase tree mortality, the authors predict trends in increasing tree density and other changes to forest structure to continue, and an increase in frequency of high-severity crown fire.

37. **Crimmins, M.A. 2006.** Synoptic climatology of extreme fire-weather conditions across the southwest United States. *International Journal of Climatology: A Journal of the Royal Meteorological Society*. 26(8): 1001–1016.
<https://doi.org/10.1002/joc.1300>

Location

Southwestern United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors used three case-study wildfires to relate synoptic climate variability to the Fosberg Fire-Weather Index, a daily surface fire-weather index, to determine which synoptic weather patterns are associated with extreme fire danger across the southwestern United States.

Publication findings

The author found that extreme fire weather values are most strongly associated with circulation patterns of high gradient, southwest flow across the Southwest, creating strong winds. Early season variability in the RH also related strongly to increased levels of fire danger. Seasonal changes in RH levels, strength of height gradient, and geopotential heights were all important in modeling the relationship between synoptic circulation patterns and extreme fire-weather days.

Linkages

- **Temperature, RH, VPD on Fire behavior, fire type, fire intensity**

The author found that extreme fire weather values are most strongly associated with circulation patterns of high gradient, southwest flow across the Southwest, creating strong winds. Early season variability in the RH also related strongly to increased levels of fire danger. Seasonal changes in RH levels, strength of height gradient, and geopotential heights were all important in modeling the relationship between synoptic circulation patterns and extreme fire-weather days.

38. **Crimmins, M.A. 2011.** Interannual to decadal changes in extreme fire weather event frequencies across the southwestern United States. *International Journal of Climatology*. 31(11): 1573–1583. <https://doi.org/10.1002/joc.2184>

Location

Arizona and New Mexico, USA

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors examined the influence of ENSO and PDO on daily fire weather variability and extreme fire weather events.

Publication findings

Teleconnections between ENSO variability and fire activity are well documented across the Southwest. The authors suggest that shifts in the PDO may be a stronger gauge of the frequency of extreme fire weather than ENSO cycles for the Southwest, specifically. La Niña events typically bring dry winters to the Southwest and are related to a higher frequency of extreme fire weather events in May, especially when the PDO is in the negative phase, causing consecutive drought years. Years associated with a positive PDO phase tend to result in wet winters, and consequently, rapid accumulation of fuels. A switch to a negative PDO phase

may dry excess fuels, leading to earlier and more extreme fire activity during these cycles.

Linkages

- **Drought on Fire timing, fire seasonality**

Teleconnections between ENSO variability and fire activity are well documented across the Southwest. The authors suggest that shifts in the PDO may be a stronger gauge of the frequency of extreme fire weather than ENSO cycles for the Southwest, specifically. La Niña events typically bring dry winters to the Southwest and are related to a higher frequency of extreme fire weather events in May, especially when the PDO is in the negative phase, causing consecutive drought years. Years associated with a positive PDO phase tend to result in wet winters, and consequently, rapid accumulation of fuels. A switch to a negative PDO phase may dry excess fuels leading to earlier and more extreme fire activity during these cycles.

- **Snowpack, snow and rain on Fire timing, fire seasonality**

Teleconnections between ENSO variability and fire activity are well documented across the Southwest. The authors suggest that shifts in the PDO may be a stronger gauge of the frequency of extreme fire weather than ENSO cycles for the Southwest, specifically. La Niña events typically bring dry winters to the Southwest and are related to a higher frequency of extreme fire weather events in May, especially when the PDO is in the negative phase, causing consecutive drought years. Years associated with a positive PDO phase tend to result in wet winters, and consequently, rapid accumulation of fuels. A switch to a negative PDO phase may dry excess fuels leading to earlier and more extreme fire activity during these cycles.

- **Drought on Fire severity**

Teleconnections between ENSO variability and fire activity are well documented across the Southwest. The authors suggest that shifts in the PDO may be a stronger gauge of the frequency of extreme fire weather than ENSO cycles for the Southwest, specifically. La Niña events typically bring dry winters to the Southwest and are related to a higher frequency of extreme fire weather events in May, especially when the PDO is in the negative phase, causing consecutive drought years. Years associated with a positive PDO phase tend to result in wet winters, and consequently, rapid accumulation of fuels. A switch to a negative PDO phase may dry excess fuels leading to earlier and more extreme fire activity during these cycles.

- **Snowpack, snow and rain on Fire severity**

Teleconnections between ENSO variability and fire activity are well documented across the Southwest. The authors suggest that shifts in the PDO may be a

stronger gauge of the frequency of extreme fire weather than ENSO cycles for the Southwest, specifically. La Niña events typically bring dry winters to the Southwest and are related to a higher frequency of extreme fire weather events in May, especially when the PDO is in the negative phase, causing consecutive drought years. Years associated with a positive PDO phase tend to result in wet winters, and consequently, rapid accumulation of fuels. A switch to a negative PDO phase may dry excess fuels leading to earlier and more extreme fire activity during these cycles.

39. **Crimmins, M.A.; Comrie, A.C. 2004.** Interactions between antecedent climate and wildfire variability across south-eastern Arizona. *International Journal of Wildland Fire*. 13(4): 455–466. <https://doi.org/10.1071/WF03064>

Location

Arizona, USA

Ecosystem type(s)

Gradient: desert scrub; desert grassland; mixed-conifer forest; montane fir ecosystem; oak woodland; subalpine forest

Summary: What the authors did and why

The authors studied the relationship between antecedent climate conditions (temperature, precipitation, and PDSI) at specific lags and wildfire activity from low to high elevation.

Publication findings

The authors found that across the gradient, total area burned is significantly correlated to moisture-related (except actual precipitation) factors in the year(s) previous to the fire season. The authors suggest that this is related to the increase in fine fuel production. The lags between high and low elevation sites, however, differed. Low elevation sites were associated with wet antecedent conditions up until the fire season, whereas high elevation sites were associated with wet conditions up to 3 years prior. However, the authors did not find any correlations between total precipitation and fire at any yearly or seasonal lags. They also found that drought was not necessarily associated with increased fire activity and that in certain vegetation types, fuels dry sufficiently to burn under natural conditions.

Linkages

- **Drought on Annual area burned, fire size**

The authors found that across the gradient, total area burned is significantly correlated to moisture-related (except actual precipitation) factors in the year(s) previous to the fire season. The authors suggest that this is related to the increase in fine fuel production. The lags between high and low elevation sites, however, differed. Low elevation sites were associated with wet antecedent conditions up until the fire season, whereas high elevation sites were associated with wet condition up to 3 years prior. However, the authors did not find any correlations

between total precipitation and fire at any yearly or seasonal lags. They also found that drought was not necessarily associated with increased fire activity and that in certain vegetation types, fuels dry sufficiently to burn under natural conditions.

- **Snowpack, snow and rain on Annual area burned, fire size**

The authors found that across the gradient, total area burned is significantly correlated to moisture-related (except actual precipitation) factors in the year(s) previous to the fire season. The authors suggest that this is related to the increase in fine fuel production. The lags between high and low elevation sites, however, differed. Low elevation sites were associated with wet antecedent conditions up until the fire season, whereas high elevation sites were associated with wet condition up to 3 years prior. However, the authors did not find any correlations between total precipitation and fire at any yearly or seasonal lags.

40. **Dennison, P.E.; Brewer, S.C.; Arnold, J.D.; Moritz, M.A. 2014.** Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters*. 41(8): 2928–2933. <https://doi.org/10.1002/2014GL059576>

Location

Western United States; Omernik Level II and Level III ecoregions of the United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors examined regional trends in large fire occurrence, total area burned, fire size, and day of year of ignition from 1984 to 2011. The authors also assessed trends in climate indicators, including maximum temperature, precipitation, and PDSI.

Publication findings

The authors found positive trends in the number of large fires in most ecoregions of the western United States, including the Arizona–New Mexico Mountains, with an average increase of 0.6 large fires per year. The ecoregions with trends toward increased fire activity also concurrently displayed increasing trends in drought severity over the period of the analysis. While the authors acknowledge that it is difficult to directly correlate human-caused climate change and fire activity, they assert that regardless of cause, changes in fire activity are part of larger trends tied to higher temperature and drought that are likely to continue.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

The authors found positive trends in the number of large fires in most ecoregions of the western United States, including the Arizona–New Mexico Mountains with an average increase of 0.6 large fires per year. The ecoregions with trends toward

increased fire activity also concurrently displayed increasing trends in drought severity over the period of the analysis; however, the authors do not directly correlate climate and fire in this study.

41. **Diaz, H.F.; Swetnam, T.W. 2013.** The wildfires of 1910: Climatology of an extreme early twentieth-century event and comparison with more recent extremes. *Bulletin of the American Meteorological Society*. 94(9): 1361-1370.
<https://doi.org/10.1175/BAMS-D-12-00150.1>

Location

Western United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors assessed the climate conditions preceding and during a period of intense fire activity across the western United States in the summer of 1910. They further evaluated other large regional fire years to determine if analogous climate conditions occurred during those periods of high fire activity.

Publication findings

The authors found that anomalously warm conditions occurred during a period of intense fire activity in the summer of 1910. A strong La Niña pattern in 1910 likely contributed to warming and drought during the spring and summer prior to the fires. Furthermore, similar anomalous conditions occurred in 1998 and 2012, which were significant fire years across areas of the western United States.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

The authors found that anomalously warm conditions occurred during a period of intense fire activity in the summer of 1910. A strong La Niña pattern in the year of 1910 likely contributed to warming and drought during the spring and summer prior to the fires. Furthermore, similar anomalous conditions occurred in 1998 and 2012, which were significant fire years across areas of the western United States.

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

The authors found that anomalously warm conditions occurred during a period of intense fire activity in the summer of 1910. A strong La Niña pattern in the year of 1910 likely contributed to warming and drought during the spring and summer prior to the fires. Furthermore, similar anomalous conditions occurred in 1998 and 2012, which were significant fire years across areas of the western United States.

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42. **Dillon, G.K.; Holden, Z.A.; Morgan, P.; Crimmins, M.A.; Heyerdahl, E.K.; Luce, C.H. 2011.** Both topography and climate affected forest and woodland burn severity in two regions of the western US, 1984 to 2006. *Ecosphere*. 2(12).
<https://doi.org/10.1890/ES11-00271.1>

Location

Western United States; Northwestern United States; Southwestern United States;
LANDFIRE map zones

Ecosystem type(s)

Forested area

Summary: What the authors did and why

The authors assessed trends in burn severity from 1984 to 2006 and also analyzed the effects of topography, climate (temperature and precipitation), and weather on burn severity in forested and woodland areas in each of two U.S. regions.

Publication findings

The authors found that topography had a stronger influence on burn severity than climate (temperature and precipitation), but that climate before and during the fire was still a significant predictor of burn severity. The authors suggest that climate conditions can overwhelm topographic limitations on area burned and fire severity during dry years with widespread fire.

Linkages

- **Temperature, RH, VPD on Fire severity**

The authors found that topography had a stronger influence on burn severity than climate (temperature and precipitation), but that climate before and during the fire was still a significant predictor of burn severity. The authors suggest that climate conditions can overwhelm topographic limitations on area burned and fire severity during dry years with widespread fire.

- **Snowpack, snow and rain on Fire severity**

The authors found that topography had a stronger influence on burn severity than climate (temperature and precipitation), but that climate before and during the fire was still a significant predictor of burn severity. The authors suggest that climate conditions can overwhelm topographic limitations on area burned and fire severity during dry years with widespread fire.

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43. **Donnegan, J.A.; Veblen, T.T.; Sibold, J.S. 2001.** Climatic and human influences on fire history in Pike National Forest, central Colorado. *Canadian Journal of Forest Research*. 31(9): 1526–1539. <https://doi.org/10.1139/x01-093>

Location

Pike National Forest, Colorado, USA

Ecosystem type(s)

Gradient of forested ecosystems; ponderosa pine forest

Summary: What the authors did and why

The authors examined historical relationships between interannual and multidecadal climate variability, specifically moisture variability, and fire regimes. They also examined the effects of changes in human land use practices on fire regimes.

Publication findings

The authors found that fire activity was strongly related to interannual drought conditions typically associated with cycles of ENSO. Increased fire activity tends to occur during the La Niña cycle, in years of reduced moisture availability that often follow 2 to 4 years of increased moisture availability, associated with El Niño years.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that fire activity was strongly related to interannual drought conditions typically associated with cycles of ENSO. Increased fire activity tends to occur during the La Niña cycle, in years of reduced moisture availability that often follow 2 to 4 years of increased moisture availability, associated with El Niño years.

44. **Dugan, A.J.; Baker, W.L. 2015.** Sequentially contingent fires, droughts and pluvials structured a historical dry forest landscape and suggest future contingencies. *Journal of Vegetation Science*. 26(4): 697–710. <https://doi.org/10.1111/jvs.12266>

Location

Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Old-growth forest; ponderosa pine forest

Summary: What the authors did and why

The authors examined the effects of potential contingent influences of drought, fire, pluvial and fire-quiescent periods on postdisturbance recruitment and dry forest structure.

Publication findings

The authors found that fire-quiescent periods due to higher moisture availability had the greatest influence on regeneration pulses of ponderosa pine historically. However, fire, drought, or other mortality-inducing events played a role in

initiating regeneration pulses by opening up the canopy and reducing competition. Pluvial and quiescence periods enhanced recruitment condition and helped sustain 75 percent of regeneration pulses.

Linkages

- **Spatial pattern, landscape mosaic on Dispersal, regeneration, establishment**

Fire, drought, or other mortality-inducing events played a role in initiating regeneration pulses by opening up the canopy and reducing competition. Pluvial and quiescence periods enhanced recruitment condition and helped sustain 75 percent of regeneration pulses.

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

The authors found that fire quiescent periods due to higher moisture availability had the greatest influence on regeneration pulses of ponderosa pine (*Pinus ponderosa*) historically.

45. **Falk, D.A.; Miller, C.; McKenzie, D.; Black, A.E. 2007.** Cross-scale analysis of fire regimes. *Ecosystems*. 10(5): 809–823.

Location

North America

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors examined fire regimes across North America and quantified changes in fire frequency across spatial scales.

Publication findings

Environmental drivers of weather and climate, interacting with landform, set the overall template for individual fire events and fire regimes. Interactions between fire spread and vegetation determine the properties of fires at fine scales, while creating broad-scale landscape pattern.

Linkages

- **Temperature, RH, VPD on Fire behavior, fire type, fire intensity**

Environmental drivers of weather and climate, interacting with landform, set the overall template for individual fire events and fire regimes. Interactions between fire spread and vegetation determine the properties of fires at fine scales, while creating broad-scale landscape pattern.

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46. **Feddema, J.J.; Mast, J.N.; Savage, M. 2013.** Modeling high-severity fire, drought and climate change impacts on ponderosa pine regeneration. *Ecological Modelling*. 253: 56–69. <https://doi.org/10.1016/j.ecolmodel.2012.12.029>

Location

Southwestern United States; Gus Pearson Natural Area, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors modeled the effects of drought on ponderosa pine regeneration in high-severity fire areas using a water balance methodology that assessed thermal and moisture conditions at the project sites. They validated their model at five regenerating ponderosa pine (*Pinus ponderosa*) stands in the Southwest that burned at high severity during the drought years 1945 to 1956.

Publication findings

A previous study by Savage et al. (1996) found that moisture conditions during the year of germination highly influence ponderosa pine (*Pinus ponderosa*) regeneration. This article builds on this prior research. The authors found that sites burned at high severity fire may have reduced microclimatic water availability and extreme temperature conditions of the soil, thereby limiting seedling regeneration and establishment.

Linkages

- **Fire severity on Dispersal, regeneration, establishment**

A previous study by Savage et al. (1996) found that moisture conditions during the year of germination highly influence ponderosa pine (*Pinus ponderosa*) regeneration. This article builds on this prior research. The authors found that sites burned at high severity fire may have reduced microclimatic water availability and extreme temperature conditions of the soil, thereby limiting seedling regeneration and establishment.

47. **Finney, M.A.; McHugh, C.W.; Grenfell, I.C. 2005.** Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. *Canadian Journal of Forest Research*. 35(7): 1714–1722. <https://doi.org/10.1139/x05-090>

Location

Rodeo-Chediski Fire, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors examined the effects of prescribed fires on subsequent fire behavior and fire severity 1 to 9 years prior to the Rodeo-Chediski Fire.

Publication findings

The authors found that prescribed fire treatment effectiveness at reducing future fire severity diminished as time since fire increased. The size of the treatment was also related to its effectiveness at reducing future fire severity such that larger treatments reduced severity to a greater extent. Fire severity in untreated areas was significantly higher than in treated areas across all sites.

Linkages

- **Fire severity on Fuels**

The authors found that prescribed fire treatment effectiveness at reducing future fire severity diminished as time since fire increased. The size of the treatment was also related to its effectiveness at reducing future fire severity such that larger treatments reduced severity to a greater extent. Fire severity in untreated areas was significantly higher than in treated areas across all sites.

- **Fire frequency, fire rotation, fire return interval on Fuels**

The authors found that prescribed fire treatment effectiveness at reducing future fire severity diminished as time since fire increased. The size of the treatment was also related to its effectiveness at reducing future fire severity such that larger treatments reduced severity to a greater extent. Fire severity in untreated areas was significantly higher than in treated areas across all sites.

48. **Flannigan, M.D.; Stocks, B.J.; Wotton, B.M. 2000.** Climate change and forest fires. *Science of the Total Environment*. 262(3): 221–229.

Location

United States and Canada

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors reviewed the literature on climate change and its effects on forest fires in the United States. They also used the seasonal severity rating (SSR) to estimate future fire severity over the next century across North America under the Hadley Centre and the Canadian GCMs.

Publication findings

The authors' modeling effort found that SSR may increase by 10 to 50 percent by 2060, likely increasing area burned and fire severity across much of the United States.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

The authors' modeling effort found that seasonal severity rating may increase by 10 to 50 percent by 2060 likely increasing area burned and fire severity across much of the United States.

- **Temperature, RH, VPD on Fire severity**

The authors' modeling effort found that seasonal severity rating may increase by 10 to 50 percent by 2060 likely increasing area burned and fire severity across much of the United States.

49. **Flannigan, M.; Cantin, A.S.; De Groot, W.J.; Wotton, M.; Newbery, A.; Gowman, L. M. 2013.** Global wildland fire season severity in the 21st century. *Forest Ecology and Management*. 294: 54–61. <https://doi.org/10.1016/j.foreco.2012.10.022>

Location

Global

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors modeled future global fire season severity due to climate change using the Cumulative Severity Rating, a weather-based fire danger metric, of the Canadian Forest Fire Danger Rating System.

Publication findings

The authors found significant increases in fire severity across all GCM scenarios by the end of the century, likely due to the role that temperature plays in fire occurrence and severity. Global fire severity is expected to increase the greatest in the Northern Hemisphere—by as much as three times the baseline Cumulative Severity Rating. The authors also found that fire season length was expected to increase across all regions where the fire season is not already year-round.

Linkages

- **Fire season length on Fire severity**

The authors found significant increases in fire severity across all GCM scenarios by the end of the century, likely due to the role that temperature plays in fire occurrence and severity. They also found that fire season length was expected to increase across all regions where the fire season is not already year-round.

- **Temperature, RH, VPD on Fire severity**

The authors found significant increases in fire severity across all GCM scenarios by the end of the century, likely due to the role that temperature plays in fire occurrence and severity. Global fire severity was expected to increase the greatest

in the Northern Hemisphere—by as much as three times the baseline Cumulative Severity Rating.

50. **Floyd, M.L.; Hanna, D.D.; Romme, W.H. 2004.** Historical and recent fire regimes in piñon-juniper woodlands on Mesa Verde, Colorado, USA. *Forest Ecology and Management*. 198(1–3): 269–289. <https://doi.org/10.1016/j.foreco.2004.04.006>

Location

Mesa Verde National Park, Colorado, USA

Ecosystem type(s)

Piñon-juniper woodlands

Summary: What the authors did and why

The authors documented the historical fire regime of piñon-juniper woodlands in a national park, including the frequency of fire occurrence and the climate conditions associated with large, severe fires. They compared the frequency of large fires that occurred within the past 10 years to the historical fire regime.

Publication findings

The authors found that large fires have occurred in these piñon stands historically, and they estimated a fire return interval of approximately 400 years between large, stand-replacing fires. However, area in the park that has burned since 1995 is more than three times the total area burned in the previous century. But these fires were generally lower in severity than historical fires. The authors assert that the current fire regime is not necessarily outside of the historical range of variability; however, the amount of fire over the past decades may be unprecedented. Furthermore, based on Superposed Epoch Analysis the authors found that large fire years were associated with lower-than-normal precipitation events in the winter and spring preceding burning. Therefore, current fire activity may be a reaction to current drought conditions after an abnormally wet period in the 1970s and 1980s, which allowed for a buildup of canopy fuels.

Linkages

• **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that large fires have occurred in these piñon stands historically, and they estimated a fire return interval of approximately 400 years between large, stand-replacing fires. However, area in the park that has burned since 1995 is more than three times the total area burned in the previous century. But these fires were generally lower in severity than historical fires. The authors assert that the current fire regime is not necessarily outside of the historical range of variability; however, the amount of fire over the past decades may be unprecedented. Furthermore, based on Superposed Epoch Analysis the authors found that large fire years were associated with lower than normal precipitation events in the winter and spring preceding burning. Therefore, current fire activity may be a reaction to current

drought conditions after an abnormally wet period in the 1970s and 1980s, which allowed for a buildup of canopy fuels.

51. **Floyd, M.L.; Romme, W.H.; Hanna, D.D. 2000.** Fire history and vegetation pattern in Mesa Verde national Park, Colorado, USA. *Ecological Applications*. 10(6): 1666–1680. [https://doi.org/10.1890/1051-0761\(2000\)010\[1666:FHAVPI\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[1666:FHAVPI]2.0.CO;2)

Location

Mesa Verde National Park, Colorado, USA

Ecosystem type(s)

Petran chaparral; piñon-juniper woodlands

Summary: What the authors did and why

The authors reconstructed the long-term fire history of petran chaparral and piñon-juniper woodland communities in a national park.

Publication findings

The authors estimated the “natural” fire return interval for petran chaparral and shrubland vegetation in the study area at approximately 100 years and for piñon-juniper woodlands at approximately 400 years. The authors suggest that these long fire return intervals are unique to Mesa Verde and stands exist within the park that have not burned since A.D. 1300 and may be some of the oldest in the Four Corners region. They possess unique structural and compositional characteristics in their current condition.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors estimated the “natural” fire return interval for petran chaparral and shrubland vegetation in Mesa Verde at approximately 100 years and for piñon-juniper woodlands at approximately 400 years. The authors suggest that these long fire return intervals are unique to Mesa Verde and stands exist within the park that have not burned since A.D. 1300 and may be some of the oldest in the Four Corners region. They possess unique structural and compositional characteristics in their current condition.

52. **Fulé, P.Z. 2008.** Does it make sense to restore wildland fire in changing climate? *Restoration Ecology*. 16(4): 526–531. <https://doi.org/10.1111/j.1526-100X.2008.00489.x>

Location

Western United States

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The author discussed the relevance of reference conditions in the restoration of

surface fire-adapted forests and possible alternative forest management strategies in the face of climate change.

Publication findings

Climate change projections suggest a shift toward hotter and drier conditions across the western United States, resulting in an approximately 50 to 500 percent increase in area burned. Forest restoration based on historical conditions is consistent with resilience to the changing climate and increase in fire.

Linkages

- **Drought on Annual area burned, fire size**

Climate change projections suggest a shift toward hotter and drier conditions across the western United States, resulting in an approximately 50 to 500 percent increase in area burned.

- **Temperature, RH, VPD on Annual area burned, fire size**

Climate change projections suggest a shift toward hotter and drier conditions across the west resulting in an approximately 50 to 500 percent increase in area burned.

- **Annual area burned, fire size on Species composition, invasives, structure**

Fire will continue to play an important role in shaping future forests affected by climate change either as restoration and/or forest maintenance or as a mechanism of change via disturbance, loss or shifts in forest distribution and/or species composition.

53. **Fulé, P.Z.; Cocks, A. E.; Heinlein, T.A.; Covington, W.W. 2004a.** Effects of an intense prescribed forest fire: Is it ecological restoration? *Restoration Ecology*. 12(2): 220–230. <https://doi.org/10.1111/j.1061-2971.2004.00283.x>

Location

Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Mixed-conifer forest; ponderosa pine forest

Summary: What the authors did and why

The authors utilized an escaped high-severity prescribed fire in Grand Canyon National Park to assess the effects of postfire structure and composition on a ponderosa pine–mixed-conifer forest stand and determine if more intense prescribed fire has restoration benefits.

Publication findings

Despite issues with pseudoreplication and the limited sample size, the authors found that postfire conditions moved toward range of natural variation conditions after intense burning. Small trees and fire-susceptible understory trees were

preferentially killed by fire and forest floor woody debris was within desired conditions. The sites had adequate regeneration of seedlings with no evidence of any landscape conversion to a nonforest vegetation type.

Linkages

- **Fire severity on Mortality, survivorship, community change**

Despite issues with pseudoreplication and the limited sample size, the authors found that post-fire conditions moved toward range of natural variation conditions after intense burning. Small trees and fire-susceptible understory trees were preferentially killed by fire and forest floor woody debris was within desired conditions. The sites had adequate regeneration of seedlings with no evidence of any landscape conversion to a non-forest vegetation type.

- **Fire severity on Dispersal, regeneration, establishment**

Despite issues with pseudoreplication and the limited sample size, the authors found that post-fire conditions moved toward range of natural variation conditions after intense burning. Small trees and fire-susceptible understory trees were preferentially killed by fire and forest floor woody debris was within desired conditions. The sites had adequate regeneration of seedlings with no evidence of any landscape conversion to a non-forest vegetation type.

- **Fire severity on Species composition, invasives, structure**

Despite issues with pseudoreplication and the limited sample size, the authors found that post-fire conditions moved toward range of natural variation conditions after intense burning. Small trees and fire-susceptible understory trees were preferentially killed by fire and forest floor woody debris was within desired conditions. The sites had adequate regeneration of seedlings with no evidence of any landscape conversion to a non-forest vegetation type.

54. **Fulé, P.Z.; Covington, W.W.; Moore, M.M. 1997.** Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. *Ecological Applications*. 7(3): 895–908.

[https://doi.org/10.1890/1051-0761\(1997\)007\[0895:DRCFEM\]2.0.CO;2](https://doi.org/10.1890/1051-0761(1997)007[0895:DRCFEM]2.0.CO;2)

Location

Southwestern United States

Ecosystem type(s)

Ponderosa pine forests

Summary: What the authors did and why

The authors reconstructed the fire regime and forest structure of a southwestern ponderosa pine forest prior to Euro-American settlement to determine a set of reference conditions as a baseline for ecosystem management.

Publication findings

Historically, fire was highly synchronous across the region and appeared to be linked to climate conditions. The cessation of fire beginning around 1883 in these forests has led to an abundance of resprouting oak, a species typically highly susceptible to fire. In contrast to presettlement conditions, currently there is abundant fuel able to support high-intensity fire behavior, including torching through live fuel ladders and crown fire, in hot, dry, windy weather. However, herbaceous fuel loading is probably greatly reduced in the contemporary forest.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

Historically, fire was highly synchronous across the region and appeared to be linked to climate conditions.

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

Historically, fire was highly synchronous across the region and appeared to be linked to climate conditions.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The cessation of fire beginning around 1883 in these forests has led to an abundance of resprouting oak, a species typically highly susceptible to fire.

- **Fire behavior, fire type, fire intensity on Fuels**

In contrast to presettlement conditions, currently there is abundant fuel able to support high-intensity fire behavior, including torching through live fuel ladders and crown fire, in hot, dry, windy weather. However, herbaceous fuel loading is probably greatly reduced in the contemporary forest.

55. **Fulé, P.Z.; Covington, W.W.; Moore, M.M.; Heinlein, T.A.; Waltz, A.E. 2002.** Natural variability in forests of the Grand Canyon, USA. *Journal of Biogeography*. 29(1): 31–47. <https://doi.org/10.1046/j.1365-2699.2002.00655.x>

Location

Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Ponderosa pine

Summary: What the authors did and why

The authors reconstructed the historical forest tree structure of ponderosa pine (*Pinus ponderosa*)-dominated sites and compared these to current species composition, tree structure, and regeneration. They also considered the interacting effects of climate, fire, grazing, and other disturbance on any changes in forest structure and composition.

Publication findings

Climate fluctuations, fire suppression, and land use (e.g., grazing, timber harvest) have increased the tree densities of forests in the study area, although the patterns of composition and regeneration varied along fire regime and elevational gradients. In forests where fire has been suppressed over the long term, sites are dense and dominated by seed-reproducing conifer species, whereas regeneration on more frequent-fire sites is dominated by sprouting species in the understories of open pine forest.

Linkages

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

In forests where fire has been suppressed over the long term, sites are dense and dominated by seed-reproducing conifer species, whereas regeneration on more frequent-fire sites is dominated by sprouting species in the understories of open pine forest.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

Both climate fluctuations, fire suppression, and land use (e.g., grazing, timber harvest) have increased the tree densities of forests in the study area, although the patterns of composition and regeneration varied along fire regime and elevational gradients.

56. **Fulé, P.Z.; Covington, W.W.; Stoddard, M.T.; Bertolette, D. 2006.** “Minimal-impact” restoration treatments have limited effects on forest structure and fuels at Grand Canyon, USA. *Restoration Ecology*. 14(3): 357–368.
<https://doi.org/10.1111/j.1526-100X.2006.00144.x>

Location

Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest; mixed-conifer forest

Summary: What the authors did and why

The authors tested a series of minimal-impact treatments—thinning of small trees (diameter ≤ 12.7 cm) and prescribed fire; thinning of small trees located close to large old trees and prescribed fire; prescribed fire only; and control—to determine their effectiveness at reducing hazardous fuels and restoring historical forest conditions.

Publication findings

The authors found minimal changes to forest structure under the thinning treatments. These treatments reduced duff and litter in the understory, but did not affect the canopy significantly. The prescribed fire treatments constituted

the greatest treatment impact on future crown fire behavior potential by raising the canopy base height. The thin and burn treatment and prescribed fire only treatment had nearly indistinguishable effects on forest structure, suggesting that resources may be better spent on increasing prescribed fire than on minimal thinning activities.

Linkages

- **Spatial pattern, landscape mosaic on Fuels**

The authors found minimal changes to forest structure under the thinning treatments. These treatments reduced duff and litter in the understory, but did not affect the canopy significantly. The prescribed fire treatments constituted the greatest treatment impact on future crown fire behavior potential by raising the canopy base height. The thin and burn treatment and prescribed fire only treatment had nearly indistinguishable effects on forest structure, suggesting that resources may be better spent on increasing prescribed fire than on minimal thinning activities.

- **Fire severity on Fuels**

The prescribed fire treatments constituted the greatest treatment impact on future crown fire behavior potential by raising the canopy base height. The thin and burn treatment and prescribed fire only treatment had nearly indistinguishable effects on forest structure, suggesting that resources may be better spent on increasing prescribed fire than on minimal thinning activities.

- **Fire behavior, fire type, fire intensity on Fuels**

The prescribed fire treatments constituted the greatest treatment impact on future crown fire behavior potential by raising the canopy base height. The thin and burn treatment and prescribed fire only treatment had nearly indistinguishable effects on forest structure, suggesting that resources may be better spent on increasing prescribed fire than on minimal thinning activities.

57. **Fulé, P.Z.; Crouse, J. E.; Cocke, A.E.; Moore, M.M.; Covington, W.W. 2004b.** Changes in canopy fuels and potential fire behavior 1880–2040: Grand Canyon, Arizona. *Ecological Modelling*. 175(3): 231–248.
<https://doi.org/10.1016/j.ecolmodel.2003.10.023>

Location

Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Forested ecosystems: aspen; mixed-conifer; ponderosa pine; spruce-fir

Summary: What the authors did and why

The authors reconstructed fuel and fire behavior variables across an elevational

gradient to estimate the change in canopy fuels since 1880 and to project future canopy fuels and associated potential fire behavior into the near future (2040).

Publication findings

Historically, high wind speeds were required to initiate crown fire behavior across all forest types within the project area. By the year 2000, common windspeeds of 45 km hr⁻¹ were projected to be sufficient to initiate crown fire at most sites due to changes in canopy bulk density. The increase in canopy fuels continuity has already led to and is expected to continue to lead to broad-scale crown fire instead of the highly mixed pattern of burn severity that was common historically.

Linkages

- **Fire behavior, fire type, fire intensity on Fuels**

Historically, high wind speeds were required to initiate crown fire behavior across all forest types within the project area. By the year 2000, common windspeeds of 45 km hr⁻¹ were projected to be sufficient to initiate crown fire at most sites due to changes in canopy bulk density. The increase in canopy fuels continuity has already led to and is expected to continue to lead to broad-scale crown fire instead of the highly mixed pattern of burn severity that was common historically.

58. **Fulé, P.Z.; Crouse, J.E.; Heinlein, T.A.; Moore, M.M.; Covington, W.W.; Verkamp, G. 2003a.** Mixed-severity fire regime in a high-elevation forest of Grand Canyon, Arizona, USA. *Landscape Ecology*. 18(5): 465–486.

Location

Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Mixed-conifer forest; spruce-fir forest

Summary: What the authors did and why

The authors reconstructed the spatial and temporal patterns of the fire regime on the North Rim of Grand Canyon National Park to assess how fire transitioned from surface to stand-replacing fire across aspect, elevation, and forest type.

Publication findings

The authors found that currently the forest in the study area is dominated by dense stands of spruce-fir (*Picea* spp.–*Abies* spp.), mixed conifer, and aspen (*Populus tremuloides*). Historically, conditions would have been very open prior to fire exclusion. Fire-initiated tree groups composed approximately 60 percent of the project site, and likely originated after severe fires in the 1780s. The authors also found synchrony between fires during dry years as measured by PDSI, with severe drought common in regional fire years.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found synchrony between fires during dry years as measured by PDSI, with severe drought common in regional fire years.

- **Fire severity on Species composition, invasives, structure**

The authors found that currently the forest on the North Rim of Grand Canyon National Park is dominated by dense stands of spruce-fir (*Picea* spp.–*Abies* spp.), mixed conifer, and aspen (*Populus tremuloides*). Historically, conditions would have been very open prior to fire exclusion. Fire-initiated tree groups composed approximately 60 percent of the project site, and likely originated after severe fires in the 1780s.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors found that currently the forest on the North Rim of Grand Canyon National Park is dominated by dense stands of spruce-fir, mixed-conifer, and aspen. Historically, conditions would have been very open prior to fire exclusion.

59. **Fulé, P.Z.; Heinlein, T.A.; Covington, W.W.; Moore, M.M. 2003b.** Assessing fire regimes on Grand Canyon landscapes with fire-scar and fire-record data. *International Journal of Wildland Fire*. 12(2): 129–145.

Location

Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest; mixed-conifer forest

Summary: What the authors did and why

The authors reconstructed the fire regime of remote sites on the North Rim of Grand Canyon National Park to determine how the regime has changed since European settlement, including fire frequency, size, and climate–fire relationships.

Publication findings

The authors found that climate–fire relationships varied across the vegetation gradient. Typically fire years occurred during dry years following wet years, except at the lowest elevation sites, which were not significantly drier than normal. At the highest elevation, fires occurred during periods that were significantly drier than the 99th percentile.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that climate–fire relationships varied across the vegetation gradient. Typically fire years occurred during dry years following wet years, except

at the lowest elevation sites, which were not significantly drier than normal. At the highest elevation, fires occurred during periods that were significantly drier than the 99th percentile.

60. **Fulé, P.Z.; Korb, J.E.; Wu, R. 2009.** Changes in forest structure of a mixed conifer forest, southwestern Colorado, USA. *Forest Ecology and Management*. 258(7): 1200–1210. <https://doi.org/10.1016/j.foreco.2009.06.015>

Location

San Juan National Forest, Colorado, USA

Ecosystem type(s)

Mixed-conifer forest

Summary: What the authors did and why

The authors reconstructed the historical fire regime and stand structure of a mixed-conifer forest in southwestern Colorado to determine how stand structure and composition have changed over time.

Publication findings

The authors found an abrupt cessation of fire after 1868, concurrent with Euro-American settlement, although they also found fire-quiescent around 1685 to 1735 and again from 1824 to 1861 related to increased moisture patterns. At the current study site, shade-tolerant species, such as white fir (*Abies concolor*) and Douglas-fir (*Pseudotsuga menziesii*), dominated the understory and were regenerating most abundantly; however, during the historical periods of frequent fire, ponderosa pine dominated the stand until fire ceased in the region. The authors also found an increase in fire area burned in the mixed-conifer stand when dry years were preceded by one or two wet years, resulting in an accumulation of fuels.

Linkages

- **Snowpack, snow and rain on Fire frequency, fire rotation, fire return interval**

The authors found an increase in fire area burned in the mixed-conifer stand when dry years were preceded by one or two wet years resulting in an accumulation of fuels.

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

The authors found an abrupt cessation of fire after 1868, concurrent with Euro-American settlement, although they also found fire-quiescent periods around 1685 to 1735 and again from 1824 to 1861 related to increased moisture patterns. At the current study site, shade-tolerant species, such as white fir (*Abies concolor*) and Douglas-fir (*Pseudotsuga menziesii*), dominated the understory and were regenerating most abundantly; however, during the historical periods of frequent fire, ponderosa pine dominated the stand until fire ceased in the region.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors found an abrupt cessation of fire after 1868, concurrent with Euro-American settlement, although they also found fire-quiescent periods around 1685 to 1735 and again from 1824 to 1861 related to increased moisture patterns. At the current study site, shade-tolerant species, such as white fir (*Abies concolor*) and Douglas-fir (*Pseudotsuga menziesii*), dominated the understory and were regenerating most abundantly; however, during the historical periods of frequent fire, ponderosa pine dominated the stand until fire ceased in the region.

61. **Fulé, P.Z.; Laughlin, D.C. 2007.** Wildland fire on forest structure over an altitudinal gradient, Grand Canyon National Park, USA. *Journal of Applied Ecology*. 44: 136–146. <https://doi.org/10.1111/j.1365-2664.2006.01254.x>

Location

North Rim of Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Forested ecosystems: aspen; Douglas-fir; Engelmann spruce; Gambel oak; ponderosa pine; subalpine fir; white fir

Summary: What the authors did and why

The authors studied four wildland fire-use fires across an elevational gradient to examine the restorative effects of wildfire on areas that experienced unusually long fire-free periods. The authors stratified study sites by elevation with the lowest elevation site dominated by ponderosa pine (*Pinus ponderosa*) and Gambel oak (*Quercus gambelii*), the mid-elevation site dominated by ponderosa pine, white fir (*Abies concolor*), aspen (*Populus tremuloides*), and Douglas-fir (*Pseudotsuga menziesii*), and the high elevation sites dominated by subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*).

Publication findings

At the higher elevation sites, despite long fire-free periods, fire severity was consistent with historical fire regime patterns and resulted in fuel conditions closer to the historical range of variability. Furthermore, the authors found that regeneration success was not tied to fire severity, but fire-susceptible species, typically resprouting species, were favored. Fire effects on cool, mixed-conifer ecosystems may allow the composition and structure of these ecosystems to be more resilient to the effect of catastrophic wildfire due to climate change.

Linkages

- **Fire severity on Dispersal, regeneration, establishment**

Regeneration success was not tied to fire severity, but fire-susceptible species, typically resprouting species, were favored.

- **Fire severity on Fuels**

At the higher elevation sites, despite long fire-free periods, fire severity was consistent with historical fire regime patterns and resulted in fuel conditions closer to the historical range of variability. Fire effects on cool, mixed-conifer ecosystems may allow the composition and structure of these ecosystems to be more resilient to the effect of catastrophic wildfire due to climate change.

- **Fire severity on Species composition, invasives, structure**

Fire effects on cool, mixed-conifer ecosystems may allow the composition and structure of these ecosystems to be more resilient to the effect of catastrophic wildfire due to climate change.

62. **Fulé, P.Z.; Yocom, L.L.; Montaña, C.C.; Falk, D.A.; Cerano, J.; Villanueva-Díaz, J. 2012.** Testing a pyroclimatic hypothesis on the Mexico–United States border. *Ecology*. 93(8): 1830–1840. <https://doi.org/10.1890/11-1991.1>

Location

Chihuahua, Mexico

Ecosystem type(s)

Mixed-conifer forest

Summary: What the authors did and why

The authors reconstructed the fire regime of a relict unharvested stand in a remote Mexican mixed-conifer forest and compared it to previously published fire regime data from a similar site in the Chiricahua Mountains of southeastern Arizona. The authors tested the pyroclimatic hypothesis to understand the relative influence of climate on ecologically and climatically similar sites, but with differing cultural influences.

Publication findings

Prior to 1892, fire occurrence was significantly associated with drought on both sides of the United States–Mexico border. After 1892, however, the fire regime was interrupted at the sites in Arizona, while it continued in Mexico, suggesting that bottom-up factors such as livestock grazing and other land use by humans had a stronger influence on fire at finer spatial scales than climate in this case, producing different fire regimes on the same mountain range.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

Prior to 1892, fire occurrence was significantly associated with drought on both sides of the U.S.-Mexico border. After 1892, however, the fire regime was interrupted at the sites in Arizona, while it continued in Mexico, suggesting that bottom-up factors such as livestock grazing and other land use by humans had a

stronger influence on fire at finer spatial scales than climate in this case, producing different fire regimes on the same mountain range.

63. **Gartner, M.H.; Veblen, T.T.; Sherriff, R.L.; Schoennagel, T.L. 2012.** Proximity to grasslands influences fire frequency and sensitivity to climate variability in ponderosa pine forests of the Colorado Front Range. *International Journal of Wildland Fire*. 21(5): 562–571. <https://doi.org/10.1071/WF10103>

Location

Colorado Front Range, Colorado, USA

Ecosystem type(s)

Ponderosa pine forests; grasslands

Summary: What the authors did and why

The authors examined the relationship between fire frequency in ponderosa pine forests and their proximity to grassland and shrubland sites as well as the sensitivity to climate variability also related to the adjacency to these sites.

Publication findings

The authors found that ponderosa pine forest stands that are closer in proximity to grassland- and shrubland-dominated sites burn at higher frequencies, and furthermore, grassland-adjacent stands are more sensitive to fluctuations in climate. Fire years in grassland ecosystems in the Colorado Front Range are synchronous with year-of-drought and 2-year lagged moisture conditions, which promote increased fuel growth and continuity. Grassland-adjacent forests are more likely to burn due to the increased continuity of fuels when conditions permit fire in grasslands, whereas forest farther from grasslands may be fuel limited during drought years.

Linkages

- **Drought on Spatial pattern, landscape mosaic**

The authors found that ponderosa pine forest stands that are closer in proximity to grassland- and shrubland-dominated sites burn at higher frequencies, and furthermore, grassland-adjacent stands are more sensitive to fluctuations in climate. Fire years in grassland ecosystems in the Colorado Front Range are synchronous with year-of-drought and 2-year lagged moisture conditions, which promote increased fuel growth and continuity. Grassland-adjacent forests are more likely to burn due to the increased continuity of fuels when conditions permit fire in grasslands, whereas forest farther from grasslands may be fuel limited during drought years.

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64. **Grissino-Mayer, H.D.; Swetnam, T.W. 2000.** Century scale climate forcing of fire regimes in the American Southwest. *The Holocene*. 10(2): 213–220.
<https://doi.org/10.1191/095968300668451235>

Location

El Malpais National Monument, New Mexico, USA

Ecosystem type(s)

Mixed-conifer forests; pygmy forest

Summary: What the authors did and why

The authors examined climate–fire relationships across seasonal and century-long timescales within a unique volcanic landscape.

Publication findings

The authors’ reconstructions of fire and climate within the study area show a cessation of fire occurrence around 1790. Prior to 1790, fire was frequent and synchronous with periods of drought. After 1790, an increase in annual precipitation decreased fire frequency and shifted the fire season from midsummer to late spring.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors’ reconstructions of fire and climate within the study area show a cessation of fire occurrence around 1790. Prior to 1790, fire was frequent and synchronous with periods of drought. After 1790, an increase in annual precipitation decreased fire frequency and shifted the fire season from midsummer to late spring.

65. **Grissino-Mayer, H.D.; Swetnam, T.W. 1997.** Multi-century history of wildfire in the ponderosa pine forests of El Malpais National Monument. *New Mexico Bureau of Mines and Mineral Resources Bulletin*. 156: 163–171.

Location

El Malpais National Monument, New Mexico, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors reconstructed the fire regime and forest structure of a southwestern ponderosa pine forest prior to Euro-American settlement within a unique landscape to determine a set of reference conditions as a baseline for ecosystem management.

Publication findings

Fire suppression beginning in the 1800s and improvements in fire suppression

techniques after the 1940s led to an increase in numerous ponderosa pine thickets throughout the park.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

Fire suppression beginning in the 1800s and improvements in fire suppression techniques after the 1940s led to an increase in numerous ponderosa pine thickets throughout the park.

66. **Guyette, R.P.; Thompson, F.R.; Whittier, J.; Stambaugh, M.C.; Dey, D.C. 2014.** Future fire probability modeling with climate change data and physical chemistry. *Forest Science*. 60(5): 862–870. <https://doi.org/10.5849/forsci.13-108>

Location

Contiguous United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors produced a model to predict a spatially explicit map of future fire probability and fire frequency based on climate projection models across the United States.

Publication findings

The authors found that future fire probabilities increased with increasing temperature; however, predictions for each of the climate models diverged for the southwestern United States. Scenarios under CGCM data resulted in decreased future fire probability (0 to -30 percent) whereas the GFDL scenarios resulted in increased fire probability (near 0 to greater than 40 percent). The authors suggest this discrepancy is due to the limitations in predicting precipitation and moisture conditions and their effect on fuel production.

Linkages

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

The authors found that future fire probabilities increased with increasing temperature; however, predictions for each of the climate models diverged for the southwestern United States. Scenarios under CGCM data resulted in decreased future fire probability (0 to -30 percent) whereas the GFDL scenarios resulted in increased fire probability (near 0 to greater than 40 percent). The authors suggest this discrepancy is due to the limitations in predicting precipitation and moisture conditions and their effect on fuel production.

- **Snowpack, snow and rain on Fire frequency, fire rotation, fire return interval**

Predictions for each of the climate models diverged for the southwestern United States. Scenarios under CGCM data resulted in decreased future fire probability (0 to -30 percent) whereas the GFDL scenarios resulted in increased fire probability (near 0 to greater than 40 percent). The authors suggest this discrepancy is due to the limitations in predicting precipitation and moisture conditions and their effect on fuel production.

67. **Haffey, C.; Sisk, T.D.; Allen, C.D.; Thode, A.E.; Margolis, E.Q. 2018.** Limits to ponderosa pine regeneration following large high-severity forest fires in the United States Southwest. *Fire Ecology*. 14(1): 143.
<http://dx.doi.org/10.1016/j.foreco.2017.09.005>

Location

Arizona and New Mexico, USA

Ecosystem type(s)

Ponderosa pine forest ecosystem

Summary: What the authors did and why

The authors looked at large patches of high severity, stand-replacing fire in ponderosa pine ecosystems along a gradient of topography and climate as a stand-in for climate variability to understand the likelihood of postfire regeneration due to topography, climate, drought, and distance to seed source. They selected fires that burned between 1996 and 2006 as this period of time was particularly dry across the Southwest.

Publication findings

The authors found that distance to seed source was the most important predictor of ponderosa pine regeneration after high severity fire in this study, although climate also was significant, suggesting that areas that are more affected by drought stress are less likely to regenerate naturally or may regenerate slowly. Under projected climate change, large patches of high severity fire may not regenerate to forest stands for decades to centuries or may shift toward novel ecosystems such as herbaceous or shrub- and grass-dominated communities.

Linkages

- **Fire severity on Dispersal, regeneration, establishment**

The authors found that distance to seed source was the most important predictor of ponderosa pine regeneration after high severity fire in this study, although, climate also was significant, suggesting that areas that are more affected by drought-stress are less likely to regenerate naturally or may regenerate slowly. Under projected climate change, large patches of high severity fire may not regenerate to forest stands for decades to centuries or may shift toward novel ecosystems such as herbaceous or shrub- and grass-dominated communities.

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68. **Haire, S.L.; McGarigal, K. 2008.** Inhabitants of landscape scars: succession of woody plants after large, severe forest fires in Arizona and New Mexico. *The Southwestern Naturalist*. 53(2): 146–162.

[https://doi.org/10.1894/0038-4909\(2008\)53\[146:IOLSSO\]2.0.CO;2](https://doi.org/10.1894/0038-4909(2008)53[146:IOLSSO]2.0.CO;2)

Location

La Mesa Fire, Pajarito Plateau, northern New Mexico, USA; Saddle Mountain Fire, Kaibab Plateau, northern Arizona, USA

Ecosystem type(s)

Mixed-conifer forest; piñon-juniper woodlands; ponderosa pine forest

Summary: What the authors did and why

The authors looked at the influence of the spatial heterogeneity of burn severity on the succession of the woody plant community burned at high severity across an elevational gradient and at varying distances from unburned edge.

Publication findings

Cover of woody vegetation that regenerates via seeds was more abundant at shorter distances to unburned edges, which acted as refuge seed sources. However, cover of offsite seeders did not overlap with areas of abundant sprouting species. Prefire vegetation composition and structure influenced the postfire distribution of sprouting species in high severity burns. Elevation was not an important factor in determining cover at these sites.

Linkages

- **Spatial pattern, landscape mosaic on Dispersal, regeneration, establishment**

Cover of woody vegetation that regenerates via seeds were more abundant at shorter distances to unburned edges, which acted as refuge seed sources. However, cover of offsite seeders did not overlap with areas of abundant sprouting species. Prefire vegetation composition and structure influenced the postfire distribution of sprouting species in high severity burns.

- **Fire severity on Dispersal, regeneration, establishment**

In high severity patches, cover of woody vegetation that regenerates via seeds was more abundant at shorter distances to unburned edges, which acted as refuge seed sources. Prefire vegetation composition and structure influenced the postfire distribution of sprouting species in high severity burns.

69. **Haire, S.L.; McGarigal, K. 2009.** Changes in fire severity across gradients of climate, fire size, and topography: A landscape ecological perspective. *Fire Ecology*. 5(2): 86.

Location

Arizona and New Mexico, USA

Ecosystem type(s)

Gradient of forested ecosystems: mixed conifer; piñon-juniper; ponderosa pine

Summary: What the authors did and why

The authors examined the effects of climate, specifically drought, and local topography on fire severity across a gradient of fire sizes and vegetation types.

Publication findings

The authors found that most, but not all, large fires occurred during the La Niña phase of ENSO. For the Cerro Grande Fire, which occurred during an extreme La Niña event, topography had a stronger influence on reducing severity in some areas than the regional effects of climate. Conversely, on several of the fires, topography conducive to fire spread did not produce increased severity, and temperature and wind had a stronger influence on fire effects.

Linkages

- **Drought on Annual area burned, fire size**

The authors found that most, but not all, large fires occurred during the La Niña phase of ENSO. For the Cerro Grande Fire, which occurred during an extreme La Niña event, topography had a stronger influence on reducing severity in some areas than the regional effects of climate.

- **Temperature, RH, VPD on Fire severity**

For the Cerro Grande Fire, which occurred during an extreme La Niña event, topography had a stronger influence on reducing severity in some areas than the regional effects of climate. Conversely, on several of the fires, topography conducive to fire spread did not produce increased severity, and temperature and wind had a stronger influence on fire effects.

70. **Haire, S.L.; McGarigal, K. 2010.** Effects of landscape patterns of fire severity on regenerating ponderosa pine forests (*Pinus ponderosa*) in New Mexico and Arizona, USA. *Landscape Ecology*. 25(7): 1055–1069.

Location

La Mesa Fire, Pajarito Plateau, northern New Mexico, USA; Saddle Mountain Fire, Kaibab Plateau, northern Arizona, USA

Ecosystem type(s)

Mixed-conifer forest; piñon-juniper woodlands; ponderosa pine forest

Summary: What the authors did and why

The authors examined how the spatial patterns of fire severity affect long-term (30 to 50 years) ponderosa pine regeneration under current altered fire regimes. They considered how subsequent entries of fire influenced seedling survival, and also biotic and abiotic factors that affect survival, germination, and growth of ponderosa pine.

Publication findings

Despite subsequent management and other disturbance, including fire, on these study sites, the authors found that the spatial pattern of fire severity was still significantly tied to ponderosa pine regeneration patterns and still impacted the sites decades after the fire. Regenerating seedling density of ponderosa pine decreased with increasing distance to seed source in the high severity patches of fire, although long-distance dispersal did occur.

General climate trends after the fires did not relate clearly to forest regeneration for either site, and despite periods of wet years and drought years, forest regeneration occurred at both sites. Therefore, the authors stated that future large fires are not necessarily catastrophic to ecosystems and that process-based restoration may provide resilience in the forests in the face of changing fire regimes.

Linkages

- **Spatial pattern, landscape mosaic on Dispersal, regeneration, establishment**

Despite subsequent management and other disturbance, including fire, on these study sites, the authors found that the spatial pattern of fire severity was still significantly tied to ponderosa pine regeneration patterns and still impacted the sites decades after the fire. Regenerating seedling density of ponderosa pine decreased with increasing distance to seed source in the high severity patches of fire, although long-distance dispersal did occur.

- **Fire severity on Dispersal, regeneration, establishment**

Despite subsequent management and other disturbance, including fire, on these study sites, the authors found that the spatial pattern of fire severity was still significantly tied to ponderosa pine regeneration patterns and still impacted the sites decades after the fire. Regenerating seedling density of ponderosa pine decreased with increasing distance to seed source in the high severity patches of fire, although long-distance dispersal did occur.

71. **Haire, S.L.; McGarigal, K.; Miller, C. 2013.** Wilderness shapes contemporary fire size distributions across landscapes of the western United States. *Ecosphere*. 4(1): 1–20. <https://doi.org/10.1890/ES12-00257.1>

Location

Southwestern United States; Sierra Nevada and Northern Rockies, USA

Ecosystem type(s)

Gradient of forested ecosystems

Summary: What the authors did and why

The authors modeled the effects of wilderness on the fire size distribution along

forest gradients, while accounting for the effects of topography, weather, and climate.

Publication findings

The authors found that in the Southwest, the effects of natural burning within wilderness areas promote heterogeneity of burn mosaics and limit the size and spread of subsequent fires. They did not find this same pattern in the Sierra Nevada or Northern Rockies. In the Northern Rockies, they found that winter and fire season precipitation was the most important factor in limiting fire size and occurrence.

Linkages

- **Snowpack, snow and rain on Annual area burned, fire size**

In the Northern Rockies, the authors found that winter and fire season precipitation was the most important factor in limiting fire size and occurrence.

- **Annual area burned, fire size on Fuels**

The authors found that in the Southwest, the effects of natural burning within wilderness areas promote heterogeneity of burn mosaics and limit the size and spread of subsequent fires. They did not find this same pattern in the Sierra Nevada or Northern Rockies.

72. **Heinlein, T.A.; Moore, M.M.; Fulé, P.Z.; Covington, W.W. 2005.** Fire history and stand structure of two ponderosa pine–mixed conifer sites: San Francisco Peaks, Arizona, USA. *International Journal of Wildland Fire*. 14(3): 307–320.
<https://doi.org/10.1071/WF04060>

Location

San Francisco Peaks, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest; mixed-conifer forest

Summary: What the authors did and why

The authors reconstructed the contemporary and historical fire regime of a ponderosa pine forest and a mixed-conifer forest to determine how fire exclusion may have affected the forests' structure and composition.

Publication findings

The author found that historically, the San Francisco Peaks of northern Arizona were dominated by ponderosa pine with an understory of scattered individuals of Douglas-fir (*Pseudotsuga menziesii*), limber pine (*Pinus flexilis*), and white fir (*Abies concolor*). Currently, however, the species composition has shifted due to fire suppression to dense stands of less fire-tolerant Douglas-fir and white fir.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The author found that historically, the San Francisco Peaks of northern Arizona were dominated by ponderosa pine with an understory of scattered individuals of Douglas-fir (*Pseudotsuga menziesii*), limber pine (*Pinus flexilis*), and white fir (*Abies concolor*). Currently, however, the species composition has shifted due to fire suppression to dense stands of less fire-tolerant Douglas-fir and white fir.

73. **Hessl, A.E. 2011.** Pathways for climate change effects on fire: models, data, and uncertainties. *Progress in Physical Geography*. 35(3): 393–407.
<https://doi.org/10.1177/0309133311407654>

Location

Global

Ecosystem type(s)

Not specified

Summary: What the authors did and why

This article reviews models and fire-history studies of climate change and fire and proposes three potential pathways of how climate may affect fire regimes.

Publication findings

The author proposes that climate change may affect fire activity via alteration of fuel conditions, fuel loading, or changes in ignitions. Changes in moisture regimes and length of the fire season could alter fuel conditions, increasing their flammability.

Linkages

- **Fire season length on Fire timing, fire seasonality**

The author proposes that climate change may affect fire activity via alteration of fuel conditions, fuel loading, or changes in ignitions. Changes in moisture regimes and length of the fire season could alter fuel conditions, increasing their flammability.

74. **Higgins, A.M.; Waring, K.M.; Thode, A.E. 2015.** The effects of burn entry and burn severity on ponderosa pine and mixed conifer forests in Grand Canyon National Park. *International Journal of Wildland Fire*. 24(4): 495–506.

Location

North Rim of Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Dry mixed-conifer forest; ponderosa pine forest

Summary: What the authors did and why

The authors investigated the effects of multiple burn entries and burn severity on stand structure, composition and regeneration on a dry mixed-conifer stand and a ponderosa pine stand with white fir (*Abies concolor*) encroachment.

Publication findings

The authors found that a single entry, low severity fire was not effective in reducing tree densities in ponderosa pine (*Pinus ponderosa*) trees with white fir (*Abies concolor*) encroachment, although a second entry fire did reduce white fir populations. Low severity fire, however, reduced fuel load density in the dry mixed-conifer stands. They also found that aspen (*Populus tremuloides*) regeneration after high severity fire was abundant. For ponderosa pine, seedlings did increase after fire; however, due to the dense overstory canopy, survival into adulthood was uncertain for both stand types.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors found that a single entry, low severity fire was not effective in reducing tree densities in ponderosa pine (*Pinus ponderosa*) trees with white fir encroachment, although a second entry fire did reduce white fir (*Abies concolor*) populations.

- **Fire severity on Fuels**

Low severity fire reduced fuel load density in the dry mixed-conifer stands, but did not reduce white fir densities in the understory.

- **Fire severity on Species composition, invasives, structure**

The authors found that a single entry, low severity fire was not effective in reducing tree densities in ponderosa pine (*Pinus ponderosa*) trees with white fir encroachment, although a second entry fire did reduce white fir (*Abies concolor*) populations. Low severity fire, however, reduced fuel load density in the dry mixed-conifer stands. They also found that aspen (*Populus tremuloides*) regeneration after high severity fire was abundant. For ponderosa pine, seedlings did increase after fire; however, due to the dense overstory canopy, survival into adulthood was uncertain for both stand types.

75. **Hoff, V.; Teske, C.C.; Riddering, J.P.; Queen, L.P.; Gdula, E.G.; Bunn, W.A. 2014.** Changes in severity distribution after subsequent fires on the North Rim of Grand Canyon National Park, Arizona, USA. *Fire Ecology*. 10(2): 48–63.

Location

Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Gradient of forested ecosystems: mixed conifer; piñon-juniper; ponderosa pine; spruce-fir ecosystems

Summary: What the authors did and why

The authors examined the effects of initial fire severity on subsequent fire severity and also how the pattern of burn severity patches is affected by initial burn conditions.

Publication findings

The authors found a positive feedback between the initial severity of a fire and the severity of a later reburn, especially concerning high-severity forest fire. Conversely, low or moderate severity fires may regulate future fires to similar severities, which follows historical patterns of frequent, low-severity fires in dry coniferous forest systems.

Linkages

- **Spatial pattern, landscape mosaic on Fuels**

The authors found a positive feedback between the initial severity of a fire and the severity of a later reburn, especially concerning high-severity forest fire. Conversely, low- or moderate-severity fires may regulate future fires to similar severities, which follows historical patterns of frequent, low-severity fires in dry coniferous forest systems.

- **Fire severity on Fuels**

The authors found a positive feedback between the initial severity of a fire and the severity of a later reburn, especially concerning high severity forest fire. Conversely, low- or moderate-severity fires may regulate future fires to similar severities, which follows historical patterns of frequent, low-severity fires in dry coniferous forest systems.

76. **Hoffman, C.M.; Sieg, C.H.; McMillin, J.D.; Fulé, P.Z. 2012.** Fuel loadings 5 years after a bark beetle outbreak in south-western USA ponderosa pine forests. *International Journal of Wildland Fire*. 21(3): 306–312.
<https://doi.org/10.1071/WF11019>

Location

National forests in Arizona, USA

Ecosystem type(s)

Ponderosa pine forests

Summary: What the authors did and why

The authors quantified surface and canopy fuel structure and loading of ponderosa pine stands 5 years after a bark beetle outbreak.

Publication finding

The authors found that stands affected by bark beetle outbreaks had higher surface fuel loadings, but lower canopy fuel loadings than unaffected stands. The bark beetle outbreaks were partially driven by tree stress due to drought conditions. The authors suggest that future trends toward more frequent and longer term drought may result in increases in bark beetle activity, alterations to fuel loads, and subsequent increases in fire hazard.

Linkages

- **Drought on Fire behavior, fire type, fire intensity**

The authors found that stands affected by bark beetle outbreaks had higher surface fuel loadings, but lower canopy fuel loadings, than unaffected stands. The bark beetle outbreaks were partially driven by tree stress due to drought conditions. The authors suggest that future trends toward more frequent and longer term drought may result in increases in bark beetle activity, alterations to fuel loads, and subsequent increases in fire hazard.

77. **Holden, Z.A.; Morgan, P.; Evans, J.S. 2009.** A predictive model of burn severity based on 20-year satellite-inferred burn severity data in a large southwestern US wilderness area. *Forest Ecology and Management*. 258(11): 2399–2406.
<https://doi.org/10.1016/j.foreco.2009.08.017>

Location

Gila National Forest, New Mexico, USA

Ecosystem type(s)

Forested ecosystems: Douglas-fir; mixed conifer; piñon–oak; ponderosa pine; spruce-fir; riparian

Summary: What the authors did and why

The authors used the Random Forest algorithm to analyze the comparative strength of a suite of topographic variables and Potential Vegetation Type (PVT) to predict high-severity fire occurrence from 1984 to 2004 in the Gila Wilderness.

Publication findings

This article found strong relationships between topographic variables and high-severity fire occurrence. Severe fire was more likely to occur on north-facing slopes at high elevations due to the interaction of biomass production and fuel accumulation, which in turn influences burn severity. Without human influence on this landscape, climate, topography, and vegetation interact strongly with each other to control burn severity in a region dominated by semiarid forest, where moisture limits vegetation production.

Linkages

- **Fire severity on Fuels**

This article found strong relationships between topographic variables and high-severity fire occurrence. Severe fire was more likely to occur on north-facing slopes at high elevations due to the interaction of biomass production and fuel accumulation, which in turn influences burn severity. Without human influence on this landscape, climate, topography, and vegetation interact strongly with each other to control burn severity in a region dominated by semiarid forest, where moisture limits vegetation production.

78. **Holden, Z.A.; Morgan, P.; Crimmins, M.A.; Steinhorst, R.K.; Smith, A.M. 2007.** Fire season precipitation variability influences fire extent and severity in a large southwestern wilderness area, United States. *Geophysical Research Letters*. 34(16). <https://doi.org/10.1029/2007GL030804>

Location

Gila National Forest, New Mexico, USA

Ecosystem type(s)

Gradient along Potential Vegetation Types

Summary: What the authors did and why

The authors examined the relationship between annual area burned and fire severity with snowpack and precipitation metrics in a wilderness area.

Publication findings

The authors found that across vegetation types, annual area burned was significantly correlated with the frequency and intensity of springtime rain events. Burn severity was significantly correlated with lack of precipitation represented by total number of days without rain and maximum consecutive number of days without rain. Snowpack was only marginally related to area burned and fire severity in the upper elevation forest types spruce-fir and mixed conifer. Finally, they found that longer fire seasons measured by an increase in the total and consecutive number of days without rain may have increased area burned by providing longer periods of weather favorable for fire activity.

Linkages

- **Fire season length on Annual area burned, fire size**

The authors found that longer fire seasons measured by an increase in the total and consecutive number of days without rain may have increased area burned by providing longer periods of weather favorable for fire activity.

- **Drought on Annual area burned, fire size**

The authors found that longer fire seasons measured by an increase in the total and consecutive number of days without rain may have increased area burned by providing longer periods of weather favorable for fire activity.

- **Snowpack, snow and rain on Annual area burned, fire size**

The authors found that across vegetation types, annual area burned was significantly correlated with the frequency and intensity of springtime rain events. Burn severity was significantly correlated with lack of precipitation represented by total number of days without rain and maximum consecutive number of days without rain. Snowpack was only marginally related to area burned and fire severity in the upper elevation forest types spruce-fir and mixed conifer.

- **Drought on Fire severity**

Burn severity was significantly correlated with lack of precipitation represented by total number of days without rain and maximum consecutive number of days without rain. Snowpack was only marginally related to area burned and fire severity in the upper elevation forest types spruce-fir and mixed conifer. Finally, they found that longer fire seasons measured by an increase in the total and consecutive number of days without rain may have increased area burned by providing longer periods of weather favorable for fire activity.

- **Snowpack, snow and rain on Fire severity**

Burn severity was significantly correlated with lack of precipitation represented by total number of days without rain and maximum consecutive number of days without rain. Snowpack was only marginally related to area burned and fire severity in the upper elevation forest types spruce-fir and mixed conifer.

79. **Holden, Z.A.; Morgan, P.; Hudak, A.T. 2010.** Burn severity of areas reburned by wildfires in the Gila National Forest, New Mexico, USA. *Fire Ecology*. 6(3): 77–85.

Location

Gila Aldo Leopold Wilderness Complex in New Mexico, USA

Ecosystem type(s)

Dry mixed-conifer forest; ponderosa pine forest

Summary: What the authors did and why

The authors analyzed the effects of the severity of a fire on the severity of a subsequent reburn based on the vegetation type. The analysis was stratified by vegetation types that burned frequently historically: piñon-juniper woodlands, ponderosa pine-dominated forests, and mixed-conifer and spruce-fir forests.

Publication findings

The authors found a positive feedback between the initial severity of a fire and the severity of the reburn fire. High severity reburns usually occurred after a high severity burn. This pattern was stronger in the mesic, high-elevation forests of the Gila National Forest, where the frequency of fire is greater. Conversely, low severity fires were typically followed by subsequent low severity fires, thereby maintaining the low-severity fire regime characteristics typical of these ecosystems.

Linkages

- **Fire severity on Fuels**

The authors found a positive feedback between the initial severity of a fire and the severity of the reburn fire. High severity reburns usually occurred after a high severity burn. This pattern was stronger in the mesic, high-elevation forests of the Gila National Forest, where the frequency of fire is greater. Conversely, low severity fires were typically followed by subsequent low severity fires, thereby maintaining the low-severity fire regime characteristics typical of these ecosystems.

- **Fire frequency, fire rotation, fire return interval on Fuels**

High severity reburns usually occurred after a high severity burn. This pattern was stronger in the mesic, high-elevation forests of the Gila National Forest where the frequency of fire is greater. Conversely, low severity fires were typically followed by subsequent low severity fires, thereby maintaining the low-severity fire regime characteristics typical of these ecosystems.

80. **Holsinger, L.; Parks, S.A.; Miller, C. 2016.** Weather, fuels, and topography impede wildland fire spread in western US landscapes. *Forest Ecology and Management*. 380: 59–69. <https://doi.org/10.1016/j.foreco.2016.08.035>

Location

U.S. Northern Rockies and southwestern United States

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

Understanding what factors impede wildfire activity has been an understudied area. The authors used matched case-control (MCC) logistic regression to assess the impact of weather, topography, and fuels in impeding fire spread in four study areas in the western United States.

Publication findings

Results showed clear differences between the Northern Rockies and the Southwest. In the Northern Rockies weather and fuels were the most important factors in

impeding fire spread while fuels and topography were the most important factors in the Southwest.

Linkages

- **Spatial pattern, landscape mosaic on Fuels**

While weather and fuels were most important in northern study areas, topography and fuels were dominant factors in the southwestern study area.

Although topography was shown to be an important factor in impeding fire spread in the Southwest, few studies have focused on topographic influences on fire in steep and rugged landscapes of the Southwest.

The authors support the concept that weather within a fire season is not a critical driver. Rather, moist conditions in the seasons prior to the fire season are more important as they produce copious fine fuels which cure and become available for fire in subsequent years.

81. **Honig, K.A.; Fulé, P.Z. 2012.** Simulating effects of climate change and ecological restoration on fire behaviour in a south-western USA ponderosa pine forest. *International Journal of Wildland Fire*. 21(6): 731–742.
<https://doi.org/10.1071/WF11082>

Location

Kaibab National Forest, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors simulated future fire behavior and forest structure under two future climate scenarios and simulated the potential effects of restoration treatments on a ponderosa pine forest stand.

Publication findings

The authors agreed with the consensus that increases in temperature will increase fire activity in the southwestern United States by the end of the century. Their results indicated fire intensity may not be significantly greater under the effects of climate change on an individual fire level; however, fire is likely to occur more frequently and burn a larger total area.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

The authors agreed with the consensus that increases in temperature will increase fire activity in the southwestern United States by the end of the century. Their results indicated fire intensity may not be significantly greater under the effects

of climate change on an individual fire level; however, fire is likely to occur more frequently and burn a larger total area.

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

The authors agreed with the consensus that increases in temperature will increase fire activity in the southwestern United States by the end of the century. Their results indicated fire intensity may not be significantly greater under the effects of climate change on an individual fire level; however, fire is likely to occur more frequently and burn a larger total area.

- **Temperature, RH, VPD on Fire behavior, fire type, fire intensity**

The authors agreed with the consensus that increases in temperature will increase fire activity in the southwestern United States by the end of the century. Their results indicated fire intensity may not be significantly greater under the effects of climate change on an individual fire level; however, fire is likely to occur more frequently and burn a larger total area.

82. **Hood, S.; Sala, A.; Heyerdahl, E.K.; Boutin, M. 2015.** Low-severity fire increases tree defense against bark beetle attacks. *Ecology*. 96(7): 1846–1855.

<https://doi.org/10.1890/14-0487.1>

Location

Idaho, Montana, Utah, and Oregon, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors tested the theory that frequent, low severity wildfire confers a heightened defense response to ponderosa pine against future bark beetle attack.

Publication findings

The authors found that frequent, low-severity fire events correlate with increased resin production in ponderosa pine, which increases protection against bark beetle infestation provided that the trees suffer only minor injury. Resin production decreases during long fire-free periods.

Linkages

- **Fire severity on Mortality, survivorship, community change**

The authors found that frequent, low-severity fire events correlate with increased resin production in ponderosa pine, which increases protection against bark beetle infestation provided that the trees suffer only minor injury. Resin production decreases during long fire-free periods.

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- **Fire frequency, fire rotation, fire return interval on Mortality, survivorship, community change**

The authors found that frequent, low-severity fire events correlate with increased resin duct defenses in ponderosa pine, which increases protection against bark beetle infestation provided the trees suffer only minor injury. This resin production decreases during long fire-free periods.

83. **Huebner, C.D.; Vankat, J.L. 2003.** The importance of environment vs. disturbance in the vegetation mosaic of central Arizona. *Journal of Vegetation Science*. 14(1): 25–34. <https://doi.org/10.1111/j.1654-1103.2003.tb02124.x>

Location

Chino Valley and Verde Ranger Districts of Prescott National Forest, Arizona, USA

Ecosystem type(s)

Chaparral; chaparral grassland; woodland; woodland grassland

Summary: What the authors did and why

The authors examined the relationships of environmental and disturbance variables to vegetation structure and composition to understand the relative importance of these variables in explaining ecosystem structure in chaparral and woodland vegetation types.

Publication findings

The authors found that environmental factors such as topographic features and soils were more important in determining vegetation structure and composition than disturbances such as fire area or fire frequency. Only woodland grasslands were likely to have been maintained by frequent fire historically.

Linkages

- **Spatial pattern, landscape mosaic on Species composition, invasives, structure**

The authors found that environmental factors such as topographic features and soils were more important in determining vegetation structure and composition than disturbances such as fire area or fire frequency. Only woodland grasslands were likely to have been maintained by frequent fire historically.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors found that environmental factors such as topographic features and soils were more important in determining vegetation structure and composition than disturbances such as fire area or fire frequency. Only woodland grasslands were likely to have been maintained by frequent fire historically.

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84. Huffman, D.W.; Crouse, J.E.; Chancellor, W.W.; Fulé, P.Z. 2012. Influence of time since fire on piñon-juniper woodland structure. *Forest Ecology and Management*. 274: 29–37.

Location

Northern Arizona, USA

Ecosystem type(s)

Piñon-juniper woodlands

Summary: What the authors did and why

The authors studied the effects of time since fire on the structural development of regeneration and complexity in piñon-juniper woodlands along a long-term chronosequence of approximately 370 years.

Publication findings

The authors found that the density of piñon-juniper woodlands did increase as the length of time since fire increased. However, seedling densities were highly variable across the study sites and did not have a significant relationship with time since fire. The authors suggest this may be because piñon-juniper woodlands are likely to require several decades to return to prefire conditions. Specifically, the authors observed that juniper (*Juniperus*) species density was positively related to time since fire while piñon (*Pinus edulis*) density was not, suggesting that juniper is more likely to establish post-fire as it is typically more drought tolerant. Site structural complexity also increased with time since fire, indicating developmental trajectories toward woodland conditions.

Linkages

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

The authors found that the density of piñon-juniper woodlands did increase as the length of time since fire increased. However, seedling densities were highly variable across the study sites and did not have a significant relationship with time since fire. The authors suggest this may be because piñon-juniper woodlands are likely to require several decades to return to prefire conditions. Specifically, the authors observed that juniper (*Juniperus*) species density was positively related to time since fire while piñon (*Pinus edulis*) density was not, suggesting that juniper is more likely to establish post-fire as it is typically more drought tolerant. Site structural complexity also increased with time since fire, indicating developmental trajectories toward woodland conditions.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors found that the density of piñon-juniper woodlands did increase as the length of time since fire increased. However, seedling densities were highly

variable across the study sites and did not have a significant relationship with time since fire. The authors suggest this may be because piñon-juniper woodlands are likely to require several decades to return to prefire conditions. Specifically, the authors observed that juniper (*Juniperus* spp.) species density was positively related to time since fire while piñon (*Pinus edulis*) species density was not, suggesting that juniper is more likely to establish post-fire as it is typically more drought tolerant. Site structural complexity also increased with time since fire, indicating developmental trajectories toward woodland conditions.

85. **Huffman, D.W.; Fulé, P.Z.; Crouse, J.E.; Pearson, K.M. 2009.** A comparison of fire hazard mitigation alternatives in piñon-juniper woodlands of Arizona. *Forest Ecology and Management*. 257(2): 628–635.
<https://doi.org/10.1016/j.foreco.2008.09.041>

Location

Kaibab National Forest, Arizona, USA

Ecosystem type(s)

Piñon-juniper woodlands

Summary: What the authors did and why

The authors compared alternative fire hazard mitigation treatments (no treatment, mechanical thinning only, prescribed fire only, and thinning followed by prescribed fire) to assess their effects on piñon-juniper structure and composition and ability to mitigate fire hazard.

Publication findings

The authors found that mechanical thinning with or without prescribed fire was effective at reducing wildfire hazard in piñon-juniper woodlands and reduced stand density and canopy fuel loads. Using low-severity surface fire alone did not affect overall fuels significantly, although it did reduce juniper tree densities more so than the control treatment.

Linkages

• **Fire behavior, fire type, fire intensity on Fuels**

The authors found that mechanical thinning with or without prescribed fire was effective at reducing wildfire hazard in piñon-juniper woodlands and reduced stand density and canopy fuel loads. Using low severity surface fire alone did not affect overall fuels significantly, although it did reduce juniper tree densities more so than the control treatment.

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86. **Huffman, D.W.; Fulé, P.Z.; Pearson, K.M.; Crouse, J.E. 2008.** Fire history of piñon-juniper woodlands at upper ecotones with ponderosa pine forests in Arizona and New Mexico. *Canadian Journal of Forest Research*. 38(8): 2097–2108.
<https://doi.org/10.1139/X08-053>

Location

Tusayan Ranger District of Kaibab National Forest, Arizona, USA; La Mesa de Las Viejas, New Mexico, USA

Ecosystem type(s)

Piñon-juniper woodlands; ponderosa pine forest

Summary: What the authors did and why

The authors reconstructed the historical fire regime using dendrochronological and forest structure analysis techniques along the ecotonal boundary of piñon-juniper woodlands and ponderosa pine forest.

Publication findings

The authors found that fires within the ponderosa pine stands did not spread to the adjacent piñon-juniper woodland. Historically, fire in piñon-juniper was typically severe and stand-replacing, but limited in size with fire return intervals of 300 to 400 years. This pattern has resulted in numerous small patches of same-aged piñon stands.

Linkages

- **Spatial pattern, landscape mosaic on Species composition, invasives, structure**

The authors found that fires within the ponderosa pine stands did not spread to the adjacent piñon-juniper woodland. Historically, fire in piñon-juniper was typically severe and stand-replacing, but limited in size with fire return intervals of 300 to 400 years. This pattern has resulted in numerous small patches of same-aged piñon stands.

- **Annual area burned, fire size on Dispersal, regeneration, establishment**

The authors found that fires within the ponderosa pine stands did not spread to the adjacent piñon-juniper woodland. Historically, fire in piñon-juniper was typically severe and stand-replacing, but limited in size with fire return intervals of 300 to 400 years. This pattern has resulted in numerous small patches of same-aged piñon stands.

- **Annual area burned, fire size on Species composition, invasives, structure**

The authors found that fires within the ponderosa pine stands did not spread to the adjacent piñon-juniper woodland. Historically, fire in piñon-juniper was typically severe and stand-replacing, but limited in size with fire return intervals of 300 to 400 years. This has resulted in numerous small patches of same-aged piñon stands.

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87. **Huffman, D.W.; Zegler, T.J.; Fulé, P.Z. 2015.** Fire history of a mixed conifer forest on the Mogollon Rim, northern Arizona, USA. *International Journal of Wildland Fire*. 24(5): 680–689. <https://doi.org/10.1071/WF14005>

Location

Apache-Sitgreaves National Forests, Arizona, USA

Ecosystem type(s)

Mixed-conifer forest

Summary: What the authors did and why

The authors reconstructed the fire regime characteristics of a warm-dry mixed-conifer forest to evaluate potential changes to the fire regime since Euro-American settlement and examine the extent of high or mixed severity fire in these ecosystems historically.

Publication findings

The authors found that current tree establishment patterns do not suggest that high severity fire was widespread historically at this site; only small patches of young trees up to 25 ha in size may have established after stand-replacing fire. Fire cessation after 1879 has led to an overall increase in density at the site and an increase in southwestern white pine (*Pinus strobiformis*) and white fir (*Abies concolor*), now co-dominant with ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*).

Linkages

- **Fire severity on Species composition, invasives, structure**

The authors found that current tree establishment patterns do not suggest that high severity fire was widespread historically at this site; only small patches of young trees up to 25 ha in size may have established after stand-replacing fire.

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

Fire cessation after 1879 has led to an overall increase in density at the site and an increase in southwestern white pine (*Pinus strobiformis*) and white fir (*Abies concolor*), now co-dominant with ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*).

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

Fire cessation after 1879 has led to an overall increase in density at the site and an increase in southwestern white pine (*Pinus strobiformis*) and white fir (*Abies concolor*), now co-dominant with ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*).

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88. **Hunter, M.E.; Iniguez, J.M.; Lentile, L.B. 2011.** Short- and long-term effects on fuels, forest structure, and wildfire potential from prescribed fire and resource benefit fire in southwestern forests, USA. *Fire Ecology*. 7(3): 108–121.
<https://doi.org/10.4996/fireecology.0703108>

Location

Gila National Forest, New Mexico, USA

Ecosystem type(s)

Piñon-juniper woodlands; ponderosa pine forests

Summary: What the authors did and why

The authors examined the effects of recent prescribed and resource benefit fires on the fuel loads, structure, and potential fire behavior in ponderosa pine and piñon-juniper woodlands. Additionally, they studied the effects of repeated resource benefit fire on these ecosystems.

Publication findings

The authors found that in ponderosa pine forests, low- and moderate-severity resource benefit fires reduced basal area and crown fire potential more effectively than prescribed fires. Areas burned multiple times for resource benefit maintained stand structure and fuel loads more consistent with historical forest conditions. Low severity fire in piñon-juniper woodlands did not have an effect on forest structure and fuels; however, moderate severity fire did have beneficial effects on these ecosystems.

Linkages

- **Fire severity on Fuels**

The authors found that in ponderosa pine forests, low- and moderate-severity resource benefit fires reduced basal area and crown fire potential more effectively than prescribed fires. Areas burned multiple times for resource benefit maintained stand structure and fuel loads more consistent with historical forest conditions. Low severity fire in piñon-juniper woodlands did not have an effect on forest structure and fuels; however, moderate severity fire did have beneficial effects on these ecosystems.

- **Fire severity on Species composition, invasives, structure**

The authors found that in ponderosa pine forests, low- and moderate- severity resource benefit fires more effectively reduced basal area and crown fire potential more so than prescribed fires. Areas burned multiple times for resource benefit maintained stand structure and fuel loads more consistent with historical forest conditions. Low severity fire in piñon-juniper woodlands did not have an effect on forest structure and fuels; however, moderate severity fire did have beneficial effects on these ecosystems.

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89. Hunter, M.E.; Omi, P.N.; Martinson, E.J.; Chong, G.W. 2006. Establishment of non-native plant species after wildfires: Effects of fuel treatments, abiotic and biotic factors, and post-fire grass seeding treatments. *International Journal of Wildland Fire*. 15(2): 271–281. <https://doi.org/10.1071/WF05074>

Location

Cerro Grande Fire, New Mexico, USA; Hi Meadow Fire, Colorado, USA; Hayman Fire, Colorado

Ecosystem type(s)

Ponderosa pine forests

Summary: What the authors did and why

The authors examined the effects of prefire and postfire management strategies on the establishment of nonnative plant species after high severity wildfire. They further considered other biotic and abiotic factors that may also influence nonnative species establishment post-fire.

Publication findings

Fuel treatments prior to fire did not significantly influence the establishment of nonnative species post-fire nor increase the potential for invasion. High severity fire, however, was a strong predictor of nonnative species establishment, and invasion was more likely with increasing fire severity, indicated in this study by depth of char.

Linkages

- **Fire severity on Species composition, invasives, structure**

High severity fire was a strong predictor of nonnative species establishment, and invasion was more likely with increasing fire severity, indicated by depth of char in this study.

90. Hurteau, M.; North, M. 2008. Mixed-conifer understory response to climate change, nitrogen, and fire. *Global Change Biology*. 14(7): 1543–1552. <https://doi.org/10.1111/j.1365-2486.2008.01584.x>

Location

Yosemite National Park, California, USA; Teakettle Experimental Forest, California, USA

Ecosystem type(s)

Mixed-conifer forest

Summary: What the authors did and why

The authors experimentally tested the effects of increasing and decreasing snowpack depth, increasing nitrogen, and prescribed fire on understory fuel diversity and biomass production in a mixed-conifer forest.

Publication findings

The authors found significant variation between treatments and across sites, underscoring the difficulty in modeling future climatic effects on ecosystem biodiversity based on limited inputs. However, they did find that increasing nitrogen and snowpack resulted in increased shrub biomass at both study sites whereas reduced snowpack resulted in increased herb biomass within shrub-dominated communities. They also found that treatments that increased shrub and herbaceous understory resulted in increased fire intensity. Increases in fire intensity then reduced shrub biomass, which the authors suggest is more in line with historical conditions of frequent fire.

Linkages

- **Snowpack, snow and rain on Fire behavior, fire type, fire intensity**

The authors found that increasing nitrogen and snowpack resulted in increased shrub biomass at both study sites whereas reduced snowpack resulted in increased herb biomass within shrub-dominated communities. The treatments that increased shrub and herbaceous understory resulted in increased fire intensity.

- **Fire behavior, fire type, fire intensity on Fuels**

The authors found that treatments that increased shrub and herbaceous understory resulted in increased fire intensity. Increases in fire intensity then reduced shrub biomass, which the authors suggest is more in line with historical conditions of frequent fire.

- **Fire behavior, fire type, fire intensity on Species composition, invasives, structure**

The authors found that treatments that increased shrub and herbaceous understory resulted in increased fire intensity. Increases in fire intensity then reduced shrub biomass, which the authors suggest is more in line with historical conditions of frequent fire.

91. **Iniguez, J.M.; Swetnam, T.W.; Baisan, C.H. 2016.** Fire history and moisture influences on historical forest age structure in the sky islands of southern Arizona, USA. *Journal of Biogeography*. 43(1): 85–95. <https://doi.org/10.1111/jbi.12626>

Location

Rincon Peak, Saguaro National Park, Arizona, USA; Rose Canyon, Santa Catalina Ranger District, Arizona

Ecosystem type(s)

Gradient of sky island ecosystems: chaparral; fir; forested; oak; piñon; piñon-juniper; ponderosa pine

Summary: What the authors did and why

The authors examined synchrony of stand age and structure between

geographically separated sites, or sky islands, to determine the influence of moisture and drought variability versus fire frequency on historical stand development.

Publication findings

The authors found that fire frequency appeared to be the primary influence on tree age structure in the sky island communities. Fire-free periods were related to age peaks. The authors suggest that climate did not limit tree establishment and regeneration; however, climate did influence fire frequency and thus indirectly influenced age structure pattern in these stands. Within the study sites, age peaks occurred synchronously in the early 19th century, coinciding with a period of increased moisture within the ENSO cycle that reduced fire activity.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors suggest that climate did not limit tree establishment and regeneration; however, climate did influence fire frequency and thus indirectly influenced age structure pattern in these stands. Within the study sites, age peaks occurred synchronously in the early 19th century, coinciding with a period of increased moisture within the ENSO cycle that reduced fire activity.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors found that fire frequency appeared to be the primary influence on tree age structure in the sky island communities. Fire free periods were related to age peaks. The authors suggest that climate did not limit tree establishment and regeneration; however, climate did influence fire frequency and thus indirectly influenced age structure pattern in these stands. Within the study sites, age peaks occurred synchronously in the early 19th century, coinciding with a period of increased moisture within the ENSO cycle that reduced fire activity.

92. **Iniguez, J.M.; Swetnam, T.W.; Baisan, C.H. 2009.** Spatially and temporally variable fire regime on Rincon Peak, Arizona, USA. *Fire Ecology*. 5(1): 3–21.
<https://doi.org/10.4996/fireecology.0501003>

Location

Rincon Peak, Arizona, USA

Ecosystem type(s)

Dry mixed-conifer ecosystems; piñon-juniper-chaparral; ponderosa pine ecosystems; sky islands

Publication findings

Fires prior to 1763 were synchronous with regionwide fire years, which coincided with periods of drought. After 1763, however, fires on the peak became asynchronous to widespread fire years throughout the region. The

authors suggest that when this occurs, bottom-up factors may have become more important in controlling the spread of fire. Specifically, Rincon Peak is isolated and surrounded by talus slopes and rock outcrops. However, they also hypothesized that a variation on ENSO, the late-18th to early-19th century transition period (LEENT), may have occurred at this time, lengthening the fire-free interval. The LEENT period decreased the ENSO signal and limited the wet and dry oscillations. Consequently, the cycles of high fuel production followed by drought, hence increased flammability, were extended. The authors' findings suggest that isolated sky island ponderosa pine forests may be especially susceptible to climate change and drought because of their separation from the larger landscape and from the frequent fire regimes that regulate severity in these ecosystems.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

Fires prior to 1763 were synchronous with region-wide fire years, which coincided with periods of drought. After 1763, however, fires on the peak became asynchronous to widespread-fire years throughout the region. The authors suggest that when this occurs, bottom-up factors may have become more important in controlling the spread of fire. Specifically, Rincon Peak is isolated and surrounded by talus slopes and rock outcrops. However, they also hypothesized that a variation on ENSO, the late-18th to early-19th century transition period (LEENT) may have occurred at this time, lengthening the fire-free interval. The LEENT period decreased the ENSO signal and limited the wet and dry oscillations. Consequently, the cycles of high fuel production followed by drought, hence increased flammability, were extended. The author's findings suggest that isolated sky island ponderosa pine forests may be especially susceptible to climate change and drought because of their separation from the larger landscape and from the frequent fire regimes that regulate severity in these ecosystems.

- **Spatial pattern, landscape mosaic on Mortality, survivorship, turnover**

The author's findings suggest that isolated sky island ponderosa pine forests may be especially susceptible to climate change and drought because of their separation from the larger landscape and from the frequent fire regimes that regulate severity in these ecosystems.

93. **Ireland, K.B.; Stan, A.B.; Fulé, P.Z. 2012.** Bottom-up control of a northern Arizona ponderosa pine forest fire regime in a fragmented landscape. *Landscape Ecology*. 27(7): 983-997.

Location

Grand Canyon-Parashant National Monument, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors investigated the relative influence of top-down climate controls versus bottom-up vegetation controls on the timing and spatial pattern of fire in a historically fragmented and patchy ponderosa pine landscape.

Publication findings

The study landscape was characterized by patches of ponderosa pine forest divided by a matrix of piñon-juniper, sagebrush shrublands, and small grasslands. The authors did not find regional synchrony between the patches of ponderosa pine within the study area, suggesting that bottom-up controls, such as fuels, may have more strongly influenced the historical occurrence of fire in this region. The authors did find, however, that as the scale of the analysis increased to larger regional areas, climate-driven fire synchrony increased, and fire was associated with dry conditions in the year of the fire and wet conditions 2 years prior to the fire. The authors suggest that climate may be less influential on fire activity in ecosystems that are fuel limited.

Linkages

- **Drought on Spatial pattern, landscape mosaic**

The study landscape was characterized by patches of ponderosa pine forest divided by a matrix of piñon-juniper, sagebrush shrublands, and small grasslands. The authors did not find regional synchrony between the patches of ponderosa pine within the study area, suggesting that bottom-up controls, such as fuels, may have more strongly influenced the historical occurrence of fire in this region than climate. The authors did find, however, that as the scale of the analysis increased to larger regional areas, climate-driven fire synchrony increased, and fire was associated with dry conditions in the year of the fire and wet conditions 2 years prior to the fire. The authors suggest that climate may be less influential on fire activity in ecosystems that are fuel limited.

- **Drought on Fire frequency, fire rotation, fire return interval**

The study landscape was characterized by patches of ponderosa pine forest divided by a matrix of piñon-juniper, sagebrush shrublands, and small grasslands. The authors did not find regional synchrony between the patches of ponderosa pine within the study area, suggesting that bottom-up controls, such as fuels, may have more strongly influenced the historical occurrence of fire in this region than climate. The authors did find, however, that as the scale of the analysis increased to larger regional areas, climate-driven fire synchrony increased, and fire was associated with dry conditions in the year of the fire and wet conditions 2 years prior to the fire. The authors suggest that climate may be less influential on fire activity in ecosystems that are fuel limited.

- **Spatial pattern, landscape mosaic on Fuels**

The study landscape was characterized by patches of ponderosa pine forest divided by a matrix of piñon-juniper, sagebrush shrublands, and small grasslands. The authors did not find regional synchrony between the patches of ponderosa pine within the study area, suggesting that bottom-up controls, such as fuels, may have more strongly influenced the historical occurrence of fire in this region than climate. The authors suggest that climate may be less influential on fire activity in ecosystems that are fuel limited.

94. **Jolly, W.M.; Cochrane, M.A.; Freeborn, P.H.; Holden, Z.A.; Brown, T.J.; Williamson, G.J.; Bowman, D.M.J.S. 2015.** Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*. 6(1): 7537.
<https://doi.org/10.1038/ncomms8537>

Location

Global

Ecosystem type(s)

Vegetated surfaces

Summary: What the authors did and why

The authors assessed global trends in fire weather season length.

Publication findings

The authors found that fire season length has significantly increased across approximately 25 percent of the Earth's vegetated area, resulting in a doubling of the global burnable area. Areas with the greatest increase in fire season length occurred where there were the greatest changes in temperature especially, but also in humidity, length of rain-free periods, and wind speeds.

Linkages

- **Fire season length on Annual area burned, fire size**

The authors found that fire season length has significantly increased across approximately 25 percent of the Earth's vegetated area resulting in a doubling of the global burnable area. Areas with the greatest increase in fire season length occurred where there were the greatest changes in temperature especially, but also in humidity, length of rain-free periods, and wind speeds.

- **Drought on Annual area burned, fire size**

The authors found that fire season length has significantly increased across approximately 25 percent of the Earth's vegetated area resulting in a doubling of the global burnable area. Areas with the greatest increase in fire season length occurred where there were the greatest changes in temperature especially, but also in humidity, length of rain-free periods, and wind speeds.

- **Temperature, RH, VPD on Annual area burned, fire size**

The authors found that fire season length has significantly increased across approximately 25percent of the Earth's vegetated area resulting in a doubling of the global burnable area. Areas with the greatest increase in fire season length occurred where there were the greatest changes in temperature especially, but also in humidity, length of rain-free periods, and wind speeds.

95. **Keyser, A.; Westerling, A.L. 2017.** Climate drives inter-annual variability in probability of high severity fire occurrence in the western United States. *Environmental Research Letters*. 12(6): 65003.

<https://doi.org/10.1088/1748-9326/aa6b10>

Location

Western United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors incorporated topography, vegetation, and fire-year climate data to develop predictive models of high severity fires for the western United States.

Publication findings

Results indicated the importance of both vegetation and fire-year climate predictors in identifying fires where a large percentage of the area is likely to burn with high fire severity. There was no significant increase in high-severity fire occurrence by month, May through October.

Linkages

- **Temperature, RH, VPD on Fire severity**

Results highlighted the importance of interannual climate variability for high-severity fire occurrence. Fire-year climate significantly changed probabilities of high-severity fire occurrence across the western United States. Stronger effects were found in Sierra Nevada and southwestern forests with mixed-severity fire regimes than in northwestern and Northern Rockies forests with high-severity fire regimes.

96. **Kitzberger, T.; Brown, P.M.; Heyerdahl, E.K.; Swetnam, T.W.; Veblen, T.T. 2007.** Contingent Pacific–Atlantic Ocean influence on multicentury wildfire synchrony over western North America. *Proceedings of the National Academy of Sciences*. 104(2): 543–548. <https://doi.org/10.1073/pnas.0606078104>

Location

North American subregions

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors examined the relationships between continental-scale drought and ENSO, PDO, and AMO to understand how interannual and multidecadal climate variability drives fire activity across continental scales.

Publication findings

The authors found that ENSO has a strong interannual influence on PDSI and, hence, fire activity across the western United States, whereas PDO captures the variation in fire across decadal scales in the Pacific Northwest. AMO influences the strength of both ENSO and PDO on multidecadal scales across the continent. In the Southwest, prior wet years, often associated with warm ENSO events, prime fuels for synchronous fire activity during the subsequent fire season.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that ENSO has a strong interannual influence on PDSI and, hence, fire activity across the western United States, whereas PDO captures the variation in fire across decadal scales in the Pacific Northwest. AMO influences the strength of both ENSO and PDO on multidecadal scales across the continent. In the Southwest, prior wet years, often associated with warm ENSO events, prime fuels for synchronous fire activity during the subsequent fire season.

97. **Kolden, C.A.; Bleeker, T.M.; Smith, A.M.S.; Poulos, H.M.; Camp, A.E. 2017.** Fire effects on historical wildfire refugia in contemporary wildfires. *Forests*. 8(10): 400. <https://doi.org/10.3390/f8100400>

Location

Swauk Late Successional Reserve, Okanogan-Wenatchee National Forest, Washington, USA

Ecosystem type(s)

Douglas-fir forest; ponderosa pine forest

Summary: What the authors did and why

Wildfire refugia provide safety for fire-sensitive species and seed banks yet are relatively understudied. The authors revisited 122 sites classified in 1994 for a prior fire refugia study, which were subsequently burned by two wildfires in 2012. They assessed the fire effects for historically persistent fire refugia at 109 sites and compared them to the surrounding nonrefugial forest matrix.

Publication findings

Only 6 (5.5 percent) of the 109 paired plots that were established initially in 1994 and that were revisited after the 2012 wildfires, did not experience any fire effects in 2012 and were left unburned. Only one of these six unburned plots was classified as a fire refugium in 1994; however, this was not statistically significant (chi-square test of independence, $c^2 = 0.768$, $p = 0.381$) due to the low number

of samples. Refugial sites burned more severely and experienced higher tree mortality when compared to nonrefugial plots.

Linkages

- **Fire severity on Fuels**

Refugial plots burned more severely than nonrefugial plots as assessed through the total plot CBI metric ($W = 1015.5$, $p = 0.0582$).

- **Fire severity on Mortality, survivorship, turnover**

For the tree-level severity metrics, the percent total tree mortality ($W = 921.5$, $p = 0.0196$), percent understory tree mortality ($W = 867$, $p = 0.0116$), average bole char height ($W = 1042$, $p = 0.0802$), and average foliage scorched ($W = 899$, $p = 0.00754$) were all significantly higher for refugial plots (at $\alpha = 0.1$, used due to nonnormal data and a greater number of nonrefugial plots).

98. **Korb, J.E.; Fulé, P.Z.; Wu, R. 2013.** Variability of warm/dry mixed conifer forests in southwestern Colorado, USA: Implications for ecological restoration. *Forest Ecology and Management*. 304: 182–191. <https://doi.org/10.1016/j.foreco.2013.04.028>

Location

San Juan National Forest, Colorado, USA

Ecosystem type(s)

Dry mixed-conifer forest

Summary: What the authors did and why

The authors compared the forest composition and structure along three transects at similar latitude and elevation to determine if climate synchronized fire occurrence across the large regional area historically.

Publication findings

The authors observed that increases in fire occurrence typically took place during years of drier- than-average conditions with 1 to 3 moist years preceding the fire year at all of their study sites; however, synchronous fire years were less common than unique fire years at any one study site, suggesting that local conditions may more strongly influence fire activity.

Linkages

- **Drought on Spatial pattern, landscape mosaic**

The authors observed that increases in fire occurrence typically took place during years of drier- than-average conditions with 1 to 3 moist years preceding the fire year at all of their study sites; however, synchronous fire years were less common than unique fire years at any one study site, suggesting that local conditions may more strongly influence fire activity.

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99. **Krawchuk, M.A.; Moritz, M.A. 2011.** Constraints on global fire activity vary across a resource gradient. *Ecology*. 92(1): 121–132. <https://doi.org/10.1890/09-1843.1>

Location

Global

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors examined the potential relationship between global fire activity and biomass resource availability based on monthly soil moisture metrics before and during the fire season. They also examined the efficacy of a potential global fire weather metric: anomaly in mean monthly 500 hPa geopotential height.

Publication findings

The authors' results support the "varying constraints" hypothesis that wildfire occurrence requires key biophysical factors to coincide; however, the relationship between fuel moisture and fuel availability varies along fairly predictable spatial patterns. In areas where fuel is abundant, fuel moisture availability has the strongest constraint on fire activity, whereas in fuel-limited systems, fire is constrained more strongly by fuel availability. In these ecosystems, lagged fuel moisture is more representative of subsequent potential fire activity.

Linkages

- **Temperature, RH, VPD on Fire behavior, fire type, fire intensity**

The authors' results support the "varying constraints" hypothesis that wildfire occurrence requires key biophysical factors to coincide; however, the relationship between fuel moisture and fuel availability varies along fairly predictable spatial patterns. In areas where fuel is abundant, fuel moisture availability has the strongest constraint on fire activity, whereas in fuel-limited systems, fire is constrained more strongly by fuel availability. In these ecosystems, lagged fuel moisture is more representative of subsequent potential fire activity.

100. **Krawchuk, M.A.; Moritz, M.A.; Parisien, M.A.; Van Dorn, J.; Hayhoe, K. 2009.** Global pyrogeography: The current and future distribution of wildfire. *PLoS ONE*. 4(4): e5102. <https://doi.org/10.1371/journal.pone.0005102>

Location

Global

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors quantified environmental drivers of global wildfire including climate conditions at a coarse spatiotemporal resolution in order to model future projections of global fire patterns under climate change models.

Publication findings

The authors found that globally, changes in temperature and precipitation may result in a rearrangement of fire probabilities, where fire activity will increase in some areas and decrease in others under climate change.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

The authors found that globally, changes in temperature and precipitation may result in a rearrangement of fire probabilities, where fire activity will increase in some areas and decrease in others under climate change.

- **Snowpack, snow and rain on Annual area burned, fire size**

The authors found that globally, changes in temperature and precipitation may result in a rearrangement of fire probabilities, where fire activity will increase in some areas and decrease in others under climate change.

101. Kulakowski, D.; Kaye, M.W.; Kashian, D.M. 2013. Long-term aspen cover change in the western US. *Forest Ecology and Management*. 299: 52–59.

<https://doi.org/10.1016/j.foreco.2013.01.004>

Location

Western United States

Ecosystem type(s)

Aspen stands

Summary: What the authors did and why

The authors conducted a review of long-term and broad-scale trends in aspen (*Populus tremuloides*) cover across the western United States.

Publication findings

The literature generally agrees that stand-replacing fire both reduces encroaching conifer populations and creates favorable conditions for aspen to resprout post-fire. Because fire return intervals in upland, mesic sites are generally longer, it is unclear if fire suppression has affected aspen regeneration.

Linkages

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

The literature generally agrees that stand-replacing fire both reduces encroaching conifer populations and creates favorable conditions for aspen (*Populus*

tremuloides) to resprout post-fire. Because fire return intervals in upland, mesic sites are generally longer, it is unclear if fire suppression has affected aspen regeneration.

- **Fire behavior, fire type, fire intensity on Dispersal, regeneration, establishment**

The literature generally agrees that stand-replacing fire both reduces encroaching conifer populations and creates favorable conditions for aspen (*Populus tremuloides*) to resprout post-fire.

102. **Larson, A.J.; Belote, R.T.; Cansler, C.A.; Parks, S.A.; Dietz, M.S. 2013.** Latent resilience in ponderosa pine forest: Effects of resumed frequent fire. *Ecological Applications*. 23(6): 1243–1249. <https://doi.org/10.1890/13-0066.1>

Location

Bob Marshall Wilderness, Montana, USA

Ecosystem type(s)

Lodgepole pine forest; ponderosa pine forest

Summary: What the authors did and why

The authors quantified the effects of reintroducing fire to an unlogged, fire-excluded, ponderosa pine forest to examine postfire trajectories of forest regeneration and stand composition and structure and to see if ponderosa pine forests possess latent resilience to reintroduced fire.

Publication findings

The authors found that the initial reintroduction of fire reduced tree densities, but resulted in the establishment of a dense stand of lodgepole pine, trending toward an alternative trajectory. However, a second fire killed the regenerating lodgepole pine cohort along with the Douglas-fir (*Pseudotsuga menziesii*) understory, and returned the area to a ponderosa pine-dominated forest. This outcome suggests that ponderosa pine forests do possess latent resilience to reintroduced fire after extended periods of fire exclusion.

Linkages

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

The authors found that the initial reintroduction of fire reduced tree densities, but resulted in the establishment of a dense stand of lodgepole pine, trending toward an alternative trajectory. However, a second fire killed the regenerating lodgepole pine cohort along with the Douglas-fir (*Pseudotsuga menziesii*) understory and returned the area to a ponderosa pine dominated forest. This outcome suggests that ponderosa pine forests do possess latent resilience to reintroduced fire after extended periods of fire exclusion.

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103. Laughlin, D.C.; Strahan, R.T.; Huffman, D.W.; Sánchez Meador, A.J. 2017. Using trait-based ecology to restore resilient ecosystems: Historical conditions and the future of montane forests in western North America. *Restoration Ecology*. 25: S135–S146. <https://doi.org/10.1111/rec.12342>

Location

Black Mesa Ranger District of the Apache-Sitgreaves National Forests, Arizona, USA

Ecosystem type(s)

Mixed-conifer forests

Summary: What the authors did and why

The authors examined the ability of trait-based ecological restoration to enhance forest ecosystem resilience under projected climate change and increased fire frequency.

Publication findings

The authors suggest that manipulating plant assemblages based on traits, instead of historical reference conditions, that confer both drought and fire tolerance may be an effective method to increase forest resilience in an era of rapid climate and environmental change even if those communities have no analogue assemblages currently. For the western United States, this approach includes managing for species with traits such as dense wood, tough leaves, and thick bark that can withstand increased fire frequency.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors suggest that manipulating plant assemblages based on traits, instead of historical reference conditions, that confer both drought and fire tolerance may be an effective method to increase forest resilience in an era of rapid climate and environmental change even if those communities have no-analogue assemblages currently. For the western United States, this approach includes managing for species with traits such as dense wood, tough leaves, and thick bark that can withstand increased fire frequency.

104. Lentile, L.B.; Smith, F.W.; Shepperd, W.D. 2006. Influence of topography and forest structure on patterns of mixed severity fire in ponderosa pine forests of the South Dakota Black Hills, USA. *International Journal of Wildland Fire*. 15(4): 557–566. <https://doi.org/10.1071/WF05096>

Location

Black Hills, South Dakota, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors examined the effects of topography and prefire vegetation composition and structure on burn severity and fire effects in the 2000 Jasper Fire.

Publication findings

The Jasper Fire burned under extreme weather conditions and drought; however, the postfire burn severity mosaic was highly variable due to the differences in prefire forest vegetation and topography. Despite summer drought conditions and abnormally low fuel moisture content of woody fuels, the fire was not dominated by high severity fire. Instead, forest structure has the strongest influence on burn severity over topography or weather and climate conditions.

Linkages

- **Drought on Fire severity**

The Jasper Fire burned under extreme weather conditions and drought; however, the postfire burn severity mosaic was highly variable due to the differences in pre-fire forest vegetation and topography. Despite summer drought conditions and abnormally low fuel moisture content of woody fuels, the fire was not dominated by high severity fire. Instead, forest structure has the strongest influence on burn severity over topography or weather and climate conditions.

105. **Litschert, S.E.; Brown, T.C.; Theobald, D.M. 2012.** Historic and future extent of wildfires in the Southern Rockies Ecoregion, USA. *Forest Ecology and Management*. 269: 124–133. <https://doi.org/10.1016/j.foreco.2011.12.024>

Location

Southern Rockies Ecoregion; Colorado, USA; New Mexico, USA; Wyoming, USA

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors reconstructed the historical wildfire regime within the Southern Rockies Ecoregion and developed a model to both predict historical fire extent and project potential future fire extent under two climate change GCM scenarios: A2 (which projects high increases in temperature) and B1 (which projects lower temperature increases).

Publication findings

The authors found that from 1930 to 2006, the number and extent of wildfires has increased significantly due to increases in human-ignited fires and warmer temperatures, especially in the last few decades. The more moderate scenario, B1, which projects lower temperature increases, resulted in the highest increases in median area burned. The authors suggest that an increase in precipitation under the more extreme A2 scenario may moderate area burned to some extent.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

The authors found that from 1930 to 2006, the number and extent of wildfires has increased significantly due to increases in human-ignited fires and warmer temperatures, especially in the last few decades. The more moderate scenario, B1, which projects lower temperature increases, resulted in the highest increases in median area burned. The authors suggest that an increase in precipitation under the more extreme A2 scenario may moderate area burned to some extent.

106. **Littell, J.S.; McKenzie, D.; Peterson, D.L.; Westerling, A.L. 2009.** Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. *Ecological Applications*. 19(4): 1003–1021.

Location

Sixteen ecoprovinces across the western United States

Ecosystem type(s)

Course-scale vegetation types

Summary: What the authors did and why

The authors applied generalized linear models based on large-scale, interannual or seasonal climate variables of precipitation, temperature, and PDSI to area burned across vegetation types in the study area.

Publication findings

The authors found that climate–fire relationships exist across the western United States with approximately 39 percent (1916–2003) and 64 percent (1977–2003) of area burned directly related to climate; however, the strength of the seasonal or interannual effects of climate varied across the different vegetation types. Southwestern deserts and semiarid desert ecoprovinces tend to be fuel limited. Wetter conditions in the winter prior to the fire season followed by dry conditions during the year of the fire resulted in greater area burned. The authors suggest that climate change may lead to one of two paths: a reduction in fuels due to persistent drought, limiting area burned, or wetter conditions that lead to an increase in vegetation biomass along with an earlier onset of warmer temperatures that dry these fuels and increase the area burned. The mountainous ecoprovince of Arizona and New Mexico also did not correlate to year-of-fire precipitation, but did have a relationship with precipitation from the previous winter. However, temperature during the year of the fire was related to area burned in these areas and to annual (water year) PDSI.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

For the mountainous ecoprovince of Arizona and New Mexico, temperature during

the year-of-the fire was related to area burned in these areas as well as annual (water year) PDSI.

- **Snowpack, snow and rain on Annual area burned, fire size**

Southwestern deserts and semiarid desert ecoprovinces tend to be fuel limited. Wetter conditions in the winter prior to the fire season followed by dry condition during the year of the fire resulted in greater area burned. The authors suggest that climate change may lead to one of two paths: a reduction in fuels due to persistent drought, limiting area burned, or wetter conditions that lead to an increase in vegetation biomass along with an earlier onset of warmer temperatures that dry these fuels and increase the area burned. The mountainous ecoprovince of Arizona and New Mexico also did not correlate to year-of-fire precipitation, but did have a relationship with precipitation from the winter previous.

107. Liu, Y.; Goodrick, S.L.; Stanturf, J.A. 2013. Future US wildfire potential trends projected using a dynamically downscaled climate change scenario. *Forest Ecology and Management*. 294: 120–135. <https://doi.org/10.1016/j.foreco.2012.06.049>

Location

Continental United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors examined potential future (2041–2070) trends and spatial patterns of wildfire across the continental United States using downscaled regional climate change scenarios.

Publication findings

The authors found that KBDI is expected to increase, driven primarily by increasing temperature across the Southwest, Rocky Mountains, northern Great Plains, Southeast, and Pacific Coast, thereby increasing future fire potential across most of the continental United States. The fire season is also projected to increase in length, potentially by several months in some regions.

Linkages

- **Drought on Annual area burned, fire size**

The authors found that KBDI is expected to increase, driven primarily by increasing temperature across the Southwest, Rocky Mountains, northern Great Plains, Southeast, and Pacific Coast, thereby increasing future fire potential across most of the continental U.S.

- **Drought on Fire timing, fire seasonality**

The fire season is projected to increase in length, potentially by several months in some regions.

- 108. Liu, Y.; Stanturf, J.; Goodrick, S. 2010.** Trends in global wildfire potential in a changing climate. *Forest Ecology and Management*. 259(4): 685–697.

<https://doi.org/10.1016/j.foreco.2009.09.002>

Location

Global

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors simulated and projected global wildfire potential using KBDI as a proxy and future trends in fire activity under multiple climate change scenarios.

Publication findings

The authors found significant increases in fire potential across the United States, South America, Eurasia, southern Africa, and Australia. Across much of the United States, this increase in potential wildfire activity is mainly driven by warming temperatures. The future projections of KBDI for the southwestern United States were twice as high as the U.S. average. The authors also found that warming will lengthen the fire season window across these regions and will be accompanied by an increased likelihood of more extreme weather events conducive to wildfire activity.

Linkages

- **Fire season length on Fire behavior, fire type, fire intensity**

Warming will lengthen the fire season window across the United States, South America, Eurasia, southern Africa, and Australia and will be accompanied by an increased likelihood of more extreme weather events conducive to wildfire activity.

- **Temperature, RH, VPD on Fire behavior, fire type, fire intensity**

The authors found significant increases in fire potential across the United States, South America, Eurasia, southern Africa, and Australia. Across much of the United States, this increase in potential wildfire activity is mainly driven by warming temperatures. The future projections of KBDI for the southwestern United States were twice as high as the U.S. average. The authors also found that warming will lengthen the fire season window across these regions and will be accompanied by an increased likelihood of more extreme weather events conducive to wildfire activity.

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109. Liu, Z.; Wimberly, M.C. 2015. Climatic and landscape influences on fire regimes from 1984 to 2010 in the western United States. PLoS ONE. 10(10): e0140839. <https://doi.org/10.1371/journal.pone.0140839>

Location

Western United States

Ecosystem type(s)

Omernik Level III ecoregions of the United States

Summary: What the authors did and why

The authors examined the effect of climate, topography, vegetation, and human land use on the spatiotemporal patterns of fire occurrence, severity, and size across the western United States using boosted regression tree analysis.

Publication findings

Large fire occurrence was highly synchronous across broad spatial scales and significantly correlated to short-term climate anomalies. Specifically, precipitation anomalies 90 days prior to the fire had the strongest influence on large fire occurrence and percent high severity fire—more than temperature or RH. The authors suggest that short-term drought events are likely to have the strongest influence on fire synchrony throughout the western United States. However, despite the occurrence of fire during time periods of similar short-term climate conditions, differences in fire severity and fire size were observed between areas of differing vegetation types. This finding is likely the result of differences in species composition and fuel amount and condition associated with longer-term climate effects. Elevation also had a strong correlation to fire occurrence and size. The authors suggest that fire is influenced by various factors at different spatiotemporal scales and that climate change will have varied effects on local and regional fire regimes.

Linkages

- **Drought on Spatial pattern, landscape mosaic**

Large fire occurrence was highly synchronous across broad spatial scales and significantly correlated to short-term climate anomalies. Specifically, precipitation anomalies 90 days prior to the fire had the strongest influence on large fire occurrence and percent high severity fire more than temperature or RH. The authors suggest that short-term drought events are likely to have the strongest influence on fire synchrony throughout the western United States.

- **Temperature, RH, VPD on Spatial pattern, landscape mosaic**

Large fire occurrence was highly synchronous across broad spatial scales and significantly correlated to short-term climate anomalies. Specifically, precipitation anomalies 90 days prior to the fire had the strongest influence on large fire occurrence and percent high severity fire more than temperature or RH.

- **Drought on Fire severity**

Large fire occurrence was highly synchronous across broad spatial scales and significantly correlated to short-term climate anomalies. Specifically, precipitation anomalies 90 days prior to the fire had the strongest influence on large fire occurrence and percent high severity fire more than temperature or RH.

- **Temperature, RH, VPD on Fire severity**

Large fire occurrence was highly synchronous across broad spatial scales and significantly correlated to short-term climate anomalies. Specifically, precipitation anomalies 90 days prior to the fire had the strongest influence on large fire occurrence and percent high severity fire more than temperature or RH.

- **Drought on Fire severity**

Despite the occurrence of fire during time periods of similar short-term climate conditions, differences in fire severity and fire size were observed between areas of differing vegetation types. This is likely the result of differences in species composition and fuel amount and condition associated with longer-term climate effects.

- **Drought on Annual area burned, fire size**

Despite the occurrence of fire during time periods of similar short-term climate conditions, differences in fire severity and fire size were observed between areas of differing vegetation types. This is likely the result of differences in species composition and fuel amount and condition associated with longer-term climate effects.

- 110. Loehman, R.; Flatley, W.; Holsinger, L.; Thode, A. 2018.** Can land management buffer impacts of climate changes and altered fire regimes on ecosystems of the southwestern United States? *Forests*. 9(4):192. <https://doi.org/10.3390/f9040192>

Location

Jemez Mountains, New Mexico, USA; Kaibab Plateau, Arizona, USA

Ecosystem type(s)

Dry pine and mixed-conifer forests

Summary: What the authors did and why

The authors applied mechanistic ecosystem–fire models in two forested landscapes of the Southwest—FireBGCv2 in the Jemez Mountains, hereafter, FireBGCv2-Jemez; and LANDIS-II in the Kaibab National Forest, hereafter, LANDIS-II-Kaibab—to simulate climate- and management-driven changes in forests and fire regimes. Modeled scenarios included combinations of two future emissions scenarios (“warm-dry” and “hot-arid”) and four management strategies (suppression only, a current treatment intensity, and two amplified treatment intensities). The intent of

the study was to determine whether management actions may be able to buffer the effects of climate and fire regime changes on forest composition and structure.

Publication findings

Increased fire frequency and area burned in high severity fire occurred for the FireBGCv2-Jemez landscape as the result of projected increasing temperature and moisture deficit. Both FireBGCv2-Jemez and LANDIS-II-Kaibab produced fundamental and persistent shifts in forest structure and composition. Hot-arid climate and increased fire activity resulted in conversion of ponderosa pine forests. Mixed-conifer forests were affected to a lesser degree.

Management actions, modeled at varying intensities, did not prevent structural and compositional changes to either ecosystem or changes in fire activity, suggesting that novel management approaches will be necessary to counteract the effects of climate change.

Linkages

- **Temperature, RH, VPD on Fire severity**

FireBGCv2-Jemez projected an increase in fire frequency and area burned in high severity fire due to the predicted increases in temperature and moisture deficit.

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

FireBGCv2-Jemez projected an increase in fire frequency and area burned in high severity fire due to the predicted increases in temperature and moisture deficit.

- **Fire severity on Species composition, invasives, structure**

FireBGCv2-Jemez and LANDIS-II-Kaibab projected fundamental and persistent shifts in forest structure and composition. Hot-arid climate and increased fire activity resulted in conversion of ponderosa pine forests. Mixed-conifer forests were affected to a lesser degree.

Management actions, modeled at varying intensities, did not prevent structural and compositional changes to either ecosystem or changes in fire activity, suggesting that novel management approaches will be necessary to counteract the effects of climate change.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

FireBGCv2-Jemez and LANDIS-II-Kaibab projected fundamental and persistent shifts in forest structure and composition. Hot-arid climate and increased fire activity resulted in conversion of ponderosa pine forests. Mixed-conifer forests were affected to a lesser degree.

Management actions, modeled at varying intensities, did not prevent structural and compositional changes to either ecosystem or changes in fire activity, suggesting that novel management approaches will be necessary to counteract the effects of climate change.

- 111. Lutz, J.A.; van Wagtendonk, J.W.; Thode, A.E.; Miller, J.O.; Franklin, J.F. 2009.** Climate, lightning ignitions, and fire severity in Yosemite National Park, California, USA. *International Journal of Wildland Fire*. 18: 765–774.

Location

Yosemite National Park, California, USA

Ecosystem type(s)

Lower montane, subalpine, and upper montane vegetation

Summary: What the authors did and why

The authors examined fire–climate relationships between snowpack accumulation and fire ignition, size, and severity of lightning-ignited fires from 1984 to 2005.

Publication findings

The authors found that the 1 April SWE is correlated with the number of lightning-ignited fires and area burned. High levels of persistent snowpack later into the year decrease the possibility of lightning-ignited fires during the fire season. Conversely, low levels lead to an increase in fire activity earlier in the fire season. The type and duration of winter precipitation greatly affect the fuel moisture conditions of the early fire season, and to a lesser extent, the late fire season as fuels are typically dry regardless of the previous winter's precipitation. However, the relationship between SWE and area burned was weaker as bottom-up controls were stronger predictors of fire behavior on the landscape. Nonetheless, the authors found that fire season length is not directly related to fire severity in that a longer fire season does not necessarily result in more severe fire across the landscape, especially in more drought tolerant ecosystems. Convective instability associated with high temperatures may also lead to increased lightning occurrence and thus increased ignition rates. Should spring SWE decrease, landscape flammability may increase and become more variable.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

Convective instability associated with high temperatures may also lead to increased lightning occurrence and thus increased ignition rates.

- **Snowpack, snow and rain on Annual area burned, fire size**

The authors found that the 1 April SWE is correlated with the number of lightning-ignited fires and area burned. High levels of persistent snowpack later into the year decreases the possibility of lightning-ignited fires during the fire season. Conversely, low levels lead to an increase in fire activity earlier in the fire season.

The type and duration of winter precipitation greatly affect the fuel moisture conditions of the early fire season, and to a lesser extent, the late fire season as fuels are typically dry regardless of the previous winter's precipitation. However, the relationship between SWE and area burned was weaker as bottom-up controls were stronger predictors of fire behavior on the landscape. Should spring SWE decrease, landscape flammability may increase and become more variable.

- **Fire season length on Fire severity**

The authors found that the 1 April SWE is correlated with the number of lightning-ignited fires and area burned. High levels of persistent snowpack later into the year decreases the possibility of lightning-ignited fires during the fire season. Conversely, low levels lead to an increase in fire activity earlier in the fire season. The type and duration of winter precipitation greatly affect the fuel moisture conditions of the early fire season, and to a lesser extent, the late fire season as fuels are typically dry regardless of the previous winter's precipitation. However, the relationship between SWE and area burned was weaker as bottom-up controls were stronger predictors of fire behavior on the landscape. However, they found that fire season length is not directly related to fire severity in that a longer fire season does not necessarily result in more severe fire across the landscape, especially in more drought tolerant ecosystems.

- 112. Margolis, E.Q.; Balmat, J. 2009.** Fire history and fire–climate relationships along a fire regime gradient in the Santa Fe Municipal Watershed, NM, USA. *Forest Ecology and Management*. 258(11): 2416–2430. <https://doi.org/10.1016/j.foreco.2009.08.019>

Location

Santa Fe River watershed, New Mexico, USA

Ecosystem type(s)

Mixed-conifer forest; ponderosa pine forest; spruce-fir forests

Summary: What the authors did and why

The authors reconstructed the historical fire regime along a gradient of elevation and forest type using dendroecological techniques and assessed historical climate–fire relationships between forest types in the Santa Fe River watershed.

Publication findings

Consistent with other literature in the Southwest, the authors found that fire activity was associated with anomalously wet years followed by anomalously dry years, typically within the ENSO cycle. However, fire occurrence in mixed-conifer forests generally required more extreme drought to burn compared to ponderosa pine forest ecosystems. The connectivity between the forest types may have influenced the fire frequency and fire–climate relationship in mixed-conifer forest as fire moved upslope from the ponderosa pine forest. Mixed-conifer forests are generally not fuel limited, so the authors suggest that the connectivity with the ponderosa pine forests as a fire source may explain the relationship

between fire occurrence in the mixed-conifer forest and the wet-year lags. The authors also found that the last major fire in spruce-fir-dominated forest at the highest elevations occurred during the worst single-year drought in 1685 and was synchronized across distant mountain ranges regionally.

Linkages

- **Drought on Spatial pattern, landscape mosaic**

Fire occurrence in mixed-conifer forests generally required more extreme drought to burn compared to ponderosa pine forest ecosystems. However, the connectivity between the forest types may have influenced the fire frequency in mixed conifer as fire moved upslope. Mixed conifer forests are generally not fuel limited, so the authors suggest the connectivity may explain the relationship between fire occurrence in the mixed-conifer forest and the wet-year lags. The authors also found that the last major fire in spruce-fir-dominated forest at the highest elevations occurred during the worst single-year drought in 1685 and was synchronized across distant mountain ranges regionally.

- **Drought on Fire frequency, fire rotation, fire return interval**

Consistent with other literature in the Southwest, the authors found that fire occurrence was associated with anomalously wet years followed by anomalously dry years, typically within the ENSO cycle. However, fire occurrence in mixed-conifer forests generally required more extreme drought to burn compared to ponderosa pine forest ecosystems. The connectivity between the forest types may have influenced the fire frequency in mixed conifer as fire moved upslope. Mixed-conifer forests are generally not fuel limited, so the authors suggest this may explain the relationship between fire occurrence in these forest types and the wet-year lags. The authors also found that the last major fire in spruce-fir-dominated forest at the highest elevations occurred during the worst single-year drought in 1685 and was synchronized across distant mountain ranges regionally.

113. Margolis, E.Q.; Malevich, S.B. 2016. Historical dominance of low-severity fire in dry and wet mixed-conifer forest habitats of the endangered terrestrial Jemez Mountains salamander (*Plethodon neomexicanus*). *Fire Ecology and Management*. 375: 12–26. <https://doi.org/10.1016/j.foreco.2016.05.011>

Location

Near Valles Caldera National Preserve, Jemez Mountains, New Mexico, USA

Ecosystem type(s)

The sites were stratified by elevation or vegetation type as dry or wet mixed conifer based on the inclusion of ponderosa pine trees within the stand.

Summary: What the authors did and why

The authors reconstructed the historical stand structure and fire regimes along a gradient of ponderosa pine (*Pinus ponderosa*) to wet mixed-conifer and

aspen (*Populus tremuloides*) stands within the habitat of the endangered Jemez Mountains salamander. Further, they related the variability of climate to the historical fire regime.

Publication findings

The historical fire frequency of the study area ranged from 10 to 42 years mean fire return interval (MFRI). The authors found that mixed-conifer ecosystems are drought limited, not fuel limited; therefore, they do not require prior wet years to build up fuels before burning, but instead will burn when fuel moistures are low. They also found that fire severity was significantly related to drought severity.

Recent events such as the 2011 Las Conchas Fire contain high severity patches across multiple vegetation types, including ponderosa pine (*Pinus ponderosa*), that are many times larger than occurred in recent centuries. Furthermore, the authors suggest that projected increases in forest drought stress are likely to lead to more intense and severe fires in the future, especially combined with high fuel densities, the legacy of a century of fire suppression.

Linkages

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

The authors found that mixed-conifer ecosystems are drought-limited, not fuel limited; therefore, they do not require prior wet years to build up fuels before burning, but instead will burn when fuel moistures are low.

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that mixed-conifer ecosystems are drought-limited, not fuel limited; therefore, they do not require prior wet years to build up fuels before burning, but instead will burn when fuel moistures are low.

- **Drought on Fire severity**

The authors found that fire severity was significantly related to drought severity. They suggest that projected increases in forest drought stress will likely lead to more intense and severe fires in the future, especially combined with high fuel densities, the legacy of a century of fire suppression.

114. Margolis, E.Q.; Swetnam, T.W. 2013. Historical fire–climate relationships of upper elevation fire regimes in the south-western United States. *International Journal of Wildland Fire*. 22(5): 588–598. <https://doi.org/10.1071/WF12064>

Location

Southwestern United States (Arizona and New Mexico)

Ecosystem type(s)

Forested ecosystems: aspen; mesic mixed-conifer; spruce-fir; upper elevation

Summary: What the authors did and why

The authors reconstructed both regional climate teleconnections (ENSO, PDO, and AMO) and historical fire occurrence using tree-ring analysis. Their objectives were to analyze the relationship between moisture variability and regional, individual, and phase combinations of ENSO, PDO, and AMO and then compare this climate variability to fire occurrence in upper elevation forests across the Southwest.

Publication findings

Both individual and phase combinations of ENSO, PDO, and AMO were strongly associated with moisture variability. As a consequence, periods of regional drought were strongly related to regional synchrony of fire occurrence in upper elevation forests historically. The authors found that all stand-replacing fire years and 18 of 20 synchronous fire years occurred during periods of regional drought that were two to four times as dry as normal conditions. No antecedent drought lags were necessary for fire occurrence because fuels in high elevation forests are typically dense enough to burn when sufficiently dry conditions allow for successful ignition and spread. The authors suggest that ENSO strongly and consistently affects regional moisture conditions in the Southwest, and thus fire occurrence, including high severity fire occurrence, but that the effects can be tempered by phases of PDO.

Linkages

- **Drought on Fire severity**

Both individual and phase combinations of ENSO, PDO, and AMO were strongly associated with moisture variability. The authors found that all stand-replacing fire years and 18 of 20 synchronous fire years occurred during periods of regional drought that were two to four times as dry as normal conditions. The authors suggest that ENSO strongly and consistently affects regional moisture conditions in the Southwest, and thus fire occurrence, including high severity fire occurrence, but that the effects can be tempered by phases of PDO.

- **Drought on Fire frequency, fire rotation, fire return interval**

Both individual and phase combinations of ENSO, PDO, and AMO were strongly associated with moisture variability. As a consequence, periods of regional drought were strongly related to regional synchrony of fire occurrence in upper elevation forests historically. The authors found that all stand-replacing fire years and 18 of 20 synchronous fire years occurred during periods of regional drought that were two to four times as dry as normal conditions. No antecedent drought lags were necessary for fire occurrence because fuels in high elevation forests are typically dense enough to burn when sufficiently dry conditions allow for successful ignition and spread. The authors suggest that ENSO strongly and consistently affects regional moisture conditions in the Southwest, and thus fire occurrence, including high severity fire occurrence, but that the effects can be tempered by phases of PDO.

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115. Margolis, E.Q.; Swetnam, T.W.; Allen, C.D. 2007. A stand-replacing fire history in upper montane forests of the southern Rocky Mountains. Canadian Journal of Forest Research. 37(11): 2227–2241. <https://doi.org/10.1139/X07-079>

Location

Southwestern United States (Arizona and New Mexico)

Ecosystem type(s)

Forested ecosystems: aspen; mixed-conifer; upper montane

Summary: What the authors did and why

The authors reconstructed the fire regime of upper montane forests, including mixed-conifer and aspen (*Populus tremuloides*) stands, of the upper Rio Grande basin and evaluated the potential relationships between interannual climate variability and regional high severity, stand-replacing fire occurrence.

Publication findings

The authors found that regional synchronous fire years in upper montane ecosystems coincided with severe drought years and with regional surface fire years in lower elevation pine forests. No antecedent climate conditions were found to have a significant effect on fire activity.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that that regional synchronous fire years in upper montane ecosystems coincided with severe drought years. No antecedent climate conditions were found to have a significant effect on fire activity.

116. Margolis, E.Q.; Swetnam, T.W.; Allen, C.D. 2011. Historical stand-replacing fire in upper montane forests of the Madrean sky islands and Mogollon Plateau, southwestern USA. Fire Ecology. 7(3): 88–107. <https://doi.org/10.4996/fireecology.0703088>

Location

Mogollon Plateau and the Madrean sky islands of Arizona and New Mexico, USA

Ecosystem type(s)

Forested ecosystems: aspen; mixed-conifer; spruce/spruce-fir

Summary: What the authors did and why

The authors reconstructed fire dates and stand-replacing fire patch sizes using four dendrological approaches to document the historical role of high severity and stand-replacing fire in upper elevation mixed-conifer, aspen, and spruce-fir forests.

Publication findings

The authors found evidence of large patches (>100 acres; 40 ha) of stand-replacing fire in upper elevation mixed-conifer forests prior to European settlement in the region via aspen (*Populus tremuloides*) and conifer recruitment pulses, corresponding fire scar and mortality dates, and lack of surviving trees prior to large fire dates. This suggests that recent large patches of high severity fire are within the historical range of variability for upper elevation forests. In aspen stands, however, fire suppression over the past 130 years has likely affected the age and stand structure of these stands. Aspen stands shifted from frequently burned stands with dense and multiaged cohorts of trees toward a monoculture of open, same-aged trees.

Linkages

- **Fire behavior, fire type, fire intensity on Species composition, invasives, structure**

The authors found evidence of large patches (>100 acres; 40 ha) of stand-replacing fire in upper elevation mixed-conifer forests prior to European settlement in the region via aspen (*Populus tremuloides*) and conifer recruitment pulses, corresponding fire scar and mortality dates, and lack of surviving trees prior to large fire dates. This suggests that recent large patches of high severity fire are within the historical range of variability for upper elevation forests.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

In aspen (*Populus tremuloides*) stands, fire suppression over the past 130 years has likely affected the age and stand structure of these stands. Aspen stands shifted from frequently burned stands with dense and multi-aged cohorts of trees toward a monoculture of open, same-aged trees.

117. Marlon, J.R.; Bartlein, P.J.; Walsh, M.K.; Harrison, S.P.; Brown, K.J.; Edwards, M. E.; Higuera, P.E.; Power, M.J.; Anderson, R.S.; Briles, C.; Brunelle, A.; Carcaillet, C.; Daniels, M.; Hu, F.S.; Lavoie, M.; Long, C.; Minckley, T.; Richard, P.J.H.; Scott, A.C.; Shafer, D.S.; Tinner, W.; Umbanhowar, C.E., Jr.; Whitlock, C.M. 2009.

Wildfire responses to abrupt climate change in North America. Proceedings of the National Academy of Sciences. 106(8): 2519–2524.

<https://doi.org/10.1073/pnas.0808212106>

Location

North America

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors examined charcoal and pollen records of a period of abrupt climate

change beginning during the last glacial-interglacial transition to the Younger Dryas period (15,000–10,000 years before present) to assess how fire regimes across North America were affected.

Publication findings

The authors found that during the period of deglaciation, there was an increase in the level of burning and fire occurrence, although fire activity varied across the continent, likely due to spatially complex climate controls and their effects on vegetation changes.

Linkages

- **Snowpack, snow and rain on Annual area burned, fire size**

The authors found that during the period of deglaciation, there was an increase in the level of burning and fire occurrence, although fire activity varied across the continent, likely due to spatially complex climate controls and their effects on vegetation changes.

- 118. Marlon, J.; Bartlein, P.J.; Whitlock, C. 2006.** Fire-fuel-climate linkages in the northwestern USA during the Holocene. *The Holocene*. 16(8): 1059–1071.
<https://doi.org/10.1177/0959683606069396>

Location

Northwestern United States

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors reconstructed fire regimes from the Holocene (last 4,000 years) using sedimentation rates and charcoal records from lake and bog sediments. They also compared recent fire history and climate effects on sedimentation rates and charcoal records to test the efficacy of this method to determine historical trends in fire and climate in this area.

Publication findings

Charcoal records showed that regional synchronicity of fire frequency occurred historically due to fluctuations in climate. Moister climate conditions resulted in fuel buildup, followed by drier conditions that resulted in regional fire years.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

Charcoal records showed that regional synchronicity of fire frequency occurred historically due to fluctuations in climate. Moister climate conditions resulted in fuel buildup, followed by drier conditions that resulted in regional fire years.

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119. Marshall, J.D.; Blair, J.M.; Peters, D.P.; Okin, G.; Rango, A.; Williams, M. 2008. Predicting and understanding ecosystem responses to climate change at continental scales. *Frontiers in Ecology and the Environment*. 6(5): 273–280. <https://doi.org/10.1890/070165>

Location

Contiguous United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors reviewed potential ecological responses to expected changes in future climate of four key mesoscale drivers: drought, warming, snowpack disappearance, and altered fire regimes.

Publication findings

Across the continental United States, drought conditions, as measured by PDSI, are strongly correlated to the number of acres burned. The strength of the correlations between PDSI and acres burned varies across the United States at 1-, 2-, and current-year time lags.

Linkages

- **Drought on Annual area burned, fire size**

Across the continental United States, drought conditions, as measured by PDSI, are strongly correlated to the number of acres burned. The strength of the correlations between PDSI and acres burned varies across the United States at 1-, 2-, and current-year time lags.

120. Mast, J.N.; Wolf, J.J. 2004. Ecotonal changes and altered tree spatial patterns in lower mixed-conifer forests, Grand Canyon National Park, Arizona, USA. *Landscape Ecology*. 19(2): 167–180. <https://doi.org/10.1023/B:LAND.0000021718.20058.36>

Location

North Rim of Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Ecotone between mixed-conifer forests and ponderosa pine

Summary: What the authors did and why

The authors looked at species-specific patch development, establishment, and the effects of climate and disturbance regimes, including fire suppression, within ecotones of mixed-conifer and ponderosa pine (*Pinus ponderosa*) ecosystems.

Publication findings

The authors found that along the mixed-conifer and ponderosa pine ecotone there has been a shift toward increasing mixed-conifer forest, especially white fir (*Abies concolor*) and other shade-tolerant and fire-intolerant species in historical

ponderosa pine (*Pinus ponderosa*) stands due to fire suppression. Pole-sized white fir were clumped at all patch sizes due to a lack of thinning by fire. The resulting dense thickets of white fir prevent ponderosa pine regeneration.

Linkages

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

Due to fire suppression, pole-sized white fir (*Abies concolor*) were clumped at all patch sizes due to a lack of thinning by fire. The resulting dense thickets of white fir prevent ponderosa pine (*Pinus ponderosa*) regeneration.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors found that along the mixed-conifer and ponderosa pine ecotone there has been a shift toward increasing mixed-conifer forest, especially white fir (*Abies concolor*) and other shade-tolerant and fire-intolerant species in historical ponderosa pine (*Pinus ponderosa*) stands due to fire suppression. Pole-sized white fir were clumped at all patch sizes due to a lack of thinning by fire. The resulting dense thickets of white fir prevent ponderosa pine regeneration.

- 121. Mast, J.N.; Wolf, J.J. 2006.** Spatial patch patterns and altered forest structure in middle elevation versus upper ecotonal mixed-conifer forests, Grand Canyon National Park, Arizona, USA. *Forest Ecology and Management*. 236(2–3): 241–250.

Location

North Rim of Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Mid- and upper elevation ecotones of mixed-conifer forest

Summary: What the authors did and why

The authors analyzed the developmental spatial and structural patterns of mixed-conifer forest stands along an elevational gradient in response to altered disturbance regimes, specifically fire suppression.

Publication findings

Subalpine species such as Englemann spruce (*Picea engelmannii*) have encroached into upper elevations of mixed-conifer forest due to fire suppression since the late 1800s, thereby altering the composition of these stands. At the upper ecotone, no successful conifer establishment occurred during the 1870s and 1880s, but aspen (*Populus tremuloides*) cohorts regenerated, corresponding to the history of synchronized fires during this time.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

Subalpine species such as Englemann spruce (*Picea engelmannii*) have encroached into upper elevations of mixed-conifer forest due to fire suppression since the late 1800s, thereby altering the composition of these stands. At the upper ecotone, no successful conifer establishment occurred during the 1870s and 1880s, but aspen (*Populus tremuloides*) cohorts regenerated, corresponding to the history of synchronized fires during this time.

122. Mast, J.N.; Fulé, P.Z.; Moore, M.M.; Covington, W.W.; Waltz, A.E.M. 1999. Restoration of presettlement age structure of an Arizona ponderosa pine forest. *Ecological Applications*. 9(1): 228–239.
[https://doi.org/10.1890/1051-0761\(1999\)009\[0228:ROPASO\]2.0.CO;2](https://doi.org/10.1890/1051-0761(1999)009[0228:ROPASO]2.0.CO;2)

Location

Fort Valley Experimental Forest, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors reconstructed historical forest stand structure of a ponderosa pine forest prior to Euro-American settlement and compared prehistoric and post-Euro-settlement reference age structure. They also compared forest conditions after restoration treatments were applied to the site.

Publication findings

The authors found that the stand-age distribution was multimodal, with peaks of establishment due to interruptions to the historical frequent-fire regime. Due to fire exclusion, reduced understory competition, and favorable climate, abundant regeneration in the 20th century raised forest density from 60 trees ha⁻¹ in 1876 to more than 3,000 trees ha⁻¹ in 1992.

Linkages

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

The authors found that the stand-age distribution was multimodal with peaks of establishment due to interruptions to the historical frequent-fire regime. Due to fire exclusion, reduced understory competition, and favorable climate, abundant regeneration in the 20th century raised forest density from 60 trees ha⁻¹ in 1876 to more than 3,000 trees ha⁻¹ in 1992.

- **Fire frequency, fire rotation, fire return interval on Fuels**

The authors found that the stand-age distribution was multimodal with peaks of

establishment due to interruptions to the historical frequent-fire regime. Due to fire exclusion, reduced understory competition, and favorable climate, abundant regeneration in the 20th century raised forest density from 60 trees ha⁻¹ in 1876 to more than 3,000 trees ha⁻¹ in 1992.

123. **Montaño, C.C.; Fulé, P. Z.; Falk, D.A.; Villanueva-Díaz, J.; Yocom, L.L. 2012.** Linking old-growth forest composition, structure, fire history, climate and land-use in the mountains of northern México. *Ecosphere*. 3(11): 1–16.
<https://doi.org/10.1890/ES12-00161.1>

Location

Mesa de las Guacamayas Mountains, Chihuahua, Mexico

Ecosystem type(s)

Mixed-conifer forest

Summary: What the authors did and why

The authors quantified the structure and composition of old-growth conifer forest stands in northwestern Mexico. They related this information to fire regime history data from Fulé et al. (2012) to determine relationships between regional climate variability, fire, and forest structure since approximately 250 years ago to today.

Publication findings

The authors found that periods of drought were significantly related to fire occurrence during ENSO; however, this trend was interrupted in the 1940s and 1950s, likely by the introduction of logging and livestock grazing to the area. This interruption of the fire regime also resulted in an increase in tree establishment, especially oak (*Quercus* spp.) and other broadleaf tree species.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that periods of drought were significantly related to fire occurrence during ENSO; however, this trend was interrupted in the 1940s and 1950s, likely by the introduction of logging and livestock grazing in the area.

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

An interruption of the fire regime in the 1940s and 1950s, likely by the introduction of logging and livestock grazing in the area, resulted in an increase in tree establishment, especially oak (*Quercus* spp.) and other broadleaf tree species.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

An interruption of the fire regime in the 1940s and 1950s, likely by the introduction

to logging and livestock grazing in the area, resulted in an increase in tree establishment, especially oak (*Quercus* spp.) and other broadleaf tree species.

124. Moore, M.M.; Huffman, D.W. 2004. Tree encroachment on meadows of the North Rim, Grand Canyon National Park, Arizona, USA. *Arctic, Antarctic, and Alpine Research*. 36(4): 474–483.

Location

Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Montane meadow; subalpine grasslands

Summary: What the authors did and why

The authors described the species composition, structure, and temporal patterns of tree encroachment in alpine meadow and grassland ecosystems on the North Rim of the Grand Canyon to inform management on conservation of meadow habitat.

Publication findings

Although the authors did not examine the causal features of tree encroachment into meadows, a disruption in the fire regime beginning in the late 1870s and early 1880s coincided with the establishment of ponderosa pine (*Pinus ponderosa*), spruce (*Picea* spp.), and aspen (*Populus tremuloides*) stands near and within some meadow sites.

Linkages

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

Although the authors did not examine the causal features of tree encroachment into meadows, a disruption in the fire regime beginning in the late 1870s and early 1880s coincided with the establishment of ponderosa pine (*Pinus ponderosa*), spruce (*Picea* spp.), and aspen (*Populus tremuloides*) stands near and within some meadow sites.

125. Moore, M.M.; Huffman, D.W.; Fulé, P.Z.; Covington, W.W.; Crouse, J.E. 2004. Comparison of historical and contemporary forest structure and composition on permanent plots in southwestern ponderosa pine forests. *Forest Science*. 50(2): 162–176. <https://doi.org/10.1093/forestscience/50.2.162>

Location

Fort Valley Experimental Forest, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors quantified the change in forest stand structure on plots established from 1909 to 1913 and resampled ENSO in 1997 through 1999.

Publication findings

The authors found that overall species composition was similar between 1913 and 1999; however, the sites showed an increase in basal area of the more shade-tolerant species Douglas-fir (*Pseudotsuga menziesii*) and white fir (*Abies concolor*). This suggests that future forest communities may potentially undergo type conversion from forest communities dominated by fire-resistant trees to those supporting denser populations of shade-tolerant and fire-intolerant species.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors found that overall species composition was similar between 1913 and 1999; however, the sites showed an increase in basal area of the more shade-tolerant species Douglas-fir (*Pseudotsuga menziesii*) and white fir (*Abies concolor*). This suggests a future forest communities may potentially undergo type conversion from forest communities dominated by fire-resistant trees to those supporting denser populations of shade-tolerant and fire-intolerant species.

126. Moritz, M.A.; Parisien, M.A.; Batllori, E.; Krawchuk, M.A.; Van Dorn, J.; Ganz, D.J.; Hayhoe, K. 2012. Climate change and disruptions to global fire activity. *Ecosphere*. 3(6): 1–22. <https://doi.org/10.1890/ES11-00345.1>

Location

Global

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors derived future fire probability at a 0.5° resolution from a range of global climate models. Climate variables consisted of precipitation, the precipitation of the driest month, temperature seasonality, the mean temperature of the wettest month, and the mean temperature of the warmest month.

Publication findings

The authors did not find agreement in directional trends in fire activity for over 50 percent of terrestrial lands globally by 2039. Longer projections to the end of the century suggest that fire probabilities will increase in the mid- to high latitudes and decrease in the Tropics. They suggest that although future temperature is expected to rise across the globe, future fire activity seems to be driven by moisture availability in many areas.

Linkages

- **Drought on Spatial pattern, landscape mosaic**

Longer projections to the end of the century suggest that fire probabilities will increase in the mid- to high-latitudes and decrease in the tropics. They suggest that

although future temperature is expected to rise across the globe, future fire activity seems to be driven by moisture availability in many areas.

- **Temperature, RH, VPD on Spatial pattern, landscape mosaic**

Longer projections to the end of the century suggest that fire probabilities will increase in the mid- to high-latitudes and decrease in the tropics. They suggest that although future temperature is expected to rise across the globe, future fire activity seems to be driven by moisture availability in many areas.

127. O'Connor, C.D.; Falk, D.A.; Lynch, A.M.; Swetnam, T.W. 2014. Fire severity, size, and climate associations diverge from historical precedent along an ecological gradient in the Pinaleño Mountains, Arizona, USA. *Forest Ecology and Management*. 329: 264–278. <https://doi.org/10.1016/j.foreco.2014.06.032>

Location

Pinaleño Mountains, Arizona, USA

Ecosystem type(s)

Gradient along Madrean and mixed-conifer ecosystems

Summary: What the authors did and why

The authors reconstructed the fire regime before and after fire exclusion around 1880 to determine if recent large, high-severity fire is within the natural range of variability for sky island ecosystems in the study area.

Publication findings

The authors found that historically, spreading fires in ponderosa pine and dry mixed-conifer forests were associated with prior wet conditions and larger fires affecting mesic forests were more strongly associated with extreme drought conditions during the year of fire. Currently, spreading fire occurs only during persistent drought, suggesting that fire suppression has altered fuels so that dry conifer sites are no longer fuel limited, and fire regimes in these systems behave like more mesic mixed-conifer sites. Fire severity has also increased by four times that of previous large fires, resulting in high tree mortality and low regeneration in burn scars.

Linkages

- **Drought on Spatial pattern, landscape mosaic**

The authors found that historically, spreading fires in ponderosa pine and dry mixed-conifer forests were associated with prior wet conditions and larger fires affecting mesic forests were more strongly associated with extreme drought conditions during the year of fire. Currently, spreading fire only occurs during persistent drought, suggesting that fire suppression has altered fuels so that dry conifer sites are no longer fuel limited, and fire regimes in these systems behave like more mesic mixed-conifer sites.

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that historically, spreading fires in ponderosa pine and dry mixed-conifer forests were associated with prior wet conditions and larger fires affecting mesic forests were more strongly associated with extreme drought conditions during the year of fire. Currently, spreading fire occurs only during persistent drought, suggesting that fire suppression has altered fuels so that dry conifer sites are no longer fuel limited, and fire regimes in these systems behave like more mesic mixed-conifer sites.

- **Fire severity on Mortality, survivorship, turnover**

Fire severity has also increased by four times that of previous large fires, resulting in high tree mortality and low regeneration in burn scars.

- **Fire severity on Dispersal, regeneration, establishment**

Fire severity has also increased by four times that of previous large fires, resulting in high tree mortality and low regeneration in burn scars.

128. O'Connor, C.D.; Lynch, A.M.; Falk, D.A.; Swetnam, T.W. 2015. Post-fire forest dynamics and climate variability affect spatial and temporal properties of spruce beetle outbreaks on a sky island mountain range. *Forest Ecology and Management*. 336: 148–162.

Location

Pinaleño Mountains, Arizona, USA

Ecosystem type(s)

Engelmann spruce-fir forest

Summary: What the authors did and why

The authors reconstructed the species composition and structure of Engelmann spruce forest stand populations over a 319-year period between stand-replacing fire to determine how changes in the stand structure of spruce over time affect the size and severity of spruce beetle (*Dendroctonus rufipennis*) outbreaks.

Publication findings

The authors found that spruce beetle outbreaks expanded coincident with increasing populations of spruce starting 94 years after the last stand-replacing fire and remained relatively small for another century. With the onset of fire exclusion, however, the increased density of spruce-fir has resulted in longer outbreak durations in the 21st century.

Linkages

- **Fire frequency, fire rotation, fire return interval on Fuels**

The authors found that spruce beetle (*Dendroctonus rufipennis*) outbreaks expanded coincident with increasing populations of spruce starting 94 years after

the last stand-replacing fire and remained relatively small for another century. With the onset of fire exclusion, however, the increased density of spruce-fir has resulted in longer outbreak durations in the 21st century.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors found that spruce beetle (*Dendroctonus rufipennis*) outbreaks expanded coincident with increasing populations of spruce starting 94 years after the last stand-replacing fire and remained relatively small for another century. With the onset of fire exclusion, however, the increased density of spruce-fir has resulted in longer outbreak durations in the present century.

129. Ouzts, J.; Kolb, T.; Huffman, D.; Sánchez Meador, A. 2015. Post-fire ponderosa pine regeneration with and without planting in Arizona and New Mexico. *Forest Ecology and Management*. 354: 281–290. <https://doi.org/10.1016/j.foreco.2015.06.001>

Location

Arizona and New Mexico, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors measured ponderosa pine (*Pinus ponderosa*) seedling recovery of planted and unplanted areas after severe wildfire.

Publication findings

The authors found high variation in ponderosa pine regeneration and seedling survival after high severity fire. Seedling density in planted plots was generally higher than in unplanted plots, but still only half of the planted plots met restoration targets. Seedling density did, however, increase as time since fire increased. Further, likelihood of seedling survival on planted sites corresponded to observed natural regeneration; on sites with no natural regeneration, plantings also failed. Conversely, areas where planting was successful also had natural regeneration.

Linkages

- **Fire severity on Dispersal, regeneration, establishment**

The authors found high variation in ponderosa pine regeneration and seedling survival after high severity fire. Seedling density in planted plots was generally higher than in unplanted plots, but still only half of the planted plots met restoration targets. Seedling density did, however, increase as time since fire increased.

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130. Owen, S.M.; Sieg, C.H.; Sánchez Meador, A.J.; Fulé, P.Z.; Iniguez, J.M.; Baggett, L.S.; Fornwalt, P.J.; Battaglia, M.A. 2017. Spatial patterns of ponderosa pine regeneration in high-severity burn patches. *Forest Ecology and Management*. 405: 134–149. <https://doi.org/10.1016/j.foreco.2017.09.005>

Location

Pumpkin Fire, Arizona, USA; Rodeo-Chediski Fire, Arizona

Ecosystem type(s)

Ponderosa pine ecosystem

Summary: What the authors did and why

The authors studied the spatial regeneration patterns of ponderosa pine (*Pinus ponderosa*) within large patches of high severity fire, specifically, regeneration distribution and height from distance to unburned edge.

Publication findings

The authors found regeneration occurring more than 400 m from fire edge, whereas previous studies had not found regeneration beyond 200 m. It is likely this novel finding resulted from the study design, which included plots 2 orders of magnitude larger plots (10 ac [4 ha] vs. 0.1 ac [0.04 ha]). Regeneration densities of ponderosa pine (*Pinus ponderosa*) decreased with increasing distance to unburned edge. Next, ponderosa pine regeneration could be more strongly influenced by intraspecific facilitation than interspecific competition from dense sprouting species.

Linkages

- **Spatial pattern, landscape mosaic on Dispersal, regeneration, establishment**

Regeneration densities of ponderosa pine (*Pinus ponderosa*) decreased with increasing distance to unburned edge. Next, ponderosa pine regeneration could be more strongly influenced by intraspecific facilitation than interspecific competition from dense sprouting species.

131. Parisien, M.-A.; Snetsinger, S.; Greenberg, J.A.; Nelson, C.R.; Schoennagel, T.; Dobrowski, S.Z.; Moritz, M.A. 2012. Spatial variability in wildfire probability across the western United States. *International Journal of Wildland Fire*. 21(4): 313–327. <https://doi.org/10.1071/WF11044>

Location

Western United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

Reliable estimates of wildfire probability are an important ongoing field of research, particularly for the western United States. The authors used fire observations from 1984 through 2008 with the MaxEnt modeling technique and an array of environmental variables to produce spatially explicit predictions of wildfire probability. In addition, variables that had a strong anthropogenic imprint were excluded so that the authors could build an alternative model to assess the impact of humans on wildfire likelihood.

Publication findings

Wildfire probability in the western United States is far from constant, with different areas reacting to different environmental drivers. Fuel explained nearly 25 percent of the variation in the full model. Probability patterns between the full and nonanthropogenic model were similar across the study area, but differences were found at local scales. As expected, the most dramatic decreases in wildfire probability occurred around urban areas. Although the influence of anthropogenic factors on wildfire probability varied by region, humans overall inhibit fire activity in the western United States.

Linkages

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

Though the strongest predictor of wildfire likelihood in the western United States was the percentage cover of fuels, it explained only 25 percent of model variation. Gradients in topography, climate, biomass, and ignitions were also important in determining wildfire likelihood across the study area.

Nine climate variables were retained for the model building, but no single variable showed a dominant link for wildfire likelihood in the western United States. In addition, climate drivers in the Pacific Northwest were different from those in the Southwest. However, there were important contributions from both precipitation in the coldest month (mm) and temperature in the driest month (°C).

132. **Parisien, M.-A.; Miller, C.; Parks, S.A.; DeLancey, E.R.; Robinne, F.N.; Flannigan, M.D. 2016.** The spatially varying influence of humans on fire probability in North America. *Environmental Research Letters*. 11(7): 075005.
<https://doi.org/10.1088/1748-9326/11/7/075005>

Location

Conterminous United States and Canada

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors used parallel statistical models to complete a broad-scale analysis of humans on fire activity from 1984 through 2014. The United States and Canada

were partitioned into 16 hexagonal polygons. For each polygon a statistical model of fire probability was produced based on the area burned data for 1984 through 2014 as a function of climate, enduring features (topography and percentage of nonfuel), lightning, and indices of anthropogenic influence.

Publication findings

There was a nonnegligible human–wildfire association across the entire continent, even in sparsely populated areas. There was a negative relationship between fire activity and humans across the United States and Canada; fire probability generally declined with increasing human influence. A noted exception was found in remoted areas, where lower populations were associated with reduced fire activity.

Linkages

- **Temperature, RH, VPD on Spatial pattern, landscape mosaic**

Climate was the most frequent dominant control on fire activity, having the highest variable importance in all but four hexagonal polygons.

- 133. Parks, S.A.; Abatzoglou, J.T. 2020.** Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophysical Research Letters*. 47(22). <https://doi.org/10.1029/2020GL089858>

Location

Western United States

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors evaluated the trends in fire severity and their interannual relationships to climate for western U.S. forests from 1985 to 2017.

Publication findings

There was a significant, eightfold increase in the annual area burned at high severity from 1985 to 2017 in all western U.S. ecoregions except for the California Coast.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

Results showed that both annual area burned at high severity and annual area burned exhibited positive correlations with maximum VPD, maximum temperature, and climate water deficit in all ecoregions and the western United States as a whole.

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134. **Parks, S.A.; Dobrowski, S.Z.; Panunto, M.H. 2018a.** What drives low-severity fire in the southwestern USA? *Forests*. 9(4): 165. <https://doi.org/10.3390/f9040165>

Location

Arizona and New Mexico, USA

Ecosystem type(s)

Dry-conifer forests; piñon-juniper woodlands; ponderosa pine forests; savannah

Summary: What the authors did and why

The authors evaluated both climate and biophysical factors that influence the occurrence of low severity fire in the Southwest. Low severity fire is an important component of many high frequency, fire-adapted ecosystems in the Southwest, so understanding those conditions which promote low severity fire is highly relevant to land managers.

Publication findings

The presence of live fuel was the most influential factor in predicting low severity fire, followed by year-of-fire climate. They found that as live fuel decreased, the likelihood of low severity fire increased; that is, a reduction in fuel reduced fire severity. The probability of low severity fire also increased as temperatures and the climatic moisture deficit decreased. Topography and longer-term climate factors were not important predictors of low severity fire.

Linkages

- **Drought on Fire severity**

The presence of live fuel was the most influential factor in predicting low severity fire: low severity fire was more likely in settings with lower levels of fuel. Low severity fire was more likely during wetter and cooler than average years; low severity fire increased as temperatures and the climatic moisture deficit decreased. Topography and longer-term climate factors were not important predictors of low severity fire.

- **Temperature, RH, VPD on Fire severity**

The presence of live fuel was the most influential factor in predicting low-severity fire followed by year-of-fire climate. Low severity fire also increased as temperatures and the climatic moisture deficit decreased. Topography and longer-term climate factors were not important predictors of low severity fire.

- **Fire severity on Fuels**

The presence of live fuel was the most influential factor in predicting low-severity fire followed by year-of-fire climate. They found that as live fuel decreased, the likelihood of low severity fire increased; that is, a reduction in fuel reduced fire severity.

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135. Parks, S.A.; Holsinger, L.M.; Miller, C.; Nelson, C.R. 2015. Wildland fire as a self-regulating mechanism: The role of previous burns and weather in limiting fire progression. *Ecological Applications*. 25(6): 1478–1492.

Location

Three large wilderness areas in Idaho and Montana, and one site in the Gila and Aldo Leopold Wilderness area in western New Mexico

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors' objective was to research the ability of wildfire to limit the spread of a subsequent fire based on the time between the two, and also to see how weather at the time of the fire alters this effect.

Publication findings

Stands that are within unaltered, short-interval fire regimes tend to self-regulate, reducing the progression of secondary fires. This finding suggests that the initial fire moderated the burn severity of the second fire. However, this effect diminishes as time since fire increases. Specifically, in the drier forests of New Mexico, previous wildfire no longer served as a fuel break after 6 years. Weather conditions conducive to rapid fire spread, however, can weaken the effectiveness of a previous burn in limiting subsequent fire spread. Conversely, previous fires will act as a fuel break longer than 6 years under more moderate weather.

Climate change is expected to increase the frequency of extreme fire weather events, likely reducing the effectiveness of fire-created fuel breaks during extreme fire seasons. Nonetheless, the authors suggest that using fire to regulate future fire may present opportunities to increase ecosystem resilience to future fire, especially in nonextreme fire years.

Linkages

- **Temperature, RH, VPD on Spatial pattern, landscape mosaic**

Weather conditions conducive to fire ignition and spread can weaken the effectiveness of a previous burn to limit fire spread.

Climate change is expected to increase the frequency of extreme fire weather events, likely reducing the effectiveness of fire-created fuel breaks during extreme fire seasons. Nonetheless, the authors suggest that using fire to regulate future fire may present opportunities to increase ecosystem resilience to future fire, especially in nonextreme fire years.

- **Spatial pattern, landscape mosaic on Fuels**

Stands that are within unaltered, short-interval fire regimes tend to self-regulate reducing the progression of secondary fires, suggesting that the initial fire

moderated the burn severity of the second fire. However, this effect decays as time since fire increases. Specifically, in the drier forests of New Mexico, the ability of wildfire to act as a fuel break decayed after only 6 years. Weather conditions conducive to fire ignition and spread, however, can weaken the effect of a previous reburn to limit fire spread or severity.

Climate change is expected to increase the frequency of extreme fire weather events, likely reducing the effectiveness of fire-created fuel breaks during extreme fire seasons. Nonetheless, the authors suggest that using fire to regulate future fire severity may present opportunities to increase ecosystem resilience to future fire, especially in nonextreme fire years.

- **Fire frequency, fire rotation, fire return interval on Fuels**

Stands that are within unaltered, short-interval fire regimes tend to self-regulate reducing the progression of secondary fires, suggesting that the initial fire moderated the burn severity of the second fire. However, this effect decays as time since fire increases. Specifically, the drier forests of New Mexico, the ability of wildfire to act as a fuel break decayed after only 6 years. Weather conditions conducive to fire ignition and spread, however, can weaken the effect of a previous reburn to limit fire spread or severity.

136. Parks, S.A.; Holsinger, L.M.; Miller, C.; Parisien, M.-A. 2018b. Analog-based fire regime and vegetation shifts in mountainous regions of the western US. *Ecography*. 41(6): 910–921. <https://doi.org/10.1111/ecog.03378>

Location

Western United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors investigated the ecological impacts of climate change on fire frequency, fire severity in mountainous ecoregions of the western United States for the early, mid-, and late 21st century. They used the concept of climate analogues to make inferences about the response of fire regimes and vegetation to changing climate. For a given location, the reference period fire regime and vegetation were matched to the fire regime and vegetation of the location representative of its future climate, allowing an evaluation of potential shifts.

Publication findings

Results showed no overall increase or decrease in either fire frequency or severity in the mountainous regions of the western United States. All four time periods show a similar pattern where both fire return interval (FRI) and percent of replacement severity (PRS) are highest at the extremes in climatic moisture deficit (CMD) and are lowest at intermediate values (~500–625 mm yr⁻¹). In locations

with CMD values less than about 400 mm yr⁻¹ during the reference period, FRI decreases in future time periods; at higher CMD values, FRI increases in the future. Percent replacement severity follows a similar pattern, decreasing in future time periods at lower reference period CMD values and increasing at higher values (threshold ~450 mm yr⁻¹).

Linkages

- **Temperature, RH, VPD on Fire severity**

Wet and cold regions, including mesic and cold forests, generally decreased in fire severity. Moisture-limited areas, such as shrubland and grasslands, showed the opposite trend, with an increase in fire severity.

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

Wet and cold regions, including mesic and cold forests, generally increased in fire frequency while moisture-limited areas, shrubland and grasslands, showed a decrease in frequency.

137. Parks, S.A.; Holsinger, L.M.; Panunto, M.H.; Jolly, W.M.; Dobrowski, S.Z.; Dillon, G.K. 2018c. High-severity fire: Evaluating its key drivers and mapping its probability across western US forests. *Environmental Research Letters*. 13(4): 44037. <https://doi.org/10.1088/1748-9326/aab791>

Location

Western United States

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors explored the drivers of high severity fires in forested ecosystems in the western United States over the period 2002 through 2015. To assess variation in fire behavior, boosted regressions trees were employed to model fire severity in forested ecoregions as a function of live fuel, topography, climate, and fire weather.

Publication findings

Despite substantial variation across ecoregions, live fuel was the most important factor driving high severity fires (average relative influence = 53.1 percent) and was the most important factor in 14 of 19 ecoregions. The second most important variable was fire weather, with an average relative influence of 22.9 percent. Climate and topography were the least influential at 13.7 percent and 10.3 percent, respectively.

Linkages

- **Fire season length on Fire severity**

The Arizona–New Mexico Mountain ecoregion followed the average model, with

live fuels the most important factor driving high severity fires (average relative influence = 75.0 percent) and fire weather the second most important variable (average relative influence = 15.0 percent). Of note, the fire weather model for this ecoregion was built using burning index (a measure of fire intensity), maximum daily temperature, heat moisture for the year in which the fire occurred, and year-of-fire climatic moisture deficit and did not include a measure of the ERC.

- **Temperature, RH, VPD on Fire severity**

Climate was the third most important variable driving high severity fires (average relative influence = 13.7 percent). This pattern was supported in the Arizona–New Mexico Mountain ecoregion though weaker (average relative influence = 9.7 percent). The climate variables used in the final model for this ecoregion included climatic moisture deficit and evapotranspiration.

138. **Parks, S.A.; Miller, C.; Abatzoglou, J.T.; Holsinger, L.M.; Parisien, M.-A.; Dobrowski, S.Z. 2016.** How will climate change affect wildland fire severity in the western US? *Environmental Research Letters*. 11(3): 35002.
<https://doi.org/10.1088/1748-9326/11/3/035002>

Location

Western United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors used observation data from 1984 through 2012 to build a statistical model of fire severity as a function of climate for the western United States. This model was applied to various climate change projections for 2040 through 2069 under the RCP 8.5 scenario.

Publication findings

Model predictions indicate widespread decline in fire severity for large portions of the western United States. The map of contemporary (1984–2012) cooler and wetter forested areas was predicted to experience more high severity fires compared to warmer and drier regions of the western United States. This pattern was also reflected when applied to mid-21st century climate change scenarios. However, the authors' model implicitly incorporates climate-induced changes in vegetation type, fuel load, and fire frequency. Therefore, their predictions should be seen as a “potential” reduction in fire severity that may not occur.

Linkages

- **Temperature, RH, VPD on Fire severity**

Fire severity generally decreased with increasing WD (relative influence = 41.5 percent).

The authors note that while their predictions contrast with commonly held beliefs, the predicted decrease in fire severity can be attributed to climatic conditions associated with higher WDs and associated lower productivity, and less burnable biomass. Their approach and findings are based on an implicit assumption that vegetation composition and fuel load will track changes in climate. A prediction of lower fire severity implicitly accepts that vegetation composition and burnable biomass will reflect lower productivity associated with warmer and drier climates (e.g., increased WD).

- **Snowpack, snow and rain on Fire severity**

Fire severity generally increased with annual precipitation (relative influence = 29.8 percent).

- 139. Parks, S.A.; Miller, C.; Nelson, C.R.; Holden, Z.A. 2014a.** Previous fires moderate burn severity of subsequent wildland fires in two large western US wilderness areas. *Ecosystems*. 17(1): 29–42. <https://doi.org/10.1007/s10021-013-9704-x>

Location

The Gila-Aldo Leopold Wilderness Complex, New Mexico, USA; Frank Church-River of No Return Wilderness, Idaho, USA

Ecosystem type(s)

Forested ecosystems; gradient

Summary: What the authors did and why

The authors examined fire-on-fire interactions in two wilderness areas to determine the extent, if any, to which a wildfire can influence the severity of a subsequent fire and, if an effect exists, how long it lasts. They also looked at the influence of topography and vegetation on burn severity of reburned areas.

Publication findings

The authors found a positive feedback between the initial severity of a fire and the severity of a later reburn when the first fire burned at high severity. They suggest that high severity fires can leave behind dense stands of fire-killed trees, potentially creating heavy fuel loads and ladder fuels when a subsequent fire strikes. Alternatively, a shift to a shrub state after high severity fire can result in a subsequent reburn of high severity fire. However, they also found that stands that are within unaltered, short-interval fire regimes tend to self-regulate the burn severity of secondary fires, and burn at the same or lower severity, suggesting that the initial fire moderated the burn severity of the second fire. This mitigating effect lasted up to 22 years in some of the burned areas studied, but generally decayed as time since fire increased.

Linkages

- **Fire severity on Fuels**

The authors found a positive feedback between the initial severity of a fire and the severity of a later reburn when the first fire burned at high severity. They suggest that high severity fires can leave behind dense stands of fire-killed trees, potentially creating heavy fuel loads and ladder fuels when a subsequent fire strikes. Alternatively, a shift to a shrub state after high severity fire can result in a subsequent reburn of high severity fire. However, they also found that stands that are within unaltered, short-interval fire regimes tend to self-regulate the burn severity of secondary fires, and burn at the same or lower severity, suggesting that the initial fire moderated the burn severity of the second fire.

- **Fire frequency, fire rotation, fire return interval on Fuels**

The authors found that stands that are within unaltered, short-interval fire regimes tend to self-regulate the burn severity of secondary fires, and burn at the same or lower severity, suggesting that the initial fire moderated the burn severity of the second fire. This mitigating effect lasted up to 22 years in some of the burned areas studied, but generally decayed as time since fire increased.

- **Fire behavior, fire type, fire intensity on Fuels**

The authors found a positive feedback between the initial severity of a fire and the severity of a later reburn when the first fire burned at high severity. They suggest that high severity fires can leave behind dense stands of fire-killed trees, potentially creating heavy fuel loads and ladder fuels when a subsequent fire strikes. Alternatively, a shift to a shrub state after high severity fire can result in a subsequent reburn of high severity fire. However, they also found that stands that are within unaltered, short-interval fire regimes tend to self-regulate the burn severity of secondary fires, and burn at the same or lower severity, suggesting that the initial fire moderated the burn severity of the second fire. This mitigating effect lasted up to 22 years in some of the burned areas studied, but generally decayed as time since fire increased.

- 140. Parks, S.A.; Parisien, M.-A.; Miller, C.; Dobrowski, S.Z. 2014b.** Fire activity and severity in the western US vary along proxy gradients representing fuel amount and fuel moisture. PLoS ONE. 9(6): e99699.

<https://doi.org/10.1371/journal.pone.0099699>

Location

Western United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors characterized fire activity or area burned and fire severity variability along a gradient of fuel amount and fuel moisture within wilderness areas using actual evapotranspiration (AET) and WD, respectively, as regional proxies.

Publication findings

The authors found that fire activity or area burned and fire severity across the western United States increased with increasing AET, which represented fuel amount in the study. However, area burned increased with increasing WD (fuel moisture) to a threshold before fire activity subsequently decreased. Fire severity decreased with increasing WD. These results suggest that fire activity is both fuel and moisture limited. Regional areas across the western United States that have higher fuel moistures and lower WDs rarely burn because fuel is not dry enough to ignite, whereas areas with low fuel moisture and high moisture deficits are not productive enough to support fire spread.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

The authors found that fire activity or area burned and fire severity across the western United States increased with increasing actual evapotranspiration, which represented fuel amount in the study. However, area burned increased with increasing WD (fuel moisture) to a threshold before fire activity subsequently decreased. These results suggest that fire activity is both fuel and moisture limited. Regional areas across the West that have higher fuel moistures and lower WDs rarely burn because fuel is not dry enough to ignite, whereas areas with low fuel moisture and high moisture deficits are not productive enough to support fire spread.

- **Temperature, RH, VPD on Fire severity**

The authors found that fire activity or area burned and fire severity across the western United States increased with increasing actual evapotranspiration, which represented fuel amount in the study. Fire severity decreased with increasing WD (fuel moisture).

- 141. Parmenter, R.R. 2008.** Long-term effects of a summer fire on desert grassland plant demographics in New Mexico. *Rangeland Ecology & Management*. 61(2): 156–168. <https://doi.org/10.2111/07-010.1>

Location

Sevilleta National Wildlife Refuge, New Mexico, USA

Ecosystem type(s)

Chihuahuan Desert scrubland; desert grasslands; short-grass steppe

Summary: What the authors did and why

The authors examined the effects of a prescribed fire on desert short-grass steppe vegetation on plant mortality, survivorship, and regeneration. They also examined prescribed-fire effects on nonnative species composition and shrub invasions for 12 years post-fire.

Publication findings

Native grassland plant species showed a wide variety of responses to the summer prescribed fire; however, most of the 14 species studied were fire tolerant and either survived the fire or quickly resprouted post-fire within 10 to 12 years. Exceptions, such as black grama grass (*Bouteloua eriopoda*), chollas (*Cylindropuntia* spp.), snakeweed (*Gutierrezia* spp.), and fourwing saltbush (*Atriplex canescens*), were highly susceptible to fire and exhibited both high mortality and slow regeneration rates. However, established individuals of the invading shrub creosotebush (*Larrea tridentata*) were highly tolerant of fire, so prescribed fire may not be effective at removing this species. Nonetheless, the authors suggest that more frequent fire may reduce creosotebush and other woody shrub recruitment.

Linkages

- **Fire frequency, fire rotation, fire return interval on Mortality, survivorship, turnover**

Native grassland plant species showed a wide variety of responses to the summer prescribed fire; however, most of the 14 species studies were fire tolerant and either survived the fire or quickly resprouted post-fire within 10 to 12 years. Exceptions, such as black grama grass (*Bouteloua eriopoda*), chollas (*Cylindropuntia* spp.), snakeweed (*Gutierrezia* spp.), and fourwing saltbush (*Atriplex canescens*) were highly susceptible to fire and exhibited both high mortality and slow regeneration rates.

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

Native grassland plant species showed a wide variety of responses to the summer prescribed fire; however, most of the 14 species studies were fire tolerant and either survived the fire or quickly resprouted post-fire within 10 to 12 years. Exceptions, such as black grama grass (*Bouteloua eriopoda*), chollas (*Cylindropuntia* spp.), snakeweed (*Gutierrezia* spp.), and fourwing saltbush (*Atriplex canescens*) were highly susceptible to fire and exhibited both high mortality and slow regeneration rates. The authors suggest that more frequent fire may reduce creosotebush (*Larrea tridentata*) and other woody shrub recruitment.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

Native grassland plant species showed a wide variety of responses to the summer prescribed fire; however, most of the 14 species studies were fire tolerant and

either survived the fire or quickly resprouted post-fire within 10 to 12 years. Exceptions, such as black grama grass (*Bouteloua eriopoda*), chollas (*Cylindropuntia* spp.), snakeweed (*Gutierrezia* spp.), and fourwing saltbush (*Atriplex canescens*) were highly susceptible to fire and exhibited both high mortality and slow regeneration rates. However, established individuals of the invading shrub creosotebush were highly tolerant of fire, so prescribed fire may not be effective at removing these species. Nonetheless, the authors suggest that more frequent fire may reduce creosotebush (*Larrea tridentata*) and other woody shrub recruitment.

- 142. Passovoy, M.D.; Fulé, P.Z. 2006.** Snag and woody debris dynamics following severe wildfires in northern Arizona ponderosa pine forests. *Forest Ecology and Management*. 223(1–3): 237–246. <https://doi.org/10.1016/j.foreco.2005.11.016>

Location

Coconino National Forest, Arizona, USA

Ecosystem type(s)

Mixed-conifer forest; ponderosa pine forest

Summary: What the authors did and why

The authors examined postwildfire snag and down coarse woody debris characteristics including quantity, quality, and changes over time after severe wildfire.

Publication findings

Snag densities declined rapidly with increased time since high severity fire, and most snags had fallen either partially or completely after 5 years. Total coarse woody debris biomass in the surface fuel load was similar between 8- to 9-year-old fires and a 27-year-old fire, but the wood became rotten with increasing time. The authors suggest that the increase in rotten wood could increase in ignitability with increasing time since fire, but fine fuels in the study sites were relatively low.

Linkages

- **Fire severity on Fuels**

Snag densities declined rapidly with increased time since high severity fire, and most snags had fallen either partially or completely after five years. Total coarse woody debris biomass in the surface fuel load was similar between 8- to 9-year-old fires and a 27-year-old fire, but the wood became rotten with increasing time. The authors suggest that the increase in rotten wood could increase in ignitability with increasing time since fire, but fine fuels in the study sites were relatively low.

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143. Pausas, J.G.; Ribeiro, E. 2013. The global fire–productivity relationship. *Global Ecology and Biogeography*. 22(6): 728–736. <https://doi.org/10.1111/geb.12043>

Location

Global

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors tested the intermediate fire-productivity hypothesis across the world's ecoregions. This hypothesis posits that fire is most common at the intermediate levels of aridity and productivity while either very arid or very productive ecosystems tend to decrease in flammability.

Publication findings

The authors' results support the intermediate fire-productivity hypothesis across the various ecoregions of the globe. They found that increasing productivity increases fire activity until a moisture threshold is met. At that threshold moisture levels increasingly limit flammability and fire activity. Fire that occurs in moist and productive regions, where fuels are not a limiting factor, depends on changes in climate, such as increased temperatures or periods of drought, to burn. Conversely, very arid systems are fuel limited and sensitive to changes in fuel loading and continuity.

Linkages

- **Drought on Spatial pattern, landscape mosaic**

The authors' results support the intermediate fire-productivity hypothesis across the various ecoregions of the globe. They found that increasing productivity increases fire activity until a moisture threshold is met where moisture levels then increasingly limit flammability and fire activity. Fire that occurs in moist and productive regions, where fuel is not limiting, depends on changes in climate, such as increased temperatures or periods of drought, to burn. Conversely, very arid systems are fuel limited and sensitive to changes in fuel loading and continuity.

- **Temperature, RH, VPD on Spatial pattern, landscape mosaic**

The authors' results support the intermediate fire-productivity hypothesis across the various ecoregions of the globe. They found that increasing productivity increases fire activity until a moisture threshold is met where moisture levels then increasingly limit flammability and fire activity. Fire that occurs in moist and productive regions, where fuel is not limiting, depends on changes in climate, such as increased temperatures or periods of drought, to burn. Conversely, very arid systems are fuel limited and sensitive to changes in fuel loading and continuity.

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144. Pechony, O.; Shindell, D.T. 2010. Driving forces of global wildfires over the past millennium and the forthcoming century. *Proceedings of the National Academy of Sciences*. 107(45): 19167–19170. <https://doi.org/10.1073/pnas.1003669107>

Location

Global

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors developed a model that estimates global fire activity based on vegetation and climate or weather conditions along with availability of ignition sources and fire suppression rates. They used model projections to determine how climate may affect future global fire trends.

Publication findings

The authors' reconstruction of past fire activity suggests that until the late 18th century fire was driven mostly by climate. Specifically, they found that variation in global precipitation had the strongest influence on global fire activity. Post-Industrial Revolution, anthropogenic activities had a stronger influence on global fire trends. Finally, predictions of future warming due to climate change suggest an imminent shift to temperature-driven global fire activity over the next century.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

The authors reconstruction of past fire activity suggests that until the late 18th century fire was driven mostly by climate. Specifically, they found that variation in global precipitation had the strongest influence on global fire activity. Post-Industrial Revolution, anthropogenic activities had a stronger influence on global fire trends. Finally, predictions of future warming due to climate change suggest an imminent shift to temperature-driven global fire activity over the next century.

- **Snowpack, snow and rain on Annual area burned, fire size**

The authors reconstruction of past fire activity suggests that until the late 18th century fire was driven mostly by climate. Specifically, they found that variation in global precipitation had the strongest influence on global fire activity. Post-Industrial Revolution, anthropogenic activities had a stronger influence on global fire trends. Finally, predictions of future warming due to climate change suggest an imminent shift to temperature-driven global fire activity over the next century.

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145. **Pierce, J.L.; Meyer, G.A.; Jull, A.T. 2004.** Fire-induced erosion and millennial-scale climate change in northern ponderosa pine forests. *Nature*. 432(7013): 87.
<https://doi.org/10.1038/nature03058>

Location

South Fork Payette River, Idaho, USA; Yellowstone National Park, Wyoming, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors reconstructed long-term fire history of xeric ponderosa pine ecosystems during the Holocene using fire-related sediment deposits in alluvial fans to examine historical climate–fire relationships.

Publication findings

The authors found that during historically cooler periods, forests burned frequently at low severity, which they suggest was driven by increases in understory vegetation growth. Historically warm periods were linked to severe drought and an increase in high severity fires that caused large debris-flow events and fire-related erosion.

Linkages

- **Temperature, RH, VPD on Fire severity**

The authors found that during historically cooler periods, forests burned frequently at low severity, which they suggest was driven by increases in understory vegetation growth. Historically warm periods were linked to severe drought and an increase in high severity fires that caused large debris-flow events and fire-related erosion.

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

The authors found that during historically cooler periods, forests burned frequently at low severity, which they suggest was driven by increases in understory vegetation growth. Historically warm periods were linked to severe drought and an increase in high severity fires that caused large debris-flow events and fire-related erosion.

- **Drought on Fire severity**

The authors found that during historically cooler periods, forests burned frequently at low severity, which they suggest was driven by increases in understory vegetation growth. Historically warm periods were linked to severe drought and an increase in high severity fires that caused large debris-flow events and fire-related erosion.

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- 146. Pollet, J.; Omi, P.N. 2002.** Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire*. 11(1): 1–10.

Location

Webb Fire, Montana, USA; Tyee Fire, Washington, USA; Cottonwood Fire, California, USA; Hochderffer Fire, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors quantitatively compared the effects of three treatments—prescribed fire, whole-tree thinning, and thinning followed by prescribed fire—and an untreated stand at four ponderosa pine sites to test each treatment’s effectiveness at reducing fire severity and crown scorch.

Publication findings

The authors found that all of the treated stands had lower fire severity and reduced crown scorch compared to the untreated plots.

Linkages

- **Fire severity on Fuels**

The authors found that all of the treated stands had lower fire severity and reduced crown scorch compared to the untreated plots.

- 147. Poulos, H.M.; Freiburger, M.R.; Barton, A.M.; Taylor, A.H. 2021.** Mixed-severity wildfire as a driver of vegetation change in an Arizona Madrean sky island system, USA. *Fire*. 4(4): 78. <https://doi.org/10.3390/fire4040078>

Location

Chiricahua Mountains, southeastern Arizona, USA

Ecosystem type(s)

Madrean

Summary: What the authors did and why

The authors investigated wildfire effects on plant community composition and forest stand structure in the Chiricahua Mountains.

Publication findings

The authors identified three dominant prefire vegetation types with cluster analysis: juniper woodland, piñon forest, and pine-oak forest. All vegetation types faced significant mortality across size classes and species, from forests to shrublands. The degree of change varied with fire severity, which was mediated by topography. There was a significant decline in the dominance of coniferous obligate seeder trees and concomitant increase in resprouting hardwoods and other shrubs across all vegetation types in response to fire.

Linkages

- Fire severity on Species composition, non-natives, structure

Prefire stand structure significantly influenced fire severity; basal area in 2002 and 2003 positively influenced Horseshoe Two Fire severity, although this effect declined at very high basal area ($p < 0.001$). These results suggest that fire severity was higher within heavily stocked stands, and on upper slopes, higher elevations, and drier sites.

Juniper woodlands experienced the smallest shift in plant community composition, likely because they burned at lower severity than other vegetation types.

Pine-oak forests burned at the highest fire severity of all vegetation types and consequentially experienced the biggest shift in species dominance.

- 148. Price, C.; Rind, D. 1994.** The impact of a $2\times \text{CO}_2$ climate on lightning-caused fires. *Journal of Climate*. 7(10): 1484–1494.

Location

Southwestern United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors modeled the potential shift in the frequency and intensity of lightning-caused fires and thunderstorm activity induced under a doubling of carbon dioxide concentration ($2\times \text{CO}_2$) across the forested areas of the southwestern United States.

Publication findings

The authors found that lightning activity and lightning-started fires are likely to increase in a warmer climate. They found a 44 percent increase in the likelihood of lightning-caused fires for a $2\times \text{CO}_2$ climate scenario.

Linkages

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

The authors found that lightning activity and lightning-started fires are likely to increase in a warmer climate. They found a 44 percent increase in the likelihood of lightning-caused fires for a $2\times \text{CO}_2$ climate scenario.

- 149. Roccaforte, J.P.; Fulé, P.Z.; Chancellor, W.W.; Laughlin, D.C. 2012.** Woody debris and tree regeneration dynamics following severe wildfires in Arizona ponderosa pine forests. *Canadian Journal of Forest Research*. 42(3): 593–604.

<https://doi.org/10.1139/x2012-010>

Location

National forests in Arizona, USA; Grand Canyon National Park, Arizona

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors sampled postfire surface fuels, woody debris, and regeneration along a chronosequence of 18 years within ponderosa pine stands that burned at high severity to understand how surface fuels change with time since fire.

Publication findings

The authors found that snag density rapidly declined with increasing time since fire as snags fell rapidly in the first few years post-fire and transitioned to other snag condition classes soon after. Course woody debris loading increased with time since fire and peaked between 6 and 12 years post-fire, but was still within recommended management values, until it turned into rotten wood at approximately 16 years post-fire. The authors also found that after severe fires, over half of the sites lacked any ponderosa pine (*Pinus ponderosa*) regeneration and were more likely to be dominated by sprouting species, although one site did have hyperdense pine regeneration. The authors suggest that these sites may persist for decades as shrublands or grasslands, and it remains to be seen if they return to a forested state.

Linkages

- **Fire severity on Dispersal, regeneration, establishment**

The authors found that after severe fires, over half of the sites lacked any ponderosa pine (*Pinus ponderosa*) regeneration and were more likely to be dominated by sprouting species, although one site did have hyperdense pine regeneration. The authors suggest that these sites may persist for decades as shrublands or grasslands, and it remains to be seen if they return to a forested state.

- **Fire severity on Fuels**

The authors found that snag density rapidly declined as time since fire increased as snags fell rapidly in the first few years post-fire and transitioned to other snag condition classes soon after. Course woody debris loading increased with time since fire and peaked between 6 and 12 years post-fire, but was still within recommended management values, until it turned into rotten wood at approximately 16 years post-fire.

- **Fire severity on Species composition, invasives, structure**

The authors found that after severe fires, over half of the sites lacked any ponderosa pine (*Pinus ponderosa*) regeneration and were more likely to be dominated by sprouting species, although one site did have hyperdense pine regeneration. The authors suggest that these sites may go decades as shrublands or grasslands, and it remains to be seen if they return to a forested state.

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150. **Roccaforte, J.P.; Fulé, P.Z.; Covington, W.W. 2008.** Landscape-scale changes in canopy fuels and potential fire behaviour following ponderosa pine restoration treatments. *International Journal of Wildland Fire*. 17(2): 293–303.

<https://doi.org/10.1071/WF06120>

Location

Mount Trumbull, Arizona, USA

Ecosystem type(s)

Ponderosa pine ecosystem

Summary: What the authors did and why

The authors evaluated the effects of a landscape-scale restoration treatment of thinning followed by prescribed fire on reducing crown fire hazard potential using FlamMap and NEXUS models with different fuel estimation approaches.

Publication findings

Prescribed fire treatments reduced the potential for active crown fire compared to the control plots or pretreatment levels. Increases in drought and wind conditions input into either model produced increases in active crown fire; however, the crowning and torching index was two and three times higher, respectively, in areas that had been treated than in those with no treatment.

Linkages

- **Drought on Fire behavior, fire type, fire intensity**

Prescribed fire treatments reduced the potential for active crown fire compared to the control plots or pretreatment levels. Increases in drought and wind conditions input into either model produced increases in active crown fire; however, the crowning and torching index was two and three times higher, respectively, in areas that had been treated than those with no treatment.

- **Fire behavior, fire type, fire intensity on Fuels**

Prescribed fire treatments reduced the potential for active crown fire compared to the control plots or pretreatment levels. Increases in drought and wind conditions input into either model produced increases in active crown fire; however, the crowning and torching index was two and three times higher, respectively, in areas that had been treated than those with no treatment.

151. **Roccaforte, J.P.; Fulé, P.Z.; Covington, W.W. 2010.** Monitoring landscape-scale ponderosa pine restoration treatment implementation and effectiveness. *Restoration Ecology*. 18(6): 820–833. <https://doi.org/10.1111/j.1526-100X.2008.00508.x>

Location

Mount Trumbull, Arizona, USA

Ecosystem type(s)

Ponderosa pine

Summary: What the authors did and why

The authors evaluated the implementation and effectiveness of a thinning and burning forest restoration treatment to meet forest structure objectives in a ponderosa pine forest.

Publication findings

Thinning and burning significantly reduced the overall density of ponderosa pine (*Pinus ponderosa*) stems (diameter >2.5 cm) by 66 percent, although this result did not meet the objective. Large snags and logs larger than 50-cm diameter were retained within objectives. Canopy fuel loads were substantially reduced, allowing for the reintroduction of surface fires.

Linkages

- **Fire behavior, fire type, fire intensity on Species composition, invasives, structure**

Thinning and burning significantly reduced the overall density (diameter >2.5 cm) of ponderosa pine stems by 66 percent, although this did not meet the objective. Large snags and logs larger than 50-cm diameter were retained within objectives. Canopy fuel loads were substantially reduced, allowing for the reintroduction of surface fires.

152. **Romps, D.M.; Seeley, J.T.; Vollaro, D.; Molinari, J. 2014.** Projected increase in lightning strikes in the United States due to global warming. *Science*. 346(6211): 851–854. <https://doi.org/10.1126/science.1259100>

Location

Contiguous United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors estimated the projected increase in the mean annual lightning flash rate based on global climate models of convective available potential energy (CAPE) and precipitation projected for 2079 through 2088.

Publication findings

The authors estimated a mean annual lightning-strike frequency increase of 12 percent per 1 °C increase in mean annual temperature. The authors suggest this could increase the frequency of wildfire across North America.

Linkages

- Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval

The authors estimated a mean annual lightning-strike frequency increase of 12 percent per 1 °C increase in mean annual temperature. The authors suggest this could increase the frequency of wildfire across North America.

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- 153. Roos, C.I.; Swetnam, T.W. 2012.** A 1416-year reconstruction of annual, multidecadal, and centennial variability in area burned for ponderosa pine forests of the southern Colorado Plateau region, southwest USA. *The Holocene*. 22(3): 281–290. <https://doi.org/10.1177/0959683611423694>

Location

Colorado Plateau, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors reconstructed the historical fire regime of the Colorado Plateau region over the previous 1,416 years to examine changes in the fire regime in response to climate variability, specifically periods of drought, and compared models of area burned and fire frequency in relation to climate before and after approximately C.E. 1600.

Publication findings

The authors found no significant difference between their models of fire–climate relationship before and after C.E. 1600, suggesting that the historical range of variability drawn from fire chronologies from ca. C.E. 1600 to 1900 are useful analogues for current and future restoration and management purposes. The authors also found that a dry year preceded by a wet year 1 to 3 years earlier was a strong predictor of fire activity throughout the fire record (C.E. 572–1987). An atypically long fire-free period occurred between C.E. 1360 and 1455 during an unusually wet period. This timespan was followed by high severity fires during the Medieval Climate Anomaly in the late 14th or 15th century, likely driven by drought conditions and the increase in fuels from the prior century.

Linkages

• **Drought on Fire frequency, fire rotation, fire return interval**

The authors found no significant difference between their models of fire-climate relationship before and after C.E. 1600 CE, suggesting that the historical range of variability drawn from fire chronologies from ca. C.E. 1600 to 1900 are useful analogs for current and future restoration and management purposes. The authors also found that a dry year preceded by a wet year 1 to 3 years earlier was a strong predictor of fire activity throughout the fire record (C.E. 572–1987). An atypically long fire-free period occurred between C.E. 1360 and 1455 during an unusually wet period. This timespan was followed by high severity fires during the Medieval Climate Anomaly in the late 14th or 15th century, likely driven by drought conditions and the increase in fuels from the prior century.

- 154. Rother, M.T.; Grissino-Mayer, H.D. 2014.** Climatic influences on fire regimes in ponderosa pine forests of the Zuni Mountains, NM, USA. *Forest Ecology and Management*. 322: 69–77. <https://doi.org/10.1016/j.foreco.2014.02.034>

Location

Zuni Mountains, New Mexico, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors characterized the fire history of ponderosa pine forests in the Zuni Mountains and examined historical relationships between climate and fire using Superposed Epoch Analysis (SEA) and Bivariate Event Analysis (BEA).

Publication findings

The authors found that fire was highly synchronous across the region and were associated with climate conditions. Their analysis found strong relationships between dry years, preceded by one or two wetter years, with increased fire activity across the region. Specifically, widespread fire years were synchronous with negative, extreme PDSI events, whereas fire was asynchronous when PDSI was positive. The authors also found stronger relationships with interannual climate variability than with long-term, multidecadal climate cycles driven by ENSO.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that fire was highly synchronous across the region and was associated with climate conditions. Their analysis found strong relationships between dry years, preceded by one or two wetter years, with increased fire activity across the region. Specifically, widespread fire years were synchronous with negative, extreme PDSI events, whereas fire was asynchronous when PDSI was positive. The authors also found stronger relationships with interannual climate variability than with long-term, multidecadal climate cycles driven by ENSO.

155. **Rother, M.T.; Veblen, T.T.; Furman, L.G. 2015.** A field experiment informs expected patterns of conifer regeneration after disturbance under changing climate conditions. *Canadian Journal of Forest Research*. 45(11): 1607–1616. <https://doi.org/10.1139/cjfr-2015-0033>

Location

Colorado Front Range; Heil Valley Ranch Open Space, Boulder County, Colorado, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors implemented field experiments to determine the effects of an array of

temperature and moisture treatments on ponderosa pine regeneration following disturbance, such as wildfire.

Publication findings

The authors found that regeneration in the warmed and dry plots had the lowest growth rates and percent survival of seedlings. The authors suggest that increased temperatures and drought conditions are likely to inhibit recruitment and seedling survival after fire or other large-scale, rapid disturbance, potentially leading to new or novel vegetation assemblages.

Linkages

- **Spatial pattern, landscape mosaic on Dispersal, regeneration, establishment**

The authors found that regeneration in the warmed and dry plots had the lowest growth rates and percent survival of seedlings. The authors suggest that increased temperatures and drought conditions are likely to inhibit recruitment and seedling survival after fire or other large-scale, rapid disturbance, potentially leading to new or novel vegetation assemblages.

156. Ryniker, K.A.; Bush, J.K.; Van Auken, O.W. 2006. Structure of *Quercus gambelii* communities in the Lincoln National Forest, New Mexico, USA. Forest Ecology and Management. 233(1): 69–77. <https://doi.org/10.1016/j.foreco.2006.06.008>

Location

Lincoln National Forest, New Mexico, USA

Ecosystem type(s)

Gambel oak stands

Summary: What the authors did and why

The authors characterized the historical community stand dynamics of Gambel oak (*Quercus gambelii*) to understand the structure and patterns of regeneration and recruitment over time.

Publication findings

The frequency of fire necessary to maintain populations of Gambel oak (*Quercus gambelii*) is highly uncertain; however, the authors suggest that fire may play an important role in these communities by affecting the rate of succession. Because Gambel oak is fairly shade-intolerant, long fire return intervals may reduce the regeneration capacity of this species within dense canopies.

Linkages

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

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important role in these communities by affecting the rate of succession. Because Gambel oak is fairly shade-intolerant, long fire return intervals may reduce the regeneration capacity of this species within dense canopies

- 157. Savage, M.; Mast, J.N. 2005.** How resilient are southwestern ponderosa pine forests after crown fire? *Canadian Journal of Forest Research*. 35: 967–977.
<https://doi.org/10.1139/X05-028>

Location

Mogollon Rim, Arizona, USA; New Mexico, USA

Ecosystem type(s)

Ponderosa pine, including piñon-juniper woodlands at the lower elevation sites and mixed-conifer at the higher elevation sites

Summary: What the authors did and why

The authors looked at the regeneration of ponderosa pine forests after 10 high-severity crown fires that occurred from 1948 to 1977.

Publication findings

The authors found that in historically low-severity, frequent-fire forests, stand-replacing fire can result in conversion to altered species composition and structure of stands either toward even-aged cohorts of ponderosa pine (*Pinus ponderosa*) or to novel vegetation communities. Novel communities may occur through regeneration failure or changes in fire regimes, which may be exacerbated by climate change or extreme weather events (or both).

Linkages

- **Fire severity on Species composition, invasives, structure**

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- 158. Savage, M.; Swetnam, T.W. 1990.** Early 19th-century fire decline following sheep pasturing in a Navajo ponderosa pine forest. *Ecology*. 71(6): 2374–2378.
<https://doi.org/10.2307/1938649>

Location

Southwestern United States; Chuska Mountains, Arizona and New Mexico, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors documented the fire history of a ponderosa pine forest stand to

understand the effects of land use change on fire frequency, and the subsequent effects of fire decline on the forest structure.

Publication findings

The authors related the increase in sheep herding and livestock grazing, beginning in approximately 1830, to a significant reduction in fire frequency across the Chuska Mountains. The current stand is dense with even-aged cohorts that established in the early 1900s, similar to other stands in the Southwest. The authors suggest, however, that fire suppression and land use change alone were not responsible for the drastic changes to the forest structure. Instead, anthropogenic disturbance concurrent with favorable climate conditions for ponderosa pine (*Pinus ponderosa*) regeneration likely both influenced the major structural alteration of these stands.

Linkages

- **Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment**

The authors related the increase in sheep herding and livestock grazing, beginning in approximately 1830, to a significant reduction in fire frequency across the Chuska Mountains. The current stand is dense with even-aged cohorts that established in the early 1900s, similar to other stands in the Southwest. The authors suggest, however, that fire suppression and land use change alone were not responsible for the drastic changes to the forest structure. Instead, anthropogenic disturbance concurrent with favorable climate conditions for ponderosa pine (*Pinus ponderosa*) regeneration likely both influenced the major structural alteration of these stands.

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159. **Schoennagel, T.; Veblen, T.T.; Kulakowski, D.; Holz, A. 2007.** Multidecadal climate variability and climate interactions affect subalpine fire occurrence, western Colorado (USA). *Ecology*. 88(11): 2891–2902. <https://doi.org/10.1890/06-1860.1>

Location

Routt National Forest, Arapaho-Roosevelt National Forest, and White River National Forest, Colorado, USA

Ecosystem type(s)

Englemann spruce–alpine fir forest; lodgepole pine forest

Summary: What the authors did and why

The authors examined the historical relationship between interannual and multidecadal climate measures via ENSO, AMO, and PDO indices and large fire occurrence in subalpine ecosystems.

Publication findings

The authors found very strong relationships between broad-scale climate anomalies and fire activity in subalpine forest ecosystems. Fires generally occurred during periods of prolonged or extreme drought (or both) during the cool (negative) phases of ENSO, cool (negative) phase of PDO, and warm (positive) phase of AMO.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

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160. **Schoennagel, T.; Veblen, T.T.; Romme, W.H. 2004.** The interaction of fire, fuels, and climate across Rocky Mountain forests. *BioScience*. 54(7): 661–676. [https://doi.org/10.1641/0006-3568\(2004\)054\[0661:TIOFFA\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2004)054[0661:TIOFFA]2.0.CO;2)

Location

Rocky Mountains, USA

Ecosystem type(s)

Mixed-conifer forest; ponderosa pine forest; spruce-fir forest

Summary: What the authors did and why

The authors synthesized research on recent large fires and the effectiveness of fuel treatments across forest types within the study area.

Publication findings

The authors summarized findings on high-severity fire regimes in subalpine forests and found that climate variation is the predominant influence on fire frequency

and severity in this ecosystem type. They suggest that fuel reduction treatments would move stand structure away from its historical range of variability. For low severity fire regimes in low-elevation ponderosa pine forest, the authors found that fire frequency and severity were driven by the spatial and temporal variation of fine fuels more so than climate.

Linkages

- **Drought on Fire severity**

The authors summarized findings on high-severity fire regimes in subalpine forests and found that climate variation is the predominant influence on fire frequency and severity in this ecosystem type and suggest that fuel reduction treatments would move stand structure away from its historical range of variability. For low severity fire regimes in low-elevation ponderosa pine forest, the authors found that fire frequency and severity were driven by the spatial and temporal variation of fine fuels more so than climate.

- **Temperature, RH, VPD on Fire severity**

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- **Drought on Fire frequency, fire rotation, fire return interval**

The authors summarized findings on high-severity fire regimes in subalpine forests and found that climatic variation is the predominant influence on fire frequency and severity in this ecosystem type and suggest that fuel reduction treatments would move stand structure away from its historical range of variability. For low severity fire regimes in low-elevation ponderosa pine forest, the authors found that fire frequency and severity were driven by the spatial and temporal variation of fine fuels more so than climate.

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

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161. Shive, K.L.; Fulé, P.Z.; Sieg, C.H.; Strom, B.A.; Hunter, M.E. 2014. Managing burned landscapes: Evaluating future management strategies for resilient forests under a warming climate. *International Journal of Wildland Fire*. 23(7): 915–928. <https://doi.org/10.1071/WF13184>

Location

Rodeo-Chediski Fire, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

Using the Forest Vegetation Simulator (FVS), the authors examined the effects of projected climate scenarios on future forest trajectories of ponderosa pine ecosystems in the Rodeo-Chediski Fire. They also examined the potential effects of management strategies, including prescribed fire, to mitigate climate effects and increase resilience.

Publication findings

Under all projections of future climate change, the authors found that ponderosa pine (*Pinus ponderosa*) basal area was reduced significantly, and under A2 scenarios (continued increase in carbon emissions), ponderosa pine was eliminated from the site. However, those areas that burned at high severity in the Rodeo-Chediski Fire and that had received treatment prior to the wildfire had consistently higher future basal area than untreated areas in all simulations, suggesting that the spatial arrangement of treatments highly influences forest structure and recovery. The authors also found that 10- to 20-year prescribed fire intervals in areas that burned at high severity were too frequent to maintain basal areas of ponderosa pine within the historical range of variability under the most extreme climate scenarios. Prescribed fire was, however, effective at maintaining low severity sites initially dominated by smaller diameter trees.

Linkages

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

Under all projections of future climate change, the authors found that ponderosa pine (*Pinus ponderosa*) basal area was reduced significantly, and under A2 scenarios (continued increase in carbon emissions), ponderosa pine were eliminated from the site. Ten- to 20-year prescribed fire intervals in areas that burned at high severity were too frequent to maintain basal areas of ponderosa pine within the historical range of variability under the most extreme climate scenarios. Prescribed fire was, however, effective at maintaining low severity sites initially dominated by smaller diameter trees.

- **Fire severity on Species composition, invasives, structure**

Those areas that burned at high severity in the Rodeo-Chediski Fire that had

received treatment prior to the wildfire had consistently higher future basal area than untreated areas in all simulations, suggesting that the spatial arrangement of treatments highly influences forest structure and recovery.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors found that 10- to 20-year prescribed fire intervals in areas that burned at high severity were too frequent to maintain basal areas of ponderosa pine (*Pinus ponderosa*) within the historical range of variability under the most extreme climate scenarios. Prescribed fire was, however, effective at maintaining low severity sites initially dominated by smaller diameter trees.

162. Shive, K.L.; Sieg, C.H.; Fulé, P.Z. 2013. Pre-wildfire management treatments interact with fire severity to have lasting effects on post-wildfire vegetation response. *Forest Ecology and Management*. 297: 75–83.
<https://doi.org/10.1016/j.foreco.2013.02.021>

Location

White Mountain Apache Tribal Lands in Arizona, USA; Rodeo-Chediski Fire, Arizona

Ecosystem type(s)

Ponderosa pine ecosystems

Summary: What the authors did and why

The authors sampled plots 8 years post-wildfire that had been thinned and burned under prescription prior to the Rodeo-Chediski Fire to examine differences between areas that burned at high and low severity with or without treatments pre-fire. They specifically examined postfire species composition, exotic species response, and ponderosa pine (*Pinus ponderosa*) regeneration.

Publication findings

The authors found that in areas burned at high severity understory plant cover was greater than in low-severity burned areas, likely due to the increases in resources made available after the death of mature, overstory trees. Exotic plant cover was also greater in areas that burned at high severity, but generally the cover was minimal (<2 percent). Areas that had been treated prior to the wildfire had significantly higher ponderosa pine (*Pinus ponderosa*) regeneration. The difference between regeneration in treated versus untreated areas was larger for areas burned at high severity. The authors suggest this result is due to the greater heterogeneity of patch sizes of high severity fire that were created due to the treatments, allowing for a shorter distance to seed source to facilitate regeneration.

Linkages

- **Fire severity on Dispersal, regeneration, establishment**

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was greater than in low-severity burned areas, likely due to the increases in resources made available after the death of mature, overstory trees. Areas that had been treated prior to the wildfire had significantly higher ponderosa pine (*Pinus ponderosa*) regeneration. The difference between regeneration in treated versus untreated areas was larger for areas burned at high severity. The authors suggest this is due to the greater heterogeneity of patch sizes of high severity fire that were created due to the treatments, allowing for a shorter distance to seed source to facilitate regeneration.

- **Fire severity on Species composition, invasives, structure**

The authors found that in areas burned at high severity understory plant cover was greater than in low-severity burned areas, likely due to the increases in resources made available after the death of mature, overstory trees. Exotic plant cover was also greater in areas that burned at high severity, but generally the cover was minimal (< 2 percent).

- **Spatial pattern, landscape mosaic on Dispersal, regeneration, establishment**

Areas that had been treated prior to the wildfire had significantly higher ponderosa pine regeneration. The difference between regeneration in treated versus untreated areas was larger for areas burned at high severity. The authors suggest this is due to the greater heterogeneity of patch sizes of high severity fire that were created due to the treatments, allowing for a shorter distance to seed source to facilitate regeneration.

163. **Shryock, D.F.; Esque, T.C.; Chen, F.C. 2015.** Topography and climate are more important drivers of long-term, post-fire vegetation assembly than time-since-fire in the Sonoran Desert, US. *Journal of Vegetation Science*. 26(6): 1134–1147. <http://doi.org/10.1111/jvs.12324>

Location

Sonoran Desert of southwestern Arizona, USA

Ecosystem type(s)

Desert and arid shrubland ecosystem

Summary: What the authors did and why

The authors used a chronosequence to evaluate the effects of time since fire on postfire regeneration across a gradient of topography and climate conditions.

Publication findings

Climate and topography were more influential on postfire species composition than time since fire in the Sonoran Desert. Precipitation events soon after the fire had the strongest effects on recovery of vegetation height, and vegetation recovery increased with increasing elevation and the associated annual average increase in precipitation. The authors suggest that abiotic climate conditions may more

strongly influence postfire vegetation recovery than time since fire in desert and arid ecosystems

Linkages

- Fire frequency, fire rotation, fire return interval on Dispersal, regeneration, establishment

Climate and topography were more influential on post-fire species composition than time since fire in the Sonoran Desert. Precipitation events soon after the fire had the strongest effects on recovery of vegetation height, and vegetation recovery increased with increasing elevation and the associated annual average increase in precipitation. The authors suggest that abiotic climate conditions may more strongly influence post-fire vegetation recovery than time since fire in desert and arid ecosystems.

- 164. Sibold, J.S.; Veblen, T.T. 2006.** Relationships of subalpine forest fires in the Colorado Front Range with interannual and multidecadal-scale climatic variation. *Journal of Biogeography*. 33(5): 833–842.
<https://doi.org/10.1111/j.1365-2699.2006.01456.x>

Location

Rocky Mountain National Park, Colorado, USA

Ecosystem type(s)

Englemann spruce–subalpine fir forest; lodgepole pine forest

Summary: What the authors did and why

The authors examined the historical relationship between interannual and multidecadal climate measures via ENSO, AMO, and PDO indices and large fire occurrence in subalpine ecosystems.

Publication findings

The authors found very strong relationships between broad-scale climate anomalies and synchronous fire activity in subalpine forest ecosystems. Periods of synchronous fire activity generally occurred during periods of prolonged or extreme drought (or both) during the La Niña phase of ENSO, cool (negative) phase of PDO, and warm (positive) phase of AMO. The opposite phases of these indicators are associated with a protracted fire-free period from 1790 to 1850.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found very strong relationships between broad-scale climate anomalies and synchronous fire activity in subalpine forest ecosystems. Periods of synchronous fire activity generally occurred during periods of prolonged or extreme drought (or both) during the La Niña phase of ENSO, cool (negative) phase of PDO, and warm (positive) phase of AMO. The opposite phases of these indicators are associated with a protracted fire-free period from 1790 to 1850.

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165. Spracklen, D.V.; Mickley, L.J.; Logan, J.A.; Hudman, R.C.; Yevich, R.; Flannigan, M.D.; Westerling, A.L. 2009. Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *Journal of Geophysical Research: Atmospheres*. 114(D20).
<https://doi.org/10.1029/2008JD010966>

Location

Western United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors projected changes in wildfire area burned based on future climate models to understand the potential impacts of increased fire on carbonaceous aerosol air quality.

Publication findings

The authors predicted an increase in wildfire area burned across most of the western United States based on a temperature increase of 1 to 3 °C. They predicted larger increases in the Pacific Northwest and Rocky Mountains Forest ecoregions and almost no increase in the Nevada Mountains and Semidesert and the Eastern Rocky Mountains and Great Plains ecoregions. Along with predicted increases in area burned, the authors modeled a 40 percent increase in summertime organic carbon (OC) concentrations and an 18 percent increase in elemental carbon (EC) concentrations by 2050. Areas with the highest predicted future increases in carbonaceous aerosol concentrations are concomitant with the areas of greatest increases in wildfire.

Linkages

• **Temperature, RH, VPD on Annual area burned, fire size**

The authors predicted an increase in wildfire area burned across most of the western United States based on a temperature increase of 1 to 3 °C. They predicted larger increases in the Pacific Northwest and Rocky Mountains Forest ecoregions and almost no increase in the Nevada Mountains and Semidesert and Eastern Rocky Mountains and Great Plains ecoregions. Along with predicted increases in area burned, the authors modeled a 40 percent increase in summertime organic carbon (OC) concentrations and an 18 percent increase in elemental carbon (EC) concentrations by 2050. Areas with the highest predicted future increases in carbonaceous aerosol concentrations are concomitant with the areas of greatest increases in wildfire.

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166. **Stavros, E.N.; Abatzoglou, J.T.; McKenzie, D.; Larkin, N.K. 2014.** Regional projections of the likelihood of very large wildland fires under a changing climate in the contiguous western United States. *Climatic Change*. 126(3–4): 455–468.
<https://doi.org/10.1007/s10584-014-1229-6>

Location

Contiguous United States; Geographic Area Coordination Centers (GACC): Southern California (SCAL), Northern California (NCAL), Pacific Northwest (PNW), Northern Rockies (NROCK), Rocky Mountains (RM), Western Great Basin (WGB), Eastern Great Basin (EGB), and Southwest (SW)

Ecosystem type(s)

None

Summary: What the authors did and why

The authors examined the future potential and frequency for very large wildfires (>50,000 ac; 20,000 ha) based on downscaled climate projections for two representative concentration pathways and looked at the effects of specific climate predictors on very large wildfire potential through the 21st century.

Publication findings

The authors found an increased probability of very large wildfires across all of the GACCs in the contiguous United States by 2060. The strongest changes in the likelihood of very large wildfires were in areas where fire is a direct result of hot and dry climate conditions versus those regions where fire is driven by lagged climate effects.

Linkages

• **Temperature, RH, VPD on Annual area burned, fire size**

The authors found an increased probability of very large wildfires across all of the GACCs in the contiguous United States by 2060. The strongest changes in the likelihood of very large wildfires were in areas where fire is a direct result of hot and dry climate conditions versus those regions where fire is driven by lagged climate effects.

167. **Stephens, S. L.; Skinner, C.N.; Gill, S.J. 2003.** Dendrochronology-based fire history of Jeffrey pine-mixed conifer forests in the Sierra San Pedro Martir, Mexico. *Canadian Journal of Forest Research*. 33(6): 1090–1101.

Location

Sierra San Pedro Martir National Park, Mexico

Ecosystem type(s)

Jeffrey pine forest; mixed-conifer forest

Summary: What the authors did and why

The authors used dendrochronological techniques to describe the historical

fire regime of a Jeffrey pine–mixed conifer forest that experienced little fire suppression or logging (but did experience some livestock grazing impacts) in northern Mexico.

Publication findings

The authors found that fire was frequent with median intervals of less than 15 years in the Jeffrey pine-mixed conifer forests. However, a period of reduced fire occurrence from the 1790s to 1830s coincided with a similar fire-free period across the Southwest and southern South America. The authors and others found a reduction in the amplitude of ENSO during this time that likely contributed to this reduction in fire occurrence. However, an increase in livestock grazing intensity and a reduction of fire use by Native peoples occurred at the same time and likely also had strong influences on the fire regime during this period.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that fire was frequent with median intervals of less than 15 years in the Jeffrey pine–mixed conifer forests. However, a period of reduced fire occurrence from the 1790s to 1830s coincided with a similar fire-free period across the Southwest and southern South America. The authors and others found a reduction in the amplitude of ENSO during this time that likely contributed to this reduction in fire occurrence. However, an increase in livestock grazing intensity and a reduction of fire use by Native peoples occurred at the same time and likely also had strong influences on the fire regime during this period.

- 168. Stevens-Rumann, C.; Shive, K.; Fulé, P.; Sieg, C.H. 2013.** Pre-wildfire fuel reduction treatments result in more resilient forest structure a decade after wildfire. *International Journal of Wildland Fire*. 22(8): 1108–1117.
<https://doi.org/10.1071/WF12216>

Location

Rodeo-Chediski Fire, Arizona, USA

Ecosystem type(s)

Ponderosa pine with Gambel oak

Summary: What the authors did and why

The authors compared treated and untreated areas 9 years after the 2002 Rodeo-Chediski Fire to assess how stand structure and surface fuels change over longer periods of time. They further compared this information to a previous study (Strom and Fulé 2007) that installed the study plots in 2004 to assess the differences between short- and longer-term fuel responses.

Publication findings

In the Rodeo-Chediski Fire, prefire treatments resulted in reduced fire severity. Although fuel loads were high at both areas, prefire treated areas had lower levels

of surface fuel loads than untreated sites, and the difference between the two became greater over time. In treated areas, mean live basal area increased over the past decade as regeneration occurred in the open spaces left by fire-killed trees. Conversely, basal area in untreated areas has decreased due to residual tree death and limited regeneration.

Linkages

- **Fire behavior, fire type, fire intensity on Dispersal, regeneration, establishment**

In treated areas mean live basal area increased over the past decade as regeneration occurred in the open spaces left by fire-killed trees. Conversely, basal area in untreated areas has decreased due to residual tree death and limited regeneration.

- **Fire behavior, fire type, fire intensity on Fuels**

In the Rodeo-Chediski Fire, prefire treatments resulted in reduced fire severity. Although fuel loads were high at both areas, prefire treated areas had lower levels of surface fuel loads than untreated sites with the difference between the two becoming greater over time.

- **Fire behavior, fire type, fire intensity on Species composition, invasives, structure**

In the Rodeo-Chediski Fire, prefire treatments resulted in reduced fire severity. Although fuel loads were high at both areas, prefire treated areas had lower levels of surface fuel loads than untreated sites, and the difference between the two became greater over time. In treated areas mean live basal area increased over the past decade as regeneration occurred in the open spaces left by fire-killed trees. Conversely, basal area in untreated areas has decreased due to residual tree death and limited regeneration.

169. **Stoddard, M.T.; Sánchez Meador, A.S.; Fulé, P.Z.; Korb, J.E. 2015.** Five-year post-restoration conditions and simulated climate-change trajectories in a warm/dry mixed-conifer forest, southwestern Colorado, USA. *Forest Ecology and Management*. 356: 253–261. <https://doi.org/10.1016/j.foreco.2015.07.007>

Location

San Juan Mountains, Colorado, USA

Ecosystem type(s)

Mixed-conifer forest

Summary: What the authors did and why

The authors quantitatively compared restoration treatments—prescribed fire only, thinning followed by prescribed fire, and an untreated control—to test each treatment’s effect on forest structure and composition 5 years post-treatment. They

also projected potential forest trajectories using the Climate-Forest Vegetation Simulator (FVS) under various climate scenarios.

Publication findings

The authors found that thinning treatments followed by prescribed fire resulted in stands that maintained forest structure and composition within reference conditions and were the most resilient to climate change based on the Climate-Forest Vegetation Simulator (FVS) simulations.

Linkages

- **Fire behavior, fire type, fire intensity on Species composition, invasives, structure**

The authors found that thinning treatments followed by prescribed fire resulted in stands that maintained forest structure and composition within reference conditions and were the most resilient to climate change based on the Climate-Forest Vegetation Simulator (FVS) simulations.

170. **Strom, B.A.; Fulé, P.Z. 2007.** Pre-wildfire fuel treatments affect long-term ponderosa pine forest dynamics. *International Journal of Wildland Fire*. 16(1): 128–138. <https://doi.org/10.1071/WF06051>

Location

Rodeo-Chediski Fire, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors examined the effects of prefire thinning and fuel reduction treatments on postfire tree survival and forest structure and composition in high-severity burned areas versus untreated control plots.

Publication findings

The authors found that despite extreme and severe fire behavior over most of the fire, areas that were treated prior to the fire had lower tree mortality and reduced fire intensity when compared to untreated areas. The authors suggest that the arrangement of fuels may be more important for determining fire severity than the overall basal area or stand density; that is fewer larger trees have greater survivability than many smaller-diameter trees.

Linkages

- **Fire behavior, fire type, fire intensity on Fuels**

The authors found that despite extreme and severe fire behavior over most of the fire, areas that were treated prior to the fire had lower tree mortality and reduced fire intensity when compared to untreated areas. The authors suggest that the arrangement of fuels may be more important for determining fire severity than

the overall basal area or stand density; that is, fewer larger trees have greater survivability than many smaller-diameter trees.

171. **Swetnam, T.W.; Betancourt, J.L. 1990.** Fire-Southern Oscillation relations in the southwestern United States. *Science*. 249(4972): 1017–1020.
<https://doi.org/10.1126/science.249.4972.1017>

Location

Southwestern United States (Arizona and New Mexico)

Ecosystem type(s)

Mixed-conifer forest; piñon woodland; ponderosa pine forest

Summary: What the authors did and why

The authors correlated fire scars and tree-ring growth to assess potential relationships between fire and climate across pine forest ecosystems in the Southwest.

Publication findings

The authors found strong relationships between area burned and highly positive values of the Southern Oscillation Index (SOI), which is associated with reduced rainfall and severe winter–spring drought in the Southwest. They also found regional synchrony of large fires during the high-SO phase, which is associated with limited spring precipitation resulting in reduced tree growth. This finding suggests that seasonal climate, and not just local weather conditions, affects fire activity at a regional scale.

Linkages

- **Drought on Annual area burned, fire size**

The authors found strong relationships between area burned and highly positive values of the Southern Oscillation Index (SOI), which is associated with reduced rainfall and severe winter–spring drought in the Southwest. They also found regional synchrony of large fires during the high-SO phase, which is associated with limited spring precipitation resulting in reduced tree growth. This finding suggests that seasonal climate, and not just local weather conditions, affects fire activity at a regional scale.

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found strong relationships between area burned and highly positive values of the Southern Oscillation Index (SOI), which is associated with reduced rainfall and severe winter–spring drought in the Southwest. They also found regional synchrony of large fires during the high-SO phase, which is associated with limited spring precipitation resulting in reduced tree growth. This finding suggests that seasonal climate, and not just local weather conditions, affects fire activity at a regional scale.

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172. Swetnam, T.W.; Lynch, A.M. 1993. Multicentury, regional-scale patterns of western spruce budworm outbreaks. *Ecological Monographs*. 63(4): 399–424.

<https://doi.org/10.2307/2937153>

Location

Carson National Forest and Santa Fe National Forest, New Mexico, USA

Ecosystem type(s)

Mixed-conifer forests

Summary: What the authors did and why

The authors reconstructed spruce budworm infestations using tree ring chronologies from 1690 to the present and examined the potential relationships between historical spruce budworm infestations and human land use changes and climate variation.

Publication findings

Increased tree densities and a shift toward fire-intolerant white fir (*Abies concolor*) in the understory due to fire suppression have impacted the timing of infestations and the response of forest stands to outbreaks to some degree. The authors explain that white fir is more susceptible to mortality from spruce budworm, and increased mortality can lead to increased fire intensity. Regional outbreaks of spruce budworm were directly related to spring precipitation amount.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

Increased tree densities and a shift toward fire-intolerant white fir (*Abies concolor*) in the understory due to fire suppression have impacted the timing of infestations and the response of forest stands to infestations to some degree. The authors explain that white fir is more susceptible to mortality from spruce budworm, and increased mortality can lead to increased fire intensity. Regional outbreaks of spruce budworm were directly related to spring precipitation amount.

173. Tang, Y.; Zhong, S.; Luo, L.; Bian, X.; Heilman, W.E.; Winkler, J. 2015. The potential impact of regional climate change on fire weather in the United States. *Annals of the Association of American Geographers*. 105(1): 1–21.

<https://doi.org/10.1080/00045608.2014.968892>

Location

Contiguous United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors assessed potential changes in fire weather conditions across the

contiguous United States based on the Haines Index to predict how fire activity and behavior may change due to climate change.

Publication findings

Across regional climate models (RCMs) and GCMs the authors found that the number of days with a high Haines Index (HI) value (≥ 5) increased across most of the contiguous United States during the summer season. The moisture component of the HI was more influential in predicting future projected changes in conditions conducive to increased fire activity than the stability component of the HI.

Linkages

- **Temperature, RH, VPD on Fire behavior, fire type, fire intensity**

Across regional climate models (RCMs) and GCMs the authors found that the number of days with a high Haines Index (HI) value (≥ 5) increased across most of the contiguous United States during the summer season. The moisture component of the HI was more influential in predicting future projected changes in conditions conducive to increased fire activity than the stability component of HI.

174. **Tarancón, A.A.; Fulé, P.Z.; Shive, K.L.; Sieg, C.H.; Sánchez Meador, A.; Strom, B. 2014.** Simulating post-wildfire forest trajectories under alternative climate and management scenarios. *Ecological Applications*. 24(7): 1626–1637.
<https://doi.org/10.1890/13-1787.1>

Location

Apache-Sitgreaves National Forests, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors assessed potential future trajectories of forest stand structure in treated and untreated sites within the Rodeo-Chediski Fire in response to multiple scenarios of climate change using the Climate-Forest Vegetation Simulator (FVS).

Publication findings

Under the most extreme climate scenarios, an increase of 2.0 to 5.4 °C, ponderosa pine (*Pinus ponderosa*) was completely or nearly eliminated from the study sites by 2111. Conversely, the no climate change or limited climate change scenarios resulted in excessively dense stands of ponderosa pine in the absence of management. Adding a prescribed fire management regime ranging from 5 to 20 years to the Climate-FVS simulations resulted in forest conditions remaining within the historical range through the 100-year study time period under all climate scenarios except the A2 emissions scenario (which projects the highest increases in temperature).

Linkages

- **Temperature, RH, VPD on Spatial pattern, landscape mosaic**

Under the most extreme climate scenarios, an increase of 2.0 to 5.4 °C, ponderosa pine (*Pinus ponderosa*) was completely or nearly eliminated from the study sites by 2111. Conversely, the no climate change or limited climate change scenarios resulted in excessively dense stands of ponderosa pine in the absence of management. Adding a prescribed fire management regime ranging from 5 to 20 years to the Climate-FVS simulations resulted in forest conditions remaining within the historical range through the 100-year study time period under all climate scenarios except the A2 emissions scenario (which projects the highest increases in temperature).

- **Fire frequency, fire rotation, fire return interval on Mortality, survivorship, turnover**

Adding a prescribed fire management regime ranging from 5 to 20 years to the Climate-FVS simulations resulted in forest conditions remaining within the historical range through the 100-year study time period under all climate scenarios except the A2 emissions scenario (which projects the highest increases in temperature).

175. **Teske, C.C.; Seielstad, C.A.; Queen, L.P. 2012.** Characterizing fire-on-fire interactions in three large wilderness areas. *Fire Ecology*. 8: 102–106.
<https://doi.org/10.4996/fireecology.0802082>

Location

Frank Church-River of No Return Wilderness Area, Idaho; the Greater Bob Marshall Wilderness Area, Montana, USA; the Selway-Bitterroot Wilderness Area, Idaho and Montana, USA;

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors assessed fire-on-fire interactions in three wilderness areas to see how past fire area burned and fire severity affect subsequent fire.

Publication findings

The authors found that low or moderate severity fires generally regulated subsequent fires to similar severities, similar to historical patterns of frequent, low-severity fires in dry coniferous forest systems. Smaller burns created openings in both the understory and overstory vegetation, which add diversity to the landscape, provide mechanisms for plant succession, and promote differential tree establishment. In contrast to small burns, they found that large burns may create a homogeneous setting of burned areas which may not enhance species diversity following fire. Finally, the authors suggest that although previous fires

typically kept the spread of subsequent fires in check most of the time, climate and weather can override fuel limitations and lead to fire spread into recently burned landscapes.

Linkages

- **Drought on Spatial pattern, landscape mosaic**

The authors suggest that although typically previous fires kept the spread of subsequent fires in check most of the time, climate and weather can override fuel limitations and spread into recently burned landscapes.

- **Temperature, RH, VPD on Spatial pattern, landscape mosaic**

The authors suggest that although typically previous fires kept the spread of subsequent fires in check most of the time, climate and weather can override fuel limitations and spread into recently burned landscapes.

- **Spatial pattern, landscape mosaic on Fuels**

The authors found that low- or moderate severity fires generally regulated subsequent fires to similar severities, similar to historical patterns of frequent, low-severity fires in dry coniferous forest systems. Smaller burns created openings in both the understory and overstory vegetation, which add diversity to the landscape, provide mechanisms for plant succession, and promote differential tree establishment. In contrast to small burns, they found that large burns may create a homogeneous setting of burned areas which may not enhance species diversity following fire. Finally, the authors suggest that although previous fires typically kept the spread of subsequent fires in check most of the time, climate and weather can override fuel limitations and lead to fire spread into recently burned landscapes.

- **Fire severity on Fuels**

The authors found that low- or moderate-severity fires generally regulated subsequent fires to similar severities, similar to historical patterns of frequent, low-severity fires in dry coniferous forest systems. Smaller burns created openings in both the understory and overstory vegetation, which adds diversity to the landscape, provides mechanisms for plant succession, and promotes differential tree establishment. In contrast to small burns, they found that large burns may create a homogeneous setting of burned areas which may not enhance species diversity following fire. Finally, the authors suggest that although typically previous fires kept the spread of subsequent fires in check most of the time, climate and weather can override fuel limitations and spread into recently burned landscapes.

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176. Trouet, V.; Taylor, A.H.; Wahl, E.R.; Skinner, C.N.; Stephens, S.L. 2010. Fire-climate interactions in the American West since 1400 CE. *Geophysical Research Letters*. 37(4). <https://doi.org/10.1029/2009GL041695>

Location

Western United States; southwestern United States; Interior West, USA; Pacific Northwest, USA; California USA

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors developed tree-ring based fire chronologies across four regions of the western United States from approximately C.E. 1400 to the present to examine fire-climate relationships.

Publication findings

The authors found strong relationships between synchronized fire activity and summer drought in the year of the fire across all regions. Fire activity declined significantly in the late 16th century during a period of anomalously low temperature, referred to as the Little Ice Age.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found strong relationships between synchronized fire activity and summer drought in the year of the fire across all regions.

- **Temperature, RH, VPD on Annual area burned, fire size**

Fire activity declined significantly in the late 16th century during a period of anomalously low temperature, referred to as the Little Ice Age.

177. van Mantgem, P.J.; Caprio, A.C.; Stephenson, N.L.; Das, A.J. 2016. Does prescribed fire promote resistance to drought in low elevation forests of the Sierra Nevada, California, USA? *Fire Ecology*. 12(1): 13–25.

<https://doi.org/10.4996/fireecology.1201013>

Location

Yosemite National Park, Kings Canyon National Park, and Sequoia National Park, California, USA

Ecosystem type(s)

Mixed-conifer forest

Summary: What the authors did and why

The authors sampled burned and unburned mixed-conifer forest stands in the

midst of a drought (2014) to determine if prescribed fire can confer resistance to drought and reduce tree mortality in low elevation forests at three national parks.

Publication findings

The authors found that prescribed fire may increase resistance to drought and reduce tree mortality in low elevation forests in the study areas. Tree densities were significantly lower in the prescribed fire sites, suggesting that reduced competition may be responsible for the lower drought mortality response.

Linkages

- **Fire behavior, fire type, fire intensity on Mortality, survivorship, turnover**

The authors found that prescribed fire may increase resistance to drought and reduce tree mortality in low elevation forests in the study areas. Tree densities were significantly lower in the prescribed fire sites, suggesting that reduced competition may be responsible for the lower drought mortality response.

178. **van Mantgem, P.J.; Nesmith, J.C.; Keifer, M.; Knapp, E.E.; Flint, A.; Flint, L. 2013.** Climatic stress increases forest fire severity across the western United States. *Ecology Letters*. 16(9): 1151–1156. <https://doi.org/10.1111/ele.12151>

Location

Western United States

Ecosystem type(s)

Coniferous forests

Summary: What the authors did and why

The authors examined the relationship between climate and fire severity across coniferous forests of the western United States.

Publication findings

The authors found that long-term climatic stress, measured by climatic WD, predisposed trees to higher mortality from fire damage. The authors suggest that warming temperatures increase fire severity, and ultimately tree mortality, independent of fire intensity.

Linkages

- **Drought on Fire severity**

The authors found that long-term climatic stress, measured by climatic WD, predisposed trees to higher mortality from fire damage. The authors suggest that warming temperatures increase fire severity, and ultimately tree mortality, independent of fire intensity.

- **Drought on Fire behavior, fire type, fire intensity**

The authors found that long-term climatic stress, measured by climatic WD, predisposed trees to higher mortality from fire damage. The authors suggest

that warming temperatures increase fire severity, and ultimately tree mortality, independent of fire intensity.

- **Fire severity on Mortality, survivorship, turnover**

The authors found that long-term climatic stress, measured by climatic WD, predisposed trees to higher mortality from fire damage. The authors suggest that warming temperatures increase fire severity, and ultimately tree mortality, independent of fire intensity.

- **Fire behavior, fire type, fire intensity on Mortality, survivorship, turnover**

The authors found that long term climatic stress, measured by climatic WD, predisposed trees to higher mortality from fire damage. The authors suggest that warming temperatures increase fire severity, and ultimately tree mortality, independent of fire intensity.

179. **van Mantgem, P.J.; Stephenson, N.L.; Byrne, J.C.; Daniels, L.D.; Franklin, J.F.; Fulé, P.Z.; Harmon, M.E.; Larson, A.J.; Smith, J.M.; Taylor, A.H.; Veblen, T.T. 2009.** Widespread increase of tree mortality rates in the western United States. *Science*. 323(5913): 521–524. <https://doi.org/10.1126/science.1165000>

Location

Western United States; British Columbia, Canada

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors assessed the widespread tree mortality that has occurred in coniferous forests in the western United States and Canada and identified possible causes.

Publication findings

Overall, the authors found that fire and fire exclusion are unlikely to be responsible for the change in mortality rates in the coniferous western forests in the study areas. Instead, the authors suggest that warming and subsequent hydroclimate changes are directly responsible for the increased mortality rate.

Linkages

- **Fire frequency, fire rotation, fire return interval on Mortality, survivorship, turnover**

Overall, the authors found that fire and fire exclusion are unlikely to be responsible for the change in mortality rates in the coniferous western forests in the study area. Instead, the authors suggest that warming and subsequent hydroclimate changes are directly responsible for the increased mortality rate.

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180. van Mantgem, P.J.; Stephenson, N.L.; Knapp, E.; Battles, J.; Keeley, J.E. 2011. Long-term effects of prescribed fire on mixed conifer forest structure in the Sierra Nevada, California. *Forest Ecology and Management*. 261(6): 989–994. <https://doi.org/10.1016/j.foreco.2010.12.013>

Location

Sequoia National Park, California, USA

Ecosystem type(s)

Old-growth mixed-conifer forest

Summary: What the authors did and why

The authors monitored prescribed fire in old-growth mixed-conifer stands for 8 consecutive years to examine the long-term effects on forest structure and how the actual results compared to restoration objectives.

Publication findings

The authors found that prescribed fire can affect forest structure for 5 or more years post-treatment. Delayed tree mortality was observed up to 8 years post-fire, causing a 67 percent reduction in stem density within the time period of the analysis. The authors suggest that prescribed fire can alter stand structure in old-growth mixed-conifer forests over the long term.

Linkages

- **Fire behavior, fire type, fire intensity on Species composition, invasives, structure**

The authors found that prescribed fire can affect forest structure for 5 or more years post-treatment. Delayed tree mortality was observed up to 8 years post-fire, causing a 67 percent reduction in stem density within the time period of the analysis. The authors suggest that prescribed fire can alter stand structure in old-growth mixed conifer forests over the long term.

181. Vankat, J.L. 2011a. Post-1935 changes in forest vegetation of Grand Canyon National Park, Arizona, USA: Part 1—Ponderosa pine forest. *Forest Ecology and Management*. 261(3): 309–325. <https://doi.org/10.1016/j.foreco.2010.05.026>

Location

Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The author resampled vegetation study plots originally sampled in 1935 to document changes in forest structure and composition.

Publication findings

The author found that 80 percent of the resampled mesic ponderosa pine (*Pinus*

ponderosa) plots had evidence of surface fire but did not find that surface fire related to changes in forest structure and composition from 1935 through 2004. The exception was an increase in the smallest diameter classes of white fir (*Abies concolor*), in which larger size classes were likely reduced by surface fire.

Linkages

- **Fire behavior, fire type, fire intensity on Species composition, invasives, structure**

The author found that 80 percent of the resampled mesic ponderosa pine (*Pinus ponderosa*) plots had evidence of surface fire but did not find that surface fire related to changes in forest structure and composition from 1935 through 2004. The exception was an increase in the smallest diameter classes of white fir (*Abies concolor*), in which larger size classes were likely reduced by surface fire.

- 182. Vankat, J.L. 2011b.** Post-1935 changes in forest vegetation of Grand Canyon National Park, Arizona, USA: Part 2—Mixed conifer, spruce-fir, and quaking aspen forests. *Forest Ecology and Management*. 261(3): 326–341.
<https://doi.org/10.1016/j.foreco.2010.09.015>

Location

Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Forested ecosystems: aspen; mixed-conifer; spruce-fir

Summary: What the authors did and why

The author resampled vegetation study plots originally sampled in 1935 to document changes in forest structure and composition.

Publication findings

The author found a decrease in aspen (*Populus tremuloides*) density from 1935 through 2004, which is attributable to fire exclusion and herbivory. Densities of mixed conifer, spruce-fir (*Picea* spp.–*Abies* spp.), and ponderosa pine (*Pinus ponderosa*) in the study area have increased due to fire exclusion.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The author found a decrease in aspen (*Populus tremuloides*) density from 1935 through 2004, which is attributable to fire exclusion and herbivory. Densities of mixed conifer, spruce-fir (*Picea* spp.–*Abies* spp.), and ponderosa pine (*Pinus ponderosa*) in the study area have increased due to fire exclusion.

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183. Waltz, A.E.; Stoddard, M.T.; Kalies, E.L.; Springer, J.D.; Huffman, D.W.; Sánchez Meador, A. 2014. Effectiveness of fuel reduction treatments: Assessing metrics of forest resiliency and wildfire severity after the Wallow Fire, AZ. *Forest Ecology and Management*. 334: 43–52. <https://doi.org/10.1016/j.foreco.2014.08.026>

Location

Wallow Fire, Apache-Sitgreaves National Forests, Arizona, USA

Ecosystem type(s)

Dry mixed-conifer forest; ponderosa pine forest

Summary: What the authors did and why

The authors compared treated and untreated areas after the 2011 Wallow Fire to assess if fuel treatments reduced fire severity and increased ecological resilience of mixed-conifer forests based on three metrics: high severity patch size, tree survivorship, and nonnative and native herbaceous understory cover post-fire.

Publication findings

The authors found that treated sites prior to the 2011 Wallow Fire had lower tree mortality, smaller patches of high severity, and significantly higher understory herbaceous cover post-fire, suggesting that fuel treatments confer resilience to uncharacteristically severe fire in mixed-conifer ecosystems.

Linkages

- **Fire behavior, fire type, fire intensity on Mortality, survivorship, turnover**

The authors found that treated sites prior to the 2011 Wallow Fire had lower tree mortality, smaller patches of high severity, and significantly higher understory herbaceous cover post-fire, suggesting that fuel treatments confer resilience to uncharacteristically severe fire in mixed-conifer ecosystems.

- **Fire behavior, fire type, fire intensity on Fuels**

The authors found that treated sites prior to the 2011 Wallow Fire resulted in lower tree mortality, smaller patches of high severity, and significantly higher understory herbaceous cover post-fire suggesting that fuel treatments confer resilience to uncharacteristically severe fire in mixed-conifer ecosystems.

- **Fire behavior, fire type, fire intensity on Species composition, invasives, structure**

The authors found that treated sites prior to the 2011 Wallow Fire resulted in lower tree mortality, smaller patches of high severity, and significantly higher understory herbaceous cover post-fire, suggesting that fuel treatments confer resilience to uncharacteristically severe fire in mixed-conifer ecosystems.

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184. **Weisz, R.; Triepke, J.; Truman, R. 2009.** Evaluating the ecological sustainability of a ponderosa pine ecosystem on the Kaibab Plateau in northern Arizona. *Fire Ecology*. 5(1): 100–114.

Location

Kaibab National Forest, Arizona, USA

Ecosystem type(s)

Ponderosa pine ecosystem

Summary: What the authors did and why

The authors created a process for evaluating the ecological sustainability of fire-adapted ecosystems in the face of climate change and analyzed a case study in ponderosa pine forests.

Publication findings

The authors found that current and projected conditions in the structure and composition of ponderosa pine forests are approximately 97 percent departed from reference conditions on the Kaibab Plateau. Conditions in these forests are likely to persist due to the continued fire suppression and lack of management activities to reduce forest density.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors found that current and projected conditions in the structure and composition of ponderosa pine forests are approximately 97 percent departed from reference conditions on the Kaibab Plateau. Conditions in these forests are likely to persist due to the continued fire suppression and lack of management activities to reduce forest density.

185. **Weng, C.; Jackson, S.T. 1999.** Late Glacial and Holocene vegetation history and paleoclimate of the Kaibab Plateau, Arizona. *Palaeogeography, Palaeoclimatology, Palaeoecology*: 153(1–4): 179–201. [https://doi.org/10.1016/S0031-0182\(99\)00070-X](https://doi.org/10.1016/S0031-0182(99)00070-X)

Location

Kaibab National Forest, Arizona, USA

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors reconstructed fire history since the Late Glacial based on pollen and plant macrofossil records and sedimentary deposits at two lakes on the Kaibab Plateau and analyzed the relationships between climate, vegetation, and fire of the Holocene.

Publication findings

Fire was relatively rare at both sites between approximately 12,000 and 10,600 years before present. Most of this period was cool and relatively wet, which likely suppressed fire occurrence. The establishment of ponderosa pine (*Pinus ponderosa*) and spruce (*Picea* spp.) at the lower elevation sites and fir (*Abies* spp.) at higher elevations increased fire occurrence greatly after approximately 10,600 years before present. The authors suggest that the increased fire frequency likely gave ponderosa pine a competitive advantage at this time over spruce forest.

Linkages

- **Snowpack, snow and rain on Fire frequency, fire rotation, fire return interval**

Fire was relatively rare at both sites between approximately 12,000 and 10,600 years before present. Most of this period was cool and relatively wet, which likely suppressed fire occurrence.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The establishment of ponderosa pine (*Pinus ponderosa*) and spruce (*Picea* spp.) and fir (*Abies* spp.) at the lower and higher elevation sites, respectively, increased fire occurrence greatly after approximately 10,600 years before present. The authors suggest that the increased fire frequency likely gave ponderosa pine a competitive advantage at this time over spruce forest.

186. **Westerling, A.L.; Gershunov, A.; Brown, T.J.; Cayan, D.R.; Dettinger, M.D. 2003.** Climate and wildfire in the western United States. *Bulletin of the American Meteorological Society*. 84(5): 595–604. <https://doi.org/10.1175/BAMS-84-5-595>

Location

Western United States

Ecosystem type(s)

Not specified

Summary: What the authors did and why

The authors combined datasets for wildfire starts and acres burned from Federal land management agencies—the Bureau of Land Management, USDA Forest Service, National Park Service, and Bureau of Indian Affairs—to evaluate interannual relationships between climate and wildfire activity across the western United States.

Publication findings

Despite wide variation across regional and temporal gradients, moisture anomalies from 2 years up to the spring preceding the fire season are widely linked to fire activity throughout the western United States.

Linkages

- **Drought on Annual area burned, fire size**

Despite wide variation across regional and temporal gradients, moisture anomalies from 2 years up to the spring preceding the fire season are widely linked to fire activity throughout the western United States.

187. **Westerling, A.L.; Gershunov, A.; Cayan, D.R.; Barnett, T.P. 2002.** Long lead statistical forecasts of area burned in western US wildfires by ecosystem province. *International Journal of Wildland Fire*. 11(4): 257–266.
<https://doi.org/10.1071/WF02009>

Location

Western United States

Ecosystem type(s)

Aggregated by Bailey's ecosystem provinces

Summary: What the authors did and why

The authors model the relationship between seasonal area burned aggregated by Bailey's ecosystem provinces and monthly U.S. Climatological Division PDSI to forecast area burned a season in advance.

Publication findings

The authors found that, generally, in shrub- and grassland-dominated ecosystems, there was a strong relationship between area burned and increased moisture in the year before the fire season, suggesting these systems are fuel limited and burn only after moisture (inferred from PDSI) increases fuel production. For open-canopy forests, they found a strong relationship between area burned and decreased moisture immediately prior to or during the fire season, suggesting that the moisture conditions of the heavier fuels drive fire activity.

Linkages

- **Drought on Annual area burned, fire size**

The authors found that, generally, in shrub- and grassland-dominated ecosystems, there was a strong relationship between area burned and increased moisture in the year before the fire season, suggesting these systems are fuel limited and burn only after moisture (inferred from PDSI) increases fuel production. For open-canopy forests, they found a strong relationship between area burned and decreased moisture immediately prior to or during the fire season, suggesting that the moisture conditions of the heavier fuels drive fire activity.

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188. Westerling, A.L.; Hidalgo, H.G.; Cayan, D.R.; Swetnam, T.W. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science*. 313(940): 14–26. <https://doi.org/10.1126/science.1128834>

Location

Western United States

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors compared the annual frequency of large wildfires (>400 ha) to hydroclimatic and land surface variables, specifically mean temperature (March–August), timing of spring snowmelt, and fire season length to determine if the fire frequency of large fires has changed and if that change is due to climate factors.

Publication findings

The authors found that large fire occurrence has been increasing in response to earlier snowmelt and increasingly warmer temperatures in the early spring months in many areas of the western United States since the early 1980s. Fire season length has increased by 78 days since 1970, and annual area burned has also significantly increased by at least 6.5 times over the same time period. These increases were strongly correlated with average summer temperatures and the timing of spring snowmelt.

The authors suggest that the earlier spring snowmelt and higher early season temperatures may lead to longer and drier dry seasons, providing increased opportunities for fire ignition and spread, and as temperatures continue to warm, wildfires will become larger and more frequent.

Linkages

- **Fire season length on Fire timing, fire seasonality**

Fire season length has increased by 78 days between the time periods of 1970 to 1986 and 1987 to 2003 due to earlier ignitions and later control dates, as well as longer burning fires.

- **Temperature, RH, VPD on Annual area burned, fire size**

Increasingly warm temperatures have significantly increased annual area burned by at least 6.5 times between the time periods of 1970 to 1986 and 1987 to 2003. The authors suggest that as temperatures continue to warm, wildfires will become larger and more frequent.

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

The interannual variability in wildfire frequency had a strong relationship

with regional spring and summer temperature. The authors suggest that as temperatures continue to warm, wildfires will become larger and more frequent.

- **Snowpack, snow and rain on Fire timing, fire seasonality**

Large fire occurrence has been increasing in response to earlier snowmelt and increasingly warmer temperatures in the early spring months in many areas of the western United States since the early 1980s.

- **Snowpack, snow and rain on Fire frequency, fire rotation, fire return interval**

The interannual variability in wildfire frequency had a strong relationship with the timing of spring snowmelt.

189. **Westerling, A.L.; Turner, M.G.; Smithwick, E.A.; Romme, W.H.; Ryan, M.G. 2011.** Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *Proceedings of the National Academy of Sciences*. 108(32): 13165–13170. <https://doi.org/10.1073/pnas.1110199108>

Location

Greater Yellowstone ecosystem, Wyoming, USA

Ecosystem type(s)

Mixed-conifer forests

Summary: What the authors did and why

The authors projected how large fire (>200 ha) occurrence, size, and spatial location may be affected by climate change in the forests of the Greater Yellowstone area.

Publication findings

The authors predicted an increase in fire occurrence, frequency, and size by the mid-21st century in the Greater Yellowstone ecosystem due to projected increases in average spring and summer temperatures. They suggest a shift toward a novel fire–climate–vegetation relationship as the increase in fire frequency becomes incompatible with the persistence of the current vegetation in the region.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

The authors predicted an increase in fire occurrence, frequency, and size by the mid-21st century in the Greater Yellowstone ecosystem due to projected increases in average spring and summer temperatures.

- **Temperature, RH, VPD on Fire frequency, fire rotation, fire return interval**

The authors predicted an increase in fire occurrence, frequency, and size by the

mid-21st century in the Greater Yellowstone ecosystem due to projected increases in average spring and summer temperatures.

- **Annual area burned, fire size on Species composition, invasives, structure**

The authors suggest a shift toward a novel fire–climate–vegetation relationship as the increase in fire frequency becomes incompatible with the persistence of the current vegetation in the region.

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors suggest a shift toward a novel fire–climate–vegetation relationship as the increase in fire frequency becomes incompatible with the persistence of the current vegetation in the region.

190. **White, A.S. 1985.** Presettlement regeneration patterns in a southwestern ponderosa pine stand. *Ecology*. 66(2): 589–594.

Location

Gus Pearson Natural Area, Arizona, USA

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The author analyzed the age structure and spatial distribution of an old-growth ponderosa pine (*Pinus ponderosa*) stand to determine patterns of historical regeneration.

Publication findings

The author found that the stand of ponderosa pine (*Pinus ponderosa*) under study was fairly heterogeneous and did not regenerate in large, even-aged groups following large patches of mortality. The patches of additional fuel surrounding single or small groups of trees are thought to have led to smaller patches of mortality during low-severity surface fires, which would create openings and seedbeds for new seedlings.

Linkages

- **Spatial pattern, landscape mosaic on Dispersal, regeneration, establishment**

The author found that the stand of ponderosa pine (*Pinus ponderosa*) under study was fairly heterogeneous and did not regenerate in large, even-aged groups following large patches of mortality. The patches of additional fuel surrounding single or small groups of trees are thought to have led to smaller patches of mortality during low-severity surface fires, which would create openings and seedbeds for new seedlings.

- **Fire severity on Dispersal, regeneration, establishment**

The author found that the stand of ponderosa pine (*Pinus ponderosa*) under study was fairly heterogeneous and did not regenerate in large, even-aged groups following large patches of mortality. The patches of additional fuel surrounding single or small groups of trees are thought to have led to smaller patches of mortality during low-severity surface fires, which would create openings and seedbeds for new seedlings.

191. **White, J.D.; Gutzwiller, K.J.; Barrow, W.C.; Randall, L.J.; Swint, P. 2008.** Modeling mechanisms of vegetation change due to fire in a semi-arid ecosystem. *Ecological Modelling*. 214(2–4): 181–200. <https://doi.org/10.1016/j.ecolmodel.2008.02.032>

Location

Chihuahuan Desert, Big Bend National Park, Texas, USA

Ecosystem type(s)

Lowland desert

Summary: What the authors did and why

The authors created and tested the accuracy of a model called the Landscape and Fire Simulator that simulates changes in vegetation cover due to fire disturbance for semiarid landscapes.

Publication findings

Historically, frequent fire maintained open grasslands across the semiarid desert. However, fire cessation has allowed for shrub encroachment, and consequently, a reduction in grass and contiguous fuels. The model predicted only 4 percent of the landscape to burn over the 50-year simulations. The authors suggest that future fire events may have minimal impact on moving the current ecosystem, which is dominated by woody shrubs, back to a grassland state.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

Historically, frequent fire maintained open grasslands across the semi-arid desert. However, fire cessation has allowed for shrub encroachment, and consequently, a reduction in grass and contiguous fuels. The model predicted only 4 percent of the landscape to burn over the 50-year simulations. The authors suggest that future fire events may have minimal impact on moving the current ecosystem, which is dominated by woody shrubs, back to a grassland state.

192. **White, M.A.; Vankat, J.L. 1993.** Middle and high elevation coniferous forest communities of the North Rim region of Grand Canyon National Park, Arizona, USA. *Vegetatio*. 109(2): 161–174.

Location

Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Mixed-conifer forests

Summary: What the authors did and why

The authors examined the structure and composition of forest stands along environmental gradients in Grand Canyon National Park to classify forest communities and determine what potential changes to structure and composition occurred in these stands following Euro-American settlement.

Publication findings

The authors found that fire suppression policies in the early 20th century have resulted in increasingly homogeneous species composition in mixed-conifer forests with greater horizontal and vertical fuel continuity. These changes make these stands more susceptible to high severity fires.

Linkages

- **Fire frequency, fire rotation, fire return interval on Species composition, invasives, structure**

The authors found that fire suppression policies in the early 20th century have resulted in increasingly homogeneous species composition in mixed-conifer forests with greater horizontal and vertical fuel continuity. These changes make these stands more susceptible to high severity fires.

193. Williams, A.P.; Allen, C.D.; Millar, C.I.; Swetnam, T.W.; Michaelsen, J.; Still, C.J.; Leavitt, S.W. 2010. Forest responses to increasing aridity and warmth in the southwestern United States. *Proceedings of the National Academy of Sciences*. 107(50): 21289–21294. <https://doi.org/10.1073/pnas.0914211107>

Location

Conterminous United States; southwestern United States

Ecosystem type(s)

Forested area

Summary: What the authors did and why

The authors related tree-ring growth responses to the variability in precipitation, temperature, and RH in southwestern forests and woodlands and projected trends in these relationships based on future climate change scenarios. They further analyzed trends in disturbance regimes, specifically wildfire and bark beetle outbreaks.

Publication findings

From 1984 to 2006, fire and bark beetle outbreaks have caused approximately 14 to 18 percent of the mortality in forested areas of the Southwest, and the area burned has increased substantially with a greater proportion burning at high severity since 1984. Recent elevated temperatures are thought to have led to both the increase in bark beetle outbreak and high severity fire.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

From 1984 to 2006, fire and bark beetle outbreaks have caused approximately 14 to 18 percent of the mortality in forested areas of the Southwest, and the area burned has increased substantially with a greater proportion burning at high severity since 1984. Recent elevated temperatures are thought to have led to both the increase in bark beetle outbreak and high severity fire.

194. **Williams, A.P.; Seager, R.; Berkelhammer, M.; Macalady, A.K.; Crimmins, M.A.; Swetnam, T.W.; Trugman, A.T.; Buening, N.; Hryniw, N.; McDowell, N.G.; Noone, D. 2014.** Causes and implications of extreme atmospheric moisture demand during the record-breaking 2011 wildfire season in the southwestern United States. *Journal of Applied Meteorology and Climatology*. 53(12): 2671–2684.
<https://doi.org/10.1175/JAMC-D-14-0053.1>

Location

Southwestern United States

Ecosystem type(s)

Forested area

Summary: What the authors did and why

The authors examined the large-scale climate processes driving drought and high VPD during the extreme fire season of 2011. They projected future climate conditions to determine if projected trends in an ensemble of climate variables may resemble conditions from the 2011 fire season in future years.

Publication findings

During the 2011 fire season, which was characterized by record-breaking area burned in the Southwest, temperature was not anomalously warm, but low precipitation led to exceptionally low atmospheric moisture content and subsequent record-breaking VPD. The authors' model projections show that the climate conditions like those exhibited in 2011 are likely to occur more frequently in coming decades as temperatures are predicted to increase. The authors suggest that increasing trends in VPD could lead to increasingly common catastrophic wildfires if fuels are not limiting.

Linkages

- **Temperature, RH, VPD on Annual area burned, fire size**

During the 2011 fire season, which was characterized by record-breaking area burned in the Southwest, temperature was not anomalously warm, but low precipitation led to exceptionally low atmospheric moisture content and subsequent record-breaking VPD. The authors' model projections show that the climate conditions like those exhibited in 2011 are likely to occur more frequently in coming decades as temperatures are predicted to increase. The authors suggest

that increasing trends in VPD could lead to increasingly common catastrophic wildfires if fuels are not limiting.

195. Williams, A.P.; Seager, R.; Macalady, A.K.; Berkelhammer, M.; Crimmins, M.A.; Swetnam, T.W.; Trugman, A.T.; Buening, N.; Noone, D.; McDowell, N.G.; Hryniw, N.; Mora, C.I.; Rahn, T. 2015. Correlations between components of the water balance and burned area reveal new insights for predicting forest fire area in the southwest United States. *International Journal of Wildland Fire*. 24(1): 14–26. <https://doi.org/10.1071/WF14023>

Location

Southwestern United States, defined as Arizona, New Mexico and areas of Texas, Oklahoma, Colorado, and Utah that lie south of 38.08°N, north of 28.58°N, and west of 100.08°W

Ecosystem type(s)

Forested and nonforested ecosystems

Summary: What the authors did and why

The authors correlated 15 standard climate variables and drought-related metrics, including VPD, to annual area burned and annual area burned at high severity using data from the Monitoring Trends in Burn Severity dataset (1984–2013) in the Southwest. They used Spearman's Rank Correlation analysis and Pearson's correlation analysis to quantify the relationships for comparison.

Publication findings

The authors found that total area burned in the Southwest has increased since 1984 at a rate of 10.2 percent yr⁻¹, and that the rate of increase is greater for forests at higher elevations. Furthermore, March through August VPD, a measure of the ability of the atmosphere to extract moisture from surface vegetation, is more strongly correlated with total area burned and area burned at high severity than temperature alone for the Southwest. The authors explain that air temperature is commonly correlated with severity; however, it is often used as a proxy for atmospheric water demand as high temperatures in a low-humidity environment cause dry fuel conditions in the Southwest. Extended periods when the value of VPD remains high can directly affect the rate of transpiration or water loss from the foliage and can lead to plant desiccation and mortality, causing increased flammability. More importantly, vapor pressure at saturation increases exponentially with increasing temperature. Consequently, small increases in temperature will exponentially increase VPD, potentially resulting in more frequent drought and increased wildfire risk until fuels become limiting.

Linkages

• **Temperature, RH, VPD on Annual area burned, fire size**

March through August VPD, a measure of the ability of the atmosphere to extract

moisture from surface vegetation, is more strongly correlated with area burned than temperature alone for the Southwest region.

- **Temperature, RH, VPD on Fire severity**

March through August VPD, a measure of the ability of the atmosphere to extract moisture from surface vegetation, is more strongly correlated with area burned at high severity than temperature alone for the Southwest region.

- 196. Williams, M.A.; Baker, W.L. 2013.** Variability of historical forest structure and fire across ponderosa pine landscapes of the Coconino Plateau and South Rim of Grand Canyon National Park, Arizona, USA. *Landscape Ecology*. 28(2): 297–310.

Location

Coconino Plateau, Arizona, USA; Grand Canyon National Park, Arizona

Ecosystem type(s)

Ponderosa pine forest

Summary: What the authors did and why

The authors examined ponderosa pine (*Pinus ponderosa*) stands on the Coconino Plateau and Grand Canyon National Park and used historical General Land Office (GLO) land survey data to reconstruct forest structure and fire regimes before widespread European settlement.

Publication findings

The authors suggest that although the majority of the landscape on the Coconino Plateau was dominated by low severity fire, there is also evidence of a large amount of mixed severity fire and large patches of high severity were not uncommon. The mixed severity fire may explain the greater variability in forest structure and composition observed at fine scales across the Coconino Plateau.

Additional article of direct relevance: Fulé, P.Z.; Swetnam, T.W.; Brown, P.M.; Falk, D.A.; Peterson, D. L.; Allen, C.D.; Aplet, G.H.; Battaglia, M.A.; Binkley, D.; Farris, C.; Keane, R.E.; Margolis, E.Q.; Grissino-Mayer, H.; Miller, C.; Sieg, C.H.; Skinner, C.; Stephens, S.L.; Taylor, A. 2014. Unsupported inferences of high-severity fire in historical dry forests of the western United States: Response to Williams and Baker. *Global Ecology and Biogeography*. 23(7): 825–830. <https://doi.org/10.1111/geb.12136>

Linkages

- **Fire severity on Species composition, invasives, structure**

The authors suggest that although the majority of the landscape on the Coconino Plateau was dominated by low severity fire, there is also evidence of a large amount of mixed severity fire and large patches of high severity were not uncommon. The mixed-severity fire may explain the greater variability in forest structure and composition observed at fine scales across the Coconino Plateau.

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197. **Wotton, B.M.; Flannigan, M.D. 1993.** Length of the fire season in a changing climate. *The Forestry Chronicle*. 69(2): 187–192. <https://doi.org/10.5558/tfc69187-2>

Location

Canada

Ecosystem type(s)

Forested ecosystems

Summary: What the authors did and why

The authors modeled the potential shift in fire season length between current and future carbon dioxide climate scenarios (1× CO₂ and 2× CO₂, respectively) across the forested areas of Canada.

Publication findings

The authors found a significant shift in the fire season—both an earlier beginning and a later end— for the future 2× CO₂ scenario across all regions. They predicted an increase in the fire season of almost 30 days on average. The authors further mention that this shift would result in a longer period of increased temperatures during the fire season, and therefore, an increase in fire activity across the region.

Linkages

- **Temperature, RH, VPD on Fire timing, fire seasonality**

The authors found a significant shift in the fire season—both an earlier beginning and a later end— for the future 2× CO₂ scenario across all regions. They predicted an increase in the fire season of almost 30 days on average. The authors further mention that this shift would result in a longer period of increased temperatures during the fire season, and therefore, an increase in fire activity across the region.

198. **Yocom, L.L.; Fulé, P.Z.; Brown, P.M.; Cerano, J.; Villanueva-Díaz, J.; Falk, D.A.; Cornejo-Oviedo, E. 2010.** El Niño–Southern Oscillation effect on a fire regime in northeastern Mexico has changed over time. *Ecology*. 91(6): 1660–1671. <https://doi.org/10.1890/09-0845.1>

Location

Peña Nevada Peak, Nuevo León, Mexico

Ecosystem type(s)

Hartweg's pine forest

Summary: What the authors did and why

The authors characterized the historical fire regime of a Hartweg's pine (*Pinus hartwegii*) stand to determine the effects of climate, specifically ENSO, on regional fire occurrence.

Publication findings

The authors found that fire activity was most common during dry years.

Precipitation 2 years preceding fire years resulted in widespread synchrony across

all three sites. They also found a significant shift in the effects of La Niña before and after the 1830s. Prior to the 1830s, La Niña years were significantly associated with fire activity. After 1830, the relationship between fire and La Niña at Peña Nevada was not significant. Extreme ENSO events have been more erratic in this area since the 1970s. Large fire years in 1983 and 1998 occurred during the El Niño phase, but were extremely dry; however, the 1992 extreme El Niño was very wet. The authors suggest that ENSO may no longer be a reliable predictor of precipitation or the associated fire activity in this region.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that fire activity was most common during dry years. Precipitation 2 years preceding fire years resulted in widespread synchrony across all three sites. They also found a significant shift in the effects of La Niña before and after the 1830s. Prior to the 1830s, La Niña years were significantly associated with fire activity. After 1830, the relationship between fire and La Niña at Peña Nevada was not significant. Extreme ENSO events have been more erratic in this area since the 1970s. Large fire years in 1983 and 1998 occurred during the El Niño phase, but were extremely dry; however, the 1992 extreme El Niño was very wet. The authors suggest that ENSO may no longer be a reliable predictor of precipitation or the associated fire activity in this region.

199. **Yocom, L.L.; Fulé, P.Z.; Falk, D.A.; García-Domínguez, C.; Cornejo-Oviedo, E.; Brown, P.M.; Villanueva-Díaz, J.; Cerano, J.; Cortés Montañó, C. 2014.** Fine-scale factors influence fire regimes in mixed-conifer forests on three high mountains in Mexico. *International Journal of Wildland Fire*. 23(7): 959–968.
<https://doi.org/10.1071/WF13214>

Location

Sierra Madre Oriental Mountains, Mexico

Ecosystem type(s)

Mixed-conifer forests

Summary: What the authors did and why

The authors characterized the historical fire regimes of three parallel but isolated mountains in the same range to assess potential fire synchrony between sites and determine the effects of climate, specifically ENSO, on regional fire occurrence.

Publication findings

The authors found that fire was highly asynchronous between the three sites despite similar fire regimes, suggesting that at the scale of the study, fine-scale factors were more influential on fire occurrence than regional climate. At long-term scales, ENSO, specifically La Niña events (drought), were correlated with higher fire occurrence at the study sites until approximately 1830.

Linkages

- **Drought on Fire frequency, fire rotation, fire return interval**

The authors found that fire was highly asynchronous between the three sites despite exhibiting similar fire regimes, suggesting that at the scale of the study, fine-scale factors were more influential on fire occurrence than regional climate. At long-term scales, ENSO, specifically La Niña events (drought), were correlated with higher fire occurrence at the study sites until approximately 1830.

200. **Yocom-Kent, L.L.; Fulé, P.Z.; Bunn, W.M.; Gdula, E.G. 2015.** Historical high-severity fire patches in mixed-conifer forests. *Canadian Journal of Forest Research*. 45(11): 1587–1596. <https://doi.org/10.1139/cjfr-2015-0128>

Location

North Rim of Grand Canyon National Park, Arizona, USA

Ecosystem type(s)

Aspen; mixed-conifer forests

Summary: What the authors did and why

The authors examined the size of historical high-severity fire in mixed-conifer and aspen (*Populus tremuloides*) stands in the study area and compared them to present-day patches of high severity fire. They further explored historical climate conditions that produced the largest patches of high severity fire prior to Euro-American settlement.

Publication findings

Dendrochronological analysis found that fairly large patches of high severity fire were relatively common in the study area. In dry mixed-conifer forests, high-severity fire years historically were significantly drier than normal based on reconstructed PDSI, while years of low severity fire were slightly, though not significantly, drier than normal. They also found that for mixed-conifer ecosystems, prior wet years (typically needed to build up fuels in drier southwestern forests) were not necessary for severe fire to occur. Finally, spikes in regeneration of aspen (*Populus tremuloides*) often correspond to years where high severity fire was common across the greater landscape.

High severity fire was historically common in mixed-conifer forests; however, changes in species composition and density due to fire suppression over the last century have changed how fire burns on these landscapes. Maintaining heterogeneity may provide resilience against future climate change.

Linkages

- **Drought on Fire severity**

Dendrochronological analysis found that fairly large patches of high severity fire were relatively common in the study area. In dry mixed-conifer forests, high-severity fire years historically were significantly drier than normal based on

reconstructed PDSI, while years of low severity fire were only slightly, though not significantly, drier than normal. They also found that for mixed-conifer ecosystems, prior wet years (typically needed to build up fuels in drier southwestern forests) were not necessary for severe fire to occur.

- **Fire severity on Fuels**

High-severity fire was historically common in mixed-conifer forests; however, changes in species composition and density due to fire suppression over the last century have changed how fire burns on these landscapes. Maintaining heterogeneity may provide resilience against future climate change.

- **Fire severity on Dispersal, regeneration, establishment**

Spikes in regeneration of aspen (*Populus tremuloides*) often correspond to years where high severity fire was common across the greater landscape.

GLOSSARY

Burn severity, sometimes used interchangeably with **fire severity**, usually denotes only the loss of organic matter in or on the soil surface (such as canopy mortality effects captured by remote sensing applications such as the differenced Normalized Burn Ratio [dNBR] index).

Drought is a multiyear period of below-average precipitation (precipitation deficit) in a given region, resulting in prolonged shortages in its atmospheric, surface water, or ground water supply.

Energy Release Component (ERC) is a number related to the available energy (e.g., British thermal units, or BTU) per unit area (e.g., square foot) within the flaming front at the head of a fire. The computation is used in the National Fire Danger Rating System (NFDRS). Daily variations in ERC are due to changes in moisture content of live and dead fuels. Since this number represents the potential "heat release" per unit area in the flaming zone, it can provide guidance to several important fire activities. It may also be considered a composite fuel moisture value as it reflects the contribution that all live and dead fuels have to potential fire intensity. The ERC is a cumulative or "build-up" type of index. As live fuels cure and dead fuels dry, the ERC values get higher, thus providing a good reflection of drought conditions. The scale is open-ended or unlimited and, as with other NFDRS components, is relative. Conditions producing an ERC value of 24 represent a potential heat release twice that of conditions resulting in an ERC value of 12. The ERC is a function of the fuel model and live and dead fuel moistures. Fuel loading, woody fuel moistures, and larger fuel moistures all have an influence on the ERC, while the lighter fuels have less influence and wind speed has none. ERC has low variability, and is the best fire danger component for indicating the effects of intermediate to long-term drying (if it is a significant factor) on fire behavior although it is not intended for use as a drought index.

Fire behavior is commonly defined as the manner in which fuel ignites, flame develops, and fire spreads and exhibits other related phenomena as determined by the interaction of fuels, weather, and topography.

Fire danger is "the resultant descriptor of the combination of both constant and variable factors which affect the initiation, spread and difficulty of control of wildfires on an area" (from Deeming 1972).

Fire Danger Rating (e.g., National Fire Danger Rating System, or NFDRS) is a system that integrates the effects of existing and expected states of selected fire danger factors into one or more qualitative or numeric indices that reflect an area's protection needs. These factors can be biophysical (current and antecedent weather, fuel types, live and dead fuel moisture) and administrative (staffing levels, preparedness).

Fire intensity is the energy release rate per unit length of fireline, and is a physical parameter that can be empirically related to flame length. It can be determined from the product of biomass consumption (energy) and rate of spread of the fire. Two fires of the same fireline intensity can have very different effects between an old-growth

mixed-conifer forest and a young plantation of similar species because the smaller plantation trees will be more easily scorched and have thinner bark. The fire in the old growth may be of low severity while the plantation fire is of high severity.

Fire season length is the amount of time in the year or period(s) of the year during which wildland fires are likely to occur, spread, and affect resource values sufficient to warrant organized fire management activities.

Fire severity is defined several different ways in the literature. The term is used (1) to describe the degree or amount of loss or change in aboveground and belowground organic matter resulting from a fire (Keeley 2009), a definition that separates the fire severity metric from postfire ecological responses such as vegetation recovery or erosion; or (2) as a measure of the intensity of fire and its ecosystem effects (Agee 1993; Bond and van Wilgen 1996; Sugihara et al. 2006). In either case, an assessment of fire severity is specific to the structure and function of a particular ecosystem. For example, low severity fires are typical in many ponderosa pine forests, which historically burned frequently enough to maintain low fuel loads and an open stand structure, producing a landscape in which fire-caused mortality of mature trees was rare (Agee 1998; Jenkins et al. 2012; Moritz et al. 2011). Conversely, high severity fires are typical in subalpine forests and tend to result in high mortality of mature trees (“stand replacement”) because long intervals between fires result in dense, multistoried forest structures that are susceptible to crown fires (Agee 1998).

Fire type refers to the fuels that are primarily supporting the fire or the type of spread (or both). Fire type may be ground fires, which burn organic matter in the soil beneath surface litter and are sustained by glowing combustion; surface fires, which spread with a flaming front and burn leaf litter, fallen branches, and other fuels located at ground level; or crown fires, which burn through the top layer of foliage on a tree, known as the canopy.

Fuel moistures are measured for live herbaceous (annual and perennial) and woody (shrubs, branches, and foliage) fuels and dry (dead) fuels. Live fuel moisture is the water content of live herbaceous plants expressed as a percentage of the oven-dry weight of the plant. Typical herbaceous fuel moisture values start low and increase rapidly as the growing season progresses. Lower values indicate drier materials and higher fire danger. Dead fuel moisture is the moisture content of dead organic fuels, expressed as a percentage of the oven-dry weight of the sample. Dead fuel moisture is controlled solely by exposure to environmental conditions and is critical in determining fire potential.

Palmer Drought Severity Index (PDSI) uses temperature and precipitation data to estimate relative dryness. It is a standardized index that spans -10 (dry) to +10 (wet). It has been reasonably successful at quantifying long-term drought. As it uses temperature data and a physical water balance model, it can capture the basic effect of global warming on drought through changes in potential evapotranspiration. Monthly PDSI values do not capture droughts on time scales less than about 12 months.

Relative humidity (RH), expressed as a percentage, is the ratio of the amount of moisture in the air to the amount of moisture necessary to saturate the air at the same temperature and pressure. Relative humidity is important because dead forest fuels and the air are always exchanging moisture. Low humidity takes moisture from the fuels, and fuels take moisture from the air when the humidity is high. Light fuels, such as grass and pine needles, gain and lose moisture quickly with changes in relative humidity. When the RH drops, fire behavior increases because these fine fuels become drier. Heavy fuels, on the other hand, respond to humidity changes more slowly. To see significant changes in heavy fuel moisture there must be significant moisture, usually more than a single storm.

Snow water equivalent (SWE) is a common snowpack measurement. It represents the amount of water contained within the snowpack, and can be thought of as the depth of water that would theoretically result if the entire snowpack melted instantaneously.

Vapor pressure deficit (VPD) is an absolute measure of the difference between the water vapor content of the air and its saturation value and measures the ability of the atmosphere to extract moisture from the land surface (vegetation), thus reflecting variations in the moisture content and flammability of forests.

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APPENDIX. Summary of Annotated Publications

The following exhibit provides the ecosystem; assigned ecotype; spatial scale; primary interacting agents; and research location for each of the 200 annotated publications. For some papers we summarized ecosystems into six broader ecotypes. The **Desert, grasslands, shrubland** ecotype includes sites within desert; rangelands; grasslands; and shrublands. **Forest** includes forested; ponderosa pine; oak; mixed conifer; subalpine; Madrean; conifer; piñon-juniper woodland; montane; pine; fir; aspen; spruce-fir; chaparral; piñon-oak; and lodgepole pine. The **Forested, nonforested** ecotype includes alpine; subalpine/grasslands; ponderosa pine/grasslands; chaparral/woodland/grasslands; ponderosa pine/mixed conifer/piñon-juniper/chaparral; and montane/subalpine grasslands. The **Forested, nonforested, desert** ecotype encompasses desert; shrubland; woodland; and montane ecosystems. **Multiple** was assigned to broad-scale studies that considered all ecosystems within a state or the contiguous United States. One study considered only Gambel oak and was designated **Oak**.

Spatial scale was determined to be **local** (single defined location); **state** (comprehensive); **regional** (containing several localized sites or comprising multiple states); or **global** (worldwide).

Exhibit— Summary of the 200 publications in the Southwest FireCLIME annotated bibliography.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Abatzoglou and Kolden 2011	Rangelands	Desert; grasslands; shrubland	Regional	Climate-vegetation	Western United States
Abatzoglou and Kolden 2013	Forested; nonforested	Desert; forested; nonforested	Regional	Climate-fire	Western United States
Abatzoglou et al. 2016	Forested	Forested	Regional	Climate-fire	Western United States
Abella 2009	Desert	Desert; grasslands; shrubland	Regional; global	Fire-vegetation	Mojave and Sonoran Deserts; southwestern United States and Mexico
Abella and Fornwalt 2015	Ponderosa pine	Forested	Local	Fire-vegetation	Hayman Fire, Colorado; USA
Abella and Fulé 2008	Oak; ponderosa pine	Forested	Local; regional	Fire-vegetation	Colorado Plateau, USA

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Allen et al. 2008	Mixed conifer	Forested	Local	Climate-fire	Chihuahueros and Alamo Bogs; Jemez Mountains; New Mexico; USA
Allen et al. 2010	Forested	Forested	Global	Climate-vegetation	Global
Amato et al. 2013	Ponderosa pine	Forested	Local	Fire-vegetation	Trigo Fire; Manzano Mountains; New Mexico; USA
Anderson et al. 2008	Alpine; mixed conifer; subalpine	Forested; nonforested	Regional; multistate	Climate-fire-vegetation	Southern Rocky Mountains; Colorado and New Mexico; USA
Andrus et al. 2016	Subalpine	Forested	Local	Fire-vegetation	Colorado Rocky Mountains; Colorado; USA
Arkle et al. 2012	Mixed conifer	Forested	Local	Fire-vegetation	Payette National Forest; Idaho; USA
Baisan and Swetnam 1990	Mixed conifer; pine	Forested	Local	Climate-fire-vegetation	Rincon Mountain Wilderness; Saguaro National Park Wilderness Area; Arizona; USA
Baker et al. 2007	Mixed conifer; ponderosa pine	Forested	Regional	Fire-vegetation	Rocky Mountains; USA
Barbero et al. 2014	Desert; forested; nonforested	Desert; forested; nonforested	Regional	Climate-fire	Contiguous United States; 13 Omernik Level II ecoregions of the United States
Barbero et al. 2015	Desert; forested; nonforested	Desert; forested; nonforested	Regional	Climate-fire	Contiguous United States; 13 Omernik Level II ecoregions of the United States
Barton 1999	Madrean	Forested	Multistate	Fire-vegetation	Southeastern Arizona; USA
Barton and Poulos 2018	Madrean	Forested	Local	Fire-vegetation	Chiricahua Mountains; southeastern Arizona; USA
Baumgartner and Fulé 2007	Oak; ponderosa pine	Forested	Local	Fire-vegetation	Mogollon Rim; Arizona; USA

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Bessie and Johnson 1995	Conifer; subalpine	Forested	State	Climate-fire	Kananaskis Valley; Alberta; Canada; Vermillion Pass area of Banff and Kootenay National Parks; Canada
Bigler et al. 2005	Subalpine	Forested	Local	Fire-vegetation	Flat Tops Wilderness; White River National Forest; Colorado; USA
Biondi et al. 2011	Piñon-juniper	Forested	Regional	Climate-fire	Great Basin; Nevada; USA
Birch et al. 2015	Forested	Forested	Multi-state	Fire-vegetation	Idaho; USA; Montana; USA
Blomdahl et al. 2019	Mixed conifer; montane; pine	Forested	Local	Fire-vegetation	Yosemite Rim Fire; California; USA
Brooks and Matchett 2006	Desert; shrubland; woodland	Desert; forested; nonforested	Regional	Fire	Mojave Desert; USA
Brown et al. 2005	Grasslands	Desert; grasslands; shrubland	Local	Climate-fire	Kettle Lake; North Dakota; USA
Brown 2006	Ponderosa pine	Forested	Local	Climate-fire-vegetation	Black Hills; South Dakota; USA
Brown and Wu 2005	Fir; oak; piñon-juniper; ponderosa pine	Forested	Local	Climate-fire-vegetation	Archuleta Mesa; Colorado; USA
Brown et al. 1999	Montane; ponderosa pine	Forested	Local	Fire-vegetation	Chessman Lake watershed; Colorado; USA
Brown et al. 2001	Mixed conifer; piñon-juniper; ponderosa pine	Forested	Local	Climate-fire-vegetation	Sacramento Mountains; New Mexico; USA
Cocke et al. 2005	Aspen; mixed conifer; ponderosa pine; spruce-fir	Forested	Local	Fire-vegetation	San Francisco Peaks; Arizona; USA
Collins et al. 2006	Not specified	Multiple	Regional	Climate-fire	Interior West; Southwestern United States; Colorado; USA
Coop and Givinish 2007	Montane and subalpine grasslands	Forested; nonforested	Local	Climate-vegetation	Valles Caldera; New Mexico; USA

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Coop et al. 2015	Mixed conifer; ponderosa pine	Forested	Local	Fire-vegetation	Las Conchas fire; New Mexico; USA
Coppoletta et al. 2016	Mixed conifer	Forested	Regional	Climate-fire	Sierra Nevada Mountains; California; USA
Covington and Moore 1994	Ponderosa pine	Forested	Local	Fire-vegetation	Bar-M Canyon; Arizona; USA
Crimmins 2006	Not specified	Multiple	Regional	Climate-fire	Southwestern USA
Crimmins 2011	Not specified	Multiple	Multistate	Climate-fire	Arizona and New Mexico; USA
Crimmins and Comrie 2004	Desert grasslands; desert scrub; mixed conifer; montane fir; oak; subalpine	Desert; forested; nonforested	State	Climate-fire	Arizona; U.S. Gradient
Dennison et al. 2014	Not specified	Multiple	Regional	Climate-fire	Western United States; Omernik ecoregions Level II and Level III
Diaz and Swetnam 2013	Not specified	Multiple	Regional	Climate-fire	Western United States
Dillon et al. 2011	Forested	Forested	Regional	Climate-fire	Northwestern United States; Southwestern United States; LANDFIRE map zones
Donnegan et al. 2001	Forested; ponderosa pine	Forested	Local	Climate-fire	Pike National Forest; Colorado; USA
Dugan and Baker 2015	Ponderosa pine	Forested	Local	Fire-vegetation	Grand Canyon National Park; Arizona; USA
Falk et al. 2007	Forested	Forested	Regional	Climate-fire	North America
Feddema et al. 2013	Ponderosa pine	Forested	Local; regional	Fire-vegetation	Southwest; U.S.; Gus Pearson Natural Area; Arizona; USA
Finney et al. 2005	Ponderosa pine	Forested	Local	Fire	Rodeo-Chediski Fire; Arizona; USA
Flannigan et al. 2000	Forested	Forested	Global	Climate-fire	United States and Canada

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Flannigan et al. 2013	Not specified	Multiple	Global	Climate-fire	Global
Floyd et al. 2004	Piñon-juniper	Forested	Local	Fire-vegetation	Mesa Verde National Park; Colorado; USA
Floyd et al. 2000	Piñon-juniper; chaparral	Forested; nonforested	Local	Fire-vegetation	Mesa Verde National Park; Colorado; USA
Fulé 2008	Forested	Forested	Regional	Climate-fire-vegetation	Western United States
Fulé et al. 2004a	Mixed conifer; ponderosa pine	Forested	Local	Fire-vegetation	Grand Canyon National Park; Arizona; USA
Fulé et al. 1997	Ponderosa pine	Forested	Regional	Fire-vegetation	Southwestern United States
Fulé et al. 2002	Ponderosa pine	Forested	Local	Climate-fire-vegetation	Grand Canyon National Park; Arizona; USA
Fulé et al. 2006	Mixed conifer; ponderosa pine	Forested	Local	Fire-vegetation	Grand Canyon National Park; Arizona; USA
Fulé et al. 2004b	Aspen; mixed conifer; ponderosa pine; spruce-fir	Forested	Local	Fire-vegetation	Grand Canyon National Park; Arizona; USA
Fulé et al. 2003a	Mixed conifer; spruce-fir	Forested	Local	Fire-vegetation	Grand Canyon National Park; Arizona; USA
Fulé et al. 2003b	Ponderosa pine; mixed conifer	Forested	Local	Climate-fire-vegetation	Grand Canyon National Park; Arizona; USA
Fulé et al. 2009	Mixed conifer	Forested	Local	Fire-vegetation	San Juan National Forest; Colorado; USA
Fulé and Laughlin 2007	Aspen; oak; ponderosa pine; spruce-fir; subalpine	Forested	Local	Fire-vegetation	North Rim of Grand Canyon National Park; Arizona; USA
Fulé et al. 2012	Mixed conifer	Forested	Local; global	Climate-fire	Chihuahua; Mexico
Gartner et al. 2012	Grasslands; ponderosa pine	Forested; nonforested	Local	Climate-fire-vegetation	Colorado Front Range; Colorado; USA

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Grissino-Mayer and Swetnam 2000	Mixed conifer	Forested	Local	Climate-fire	El Malpais National Monument; New Mexico; USA
Grissino-Mayer and Swetnam 1997	Ponderosa pine	Forested	Local	Climate-fire	El Malpais National Monument; New Mexico; USA
Guyette et al. 2014	Not specified	Multiple	Regional	Climate-fire	Contiguous United States
Haffey et al. 2018	Ponderosa pine	Forested	Multistate	Climate-fire-vegetation	Arizona and New Mexico; USA
Haire and McGarigal 2008	Mixed conifer; piñon-juniper; ponderosa pine	Forested	Multistate	Fire-vegetation	La Mesa Fire; Pajarito Plateau; northern New Mexico; USA; Saddle Mountain Fire; Kaibab Plateau; northern Arizona; USA
Haire and McGarigal 2009	Ponderosa pine	Forested	Multistate	Climate-fire	Arizona and New Mexico; USA
Haire and McGarigal 2010	Mixed conifer; piñon-juniper; ponderosa pine	Forested	Multistate	Fire-vegetation	La Mesa Fire; Pajarito Plateau; northern New Mexico; USA; Saddle Mountain Fire; Kaibab Plateau; northern Arizona; USA
Haire et al. 2013	Forested	Forested	Regional; multistate	Climate-fire	Southwestern United States; Sierra Nevada and Northern Rockies; USA
Heinlein et al. 2005	Mixed conifer; ponderosa pine	Forested	Local	Fire-vegetation	San Francisco Peaks; Arizona; USA
Hessl 2011	Not specified	Multiple	Global	Climate-fire	Global
Higgins et al. 2015	Mixed conifer; ponderosa pine	Forested	Local	Fire-vegetation	North Rim of Grand Canyon National Park; Arizona; USA
Hoff et al. 2014	Mixed conifer; piñon-juniper; ponderosa pine; spruce-fir	Forested	Local	Fire	Grand Canyon National Park; Arizona; USA
Hoffman et al. 2012	Ponderosa pine	Forested	Local	Vegetation	National forests in Arizona; USA

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Holden et al. 2009	Forested; fir; mixed conifer; oak; piñon-oak; ponderosa pine; riparian; spruce-fir	Forested	Local	Fire-vegetation	Gila National Forest; New Mexico; USA
Holden et al. 2007	Fir; mixed conifer; piñon-juniper; ponderosa pine; spruce-fir	Forested	Local	Climate-fire	Gila National Forest; New Mexico; USA
Holden et al. 2010	Mixed conifer; ponderosa pine	Forested	Local	Fire-vegetation	Gila Aldo Leopold Wilderness Complex in New Mexico; USA
Holsinger et al. 2016	Varied by study area: CCE; in order of abundance: subalpine; ponderosa pine; mixed conifer; SBW: subalpine forest; Douglas-fir; mixed conifer; FCW: mixed conifer; subalpine; some ponderosa; GAL: ponderosa pine; piñon-juniper; mixed conifer	Multiple	Regional	Climate-fire-vegetation	Northern Rockies and Southwestern United States
Honig and Fulé 2012	Ponderosa pine	Forested	Local	Climate-fire	Kaibab National Forest; Arizona; USA
Hood et al. 2015	Ponderosa pine	Forested	Multistate	Fire-svegetation	Idaho; Montana; Utah and Oregon; USA
Huebner and Vankat 2003	Chaparral; grasslands; woodland	Forested; nonforested	Local	Vegetation	Chino Valley and Verde Ranger Districts of Prescott National Forest; Arizona; USA
Huffman et al. 2012	Piñon-juniper	Forested	Local	Fire-vegetation	Northern Arizona; USA
Huffman et al. 2009	Piñon-juniper	Forested	Local	Fire-vegetation	Kaibab National Forest; Arizona; USA
Huffman et al. 2008	Piñon-juniper; ponderosa pine	Forested	Multistate	Fire-vegetation	Tusayan Ranger District of Kaibab National Forest; Arizona; USA; La Mesa de Las Viejas; New Mexico; USA

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Huffman et al. 2015	Mixed conifer	Forested	Local	Fire-vegetation	Apache-Sitgreaves National Forests; Arizona; USA
Hunter et al. 2011	Piñon-juniper; ponderosa pine	Forested	Local	Fire-vegetation	Gila National Forest; New Mexico; USA
Hunter et al. 2006	Ponderosa pine	Forested	Multistate	Fire-vegetation	Cerro Grande Fire; New Mexico; USA; Hi Meadow Fire; Colorado; USA; Hayman Fire; Colorado
Hurteau and North 2008	Mixed conifer	Forested	Local	Climate-fire-vegetation	Yosemite National Park; California; USA; Teakettle Experimental Forest; California; USA
Iniguez et al. 2016	Chaparral; fir; forested; oak; piñon; piñon-juniper; ponderosa pine	Multiple	State	Fire-vegetation	Rincon Peak (sky islands); Saguaro National Park; Arizona; USA; Rose Canyon; Santa Catalina Ranger District; Arizona
Iniguez et al. 2009	Chaparral; mixed conifer; piñon-juniper; ponderosa pine	Forested; nonforested	Local	Climate-fire-vegetation	Rincon Peak (sky islands); Arizona; USA
Ireland et al. 2012	Ponderosa pine	Forested	Local	Climate-fire-vegetation	Grand Canyon-Parashant National Monument; Arizona; USA
Jolly et al. 2015	Not specified	Multiple	Global	Climate-fire-vegetation	Global
Keyser and Westerling 2017	Not specified	Multiple	Regional	Climate-fire-vegetation	Western United States
Kitzberger et al. 2007	Forested	Forested	Regional	Climate-fire	North America subregions
Kolden et al. 2017	Douglas-fir; ponderosa pine	Forested	Local	Fire-vegetation	Swauk Late Successional Reserve; Okanogan-Wenatchee National Forest; Washington; USA
Korb et al. 2013	Mixed conifer	Forested	Local	Climate-fire-vegetation	San Juan National Forest; Colorado; USA
Krawchuck and Moritz 2011	Not specified	Multiple	Global	Fire-vegetation	Global

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Krawchuk et al. 2009	Not specified	Multiple	Global	Climate-fire	Global
Kulakowski et al. 2013	Aspen	Forested	Regional	Fire-vegetation	Western United States
Larson et al. 2013	Lodgepole pine; ponderosa pine	Forested	Local	Fire-vegetation	Bob Marshall Wilderness; Montana; USA
Laughlin et al. 2017	Mixed conifer	Forested	Local	Climate-fire-vegetation	Black Mesa Ranger District of the Apache-Sitgreaves National Forests; Arizona; USA
Lentile et al. 2006	Ponderosa pine	Forested	Local	Fire-vegetation	Black Hills; South Dakota; USA
Litschert et al. 2012	Not specified	Multiple	Regional	Climate-fire	Southern Rockies Ecoregion; Colorado; USA; New Mexico; USA; Wyoming; USA
Littell et al. 2009	Coarse-scale vegetation types	Multiple	Regional	Climate-fire-vegetation	16 ecoprovinces across the western United States
Liu et al. 2013	Not specified	Multiple	Regional	Climate-fire	Continental United States
Liu et al. 2010	Not specified	Multiple	Global	Climate-fire	Global
Liu and Wimberly 2015	Not specified	Multiple	Regional	Climate-fire-vegetation	Western United States
Loehman et al. 2018	Mixed conifer; pine	Forested	Multistate	Climate-fire-vegetation	Jemez Mountains; New Mexico; USA; Kaibab Plateau; Arizona; USA
Lutz et al. 2009	Montane; subalpine	Forested	Local	Climate-fire	Yosemite National Park; California; USA
Margolis and Balmat 2009	Mixed conifer; ponderosa pine; spruce-fir	Forested	Local	Climate-fire-vegetation	Santa Fe River watershed; New Mexico; USA
Margolis and Malevich 2016	Mixed conifer	Forested	Local	Fire-vegetation	Near Valles Caldera National Preserve; Jemez Mountains; New Mexico; USA
Margolis and Swetnam 2013	Mixed conifer; aspen; spruce-fir	Forested	Regional; multistate	Climate-fire-vegetation	Southwestern United States (Arizona and New Mexico)

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Margolis et al. 2007	Mixed conifer; aspen	Forested	Regional; multistate	Climate-fire-vegetation	Southwestern United States (Arizona and New Mexico)
Margolis et al. 2011	Aspen; Madrean; mixed conifer; spruce-fir	Forested	Multistate	Fire-vegetation	Mogollon Plateau and the Madrean Sky Islands of Arizona and New Mexico; USA
Marlon et al. 2009	Not specified	Multiple	Regional	Climate-fire	North America
Marlon et al. 2006	Forested	Forested	Regional	Climate-fire	Northwestern United States
Marshall et al. 2008	Not specified	Multiple	Regional	Climate-fire	Contiguous United States
Mast and Wolf 2004	Mixed conifer; ponderosa pine	Forested	Local	Fire-vegetation	North Rim of Grand Canyon National Park; Arizona; USA
Mast and Wolf 2006	Mixed conifer	Forested	Local	Fire-vegetation	North Rim of Grand Canyon National Park; Arizona; USA
Mast et al. 1999	Ponderosa pine	Forested	Local	Fire-vegetation	Fort Valley Experimental Forest; Arizona; USA
Montaño et al. 2012	Mixed conifer	Forested	Local	Climate-fire-vegetation	Mesa de las Guacamayas Mountains; Chihuahua; Mexico
Moore and Huffman 2004	Montane; subalpine grasslands	Forested; nonforested	Local	Vegetation	Grand Canyon National Park; Arizona; USA
Moore et al. 2004	Ponderosa pine	Forested	Local	Vegetation	Fort Valley Experimental Forest; Arizona; USA
Moritz et al. 2012	Not specified	Multiple	Global	Climate-fire	Global
O'Connor et al. 2014	Madrean; mixed conifer	Forested	Local	Fire-vegetation	Pinaleño Mountains; Arizona; U.S. Gradient
O'Connor et al. 2015	Spruce-fir	Forested	Local	Fire-vegetation	Pinaleño Mountains; Arizona; USA
Ouzts et al. 2015	Ponderosa pine	Forested	Multistate	Fire-vegetation	Arizona and New Mexico; USA
Owen et al. 2017	Ponderosa pine	Forested	Local	Fire-vegetation	Pumpkin Fire; Arizona; USA; Rodeo-Chediski Fire; Arizona

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Parisien et al. 2012	Not specified	Multiple	Regional	Climate–fire–vegetation	Western United States
Parisien et al. 2016	Not specified	Multiple	Global	Climate–fire	Conterminous United States and Canada
Parks and Abatzoglou 2020	Forested	Forested	Regional	Climate–fire	Western United States
Parks et al. 2018a	Dry conifer; piñon-juniper; ponderosa pine; savannah	Forested; nonforested	Regional	Climate–fire	Arizona and New Mexico; USA
Parks et al. 2015	Forested	Forested	Regional	Climate–fire–vegetation	Three large wilderness areas in Idaho and Montana; USA; one site in the Gila and Aldo Leopold Wilderness in western New Mexico; USA
Parks et al. 2018b	Not specified	Multiple	Regional	Climate–fire–vegetation	Western United States
Parks et al. 2018c	Forested	Forested	Regional	Climate–fire–vegetation	Western United States
Parks et al. 2016	Not specified	Multiple	Regional	Climate–fire	Western United States
Parks et al. 2014a	Forested	Forested	Regional	Fire–vegetation	The Gila-Aldo Leopold Wilderness Complex; New Mexico; USA; Frank Church-River of No Return Wilderness; Idaho; USA
Parks et al. 2014b	Not specified	Multiple	Regional	Climate–fire	Western United States
Parmenter 2008	Chihuahuan desert scrubland; desert grasslands; short-grass steppe	Desert; grasslands; shrubland	Local	Fire–vegetation	Sevilleta National Wildlife Refuge; New Mexico; USA
Passovoy and Fulé 2006	Ponderosa pine; mixed conifer	Forested	Local	Fire–vegetation	Coconino National Forest; Arizona; USA

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Pausas and Ribeiro 2013	Not specified	Multiple	Global	Fire	Global
Pechony and Shindell 2010	Not specified	Multiple	Global	Climate-fire-vegetation	Global
Pierce et al. 2004	Ponderosa pine	Forested	Multistate	Climate-fire-vegetation	South Fork Payette River; Idaho; USA; Yellowstone National Park; Wyoming; USA
Pollet and Omi 2002	Ponderosa pine	Forested	Multistate	Fire-vegetation	Webb Fire; Montana; USA; Tye Fire; Washington; USA; Cottonwood Fire; California; USA; Hochderffer Fire; Arizona; USA
Poulos et al. 2021	Madrean	Forested	Local	Fire-vegetation	Chiricahua Mountains; southeastern Arizona; USA
Price and Rind 1994	Not specified	Multiple	Regional	Climate-fire	Southwestern United States
Roccaforte et al. 2008	Ponderosa pine	Forested	Local	Fire	Mount Trumbull; Arizona; USA
Roccaforte et al. 2010	Ponderosa pine	Forested	Local	Fire-vegetation	Mount Trumbull; Arizona; USA
Roccaforte et al. 2012	Ponderosa pine	Forested	State	Fire-vegetation	National forests in Arizona; USA; Grand Canyon National Park; Arizona
Romps et al. 2014	Not specified	Multiple	Regional	Climate-fire	Contiguous United States
Roos and Sweetnam 2012	Ponderosa pine	Forested	Regional	Climate-fire	Colorado Plateau; USA
Rother and Grissino-Mayer 2014	Ponderosa pine	Forested	Local	Climate-fire-vegetation	Zuni Mountains; New Mexico; USA
Rother et al. 2015	Ponderosa pine	Forested	Local	Climate-fire-vegetation	Colorado Front Range; Heil Valley Ranch Open Space; Boulder County; Colorado; USA

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Ryniker et al. 2006	Oak	Desert; grasslands; shrubland	Local	Fire-vegetation	Lincoln National Forest; New Mexico; USA
Savage and Mast 2005	Mixed conifer; piñon-juniper; ponderosa pine	Forested	Multistate	Fire-vegetation	Mogollon Rim; Arizona; USA; New Mexico; USA
Savage and Swetnam 1990	Ponderosa pine	Forested	Local; multistate	Fire-vegetation	Southwestern United States; Chuska Mountains; Arizona and New Mexico; USA
Schoennagel et al. 2007	Lodgepole pine; spruce-fir	Forested	State	Climate-fire	Rout National Forest; Arapaho-Roosevelt National Forest; and White River National Forest; Colorado; USA
Schoennagel et al. 2004	Mixed conifer; ponderosa pine; spruce-fir	Forested	Regional	Climate-fire-vegetation	Rocky Mountains; USA
Shive et al. 2014	Ponderosa pine	Forested	Local	Climate-fire-vegetation	Rodeo-Chediski Fire; Arizona; USA
Shive et al. 2013	Ponderosa pine	Forested	Local	Fire-vegetation	White Mountain Apache Tribal Lands in Arizona; USA; Rodeo-Chediski Fire; Arizona
Shryock et al. 2015	Desert; shrubland	Desert; grasslands; shrubland	Regional	Climate-fire-vegetation	Sonoran Desert of southwestern Arizona; USA
Sibold and Veblen 2006	Lodgepole pine; spruce-fir; subalpine	Forested	Local	Climate-fire	Rocky Mountain National Park; Colorado; USA
Spracklen et al. 2009	Not specified	Multiple	Regional	Climate-fire	Western United States

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Stavros et al. 2014	Not specified	Multiple	Regional	Climate-fire	Contiguous United States; Geographic Area Coordination Centers (GACC); Southern California (SCAL); Northern California (NCAL); Pacific Northwest (PNW); Northern Rockies (NROCK); Rocky Mountains (RM); Western Great Basin (WGB); Eastern Great Basin (EGB); and Southwest (SW)
Stephens et al. 2003	Mixed conifer; pine	Forested	Local	Fire-vegetation	Sierra San Pedro Martir National Park; Mexico
Stevens-Rumann et al. 2013	Oak; ponderosa pine	Forested	Local	Fire-vegetation	Rodeo-Chediski Fire; Arizona; USA
Stoddard et al. 2015	Mixed conifer	Forested	Local	Fire-vegetation	San Juan Mountains; Colorado; USA
Stom and Fulé 2007	Ponderosa pine	Forested	Local	Fire-vegetation	Rodeo-Chediski Fire; Arizona; USA
Swetnam and Betancourt 1990	Mixed conifer; piñon; ponderosa pine	Forested	Multistate; regional	Climate-fire-vegetation	Southwestern United States; Arizona and New Mexico; USA
Swetnam and Lynch 1993	Mixed conifer	Forested	Local	Fire-vegetation	Carson National Forest and Santa Fe National Forest; New Mexico; USA
Tang et al. 2015	Not specified	Multiple	Regional	Climate-fire	Contiguous United States
Tarancón et al. 2014	Ponderosa pine	Forested	Local	Climate-fire-vegetation	Apache-Sitgreaves National Forests; Arizona; USA
Teske et al. 2012	Forested	Forested	Multistate	Fire-vegetation	Greater Bob Marshall Wilderness Area; Montana; USA; Selway-Bitterroot Wilderness Area; Idaho and Montana; USA; Frank Church-River of No Return Wilderness Area; Idaho

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
Trouet et al. 2010	Forested	Forested	Multistate; regional	Climate-fire	Western United States; southwestern United States; Interior West; USA; Pacific Northwest; USA; California; USA
van Mantgem et al. 2016	Mixed conifer	Forested	State	Fire-vegetation	Yosemite National Park; Kings Canyon National Park; and Sequoia National Park; California; USA
van Mantgem et al. 2013	Mixed conifer	Forested	Regional	Climate-fire	Western United States
van Mantgem et al. 2009	Forested	Forested	Global	Climate-fire-vegetation	Western United States; British Columbia; Canada
van Mantgem et al. 2011	Mixed conifer	Forested	Local	Fire-vegetation	Sequoia National Park; California; USA
Vankat 2011a	Ponderosa pine	Forested	Local	Fire-vegetation	Grand Canyon National Park; Arizona; USA
Vankat 2011b	Aspen; mixed conifer; spruce-fir	Forested	Local	Fire-vegetation	Grand Canyon National Park; Arizona; USA
Waltz et al. 2014	Mixed conifer; ponderosa pine	Forested	Local	Fire-vegetation	Wallow Fire; Apache-Sitgreaves National Forests; Arizona; USA
Weisz et al. 2009	Ponderosa pine	Forested	Local	Climate-fire-vegetation	Kaibab National Forest; Arizona; USA
Weng and Jackson 1999	Forested	Forested	Local	Climate-fire-vegetation	Kaibab National Forest; Arizona; USA
Westerling et al. 2003	Not specified	Multiple	Regional	Climate-fire	Western United States
Westerling et al. 2002	Forested; grasslands	Multiple	Regional	Climate-fire-vegetation	Western United States
Westerling et al. 2006	Forested	Forested	Regional	Climate-fire	Western United States
Westerling et al. 2011	Mixed conifer	Forested	Regional	Climate-fire	Greater Yellowstone ecosystem; Wyoming; USA

Exhibit continued.

Reference	Ecosystem	Ecotype	Scale	Main agent	Location
White 1985	Ponderosa pine	Forested	Local	Fire-vegetation	Gus Pearson Natural Area; Arizona; USA
White et al. 2008	Desert	Desert; grasslands; shrubland	Local	Fire-vegetation	Chihuahuan Desert; Big Bend National Park; Texas; USA
White and Vankat 1993	Mixed conifer	Forested	Local	Fire-vegetation	Grand Canyon National Park; Arizona; USA
Williams et al. 2010	Forested	Forested	Regional	Climate-fire-vegetation	Conterminous United States; southwestern United States
Williams et al. 2014	Forested	Forested	Regional	Climate-fire	Southwestern United States
Williams et al. 2015	Forested; nonforested	Forested; nonforested	Regional	Climate-fire	Southwestern United States; Arizona; New Mexico and areas of Texas; Oklahoma; Colorado and Utah south of 38.08°N; north of 28.58°N; and west of 100.08°W
Williams and Baker 2013	Ponderosa pine	Forested	Local	Fire-vegetation	Coconino Plateau; Arizona; USA; Grand Canyon National Park; Arizona
Wotton and Flannigan 1993	Forested	Forested	Regional	Climate-fire	Canada
Yocom et al. 2010	Pine	Forested	Local	Climate-fire	Peña Nevada Peak; Nuevo León; Mexico
Yocom et al. 2014	Mixed conifer	Forested	Local	Climate-fire	Sierra Madre Oriental Mountains; Mexico
Yocom et al. 2015	Aspen; mixed conifer	Forested	Local	Fire-vegetation	North Rim of Grand Canyon National Park; Arizona; USA

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