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Climate change, fire management, and ecological services in the southwestern US

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ABSTRACT

The diverse forest types of the southwestern US are inseparable from fire. Across climate zones in California, Nevada, Arizona, and New Mexico, fire suppression has left many forest types out of sync with their historic fire regimes. As a result, high fuel loads place them at risk of severe fire, particularly as fire activity increases due to climate change. A legacy of fire exclusion coupled with a warming climate has led to increasingly large and severe wildfires in many southwest forest types. Climate change projections include an extended fire season length due to earlier snowmelt and a general drying trend due to rising temperatures. This suggests the future will be warmer and drier regardless of changes in precipitation. Hotter, drier conditions are likely to increase forest flammability, at least initially. Changes in climate alone have the potential to alter the distribution of vegetation types within the region, and climate-driven shifts in vegetation distribution are likely to be accelerated when coupled with stand-replacing fire. Regardless of the rate of change, the interaction of climate and fire and their effects on Southwest ecosystems will alter the provisioning of ecosystem services, including carbon storage and biodiversity. Interactions between climate, fire, and vegetation growth provide a source of great uncertainty in projecting future fire activity in the region, as post-fire forest recovery is strongly influenced by climate and subsequent fire frequency. Severe fire can be mitigated with fuels management including prescribed fire, thinning, and wildfire management, but new strategies are needed to ensure the effectiveness of treatments across landscapes. We review the current understanding of the relationship between fire and climate in the Southwest, both historical and projected. We then discuss the potential implications of climate change for fire management and examine the potential effects of climate change and fire on ecosystem services. We conclude with an assessment of the role of fire management in an increasingly flammable Southwest.

1. Introduction

Fire is an integral ecosystem process across tens of millions of hectares of forest in the southwestern United States. The region historically had a diversity of fire regimes, ranging from frequent surface fires to infrequent crown fires (Stephens et al., 2007). Over the past 3000 years, there has been a slight decline in western US fires, culminating in a sharp decline during the 20th century (Marlon et al., 2012). This recent policy-driven reduction in fire frequency has resulted in many of the forest types in this region experiencing changes in forest structure and increased fuel accumulation. As a result of fire exclusion and its effects on forest structure and fuel loads, wildfires are burning with increasing severity (Fulé et al., 2003; Miller et al., 2009), and large wildfires are increasingly frequent due to changing climate (Westerling et al., 2006).

The increase in large wildfire frequency has come with substantial economic and ecosystem service costs (Wu et al., 2011). The scope of the current wildfire problem already poses significant management challenges (Donovan and Brown, 2007; North et al., 2012). Globally, increasing temperature is projected to drive future fire regimes (Pechony and Shindell, 2010). Thus, a legacy of forest structural changes and fuel accumulation due to fire exclusion, coupled with increasing climate-driven flammability is likely to exacerbate the current wildfire issue in the southwestern US. Fire management is likely to play a crucial role in maintaining forests

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across the region, but development in the wildland–urban interface and concerns about air quality create impediments to reintroducing fire across forested landscapes. An understanding of the historical role of fire across different forest types must be combined with projections of future fire-forest type interactions to sustain ecosystem function.

Here we provide a broad synthesis of the role of fire in the diverse forest types of the southwestern US and how changing climatic conditions may influence future wildfire occurrence. The effects of changing climate on wildfire pose risks to ecosystem services that are integral for climate regulation and ecosystem function, such as carbon sequestration and biodiversity. We address some potential climate–fire interaction effects on the provision of ecosystem services. We conclude with an assessment of the role of fire management in an increasingly flammable Southwest.

2. Forest diversity in the SW

A diversity of forest types occur across the climatic and elevation gradients of the Southwest. The region has three distinct climatic types which influence vegetation distribution and fire regimes. The arid and semi-arid eastern portions of the Southwest in Arizona and New Mexico experience a bimodal precipitation distribution, with precipitation falling during winter months and the summer monsoon period. The 14.6 million hectares of forest and woodlands in Arizona and New Mexico are dominated by woodlands (*Pinus edulis*, *Juniperus* spp.) and drier forest types: ponderosa pine (*Pinus ponderosa*) alone or mixed with Gambel oak (*Quercus gambelii*) (19%) and mixed conifer (5%). Mixed conifer forests include white fir *(Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*), and southwestern white pine (*Pinus strobiformis*) in addition to ponderosa pine. Mesic forests of aspen (*Populus tremuloides*), Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*) are restricted to the highest elevations and comprise only 3% of the forested area. In Nevada, the intermountain west climate is characterized by cold winters, warm summers, and the majority of precipitation falling in winter and spring. Forests and woodlands occupy approximately 4 million hectares in Nevada. Forest types are a function of the basin and range geology of the state, with conifer forests and madrean oak and pine forests occupying the higher elevation ranges and the basins occupied by piñon-juniper woodlands, shrublands, and grasslands. In contrast, California has a Mediterranean climate with cool, wet winters and warm, dry summers. Characterized by a diversity of vegetation types, approximately one-third of the California's 40 million ha are forested. Forest types range from oak savannas at lower elevations to subalpine forest at high elevation in the Sierra Nevada Mountains.

3. Climate–fire interactions

In these primarily fuel limited systems, prior year precipitation is the primary determinant of the area burned by wildfire (Littell et al., 2009). Fire seasonality is largely attributed to annual precipitation patterns, with inter-annual fire activity influenced by the El Niño/Southern Oscillation (ENSO) (Swetnam and Betancourt, 1990). Historic fire seasonality, estimated from the relative location of fire injuries within the growing period of tree rings, tended to peak in spring and early-summer where the southwestern monsoon precipitation pattern is prevalent and in mid- to late-summer where the prevailing climate is Mediterranean (Baisan and Swetnam, 1990). The modern fire season also peaks during this time. Aside from seasonality, annually resolved fire records from over 400 years of tree-ring data also showed that climate synchronized fire occurrence across the Southwest, with up to half of study sites in Arizona and New Mexico burning in major fire years such as 1748 or 1851 (Swetnam and Brown, 2011). These fire events were significantly correlated with drought and the La Niña phase of the Southern Oscillation (Swetnam and Brown, 2011). Fires are also associated with La Niña conditions in the southern Sierra Nevada (Kitzberger et al., 2007; Trouet et al., 2010) and widespread and synchronous fire across vegetation types in California (Taylor et al., 2008; Westerling and Swetnam, 2003). While La Niña results in dry periods throughout most of the Southwest, this pattern is reversed in northern California, creating a weak association between El Niño and fire in the northern Sierra Nevada and southern Cascade Mountains of northern California (Taylor et al., 2008; Valliant and Stephens, 2009; Trouet et al., 2010).

Broad geographic patterns in fire activity determined by climate are refined across vegetation types. The high frequency of past fire events in the dry forest types of the Southwest, even during comparatively cool and moist periods (Beaty and Taylor, 2008), indicates that these systems occur in areas where climate and fuel conditions predispose them to being fire adapted. Forests dominated by ponderosa pine experience one of the most frequent fire return intervals.

Historic fire regimes of ponderosa pine forests of the Southwest are among the best studied in the world, due to the extensive record of fire-scarred trees and the pioneering application of dendrochronology to determine fire dates. Abundant charcoal has been associated with the arrival of ponderosa pine at the formation of modern southwestern vegetation in the Holocene, beginning around 13,000–11,000 years before present (Anderson et al., 2008; Weng and Jackson, 1999). Fires recurred at mean intervals between 2 and 16 years across the southwestern network of study sites examined by Swetnam and Baisan (1996). Using only "widespread" fires, those dates scarring 25% or more of the sampled trees, the mean intervals ranged from 4 to 36 years (Swetnam and Baisan, 1996). Frequent surface fires maintained relatively open forests of large trees with grassy understories by limiting regeneration establishment (Cooper, 1960; Covington and Moore, 1994), keeping the fuel complex resistant to severe burning. Traits of ponderosa pine, including thick bark, large buds, and the capability to recover from crown scorch, are highly adaptive for the frequent surface fire regime, reflecting the evolutionary history of this species in fire-prone, semi-arid environments (Keeley and Zedler, 1998).

Mixed conifer sites burned less frequently than ponderosa pine, but fires still recurred in mean intervals ranging from 3 to 25 or 10 to 26 years for widespread fires (Swetnam and Baisan, 1996). This decreasing fire frequency is in part driven by an increase in precipitation at higher elevations, influencing both fire type and frequency. Fire regimes in mixed conifer forest in Arizona and New Mexico historically reflected a transition from frequent surface fires at lower elevation to infrequent, stand-replacing fires at higher elevation. Fire regimes have been reconstructed over the entire elevational gradient of forest types in Grand Canyon National Park, Arizona (Fulé et al., 2003), and the Sangre de Cristo Mountains, New Mexico (Margolis and Balmat, 2009). At both sites the length of fire return intervals increased with increasing elevation, and fire events were synchronized across ponderosa pine and mixed conifer in years with drier climates. The infrequent fires in the spruce-fir forests found at higher elevations burned during years of exceptional drought at multi-century intervals (Margolis and Balmat, 2009; Margolis et al., 2011). Historic mixed conifer forest structure was more dense than that of contemporaneous ponderosa pine forests (Lang and Steward, 1910), but was significantly less susceptible to severe fire than modern mixed conifer forests (Fulé et al., 2003).

As in Arizona and New Mexico, historic fire frequency decreased with increasing elevation in California. Mixed conifer forests