Past and present fire regimes of the Grand Canyon

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Abstract

Ever since the appearance of terrestrial plants, fire has been a dominant process in shaping biodiversity across the globe, including the arid southwest landscape of the United States. Fire influences carbon and nutrient cycling and ecosystem function, yet increasingly destructive wildfires due to fire exclusion pose severe risks to fire-dependent ecosystems. The Grand Canyon is generally recognized for its geological significance and beauty, but the historic pattern of fire (henceforth, fire regime) is a critical component to the health and resilience of the Grand Canyon's diverse vegetation types. Most recently, the historic fire regimes of the Grand Canyon have been disrupted due to climate, grazing, and complete fire suppression. However, progressive land management in the area is working to restore these natural fire regimes. This paper will review the historic fire history of the complex mosaic of forest communities across the Grand Canyon, and how these fire regimes have changed over time.

Introduction

Fire is a process that has operated on Earth for millions of years, and influences vegetation distribution, the carbon cycle, and climate (Bowman et al. 2009). It is a dynamic ecological process that shapes the composition of vegetation, however, due to a changing climate, altered land management practices, and increased urbanization we are seeing a shift in the natural fire regime across the globe (Westerling et al. 2006; Abatzoglou and Williams 2016; Lohman et al.

2007; Marlon et al. 2013). These changing fire regimes pose enormous threats to biodiversity, human health, and the economy (Steel et al. 2019; Lohman et al. 2007).

A fire regime refers to the variation of fire activity and fire effects over a given area, including the frequency, size, seasonality, intensity, severity, type, and mode of combustion (McLaughlin et al. 2020). There is an immense diversity of fire regimes on earth, each with diverse species that have evolved to withstand a certain pattern of fire characteristics. Detecting and quantifying variation in fire regimes is vital for understanding and predicting the ecological consequences of shifts in the historical fire regime. Palaeoecological proxy archives are a primary way to determine past fire activity (McLaughlin et al. 2020). These proxies include identifying fire scars in tree rings, stand age data, and charcoal particles preserved in lake sediment or ice cores. Fire scar methods rely on nonlethal cambial injury created by surface fires and can be cross dated to the exact year of injury. Stand age data relies on the formation of distinct postfire cohorts following a stand-replacing fire. These methods used together can provide the most information about the fire history of a certain area.

The historic fire regimes of the western United States, including the Colorado River Basin, have been disrupted due to climate (Westerling et al. 2006), intensive grazing, and complete exclusion of fire (Stephens et al. 2003). In forested ecosystems across the western United States, we have seen a shift from local controls, including fuel availability and ignitions, to more regional controls, such as climate (Metlen et al. 2018). Areas that historically experienced frequent low- to mixed-severity fires (e.g., mixed conifer forests) are now experiencing an increase in high-severity fires, transitioning the landscape to a new stable state (Hessburg et al. 2016).

Fire regimes of the Grand Canyon National Park

The Grand Canyon is recognized as a place of significant and universal value, harboring scenic qualities, recreational opportunities, and a multitude of cultural and natural resources. Located on the Colorado Plateau, the region is characterized by plains, basins, and canyons, with elevations ranging from over 9,000 feet near the North Rim to 1,000 feet at the river's western end. Generally, we find that elevational gradients affect fuel moisture, ignitions, vegetation composition, and productivity thereby influencing fire (Fule et al. 2003). In the Grand Canyon, vegetation types are distributed across an elevational and topographic-moisture gradient (GCNP 2012). The five major vegetation types most affected by fire in this area are spruce-fir forests, mixed-conifer forests, montane-subalpine grassland, ponderosa pine forest, and pinyon-juniper woodlands. Fire has been a dominant part of these habitat types for thousands of years. The interaction between lightning activity during warm, dry periods and fuel is the main source of fire ignitions and fire spread in this region (Swetnam and Betancourt 1990). However, each dominant vegetation type has a different historic fire regime.

Spruce-fir forests

The highest-elevation forests are the least common coniferous forest in the southwest and are dominated by Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa)*, and quaking aspen (*Populus tremuloides)* (Moir 1979). These forests generally show topographically distinct burning patterns and generally had less frequent, mixed-severity fire every 35-100+ years with a mix of passive crown fire under appropriate weather conditions and small surface fires, especially on the drier south and west-facing slopes. Dominant tree species have low fire tolerance, so stand-replacing fire effects are generally expected in this vegetation type. Site-specific reconstructions by Fule et al. 2003 indicate that these forests generally had an average basal area of 10 m^2/ha and 150 trees/ha. Since these forests are far away from human habitation, there has been generally a small effect of Euro-American settlement of these spruce-fir forests. Despite this, tree age data from White and Vankat (1993) show an increase in total density since 1880.

Mixed-Conifer and ponderosa pine Forests

With a decrease in elevation, there is a transition from high-elevation forests to mixed-conifer forests. These forests comprise a mosaic of patches dominated by ponderosa pine (*Pinus ponderosa var. scopulorum)*, Douglas fir (*Pseudotsuga menziesii)*, white fir (*Abies concolor)*, blue spruce (*Picea pungens)*, and quaking aspen (*Populus tremuloides)*. Moving even further down in elevation, mixed-conifer forests transition gradually into ponderosa pine-dominated forests. Frequent low-intensity surface fires from lightning and Native Americans generally burned these forests until the disruption of the fire regime in 1880 (Figure 1; Wolf and Mast 1998, Fule et al. 2000, Fule et al. 2003). The mean fire return interval (MFI) for this area was 5-10 years for low-elevation mixed conifer/ponderosa pine forests and 6-16 for higher-elevation forests. Mixed-conifer forests experienced a mixed-severity fire regime with mainly low-intensity surface fire and some individual and group tree torching occurring in some areas. Ponderosa pine, on the other hand, generally experienced only low-intensity surface fire. The return interval for each forest type varied with topography, with south aspects generally having a shorter MFI than northern aspects. The dendrochronological record shows a correlation between large fires and drought years, specifically drought years followed by wet years (Fule et al. 2003).

Indigenous people played an important role in shaping fire regimes across the southwest, especially in mixed-conifer and ponderosa pine forests. The lower elevations of the Grand Canyon were densely populated by Indigenous tribes - the Paiute, Hopi, Havasupai, Hualapai, Navajo, and Zuni (Altshul and Fairley 1989). These tribes altered fire frequency and fuel availability in lower-elevation mixed-conifer and ponderosa pine forests by altering ignition patterns to clear vegetation for fields, forage, and drive game (Carter et al. 2021). Further, indigenous burning has been shown to obscure the role of climate on the fire regime. During the peak of Indigenous farming, frequent fire was used to reduce surface fuels thus mitigating the possibility of large fires during periods of extreme drought (Carter et al. 2021).

Disruption of this fire regime by Euro-American settlement led to full-on fire suppression of wildland fire. Historically, these forests were generally quite open creating a heterogenous landscape with a mosaic of individual trees, clumps of trees, and wide openings giving rise to herbaceous plants (Larson and Churchill 2012). However, fire suppression increased the density of mesic, shade-tolerant species (including white fir), reduced shade-intolerant species adapted to this fire regime (*Pinus ponderosa*) and increased the fuel loading thus increasing the probability of high severity, more contiguous fire (Fule et al. 2003, Fule et al. 2004). The expansion of white fir poses an issue since these young trees outcompete larger, more fire-resistant pine trees for water and nutrients (Mast and Wolf 2004).

Pinyon-Juniper Woodland

Often with very patch distribution, pinyon-juniper woodlands are at the lowest elevation and are dominated by pinyon pine (*Pinus edulis)* and Utah juniper (*Juniperus osteosperma).* This is a dominant vegetation type across the southwest (Brown 1994) and can vary in species composition due to climate and soil characteristics (West 1999). Due to these differences, this vegetation type can have variable fuel structure and potential fire regimes (Huffman et al. 2008). These species are typically not fire-resistant, and we find patchy, high-severity fires occurring in these woodlands every 400-600 years (Floyd et al. 2000; Huffman et al. 2008). Historically, these areas would have stand-replacing fire with high tree mortality followed by tree recruitment and establishment. Fire is undoubtedly an important component of pinyon-juniper woodlands, but there is still some uncertainty in these systems. Due to their high-severity nature, stand age data is the best way to document the temporal and spatial characteristics of fire. Although general trends are generally known, this is the least understood vegetation type.

Due to the infrequent fire rotation, forest condition is generally similar to historic conditions with few effects from fire suppression. Despite this, this vegetation type is threatened by drought as well as invasion by cheatgrass and other invasive species (Flake and Weisberg 2021). Cheatgrass (*Bromus tectorum)* is a highly fire-dependent species that creates a larger and more continuous fuel bed that has a higher ignition probability.

Montane grasslands

Montane grasslands are another important ecosystem across the Colorado Basin and occur throughout all forest types - from pinyon-juniper woodlands to high-elevation subalpine forests. Typically, these grasslands are dominated by native bunchgrass, including fescue (*Festuca* spp.), muhly (*Muhlenbergia* spp.), and oatgrass (*Danthonia* spp.), as well as many other native forbs and graminoids (Coop and Givnish 2007). Although they only cover less than 2% of land area in the Grand Canyon (Warren et al. 1982), they provide key ecosystem services, from processing water and nutrients to providing habitat for species (Falk et al. 2011). Soil, temperature, and precipitation are all driving forces in determining the distribution of montane grasslands, but fire is one of the most dynamic disturbance processes regulating the location of montane grasslands. Tree ring samples collected from the ecotone between these montane grasslands and forest have shown high fire frequency in these grasslands, with a mean fire return interval between 1-7 years (Falk et al. 2011). Similar to mixed conifer and ponderosa pine forests, fires generally occurred during drought years with the most widespread fires occurring during drought years that followed years with cool-wet conditions.

During the past century these grasslands have been reduced in size, and in some cases completely eliminated, due to conifer and aspen encroachment (Brown 1994). Montane meadows of the North Rim of the Grand Canyon have been encroached by a combination of aspen, spruce, subalpine fir, and white fir, with over 90% of these trees established after the mid-1930s (Moore and Huffman 2004). Further, there is little evidence of historical tree occurrence (snags, stumps, downed woody debris) inside meadow interiors. This data suggests that following fire regime disruption around 1879, these meadow habitats have been dwindling in size due to the encroachment of montane tree species. Some high-elevation subalpine meadows were thought to persist indefinitely without invasion of tree species in areas where soils are extremely rocky or gravelly or remain saturated during the growing season (Mead 1930). However, more recent studies have shown significant tree establishment in these sites suggesting that these meadows could be completely replaced by forest habitat within the next few decades (Moore and Huffman 2004).

Management Implications

Mixed conifer and ponderosa pine forests have been one of the most altered forest types of the Grand Canyon. Decades of grazing and fire exclusion after euro-American settlement throughout the southwest led to uncharacteristically large, homogeneous wildfires in these forest types. As such, there have been subsequent changes in fire policy and management. By the late 1960s, there was a push to return fire to fire-dependent ecosystems in an attempt to restore these forests to their state prior to Euro-American settlement. By 1978 Grand Canyon National Park decided to promote and conduct prescribed burns across these forests to reduce fuel loads during the time of year when moisture and humidity minimize the risk of catastrophic fire. A new fire management plan was created in 1992 that started using more prescribed and managed wildfires, which are lightning-caused fires allowed to burn relatively freely (Fig. 2). Prescribed fire and managed wildfires are used as a tool to restore resilience to fire-dependent forests by reducing surface fuel loads and restoring spatial heterogeneity to the landscape. In the Grand Canyon, managed wildfires and prescribed fire have been successful at maintaining and creating heterogeneous landscape conditions as well as increasing species that are more fire- and drought-tolerant (Stoddard et al. 2020).

Due to the long fire-free intervals in pinyon-juniper woodlands, there have not been significant effects of 20th-century fire suppression. Unlike mixed conifer and ponderosa pine forests, prescribed burning and mechanical thinning of these woodlands would not restore these areas but rather cause long-term damage and exacerbate the invasion of invasive species. To retain the natural fire regime of pinyon-juniper woodlands, control of invasive species, specifically *Bromus tectorum,* is the primary management concern (Kennard & Moore 2012).

Conclusions

Fire is a fundamental component of the Grand Canyon's forested ecosystems. Yet with the advent of Euro-American settlement, the natural fire regimes of the Grand Canyon's diverse mosaic of vegetation have been disrupted. As such, extensive research has been conducted in this area to understand the diversity of fire regimes in this region, and how these have changed with the exclusion of fire, intensive grazing, and a changing climate. Generally, we find no significant effects of 20th-century fire suppression in forests with historically long fire-free intervals (spruce-fir, pinyon-juniper), however, we are finding shifts in the natural fire regime and species composition in forests that historically had a frequent fire regime (mixed conifer, ponderosa pine, & montane grasslands).

The effects of changing fire regimes not only have detrimental effects on ecosystem resilience and natural resources, but they also pose a major concern on water quality and quantity. Wildfires alter runoff and erosion rates, thus impacting site productivity, peak flows, water quality, and reservoir sedimentation (Moody and Martin 2001, Smith et al. 2011). Forests are generally recognized to produce clean water and limit flooding due to the lack of bare soil and high water infiltration rates (National Research Council 2008). Uncharacteristically high-severity fires shift normal subsurface flows to overland flows, reducing infiltration rates (Rocca et al. 2014). Reduced infiltration rates deposit much more coarse mineral sediment and degrade water quality due to the suspension of ash and finer particles (Moody and Martin 2001). In contrast, low-severity fires have minimal effects on runoff and erosion rates due to the limited removal of the forest canopy. The impacts of increasingly high severity wildfires are exacerbated by the fact that these historically frequent-fire forests generally have higher annual rainfall and rainfall erosivity compared to spruce-fir forests and pinyon-juniper woodlands (Renard et al. 1997).

With an increase in hotter and drier conditions with climate change, substantial increases in the area burned across the western US are expected (National Resource Council 2011). Alternative fire management approaches are imperative for returning the natural fire regime to forests that have been significantly altered by fire exclusion (mixed-conifer and ponderosa pine forests). In the Grand Canyon, restoration treatments have been shown to restore reference conditions of forest structure and decrease crown fire susceptibility (Fule et al. 2001). These treatments include thinning trees to emulate stand structure prior to fire regime disruption, forest floor fuel treatment, and prescribed burning. Restoring natural fire regimes have been shown to increase drought tolerance and build ecosystem resilience to climate change.

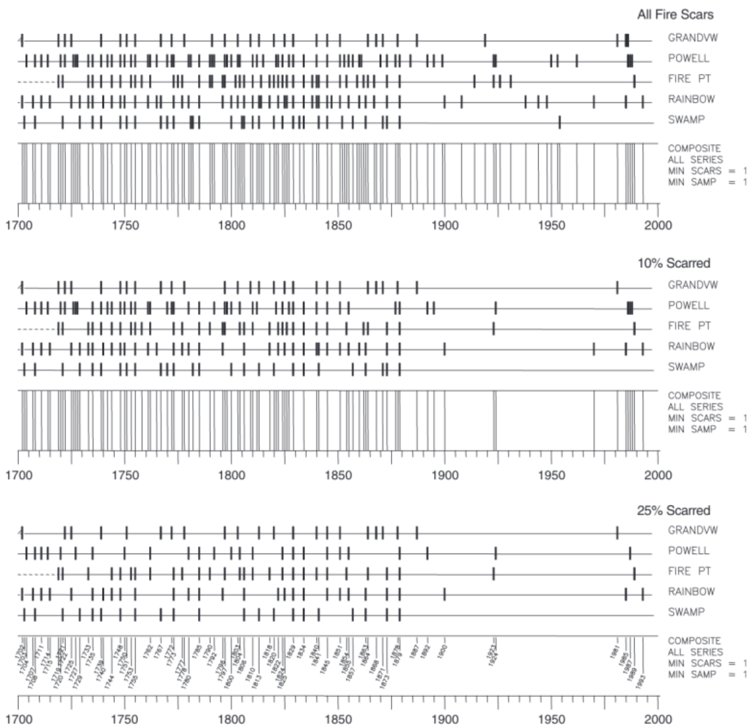

Figure 1: Fire history of mixed conifer and ponderosa pine-dominated forests of The Kaibab National Forest from Fule et al. 2003. Each horizontal line represents the composite of all sampled trees on a site, and the short vertical lines note the year of fire occurrence. The top figure shows all fires, even if the fire scared only one tree, the middle figure shows fires burning 10% or more of the sample trees, and the bottom figure shows fires burning 25% or more of the sample trees.

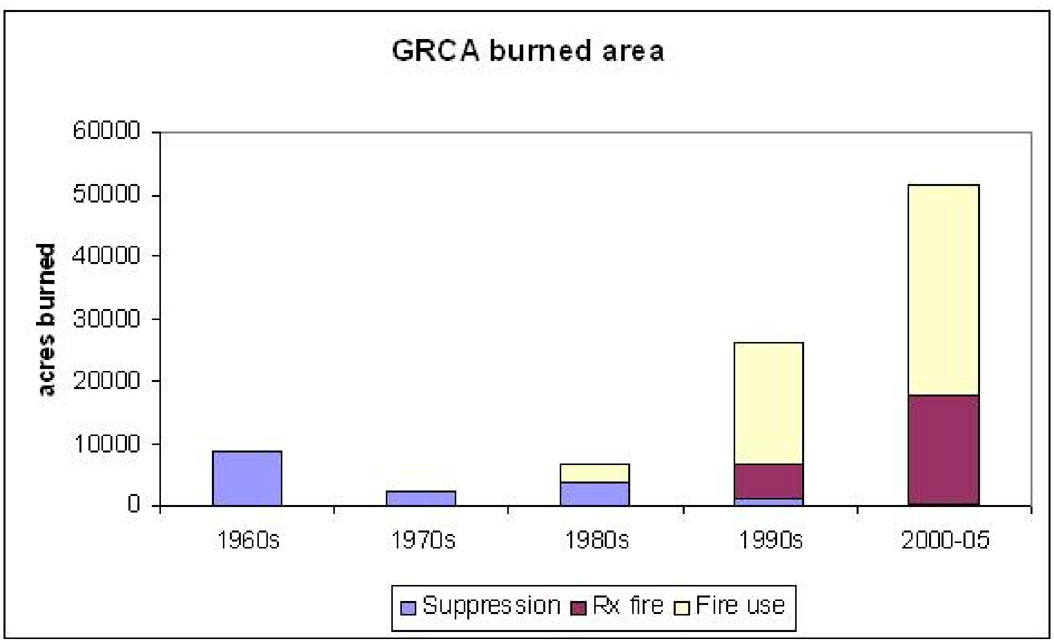

Figure 2: An increase in prescribed fire (Rx fire) and managed wildfire (Fire use) burned area in Grand Canyon National Park since 1960. Adapted from Stephen Pyne

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