A SYNTHESIS OF THE BEST AVAILABLE SCIENCE ON WILDLAND FIRE RELATED TOPICS IN THE SOUTHWESTERN US IN 2023

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Cover Photo: The Land Corral Prescribed Fire conducted by the BLM on February 18, 2021 in the St. David Cienega region of the San Pedro Riparian National Conservation Area near Sierra Vista, AZ. The actual consumption of fuel was greater than 90% in wetland regions and estimated at 30-40% in the dry sections.

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Introduction

Fire is an integral component of many Southwest ecosystems; however, fire regimes across the region have been affected by climate change, creating conditions to which these ecosystems have not adapted. Since 1980, fire frequency, size and severity have increased in many ecosystems in the western US due to changes in climate combined with a history of fire suppression and other forest management practices, such as grazing and logging (Westerling 2016, Singleton et al. 2019, Mueller et al. 2020). These changes have prompted a plethora of research into topics such as smoke and air quality, human dimensions of fire, Indigenous fire, vegetation change, watershed impacts, changes in carbon, fire behavior, and operational considerations. In addition, warmer temperatures and changes in precipitation associated with climate change are already impacting North America and are expected to have increasing impacts in the coming decades. In the Southwest, increasing surface air temperatures associated with anthropogenic climate change are expected to strongly impact many forest, grassland, desert, and riparian systems. These impacts include drought events, species range shifts, vegetation type changes, impacts to natural tree regeneration, and significant changes to fire regimes (Abatzoglou et al. 2017, Coop et al. 2020, Petrie et al. 2023, Serra-Diaz 2015, Seager et al. 2023).

The goal of this synthesis is to provide a summary of the literature, published in 2023, on fire and fire-related topics. These topics were defined in a nationwide effort by the Joint Fire Science Program and refined by the Southwest Fire Science Consortium's executive board which is composed of researchers and land managers from Arizona and New Mexico. The topics include climate change, fire behavior, watershed and hydrology, regeneration, fire regimes, human dimensions of fire, and wildlife (a full list of terms is outlined in ***Table 1***). Four databases were used: Web of Science, CAB abstracts, BIOSIS, and Google Scholar. Search terms were selected based on their relation to the topic areas for 2023. The search used in all databases was "fire OR wildfire OR burn OR "wildland urban" OR WUI OR fuels AND Arizona OR "New Mexico" OR "southwestern states of USA" OR southwest" NOT China".

Results

This paper includes research from 86 publications covering fire topic areas (full list in ***Table 2***). This synthesis summarizes articles published in 2023 by major findings and contributions to the field by subject area and presents the best available science in 2023 for these topic areas.

Table 1: Topic areas found in this review for articles published in 2023.

Climate Change & Carbon	Regeneration
Fire Behavior	Smoke and Air Quality
Fire Ecology	Suppression, Operations, and Management
Fire Regimes and Fire History	Vegetation Change
Fuels Reduction and Restoration	Watershed and Hydrology
Human Dimensions of Fire	Wildland Urban Interface (WUI)
Indigenous and Cultural Fire	Wildlife
Invasive Species	

Climate Change and Carbon

The southwestern US is expected to experience hotter and drier conditions in the coming century, which will lead to drought events and heat stress that impact ecosystems and humans. These conditions will affect tree seedling survival, tree regeneration, tree mortality, and species ranges, and have social and economic effects. Greenhouse gas-induced warming is a primary driver of the increased frequency and duration of extreme hot and dry events, and urban development amplifies the warming in cities (Ghanbari et al. 2023), which has implications for large populations of people in areas such as Phoenix as summers become dangerously hot. In addition to increasing air temperatures, the Southwest is undergoing severe changes in its hydroclimatic cycle and intensity, and there are challenges in addressing these hotter-drier conditions (Zhang 2023). The ongoing 21st century megadrought is attributed to a decline in cool season precipitation that dries soils into the summer. The aridification of the southwestern US may continue, and climate variability that is driven by decadal variations of sea surface temperatures will not prevent the Southwest from becoming increasingly arid (Seager et al. 2023).

Climate change, drought conditions, and changes in precipitation will impact trees via decreasing tree growth and increased tree mortality in many forested ecosystems. Modeling efforts show that by the late 21st century, mesic tree species in the Southwest such as Douglas fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*) and Engelmann spruce (*Picea engelmannii*) will experience adult tree mortality as they are more susceptible to hot and dry periods. Existing populations of the more xeric pinyon pine (*Pinus edulis*) and ponderosa pine (*Pinus ponderosa*) are predicted to experience more seedling-killing conditions, affecting the future growth of these species (Crockett and Hurteau 2023). Pinyon pine (*P. edulis*) and one-seed juniper (*Juniperus monosperma)* are projected to experience population declines driven by both rising mortality and decreasing recruitment rates, and these declines are consistent across various climate futures causing vegetation type transformations across elevational gradients (Noel et al. 2023). By the end of the 21st century, climate conditions will increase seedling mortality of Southwestern tree species across the Southwestern range and vegetation type changes are expected and will be amplified by physiological limitations (Crockett and Hurteau 2023).

Forests sequester and store carbon: live trees actively remove carbon from the atmosphere and store it. Wildfire is a threat to carbon stores in live trees and vegetation, soils, dead wood and litter, as carbon is released into the atmosphere during wildfire events. Forest management practices can mitigate the risk of wildfire-caused carbon loss in forests by focusing on increasing carbon uptake in the long-term. More carbon is lost in wildfire events in untreated areas than in treated stands, where treated stands that burn will continue to retain more carbon in live vegetation and soils post-fire than their untreated counterparts. Peeler et al. (2023) evaluated exposure (high burn probability relative to total carbon) and sensitivity (carbon loss and recovery) of western US conifer forests to wildfire-induced carbon loss and identified areas where management via thinning and prescribed burning can reduce wildfire caused carbon loss. They found that western states such as California, New Mexico, and Arizona contained the greatest proportion of forest carbon most vulnerable to wildfire-caused loss relative to their total forested area (Peeler et al. 2023). Implementation of widespread prescribed burns can reduce the amount of carbon released in fire events across the

Western US, because these prescribed fires release less carbon dioxide than wildfires (Weidinmyer and Hurteau 2010).

Simulation of restoration treatments on the Kaibab and Coconino National Forests in Arizona found that in the short term, scenarios without forest restoration increased live tree carbon, but also increased the likelihood of carbon loss during wildfire activity driven by extreme fire weather (Young and Ager 2023). Scenarios most effective at restoring fire-excluded ponderosa pine forests to historical old growth conditions came at a short-term cost of lost carbon, but with the long-term benefit of substantially increasing fire-resistant live tree carbon (Young and Ager 2023).

As the climate becomes increasingly hot and arid, many regions are predicted to experience alterations to the historic fire regime (the severity, intensity, frequency, seasonality, size, and type of fire). Warmer temperatures, drought conditions, fuels, and weather are important drivers of fire severity. Recent increases in fire severity are attributed to changes in climatic water deficit (CMD), vapor pressure deficit (VPD), evapotranspiration (ET), and the abundance of fuels (Wasserman and Mueller 2023). Fire weather and vegetation species composition also influence fire severity. Future increases in fire severity are likely to impact forest resilience and increase the probability of forest type conversions in many ecosystems.

Climate change will decrease the number of favorable days for prescribed fire across most of the western US, with widespread decreases of approximately 15–30 prescribed fire days per year across the Pacific, Southwest, and Four Corners regions (Swain et al. 2023). A +2°C (+ 35.6 °F) temperature increase by 2060 will reduce prescribed fire days overall (−17%), particularly during spring (−25%) and summer (−31%). However, winter (+4%) may increasingly emerge as a comparatively favorable window for prescribed fire especially in northern states (Swain et al. 2023).

Climate change has impacts on socioeconomic values, infrastructure, and property values in the US. Homes located in fire prone areas have increased risk due to climate-induced hazards such as wildfire risk, post-fire flooding, erosion, exposure to smoke, and other disturbances. Under future climate scenarios, these risks will increase with climate stress and tree mortality. Properties in California, the southwestern US, and the Rocky Mountain West exposed to climate stress and tree mortality is projected to rise dramatically (Anderegg et al. 2023). Understanding climate exposure and disturbance risk to property values can inform risk management and policy efforts.

Fire Ecology

Climate change is affecting fire regimes and climate-fire interactions causing ecological transformation in many areas of the western US. Fire refugia are locations that burn less frequently or less severely than the surrounding landscape, may be resistant to fire, and promote post-fire recovery in adjacent areas (Rodman et al. 2023). Refugia may provide habitat for fire-sensitive species and maintain forest type under current and future conditions. Across the Southwest and Colorado Plateau, potential fire refugia were 36.4% (under moderate fire weather scenarios) and 31.2% (under extreme fire weather scenarios) more common in forests that experienced recent fires due to lower fuels and biomass accumulating. Researchers also found that an increased use of prescribed and resource objective fires during moderate fire weather conditions can promote refugia and fire-resistant landscapes (Rodman et al. 2023). When overlaid with models of tree recruitment, 23.2% of forests under moderate fire weather and 6.4% of forests under extreme fire weather were classified as refugia with a high potential to support post-fire tree recruitment in the surrounding landscape (Rodman et al. 2023). Platt et al. (2023) found that areas of fire refugia increased within fire footprints in the Arizona and New Mexico mountains ecoregion showing that areas that experience frequent low severity fire become more resilient to future disturbance events. Additionally, fire footprints in this region had a higher proportion of reburned areas and did not occur at higher elevation or within greener areas. Post-fire, areas of refugia remain which could support post-fire recovery dependent on the availability of seed sources for neighboring burned patches (Platt et al. 2023).

Wilderness and other protected areas with less human impact and management provide opportunities to study the effects of natural disturbances on ecosystem structure and dynamics. These studies include topics on fire effects, vegetation structure and composition, changes to climate and fire regimes, and other ecosystem dynamics; these studies will help inform managers on the natural range of variations and natural dynamics (Kreider et al. 2023). Kreider et al. (2023) review wilderness fire management issues and identify major scientific contributions, including self-limitation of fire, the effects of active fire regimes on forest and aquatic systems, barriers and potential solutions to wilderness fire management, and the effect of fire on wilderness recreation and visitor experiences. In the review, the authors identify priorities for future wilderness fire research, including the past and potential future role of Indigenous and prescribed burning, the effects of changing climate and fire regimes on ecosystem processes, and how to overcome barriers to wilderness fire management (Kreider et al. 2023).

Fire Behavior

Downslope winds are a primary driver of disastrous wildfires that threaten populated regions in the WUI and adjacent to mountain ranges in the western US. From 1992–2020, there was a 25% increase in the annual number of downslope wind-driven fires, and a 140% increase in the respective annual area burned is documented, which partially reflects trends toward drier fuels (Abatzoglou et al. 2023). Fire tends to spread more quickly uphill, where smoke and heat dry out fuel up the slope. Therefore, downslope wind-driven fires require increased fire prevention and adaptation strategies to minimize losses to populated WUI areas. Additionally, the change in human-ignitions, fuel availability and dryness, and downslope wind occurrence should be evaluated to understand future fire risk (Abatzoglou et al. 2023). An example of extreme fire behavior driven by wind is the Yarnell Hill Fire in central Arizona in 2013. During this extreme event, erratic and dynamic winds were present, and the atmosphere transitioned from a deep and long-lived convective density current to elevated dry microbursts with mass and wind outflow into a canyon. These winds redirected the wildfire and impacted the escape route of firefighters resulting in the death of 19 members of the Granite Mountain Hotshots (Kaplan et al. 2023).

Using climate data for the US, Pokhrel et al. (2023) produced national maps that estimate wildfire risk and fire-related tree mortality. In their model, the fire season temperature and moisture conditions in an area significantly impacted the wildfire probabilities, where the temperature had a positive effect, precipitation and evapotranspiration had a negative effect, and higher spring temperatures negatively affected wildfire probability with increased biomass growth, and therefore produced more fuels on the landscape (Pokhrel et al. 2023). Tree mortality is impacted by moisture conditions during the fire season, with higher levels of moisture leading to lower tree mortality. Wildfire probabilities and tree mortality varied by land ownership, where US federal lands were more likely to have wildfires than private and state forest lands, likely due to past management practices and build-up of fuels, and because most federally owned forests are in the drier western US (Pokhrel et al. 2023).

Quantifying wildfire risk is important to protect communities, ecosystems, wildlife habit, and values at risk. Fire danger indices (FDIs) that incorporate weather and fuel conditions are used to support wildfire predictions and risk assessment. In a recent study, four FDIs (temperature, precipitation, wind speed, and fuel type) were used to predict changes in future fire potential with future climate scenarios and fuel datasets across the United States (Yu et al. 2023). Results of this study suggest an overall higher fire potential and a prolonged wildfire season under future climate conditions (2085-2094) in the southwestern US driven by increases in temperature, daily minimum relative humidity, and wind speed (Yu et al. 2023).

Assessing wildfire risk can aid in resource protection and community safety. Models of wildfire risk based on resilience, vulnerability, values at risk, and population in a given area can help evaluate risk at the county and community levels and provide a framework for ranking risk and safety for communities (Pishahang et al. 2023). A recent review of modeling approaches to estimating fire risk found that wildfire danger is a function of seven thematic groups of variables: meteorology, vegetation, topography, hydrology, socio-economy, land use and climate (Zacharakis and Tsihrintzis 2023). These themes can additively be used to understand the level of wildfire risk in vulnerable landscapes.

Fire Regimes and Fire History

Understanding historical fire regimes can provide insight into fire-climate-forest interactions and the conditions under which existing forest communities have established and adapted over centuries. Exploring how these forested areas will adapt to future climate conditions is challenging due to the rapid pace of climate change, including temperature and precipitation changes. On the San Francisco Peaks in northern Arizona, a study of fire scars and fire histories revealed that fires occurred in the early to mid growing season, and fire events were linked to climate across all elevations, with a stronger association to drought than to El Niño-Southern Oscillation prior to 1879 (Fulé et al. 2023). In dry conifer forests of the western US, more stand-replacing fire (area burned) has occurred since 1985 compared to the historical reference period (1600-1875), and overall, the southwestern US ecoregion experienced 5.9 times more stand-replacing fire than it did historically (Parks et al. 2023).

Fuels Reduction and Restoration

Fuels reduction and restoration treatments are a strategy to reduce wildfire risk and restore forests to their natural range of variation. Fuel treatments slow the spread of fire, facilitate fire suppression efforts, and reduce the risk of high severity fire. A systematic review of landscape-level fuel treatment effects on wildfire based on empirical data, model simulations, and case studies was conducted across North America. The authors found that landscape-level fuel treatments were effective at reducing the overall frequency of wildfire and the number of acres burned at high severity, while also leading to lower severity fire in many places (Ott et al. 2023). Additionally, they found that the outcomes of wildfires were influenced by treatment extent, location, size, prescription, and timing, and other factors beyond the control of land managers such as weather, climate, fire/fuel attributes, and other management model inputs (Ott et al. 2023).

Landscape treatments that include thinning and burning can reduce the risk of crown fire, lower fire severity, and aid in ecological restoration efforts that aim to return these areas to their natural range of variation in terms of tree density, trees per acre, and fire return interval. In the ponderosa pine forests of northern Arizona, simulations of various ecological restoration efforts that include resource objective wildfire were found to be highly effective at returning old growth structure, restoring the historic fire return interval, and stabilizing aboveground carbon stocks (Young and Ager 2023).

Stand density and seasonal precipitation patterns in Southwestern ponderosa pine forests have impacts on species composition and plant productivity. Climate change is driving higher levels of variability in winter and monsoon precipitation, and treatments may help buffer some of these impacts. Studies in northern Arizona found that grasses and seedlings predominantly used monsoon water in August and October, while pine saplings and mature trees mostly used winter water during all sampling months (Kerhoulas et al. 2023). Thinning treatments increased soil moisture throughout the year and in deeper soil layers and can positively impact areas where mature trees rely predominantly on winter precipitation. Monsoon precipitation is important for herbaceous species and younger, regenerating overstory trees (Kerhoulas et al. 2023). Seedlings and saplings used both winter and monsoon seasonal water sources and may rely more on monsoon precipitation if winter precipitation changes drastically with climate change.

Studying the effects of long-term thinning and burning treatments helps elucidate climate and treatment trends over time. In ponderosa pine-dominated forests in the southwestern US, thinning and prescribed burning treatments increased native grass and shrub cover and increased native species richness by about 50% relative to untreated controls (Springer et al. 2023). These effects persisted for over a decade post-treatment, even under the influence of significant and persistent drought. Additionally, native species in wetter areas still experienced a reduction in cover for up to five years after the treatment relative to those with southern (warmer-drier) sites, indicating that both management actions and interannual climate variability may foster shifts to plant communities that are more resilient to a warming climate (Springer et al. 2023).

Thinning and burning treatments affect soils and micro-environments that can impact plant and wildlife species. Fuels and restoration treatments in the Jemez Mountains of New Mexico caused large increases in solar radiation and mean and maximum wind speeds, but small changes in air temperature and humidity (Parmenter and Losleben 2023). These treatments increased the soil temperatures beneath the logs, and log retention on thinned and burned sites was found to provide microsites with increased soil temperature and moisture in the top 30 cm, which can enhance soil ecosystem processes and provide refugia for invertebrate and vertebrate wildlife (Parmenter and Losleben 2023).

Riparian areas experience stressors and changes from drought conditions and annual changes in temperature and precipitation. Restoration of riparian areas on the San Carlos Apache Reservation and Upper Gila River watershed in Arizona has increased vegetation greenness throughout the watershed despite the intensifying drought conditions, while areas within the lower watershed have shown higher rates of wildfire and other disturbances, supporting the idea that restoration can help riparian vegetation adapt to climate change (Petrakis et al. 2023).

Human Dimensions of Fire

Science co-production and stakeholder engagement can often lead to better outcomes for project implementation, decision making, policy making, and proactive management. Land management decisions and wildfire risk assessment and preparedness are better informed by stakeholder engagement with federal agencies, tribal entities, and local planners and decision makers. Analyses and co-produced products can provide the necessary tools to direct how resources will be used, understand where the gaps in resources are, and determine how to allocate future resources. Cullen et al. (2023) provide a framework that provides context and support for decision makers during fire events. They find that co-production of wildfire risk analyses with stakeholders can effectively illuminate the expected number of fires that will compete for resources, the number of fire danger days per year relative to prior norms, and changes in the length and overlap of fire season in multiple US regions (Cullen et al. 2023). This analysis can be incorporated in complex decision systems and help direct decision making and policy.

Wildfire risk mitigation in WUI communities is important and evolving, and involves human behavior, wildfire science, and social, economic, and political aspects. Cowan and Kennedy (2023) reviewed the literature and identified nine themes of social determinants affecting the implementation of wildfire mitigation measures by WUI residents. These include connection and capital, geospatial and land ownership risk perception, perceived effectiveness, perceived responsibility, education and information, capacity, demographics, and regulation (Cowan and Kennedy 2023). Assessing risk and social acceptance of risk is important to effectively implement prescribed fire and thinning treatments in the WUI. Wildfire risk assessment frameworks that identify areas susceptible to fire in conjunction with a public outreach strategy that includes general information on prescribed fire risks and benefits, regular communication about agency activities, and project-specific information aimed at helping people reduce negative impacts are effective strategies to implement prescribed fire treatments (Brunson et al. 2023).

Wildfire management is a complex problem that requires novel approaches and a shift from full suppression strategies. Collaborative efforts for dealing with wildfire risk are successful at integrating stakeholder views, state and government approaches and limits, and understanding community needs. However, additional benefits can be gained from wildfire risk governance if the efforts integrate perspectives other than technical expertise, have a collaborative learning process, include underrepresented groups in wildfire risk-governing networks, account for potential uneven distributions of risk and resources to address risk, and consider fiscal investments across spatial, institutional, and temporal scales (Essen et al. 2023). Social science aspects of wildfire adaptation such as public involvement, public support for prescribed fire and management actions, and stakeholder engagement, have grown in scope; however, public support for prescribed fire and fire prevention tactics are topics that should be more deeply explored and developed (Edgeley 2023). Social science aspects of wildfire adaptation can aid in elucidating the decision-making process, such as characterizing social and environmental influences on household evacuation during a fire event. The planning and implementation of different public safety efforts during wildfire events across scales and agencies informs subsequent human experiences and decisions (Edgeley 2023).

Post-fire flooding has become more prevalent and is a significant concern in the southwestern US. Flooding and debris flows are a risk to communities downslope from fires and require a coordinated multi-jurisdictional response. A proactive response to post-fire flood events is necessary to protect individuals, communities, and other values at risk. A rapid response protocol was developed for post-fire sediment flow after the 2022 Hermit's Peak/Calf Canyon Fire in New Mexico to monitor sediment flow and aquatic disturbances. In this protocol, researchers respond to and gather data from disturbances that can be used in engineering mitigation and restoration efforts that protect communities and the environment (Tunby et al. 2023).

A study of the 2010 Schultz Fire and the social aspects related the fire and post-fire events showed that more communication and outreach lead to higher engagement levels, where individuals in areas at risk for post-fire flooding engaged in short-term mitigation efforts with lower implementation costs, and people responded positively to communication and outreach about flood risk (Burnett and Edgeley 2023). This then motivated action, shared responsibility, and cross-jurisdictional management of post-fire flood risk (Burnett and Edgeley 2023).

Wildfires not only have lasting ecological effects but also have large social and economic costs and effects that are difficult to capture. The full financial costs of wildfire are not often quantified, but must inform effective future budgeting, resource allocation and assistance, and community impact assessments. The costs of restoration of areas that have experienced post-fire flooding can far exceed the costs of wildfire suppression. A study conducted ten years after the Schultz Fire in Flagstaff, Arizona found that these costs continued to accrue, totaling between $109 million and $114 million while suppression costs represented only 10% of the total cost (Hjerpe et al. 2023).

Watershed-level climate adaptation strategies are needed to create resilient communities, and collaborative efforts across jurisdictional lines and the removal of administrative barriers are necessary. In the Upper Rio Grande watershed in New Mexico, characteristics of adaptive governance from the relevant literature were identified and researchers found that a collaborative network with leadership from key stakeholders leveraged opportunities in the watershed to create and maintain stability, and the use of adaptive management and peer review processes built capacity by creating the feedback loops necessary to inform future work (Morgan et al. 2023).

Indigenous and Cultural Fire

Climate change and associated drought conditions are expected to impact vegetation and trees, and therefore decrease the supply of local wood sources for fuel. Many Indigenous peoples rely on local firewood for cultural practices and physical survival, as well as providing a reliable energy source. Magargal et al. (2023) found that implementation of Indigenous ecological knowledge practices is likely to promote the long-term persistence of pinyon and juniper biomass on the northern Navajo Nation when the climate is stable or experiencing low-level climate change. The long-term sustainability of Indigenous firewood harvesting is maximized under climate scenarios that include low-emissions and low-to-moderate demand, and with Indigenous ecological practices that maintain resilient socio-environmental systems. Indigenous ecological practices and their ecological legacies contribute to maintaining resilient environmental and social systems (Magargal et al. 2023).

Studies of Ancestral Puebloan societies in the southwestern US and Colorado Plateau examined the links between environmental variables and fuelwood demand and use, further illuminating the cultural use of fuelwood and acknowledging that the use of Indigenous ecological knowledge is an important part of land stewardship in these areas. Historically, in Ancestral Puebloan settlements, women were tasked with fuelwood collection and there were links between environmental variables and fuelwood demand, acquisition, and use (Osborn et al. 2023).

Understanding Indigenous fire histories can support the use of traditional ecological knowledge in management. Fire scars were used to analyze up to 400 years of fire-climate relationships in dry forests in Arizona and New Mexico within the traditional territories of the Navajo, Jemez, and Apachería. Across the southwestern US, seasonal climate conditions that were wetter one to three years before fires and warmer and drier conditions during the fire year were found to be drivers of fire activity, where wet years produced an abundance of fuels that become continuous fuels during dry years (Roos et al. 2023a). Fire scars during periods of cultural use indicate that Indigenous fire management reduced fuels and fuel connectivity to prevent large, high intensity wildfires. Restoring or emulating Indigenous fire management practices could buffer climate change impacts at local scales but would need to be implemented repeatedly at broad scales for broader regional benefits (Roos et al. 2023a).

Indigenous land use in ponderosa pine forests in east-central Arizona by two different cultural groups (Ancestral Pueblo and Western Apache) was used to reconstruct fire regime variability during four phases of different intensities of use. Elevated charcoal with domesticate pollen (*Zea* spp.) and forest pollen assemblages characterized by intensive land use by Ancestral Pueblo suggests that fire was used to support agricultural activities (Roos et al. 2023b). Pollen analyses of Pre-reservation Western Apache showed that land use included burning of fine fuels to promote economically important wild plants (Roos et al. 2023b).

Invasive Species

Invasive grasses are detrimental to ecosystem health and have increased wildfire burn severity in many areas. Across the entire Mojave Desert, hot spots of invasive grasses were correlated to soil texture, aspect, winter precipitation, and elevation, and are primarily found on the eastern and western margins of the Mojave Desert ecoregion (Smith et al. 2023). Removal of invasive plants can be difficult, but efforts to restore native plants are necessary. In the Sonoran Desert of Arizona, herbicide application three times per year was effective at killing buffelgrass (*Pennisetum ciliare*), and native plant cover and richness in the invaded treatment plots recovered to similar levels as uninvaded control plots after buffelgrass removal (Rowe et al. 2023).

Regeneration

Climate change and fire severity have interactive effects on post-fire conifer regeneration. High-severity fire limits seed availability, and hotter and drier conditions impose physiological limits on seedling establishment and survival. Across the western US under future climate scenarios (2031-2050), post-fire conifer regeneration is likely to occur following low-severity fire, but not high-severity fire, and fire severity and seed availability have a greater impact on recruitment probabilities than climate conditions (Davis et al. 2023). Hotter and drier climatic conditions are projected to reduce the probability of post-fire tree regeneration, resulting in ecological transformation and an overall loss of dominant conifer species (Davis et al. 2023). The likelihood of post-fire regeneration decreased under future climate scenarios across the western US, where the availability of seed sources and moisture control post-fire conifer regeneration patterns, and distance to seed source was an important driver (Davis et al. 2023). Management actions that reduce fire severity and especially the occurrence of large patches of high-severity fire can help offset the expected declines in climate driven post-fire regeneration.

Landscapes that experience high-severity fire often need planting to assist in site-level regeneration. Planting experiments offer insights into how to effectively implement regeneration. In the 2011 Las Conchas Fire footprint in New Mexico, three species (*Pinus ponderosa, Pinus strobiformis,* and *Psuedotsuga menziesii*) seedlings and saplings were planted and researchers found that seedling survival in post-wildfire areas was increased by planting under shrubs and in soil amended with biochar. The widespread adoption of these methods may improve the success rates of post-wildfire reforestation efforts in semi-arid areas, regaining some of the ecosystem services lost to high-severity wildfire (Marsh et al. 2023).

In the southwestern US, warmer and drier conditions will impact ponderosa pine regeneration patterns. Some areas will experience a regeneration failure, and this has a high potential to increase in a warmer climate with variable precipitation (Petrie et al. 2023). Treatments such as thinning and burning can help natural regeneration in these areas (Petrie et al. 2023). In Arizona, regeneration patterns in Engelmann spruce (*Picea engelmannii*) and Chihuahua pine (*Pinus leiophylla*) decreased during severe drought ten years after the Horseshoe Two megafire in the Chiricahua Mountains, Arizona, and the conversion of Madrean pine-oak forest to oak shrublands was prevalent six to ten years post-fire. Engelmann spruce was found to be more drought sensitive and more negatively affected by drought and fire than other species and is more sensitive to shifts in climate and wildfires than Chihuahua pine (Barton et al. 2023).

Severe wildfires due to hotter and drier conditions are impacting tree regeneration patterns, leading to tree mortality and unsuccessful post-fire regeneration. A study examining simulated regeneration rates from 2012-2099 in the Las Conchas Fire footprint using observed and projected climate data (Representative Concentration Pathway RCP 4.5 and 8.5), showed decreased regeneration events of three common Southwestern conifer tree species (*P. edulis, P. ponderosa,* and *P. menziesii).* Models showed that this decrease would lead to subsequent decreases in aboveground biomass regardless of climate scenario, suggesting that models may overestimate the amount post-fire regeneration in the southwestern United States, meaning lower regeneration rates of Southwest conifer species may be expected in the future (Jung et al. 2023).

Smoke and Air Quality

Smoke from wildfires affects air quality and ecosystems and is a threat to public health in the western United States. The aerosols from wildfires and prescribed fires contain particulate matter and gas pollutants that can penetrate human lungs. Implementing more widespread prescribed burning in local landscapes where forest restoration and wildfire risk reduction are needed may help mitigate impacts of wildfire smoke exposure to communities over the long term. Still, prescribed burns impact air quality and public health. More frequent use of prescribed fire will have more frequent air quality impacts and effects on nearby populated areas (Carrico and Karacaoglu 2023). Simulations of prescribed burn scenarios on smoke and air quality showed that implementing prescribed burns in the heavily forested areas of northern California and the Pacific Northwest benefit the entire western United States by reducing the amount of smoke that would drift to other states and reduce the number of people impacted by smoke and poor air quality. These areas should be prioritized for prescribed burns to help mitigate future smoke exposure to susceptible populations and impacts to large population centers across the West (Kelp et al. 2023).

Garg et al. (2023) looked at the effectiveness of six respiratory protection (RP) materials against wildland fire smoke inhalation and impacts to the human respiratory system. Particulate matter (PM) and gaseous filtration through different RP was measured. Bandanas provided negligible benefits for both PM and gaseous emission reduction and were found to be ineffective at filtration for the particle size range produced during a fire, whereas surgical, N95, P95, and two types of P100 filters were very effective at filtrating particulate matter and some gases (Garg et al. 2023).

Suppression, Operations, and Management

Wildfire planning requires effective incident management response and tools that are user-friendly and widely available, not deeply technical, and that provide meaningful outcomes. Potential Wildfire Operational Delineations (PODs) were developed as a planning and fire response tool and are used in incident management. In Colorado and Washington, PODs were helpful for validating fuels treatment plans and supporting communication among agency staff, and with private landowners and collaborators (Buettner et al. 2023). Wildland Fire Decision Support System (WFDSS) is used to guide decisions on complex wildfire incidents and for sharing information about wildfires and documenting management decisions. Users may need more training on the systems' use and applications; it is primarily being used as an information source and a location to store decision documents and is not being used to its full capabilities (Fillmore et al. 2023).

Vegetation Change

Understanding landscape-scale vegetation trajectories under a changing climate will inform reforestation strategies. Experiments on drought and heat stress on southwestern US tree species reveal that droughts will play a large role in juvenile tree mortality and will directly impact species at warmer climate thresholds, where heatwaves combined with drought will increase mortality of high elevation species (Lalor et al. 2023). Experiments showed that lower-elevation species that grow in warmer conditions died earlier (*P. ponderosa* in 10 weeks, *P. edulis* in 14 weeks) than did higher-elevation species from cooler conditions (*P. engelmannii* and *P. menziesii* in 19 weeks, and *P. flexilis* in 30 weeks) (Lalor et al. 2023).

Experimental warming on the understory plant community of a ponderosa pine forest in northern Arizona was conducted across a burn severity gradient. Researchers found significant and rapid responses of plant community composition, trait expression, and ecosystem function in response to burn severity, experimental warming, and their interaction (Taber and Mitchell 2023). This suggests that ecosystems experiencing severe fire under future fire climate conditions may recover in different ways than in the past, and vegetation type changes will occur (Taber and Mitchell 2023).

Big sagebrush (*Artemisia tridentata*) ecosystems across the western United States have experienced many changes in ecosystem dynamics and vegetation composition over the last century due to livestock grazing, the introduction of non-native species, and the changing climate and fire regimes. Big sagebrush presence in the Rio Grande del Norte National Monument in northern New Mexico increased significantly since 1881 when it was present on 16% of the area. In 2019, sagebrush had increased to 79% of the study area and grass declined equally in places where sagebrush increased and where there was no change in sagebrush, suggesting that changes in both vegetation types were due to overgrazing (Fox et al. 2023).

Dryland ecosystems currently occupy 45% of the terrestrial land surface and are important contributors to fluctuations in the terrestrial carbon cycle; they are expanding due to climate change and changes in land use. In the southwestern US, aboveground net primary production (ANPP) is impacted by changes in annual precipitation in water-limited ecosystems and is exacerbated by climate change. In the northern Chihuahuan Desert, ANPP across a grassland–shrubland transition zone was positively correlated with annual precipitation across this landscape, and nitrogen enrichment stimulated ANPP, whereas a one-time prescribed burn reduced ANPP for nearly a decade (Brown and Collins 2023).

Studies of past disturbance events on the Colorado Plateau illuminate that this area has historically been shaped by climate change and other factors such as erosion, fire activity, and plant communities as found in lake sediments. Historically, increases in erosion have followed transitions toward warmer and drier conditions and greater forest fire activity, suggesting aridification, the resulting vegetation succession, and increased wildfires will increase erosion rates in similar settings regionwide (Staley et al. 2023).

Watershed and Hydrology

Climate change is impacting the hydrological regime, and many areas of North America are exposed to extreme events such as prolonged droughts, floods, and extreme wildfires. These events have impacts on water resources including water supply, decreased water flows and water quality, changes in surface runoff and groundwater storage, and changes within the forested watershed (Asif et al. 2023). Overall, in North America, winter is expected to warm more than other seasons causing earlier runoff and a decline in snowmelt, and green infrastructure, innovative technologies, and an integrated water resource management framework may help alleviate these impacts (Asif et al. 2023).

The Southwestern region is projected to become hotter and drier as the century proceeds. Summer monsoon precipitation is important to forested ecosystems across the region; the monsoon precipitation recharges soil water and is used by trees for growth and stem water. Monsoon precipitation is a key driver of growing season moisture which semiarid forest trees rely on across the Southwest, specifically aspen (*Populus tremuloides*), pinyon pine (*Pinus edulis*), and Utah juniper (*Juniperus osteosperma*). In a study conducted in northern Arizona, Samuels-Crow et al. (2023) found that these species relied primarily on intermediate-to-deep (10-60 cm) moisture both before and after the onset of the monsoon.

Wildfire can alter soil-hydraulic properties, often resulting in an increased prevalence of water infiltration-excess induced overland flow and a greater potential for debris-flow hazards. Post-wildfire debris flows are a hazard to many communities and watersheds, and many areas have a high risk for debris flows one year post-fire due to the slow recovery of soil hydraulic properties and vegetation regrowth. Following the 2021 Flag Fire in northern Arizona, burned watersheds were susceptible to debris flows during monsoon storms with low recurrence intervals in the first year following the fire, while during the second monsoon season there were no major runoff events despite more intense storms (Gorr et al. 2023a). A debris flow that initiated one month following the 2022 Pipeline Fire in northern Arizona had 28 times the volume and six times the runout distance than that of a debris flow that initiated in the same watershed following a fire 12 years earlier, due to the combined effects of two high-severity fires (Schultz Fire and Pipeline Fire) (Gorr et al. 2023b).

Quantifying the hydrologic responses to forest disturbances under climate change is important for informed planning of long-term water resource operations in the Colorado River Basin. A stakeholder-engaged modeling effort in the Colorado River Basin that combined manager feedback, climate simulations, forest treatment simulations, and fire scenarios showed improved streamflow conditions by the end of the 21st century due to greater snowpack retention and lower evapotranspiration losses. Modeling scenarios used future climate forcings that predict warmer/wetter or hotter/drier climatic conditions based on general circulation climate models, and associated land cover states with differing levels of forest thinning based on stakeholder input

(Whitney et al. 2023). This study found that forest thinning increased ground snowpack and reduced evapotranspiration under climate change leading to increased streamflow and improved average runoff and baseflow under future warmer and wetter climate conditions where winter precipitation and monsoon rains are above average and do not continue when conditions become hotter and drier than usual and aridification occurs and hydrologic shifts become evident (Whitney et al. 2023).

A sensing system, named "The Navigator," was developed to characterize surface freshwater ecosystems in order to identify water quality changes associated with land use alterations along a reach of the Rio Grande, New Mexico, and to monitor post-fire disturbances and the water quality of a recreational fishing pond in the City of Albuquerque (Khandelwal et al. 2023). The Navigator generates and shares water quality and GPS data, site specific photos, and depth surveys that can support decision making to improve environmental outcomes (Khandelwal et al. 2023). In the Jemez River Basin in New Mexico, fire severity and hydrologic regimes influence the transport of nutrients after fire, and catchments that experienced high burn severity exhibited greater solute fluxes than their less severely burned counterparts (Sánchez et al. 2023).

Models of debris flow volume are used to predict the sediment yield associated with debris-laden flows. Debris flows transport large quantities of water, sediment, and wood. Post-fire landscapes will have a larger amount of large woody debris in consequent flow events. Using field and lidar data, Rengers et al. (2023) found that sediment retention by large woody debris is controlled by the slope of the channel and a high channel flow velocity is needed to break up the large woody debris that is swept up in post-fire debris flows.

In the Chihuahuan Desert, spatial distribution of sediment in the surface soil and aeolian sediment transport are driven by post-fire microsite-scale sediment redistribution, illustrating how disturbance by prescribed fire can influence aeolian processes and alter dryland soil geomorphology in which distinct soils develop over time at very fine spatial scales of individual plants (Burger et al. 2023). In the Sonoran Desert of Arizona, precipitation has significant effects on erosion rates, where there is heightened erosion along an elevation-precipitation gradient from arid to semiarid conditions (Jeong et al. 2023).

Wildfire can alter soil-hydrologic properties and result in debris flow. In steep, recently-burned watersheds, debris flows often initiate when runoff rapidly picks up sediment in low-order watersheds and transports it downhill. In recently burned areas, hydrologic models can be used to model hazard potential and debris flows. Liu et al. (2023) used mini disk tension infiltrometers and an upscaling method to estimate watershed-scale hydrologic parameters and found that hydrologic events are a result of short-duration, high-intensity rainfall and the spatial extent of the rain event. These parameters improved the ability of a hydrologic model to identify storms that are likely to produce debris flows and to parameterize post-fire hydrologic models (Liu et al. 2023).

Wildland Urban Interface (WUI)

The WUI is growing exponentially, and there are tens of millions of homeowners in the US that are now having to confront the growing risk of wildfire. Updated policies are needed to address this risk. Resources to address infrastructure and homes in the WUI that are susceptible to wildfire events and investments in wildfire mitigation programs that protect homes are needed. Insurance markets need to be available to absorb the risk of homes in the WUI that are susceptible to wildfire (Boomhower 2023). There is also a need to address the disparities in home protection and post-fire recovery for socially vulnerable populations (Boomhower 2023).

Homes in the WUI are abundant, however many residents do not understand the risks associated with living in the WUI in fire-prone areas. Fitch et al. (2023) found a positive home sale price effect associated with proximity to the national forest, but a negative price effect associated with proximity to a recent forest restoration treatment resulting in a potential degradation of the viewshed. This illustrates that many people who live in the WUI do not understand the inherent risk of living in forested areas, nor do they appreciate that thinning and burning treatments are meant to reduce the risk of wildfire. Many WUI inhabitants care more about the viewshed than reducing the risk of wildfire near their homes.

Wildfire risks to homes are increasing, especially in the WUI, where wildland vegetation and houses are in close proximity. In the United States, more houses are exposed to and destroyed by grassland and shrubland fires than by forest fires (Radeloff et al. 2023). The number of houses within wildfire perimeters has doubled since the 1990s because of both the housing growth (47% of additionally exposed houses) and 53% more area burned. The most exposed houses were in the WUI, which grew substantially during the 2010s (2.6 million new houses were built in the WUI). Any growth of the WUI increases wildfire risk to houses, and inversely, more fires increase the risk to existing WUI houses (Radeloff et al. 2023).

Wildfire reburns across western US landscapes are increasing and have a higher occurrence in the WUI (Solander et al. 2023). The effect of human activity and regional climate variability on forest fuels are important drivers in the frequency of fire reburns. In the hotter and drier climate of the southwestern US where the likelihood of wildfire reburns is lower due to fuel limitations, the occurrence of reburns has been strongly linked to periods of higher moisture that can boost fuel loads (Solander et al. 2023). When fuels reduction and restoration treatments are evaluated and compared in a risk framework, treated landscapes have reduced fire risk compared to the untreated scenarios (Thompson and Carriger 2023).

Human sprawl and growth within the WUI impact wildlife and vegetation, and conservation needs should be assessed to protect these areas from sprawl and human development. Nearly 10% of national forest lands (143,474 km^2) are susceptible to impacts from future development on inholdings. The “America the Beautiful” initiative aims to protect 30% of land and water areas by 2030 (known as the “30x30” target). An assessment to identify conservation opportunities across the United States found that the US Forest Service (USFS) is the largest public landowner in the US, and national forest inholdings represent a large portion of land near wildland vegetation. Therefore, USFS land and land adjacent to USFS lands are important areas to conserve and protect to support landscape connectivity (Carlson et al. 2023). This assessment can inform where conservation efforts can limit impacts from development on biodiversity and identify areas for 30x30 conservation goals (Carlson et al. 2023).

Social justice issues are also part of managing wildfire risk, and identifying what is perceived as fair in terms of outcomes and processes is important. Schinko et al. (2023) developed a framework for identifying and categorizing social justice and equity within wildfire risk management that found that prevention, preparedness, response, recovery, and adaptation are crucial and widely applicable aspects of distributional, procedural and restorative justice.

Wildlife

Climate change is driving transformations in wildlife habitat and impacting aquatic ecosystems. Long-term drought conditions are reducing water reservoir levels and groundwater storage, causing depressed stream flows, and more frequent drying of stream channels across the Southwest. Native fish in the Southwest are impacted by multiple stressors, and conservation and adaptation measures should work to restore or maintain populations (Gido et al. 2023). Large, high-severity wildfires have impacts on stream ecosystems and fish populations in the upper Gila River Basin, where age-0, subadult, and adult Sonora Suckers (*Catostomus insignis*) were influenced by two wildfires in 2011 and 2012. Adult densities of Sonora Suckers were significantly lower in the years after the wildfires, and juvenile fish exhibited a lack of resistance and resilience to wildfire (Hedden et al. 2023).

In the Pinaleño Mountains in Arizona, burn severity affected the foraging behavior of small mammals where generalists, such as deer mice (*Peromyscus* sp.) and cliff chipmunk (*Tamias dorsalis*), foraged across all burn severities, while specialist species, such as tree squirrels (*Sciuridae*), avoided high severity burned patches. Researchers found that vegetation structure was an important component of foraging behavior (Morandi et al. 2023). In Mt. Graham in southeastern Arizona, Mexican woodrats (*Neotoma mexicana*) heavily used logs in low severity burned areas, whereas dense vegetation was avoided in high severity burned areas (Slovikosky et al. 2023).

Interactions between climate, soil, vegetation, and land-use can influence the amount and distribution of fine fuels across a landscape. Within the Buenos Aires National Wildlife Refuge in Arizona, fine fuels increased within the wildlife refuge boundary and had lower temperature and vapor pressure deficit, higher soil organic content, and abundant annual plants and an invasive perennial grass (Wells et al. 2023). Within the Refuge, fine fuels increased with habitat suitability for the masked bobwhite quail (*Colinus virginianus ridgwayi*) within and adjacent to core quail habitat areas, meaning bobwhite quail habitat is threatened by fuels build up where higher overall mean fine fuels exist on the landscape (Wells et al. 2023).

The Mogollon Highlands of Arizona have a diverse and unique biodiversity that includes potential grizzly bear and wolf habitat and mature old growth (DellaSala et al. 2023). Management recommendations to conserve the unique biodiversity of the Mogollon Highlands in a rapidly changing climate include at least a three-fold increase in the number of protected areas, co-management of focal species with tribes, and strategic use of fuel treatments nearest to communities (DellaSala et al. 2023).

Arthropod community composition is altered based on the size of the fire footprint and distance to forest in post-fire landscapes (Mott et al. 2023). Arthropod abundance in mulch treatments for a landscape-scale fire near Flagstaff, Arizona, and a controlled experiment outside of the larger fire footprint were sampled, and researchers found that predatory beetles were more abundant in the mulch in the large landscape treatment, with no differences in abundance in the split plots. Fungivores had no significant mulch preference, and several native bark beetles were more abundant in the untreated sites (Mott et al. 2023). In a systematic review, Afzal et al. (2023) examined methods to manage rapid bark beetle infestations and outbreaks and found that effective and eco-friendly control methods such as use of semiochemicals is necessary. Semiochemicals are the basis of communication in which chemical compounds are released by an organism and messages are sent between individuals. The review determined that push-pull semiochemical treatments – a combination of attraction and repellent—effectively reduce the bark beetle populations and is also an eco-friendly technique for forest protection (Afzal et al. 2023).

High-severity stand-replacing fire causes changes to forest insect communities and can cause some species to become extirpated in a landscape post-fire. Moth communities in both mixed conifer and ponderosa pine forest types in New Mexico changed post-fire due to changes in vegetation after the 2011 Las Conchas Fire. Moth communities in both mixed conifer and ponderosa pine forest types had significantly lower numbers of individuals, species richness and diversity, and lower evenness in burned compared to unburned forests. Reductions in moth populations were tied to reduction or elimination of available host plants (conifers, oaks, and junipers) (Brantey et al. 2023). Moth communities will continue to change with climate and fire-related vegetation changes.

Discussion

This synthesis presents the newest and best available science published in 2023 on fire and climate related topics, covering research based predominately in the southwestern and western US with the inclusion of a few nationwide studies. The goal of this synthesis is to increase the accessibility and ease of use of scientific research for land managers and other users. Some highlights from 2023 came from articles focusing on watersheds and hydrology, as post-fire flooding and related disturbances have become more common and are impacting communities across the western US. These post-fire disturbance events cause changes in surface runoff and groundwater storage, and water and debris flows can impact homes and resources in the WUI (Asif et al. 2023, Gorr et al. 2023). Watershed-level climate adaptation strategies are needed to create resilient communities, and collaborative efforts across jurisdictional lines and administrative barriers are necessary (Morgan et al. 2023).

Studies examined in this synthesis reiterate that warmer and drier conditions impact landscape vegetation, biomass, seedling success, and tree regeneration. Climate change is affecting ecosystems, and the aridification of the southwestern US is likely to continue, and decadal climate variability will not ameliorate its effects (Seager et al. 2023), meaning that warmer and drier conditions will persist in the region. Heatwaves and drought will increase the mortality of high elevation species and cause juvenile tree mortality (Lalor et al. 2023). By late-century, climate conditions will increase seedling mortality of southwestern tree species across the range and vegetation type changes will occur (Crockett and Hurteau 2023). Warmer and drier conditions will impact pine tree regeneration patterns and regeneration failure will increase in warmer climates with variable precipitation (Petrie et al. 2023). Of additional importance to land managers in the Southwest, conifers are more likely to not return to areas that have experienced high-severity fire (Davis et al. 2023, Lalor et al. 2023).

Quantifying wildfire risk is important to protect communities, ecosystems, wildlife habit, and values at risk. Fire danger indices (FDIs) that incorporate weather and fuel conditions are used to support wildfire predictions and risk assessment (Yu et al. 2023). Models of wildfire risk based on resilience, vulnerability, values at risk, and population of area can help evaluate risk at the county and community levels and provide a framework for ranking risk and safety for communities (Pishahang et al. 2023). Potential Operational Delineations (PODs) can be used to validate where thinning and burning treatments should be implemented, and Wildland Fire Decision Support System (WFDSS) can be used as a guide for decision making on complex wildfire incidents. A systematic review found that landscape fuel treatments were effective at reducing the overall amount of wildfire as well as the amount of high-severity wildfire while also leading to lower severity fire in many places (Ott et al. 2023).

These studies represent some of the varied and rich research that is available in a single year (2023) on fire and fire-related topics and will help inform management with a goal of implementing adaptation to warmer and drier conditions, reducing fire risk, improving fire incident response, conducting planning and use of prescribed fire, and understanding how fire regimes have changed with climate. The intent is that managers will be able to quickly find and digest information and have sources to locate and examine when a deeper dive into this information is needed.

Table 2: List of publications in this synthesis in 2023 by subject area.

Author	Subject Area	Study Area	DOI Link
Peeler et al. 2023	Climate Change and Carbon	Western US	https://doi.org/10.1088/1748-9326/acf05a
Crockett and Hurteau 2023	Climate Change and Carbon	Southwestern US	https://doi.org/10.1093/treephys/tpad136
Ghanbari al. 2023	Climate Change and Carbon	USA	https://doi.org/10.1038/s41467-023-39205-x
Seager et al. 2023	Climate Change and Carbon	Southwestern US	https://doi.org/10.1038/s41612-023-00461-9
Zhang 2023	Climate Change and Carbon	Southwestern US	https://doi.org/10.1016/j.aosl.2023.100340
Noel et al. 2023	Climate Change and Carbon	Southwestern US	https://doi.org/10.1111/gcb.16756
Anderegg et al. 2023	Climate Change and Carbon	USA	https://doi.org/10.1088/1748-9326/ace639
Wasserman and Mueller 2023	Climate Change and Carbon	Western US	https://doi.org/10.1186/s42408-023-00200-8
Swain et al. 2023	Climate Change and Carbon	Western US	https://doi.org/10.1038/s43247-023-00993-1
Abatzoglou et al. 2023	Fire Behavior	Western US	https://doi.org/10.1029/2022EF003471
Kaplan et al. 2023	Fire Behavior	AZ	https://doi.org/10.3390/fire6040130
Pishahang et al. 2023	Fire Behavior	AZ	https://doi.org/10.3390/fire6120449
Pokhrel. 2023	Fire Behavior	USA	https://doi.org/10.3390/f14020302
Zacharakis and Tsihrintzis 2023	Fire Behavior	USA	https://doi.org/10.1016/j.scitotenv.2023.165704
Yu et al. 2023	Fire Behavior	USA	https://doi.org/10.1029/2023EF003823
Kreider al. 2023	Fire Ecology	Western US	https://doi.org/10.1186/s42408-023-00195-2
Platt et al. 2023	Fire Ecology	Western US	https://doi.org/10.1088/1748-9326/ad11bf
Rodman et al. 2023	Fire Ecology	AZ, NM, CO, UT	https://doi.org/10.1111/gcb.16939

Fulé et al. 2023	Fire Regimes and Fire History	AZ	https://doi.org/10.1186/s42408-023-00204-4
Parks et al. 2023	Fire Regimes and Fire History	Western US	https://doi.org/10.1016/j.foreco.2023.121232
Kerhoulas et al. 2023	Fuels Reduction and Restoration	AZ	https://doi.org/10.3389/ffgc.2023.1150413
Ott et al. 2023	Fuels Reduction and Restoration	USA	https://doi.org/10.1186/s42408-022-00163-2
Parmenter and Losleben 2023	Fuels Reduction and Restoration	NM	https://doi.org/10.3390/f14061117
Petrakis et al. 2023	Fuels Reduction and Restoration	AZ	https://doi.org10.3389/fenvs.2023.1179328
Young and Ager 2023	Fuels Reduction and Restoration	AZ	https://doi.org/10.1016/j.ecolmodel.2023.110573
Springer et al. 2023	Fuels Reduction and Restoration	Southwestern US	https://doi.org/10.1111/1365-2664.14538
Tunby et al. 2023	Human Dimension of Fire	NM	https://doi.org/10.3389/frwa.2023.1223338
Cullen et al. 2023	Human Dimensions of Fire	Western US	https://doi.org/10.1111/risa.14113
Brunson 2023	Human Dimensions of Fire	Western US	https://doi.org/10.22004/ag.econ.339198
Burnett and Edgeley 2023	Human Dimensions of Fire	AZ	https://doi.org/10.1016/j.ijdrr.2023.103791
Cowan and Kennedy 2023	Human dimensions of Fire	USA	https://doi.org/10.1016/j.firesaf.2023.103851
Edgeley 2023	Human Dimensions of Fire	Southwestern US	https://orcid.org/0000-0002-7283-9812
Essen et al. 2023	Human Dimensions of Fire	USA	https://doi.org/10.1080/09640568.2021.2007861
Hjerpe et al. 2023	Human Dimensions of Fire	AZ	https://doi.org/10.1071/WF23036

Morgan et al. 2023	Human Dimensions of Fire	NM	https://doi.org/10.3389/fclim.2023.1062320
Magaragal et al. 2023	Indigenous and Cultural Fire	Southwestern US	https://doi.org/10.1098/rstb.2022.0394
Osborn 2023	Indigenous and Cultural Fire	Southwestern US	https://doi.org/10.1080/00231940.2023.2259250
Roos et al. 2023a	Indigenous and Cultural Fire	AZ	https://doi.org/10.1017/qua.2023.3
Roos et al. 2023b	Indigenous and Cultural Fire	Southwestern US	https://doi.org/10.1126/sciadv.abq3221
Rowe et al. 2023	Invasive Species	AZ	https://doi.org/10.1007/s10530-023-03080-w
Smith et al. 2023	Invasive Species	Southwestern US	https://doi.org/10.1007/s10530-023-03142-z
Barton et al. 2023	Regeneration	AZ	https://doi.org/10.1016/j.scitotenv.2023.161517
Davis et al. 2023	Regeneration	Western US	https://doi.org/10.1073/pnas.2208120120
Jung et al. 2023	Regeneration	Southwestern US	https://doi.org/10.1111/gcb.16764
Marsh et al. 2023	Regeneration	NM	https://doi.org/10.1016/j.foreco.2023.120971
Petrie et al. 2023	Regeneration	Southwestern US	https://doi.org/10.1016/j.foreco.2023.121208
Carrico and Karacaoglu 2023.	Smoke and Air Quality	NM	https://doi.org/10.3390/atmos14020316
Garg et al. 2023	Smoke and Air Quality	USA	https://doi.org/10.1016/j.firesaf.2023.103811
Kelp et al. 2023	Smoke and Air Quality	Western US	https://doi.org/10.1029/2022EF003468
Buettner et al. 2023	Suppression, Operations, and Management	CO, WA	https://doi.org/10.1071/WF23022
Fillmore and Paveglio 2023	Suppression, Operations, and Management	Southwestern US	https://doi.org/doi:10.1071/WF22206
Staley et al. 2023	Vegetation Change	Southwestern US	https://doi.org/10.1029/2023JF007266
Brown and Collins 2023	Vegetation Change	Southwestern US	https://doi.org/10.1111/gcb.16744

Fox et al. 2023	Vegetation Change	NM	https://doi.org/10.1111/jvs.13202
Lalor et al. 2023	Vegetation Change	Southwestern US	https://doi.org/10.3389/ffgc.2023.1198156
Taber and Mitchell 2023	Vegetation Change	AZ	https://doi.org/10.1016/j.foreco.2023.121019
Asif et al. 2023	Watershed and Hydrology	USA	https://doi.org/10.1007/s11269-023-03474-4
Burger et al. 2023	Watershed and Hydrology	AZ	https://doi.org/10.1029/2023JF007274
Gorr et al. 2023a	Watershed and Hydrology	AZ	https://doi.org/10.1007/s11069-023-05952-9
Gorr et al. 2023b	Watershed and Hydrology	AZ	https://doi.org/10.1002/esp.5724
Jeong et al. 2023	Watershed and Hydrology	AZ	https://doi.org/10.1080/02723646.2023.2251654
Khandelwal et al. 2023	Watershed and Hydrology	NM	https://doi.org/10.1016/j.watres.2023.120577
Liu et al. 2023	Watershed and Hydrology	AZ and NM	https://doi.org/10.1002/esp.5633
Rengers et al. 2023	Watershed and Hydrology	AZ	https://doi.org/10.5194/nhess-23-2075-2023
Samuels-Crow et al. 2023	Watershed and Hydrology	Southwestern US	https://doi.org/10.3389/ffgc.2023.1116786
Sánchez et al. 2023	Watershed and Hydrology	NM	https://doi.org/10.3389/frwa.2023.1148298
Whitney et al.2023	Watershed and Hydrology	Southwestern US, CO River Basin	https://doi.org/10.1061/JWRMD5.WRENG-5905
Thompson and Carriger 2023	Wildland Urban Interface (WUI)	NM	https://doi.org/10.3389/ffgc.2023.1266413
Solander et al. 2023	Wildland Urban Interface (WUI)	Western US	https://doi.org/10.1088/2752-5295/acb079

Carlson et al. 2023	Wildland Urban Interface (WUI)	USA	https://doi.org/10.1016/j.landurbplan.2023.104810
Schinko et al. 2023	Wildland Urban Interface (WUI)	USA	https://doi.org/10.1038/s41558-023-01726-0
Radeloff et al. 2023	Wildland Urban Interface (WUI)	USA	https://doi.org/10.1126/science.ade9223
Boomhower et al. 2023	Wildland Urban Interface (WUI)	USA	https://doi.org/10.1126/science.adk7118
Fitch et al. 2023	Wildland Urban Interface (WUI)	NM	https://doi.org/10.1016/j.landurbplan.2023.104838.
Afzal et al. 2023	Wildlife	Global w/ SW implications	https://doi.org/10.3390/insects14100812
Brantley et al. 2023	Wildlife	NM	https://doi.org/10.1093/ee/nvad068
DellaSala et al. 2023	Wildlife	Southwestern US	https://doi.org/10.3390/land12122112
Gido et al. 2023	Wildlife	Southwestern US	https://doi.org/10.1002/fsh.10912
Hedden et al. 2023	Wildlife	NM	https://doi.org/10.1894/0038-4909-67.2.133
Morandini et al. 2023	Wildlife	AZ	https://doi.org/10.3390/fire6090367
Mott et al. 2023	Wildlife	AZ	https://doi.org/10.3390/f14071421
Slovikosky et al. 2023	Wildlife	AZ	https://doi.org/10.1093/jmammal/gyad117
Wells et al. 2023	Wildlife	AZ	https://doi.org/10.1186/s42408-023-00196-1

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