Chapter 11
Fire Ecology and Management of Southwestern Forests

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Abstract Forests in the southwestern USA are well adapted to dry conditions. High lightning incidence, long human habitation, and frequently windy conditions make the Southwest stand out for a high pace of burning. Forests are structured by climatic gradients created by elevation and topography. Low-elevation woodlands experience the driest conditions, but low productivity limits fuels. At the other extreme, high-elevation forests produce abundant fuels but are rarely dry enough to burn. The "sweet spot" in the middle elevations, dominated by pines and other mixed conifers, is characterized by frequently recurring weather conditions suitable for fire, and has a contiguous fuelbed of litter and herbaceous plants. This makes for one of the most frequent fire regimes in the world, comprised primarily of surface fire. Prior to Euro-American settlement, Native Americans used fire and co-existed with the landscape's fire regime, but colonists brought different perspectives and land uses, excluding fire from most southwestern forests for well over a century. Severe fires are becoming larger, threatening people and structures as well as ecosystem sustainability. Coupled with several recent decades of steadily warming temperatures and much hotter scenarios predicted through the twenty-first century,

Ecoregions 22, Arizona/New Mexico Plateau; 23, Arizona/New Mexico Mountains; 24, Chihuahuan Deserts; 25, High Plains; 26, Southwestern Tablelands; 79, Madrean Archipelago; 81, Sonoran Basin and Range

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future southwestern forests are likely to be drastically altered by interacting effects of wildfire, biotic disturbances, and drought.

Keywords Arizona · New Mexico · Climate · Wildlife · Red hats fire crews

11.1 Overview of Southwestern Forests and Fire Regimes

The Southwestern USA (SWST) is the driest and hottest region of the country. It is noted more for ancient cultures and remarkable deserts than for forests, but southwestern forest ecosystems provide critical services and foster extraordinary biodiversity (Fig. 11.1). Here, we consider the "SWST" to be the states of Arizona and New Mexico, but much of this information is applicable to adjacent parts of southern Utah and Colorado, far west Texas, and the northern region of the Mexican states of Sonora and Chihuahua.

Moisture associated with higher elevation and cooler temperatures controls the pattern of forest vegetation in the SWST. This region is associated with steep, rugged elevational gradients that range nearly four vertical km, from nearly sea level at San Luís, Arizona, to 4014 m at Wheeler Peak, New Mexico. Tree species considered in this chapter occupy the higher elevations from 1200 m to >3350 m, but it is important to note that lower elevations support gallery forests (called *bosques*) of cottonwoods (*Populus* spp.) and willows (*Salix* spp.) along streams, extensive savannas of oak (*Quercus* spp.) and mesquite (*Prosopis* spp.), and desert trees such as paloverde (*Parkinsonia* spp.). Beginning as low as 1050 m, juniper woodlands interlace with desert grasslands. Continuing upward past approximately 1200 m, pinyon pine (*Pinus edulis*) co-occurs with junipers (*Juniperus* spp.), forming the pinyon-juniper woodlands that comprise the largest forest cover type by area, with 8.4 million ha in Arizona and New Mexico (O'Brien 2002, 2003). Large-stature forests make up about 5.6 million ha in the two states. Forests cover continuous highlands in large plateaus (Mogollon Rim, Kaibab Plateau, Jemez Mountains), the southern extension of the Rocky Mountains (Sangre de Cristo range), and isolated ranges referred to as "Sky Islands" which often support endemic species (Mt Graham, Chiricahua Mountains). Ponderosa pine, often with a strong presence of Gambel oak (*Q. gambelii*), occupies highlands between approximately 1980–2400 m. Mesic conifer species increase at higher elevations, forming mixed conifer forests with Douglas-fir, southwestern white pine (*P. strobiformis*), aspen, and white fir (*Abies concolor*), grading above approximately 2900 m into the coolest and wettest forests dominated by Engelmann spruce (*Picea engelmannii*) and subalpine fir (*A. lasiocarpa*) up to timberline around 3350 m on the tallest peaks. The pioneering scientist C. Hart Merriam observed that the steep elevational gradients of the SWST bring together in close proximity ecosystems that otherwise are spread out from Mexico to Canada. His "life zone" categorization (Merriam 1890)

Fig. 11.1 Clockwise from top left: (**a**) From the 3652-m peak of Sierra Blanca on Mescalero Apache tribal lands in southern New Mexico, high-elevation spruce and subalpine fir comprise a cool forest island high above the Chihuahuan desert in the background. The fire regime of the spruce-fir forest consisted historically of infrequent, high-severity fires. Contemporary fires may increase in size and severity due to warming climate, insect-caused tree mortality (brown trees in the image), and accumulated continuous fuels; (**b**) Old ponderosa pines at approximately 2000 m elevation on the Navajo Nation forest, Chuska Mountains, at the Arizona-New Mexico border. The fuel structure of patches of trees with thick bark and lifted crowns interspersed with grass is consistent with a self-reinforcing regime of high-frequency, low-severity fires; (**c**) Fire managers ignite fuels next to a road on the North Rim of Grand Canyon National Park, Arizona. Dominant trees at this elevation, approximately 2400 m, are ponderosa pines but extended fire exclusion led to increased density of shade-tolerant Douglas-fir and white fir, creating fuel ladders. Managers integrated a complex of lightning-ignited and management-ignited fires to burn nearly 7900 ha in a strategy aimed at reintroducing fire's ecological role (Fulé and Laughlin 2007) (photo National Park Service), and; (**d**) Tree mortality and severe erosion 2 years after the Schultz Fire (2010) in the San Francisco Peaks, Arizona. Dense trees, steep slopes, and strong winds fanned an abandoned campfire to burn 6100 ha, about 40% at high-severity. No structures were burned but postfire flooding killed one person and caused millions of dollars of damage to houses and highways below. The potable water pipeline for the city of Flagstaff, running beneath the road shown in the image, elevation approximately 2450 m, was exposed in 17 places and severed in one

remains a useful ecological organizing concept, even as warming climate is causing rapid shifts in species´ ranges (Brusca et al. 2013).

SWST montane climate is dominated by winter snow and summer monsoon rains, separated by dry periods in the fall and spring. Warm, dry, and often windy conditions from May to early July define the peak of the wildfire season, but the fire season can extend from April to October. A key climatic link to fire is the El Niño-Southern Oscillation (ENSO), a phenomenon of Pacific Ocean temperatures and air pressures affecting the position of the jet stream that brings winter moisture. During El Niño events, the jet stream takes a southerly route, transporting multiple storms over the SWST. Wet El Niño winters help keep fuel moisture higher and limit forest burning, although deserts may experience higher fire spread due to good growth of annual grasses. When the 2–7-year-long ENSO cycle switches to La Niña, the jet stream moves north and the SWST experiences dry, high-pressure winter weather, leading to dry fuels and high fire activity (Swetnam and Baisan 1996). Fire seasons in the SWST are also strongly influenced by the North American monsoon which typically brings summer rains in July and August (Griffin et al. 2013).

Forests and woodlands in the SWST provide valuable habitat for wildlife species. The animal-ecosystem evolutionary tie can be so strong that some animals share a common name with the forest type. For instance, in the pinyon-juniper woodlands, key wildlife species include the pinyon jay (*Gymnorhinus cyanocephalus*), pinyon mouse (*Peromyscus truei*), black-tailed jackrabbit (*Lepus californicus*), and ringtail (*Bassariscus astutus*) (Brown 1994). The pinyon jay, a noisy, nomadic bird, co-evolved with the pinyon-juniper woodlands. Although omnivorous, this species primarily eats pinyon seeds. In flocks of up to 500, they descend on an area, searching for, feeding on, and caching seeds with some "forgotten" seeds sprouting to establish new trees (The Cornell Lab 2020). Other species such as elk (*Cervas elaphus*) and mule deer (*Odocoileus hemionus*) use pinyon-juniper woodlands seasonally, for winter habitat, avoiding the colder temperatures and deep snow that can occur at higher elevations.

Key wildlife species of ponderosa pine forests include the Abert's squirrel (*Sciurus aberti*) and Grace's warbler (*Setophaga graciae*) (Brown 1994). Grace's warblers use mature ponderosa pine forest and Abert's squirrels use a range of tree sizes, but both species are dependent on ponderosa pine (Patton 1984). The Abert's squirrel feeds on the seeds, inner bark, terminal buds, and pollen cones of ponderosa pine and even selects nest trees by specific chemical features (Snyder and Linhart 1994). Abert's squirrels will also nest in Gambel oak and feed on acorns and the presence of Gambel oak in ponderosa pine forests affects wildlife species diversity. The southwestern myotis (*Myotis auriculus*), a small bat species, forages in pine-oak and roosts in cavities in large Gambel oak trees but is not commonly observed in forests comprised of only ponderosa pine (Bernardos et al. 2004). Other species such as the pygmy nuthatch (*Sitta pygmaea*), porcupine (*Erethizon dorsatum*), and black bear (*Ursus americanus*) are common inhabitants of pine-oak systems (Brown 1994).

Animals associated with mixed conifer and aspen forests include common species such as elk, mule deer, black bear, and porcupine as well as species that are more selective for this forest type. Aspen adds value as forage for some species (Bailey and Whitham 2002); it is sometimes called "ice cream" for ungulates such as elk and mule deer. The red squirrel (*Tamiasciurus hudsonicus*) relies on cool coniferous forests, creating middens where they store cones for food. The long-legged myotis (*M. volans*), an insectivorous bat, forages on moths, flies, and other insects. In summer, they form maternity roosts in conifers that may consist of hundreds of females and their pups (Brown 1994; IUCN 2020). The red-naped sapsucker (*Sphyrapicus nuchalis*) is a woodpecker that drills holes, often in parallel rows, into the inner bark of trees such as aspen and Douglas-fir to allow sap flow to the tree's outer bark. They lap up the sap but also feed on insects that get caught in the sap. The Mexican spotted owl *(Strix occidentalis lucida*) prefers ponderosa pine/Gambel oak forests as well as mixed conifer stands. Within their range, most nests occur in mistletoe brooms or cavities in large Douglas-fir and white fir trees (Ganey et al. 2000). In the early 1990s this species was originally listed as Threatened under the Endangered Species Act (ESA) because of how late successional forests were being managed but now stand-replacing wildfire is considered a greater threat.

Birds such as the Canada jay (*Perisoreus canadensis*), ruby-crowned kinglet (*Regulus calendula*), and red-breasted nuthatch (*Sitta canadensis*) are common to cool, high-elevation spruce-fir forests. Canada jays are omnivorous but use a special saliva for packing and storing food in trees. Ruby-crowned kinglets and red-breasted nuthatches are small birds that, during winter, can join as a mixed flock to help find food (the "more eyes" principle) (The Cornell Lab 2020). These forest types, from pinyon-juniper to spruce-fir, support hundreds to thousands of invertebrate and vertebrate species, many more than are addressed here.

Fire regimes are regulated by the interaction of the components of the fire regime triangle (Parisien and Moritz 2009): vegetation (fuels), climate, and ignitions. Fuels and climate are inversely related, with the highest production of fuel occurring in the wettest environments, especially the high-elevation forests of spruce, fir, and aspen trees. These ecosystems are productive, with aboveground net primary productivity >1000 g/m^2/year (Whittaker and Niering 1975), but fires are infrequent because the typically moist environment limits fire spread except in unusually dry and hot conditions. Reconstructions of past fire regimes using charcoal and sediment data reaching back for several thousand years (Anderson 1993; Weng and Jackson 1999), and more detailed tree-ring data covering several hundred years (Margolis and Swetnam 2013), show that these forests tended to experience infrequent, severe fires, burning every one- to several centuries at lethal intensity, largely as crown fires. At the other climatic extreme, low-elevation woodland environments are commonly dry enough to support fire propagation but have limited productivity (<100 g/m^2/year). Some woodlands form savannas with grassy understories, providing continuous fine fuels that likely supported relatively frequent surface fire regimes (Romme et al. 2009), but many woodlands are tree-dominated with sparse surface fuels, resulting in a patchy regime of infrequent, severe fires pushed by strong winds (Huffman et al. 2008). The "sweet spot" for frequent fire occurrence lies between the climatic extremes at mid elevations, where ponderosa pine and dry mixed conifer forests receive enough moisture to form abundant fuels (400–800 g/m^2/year) including sufficient continuous grass and needle litter to carry surface fires, but where dry, warm, windy conditions recur nearly every summer. Fire frequency in these forests ranged from as often as an average of every 2 years to 1–2 decades between fires, predominantly with non-lethal surface fire behavior (Swetnam and Baisan 1996).

As a powerful disturbance agent throughout the evolution of forest species, fire is associated with many adaptive traits of the species occurring in distinct fire environments. Ponderosa pine and Douglas-fir are highly resistant to surface fires due to their thick bark (Stevens et al. 2020), while aspen and oaks are readily topkilled but can resprout vigorously from roots (Chap. 9). Grasses are particularly influential surface fuels in the SWST. They grow from ground-level meristematic tissues so the loss to fire of the aboveground leaves can be quickly replaced, making grassy savannas very quick in restoring fuels. The loss of grass fuels to overgrazing by livestock in the nineteenth century led to widespread fire cessation in forests (Cooper 1960). In contrast, the artificial propagation of non-native grasses like buffelgrass (*Pennisetum ciliare*) for forage and erosion control in the twentieth century brought fire into desert ecosystems where native species such as the emblematic saguaro cactus (*Carnegiea gigantean*) lacked survival adaptations (Stevens and Falk 2009).

Wildfire can have direct and indirect effects on wildlife. Many animals directly exposed to fire can physiologically tolerate temperatures up to 50 °C for short periods. Some species possess adaptations that allow them to escape fire through avoidance (insulating fur, aestivation, burrowing) or greater mobility (ability to move into refugia such as wet sites or areas outside the fire). Thus, the primary effect of fire on animals is usually indirect, with the abrupt alteration or loss of habitat (Whelan 1995).

Habitat changes can be positive, negative, or neutral, depending on the animal's habitat requirements and fire severity (Lowe et al. 1978; Smith 2000). Wildfire affects habitat across scales, from fine-scale elements such as coarse woody debris, litter, understory vegetation, or snags (by altering rates of formation, density, and distribution) to landscape patterns that influence habitat patch density, dispersion, and connectivity (Dickson et al. 2009; Kalies et al. 2010). In cases of low- or moderate-severity fire, animals such as ground-dwelling arthropods, mammals, and avifauna may tolerate changes, if resource availability remains similar to prefire conditions (Brown et al. 2014; Noble 2015; Ferrenberg et al. 2019). However, high-severity fire has dramatic effects on habitat. In southwestern forests, the hairy woodpecker (*Picoides villosus*), a primary cavity nesting species, increases in population size immediately after a fire, nesting in charred ponderosa pine snags and feeding on insects for up to 3 years postfire. Their home ranges decrease, indicating habitat quality has improved. However, as snags begin to fall and prey populations drop, so do hairy woodpecker densities. Seven years after fire, hairy woodpecker populations are similar in burned and unburned forest and their home ranges have increased because they must search larger areas for food and nest snags (Covert-Bratland et al. 2006). Other species also use high-severity burns such as Lewis's woodpeckers (*Melanerpes lewis*) and northern flickers (*Colaptes auratus*) for nesting and foraging (Chambers and Mast 2005; Chap. 8, Box 8.1). Thus, in high-severity burned areas, some species are more abundant, have higher reproductive success, or otherwise respond positively (Lowe et al. 1978).

However, not all species respond positively to wildfire. Species that rely on trees for some or all of their life history requirements will lose habitat. Abert's squirrels, Grace's warblers, foliage-gleaners, and bark gleaning birds such as brown creepers (*Certhia americana*), pygmy and white breasted nuthatches (*Sitta carolinensis*) will die if they are unable to locate to new habitat. Whether they can access new habitat will depend on how mobile they are, the "hostility" of the postfire environment, and the proximity of replacement habitat. Other species appear to avoid burned areas or habitat elements. For instance, the Arizona myotis (*M. occultus*), a forest-associated small bat, select snags with little to no bole char (Considine and Chambers *in review*). Arthropod species vary in response to burn severity and pattern but fundamental changes occur to the community. For example, there are negative, positive, and variable short-term responses to high-severity wildfire for pollinators, ground beetles, and spiders, respectively (Noble 2015). The severity of wildfire ultimately affects the wildlife community postfire since wildfire alters the trajectory of forest succession. This altered trajectory can lead to minor (e.g., in forest density), moderate (e.g., establishment of areas vulnerable to crown fire), or major (e.g., a shift to a non-forest condition; Savage and Mast 2005) changes.

11.2 People and Fire in the Southwest

People have been linked closely with forests and fire in the SWST since the formation of modern vegetation patterns after the last glacial period (>15,000 years ago). Native American inhabitants of southwestern landscapes comprise diverse groups with many languages, cultural traditions, and lifeways. Living in dry, fire-prone ecosystems, people learned to coexist and benefitted from many of the positive regulatory effects of recurring fires for maintaining productive watersheds and wildlife habitat. Igniting fires is a human characteristic worldwide, but in the southwestern uplands it is challenging to distinguish the fingerprint of human-caused ignitions against a background of high lightning strike density (Chap. 1, Fig. 1.2, 1.4, Table 1.1; Allen 2002), unlike regions where Indigenous burning patterns are more clearly distinguishable from natural fires (Stewart 2002; Anderson 2005). Detailed tree-ring studies comparing known occupied and unoccupied sites by Apache people (Kaye and Swetnam 1999), or stretching back well before European contact (Roos and Swetnam 2011), provide clues about Indigenous burning via altered seasonality of fires occurring outside the typical monsoon lightning season in ponderosa and mixed conifer forests.

Historic and contemporary Native American lifeways are linked to forest resources in many ways. Provisioning services of forests in terms of water, wildlife, timber, fuelwood, and edible and medicinal plants are relatively more important for Native Americans than the average US population due to a high incidence of rural residence, subsistence agriculture, and poverty (Voggesser et al. 2013). Indigenous nations with significant forest resources, such as the Navajo Nation, several Apache and Pueblo tribes, and the Hualapai tribe, derive an important income source from forest products and experiences such as tourism and guided trophy hunts. However, cultural services may be among the most important links for many tribes, as mountains and forests comprise sacred sites and provide resources for historic and modern day spiritual practices (Mockta et al. 2018). In many ways, the prosperity and well-being of southwestern tribal communities is intricately linked to the sustainability of the forests and fire regimes that surround them.

The earliest consequential European contact in the SWST was the expedition led by Francisco Vázquez de Coronado, which entered the present-day USA in 1540 searching for fabled treasures. Juan de Oñate led settlers from Mexico to present-day New Mexico in 1598, surviving in the area of present-day Española with the help of Native Americans from the Pueblo of Ohkay Owingeh (Simmons 1991). Spanish/Mexican colonization lasted 248 years in the SWST until the American occupation in 1846. While it never controlled more than a small area of the SWST, and was temporarily exiled for over a decade after the Pueblo Revolt led by Popé in 1680, Spanish colonization left lasting legacies in terms of the introduction of horses and livestock, firearms, Christianity, forced labor, and infectious diseases that decimated Native populations.

For several centuries, the Native American and Hispanic livestock, social patterns, and fire coexisted in complex ways to influence forest fire regimes at fine scales (Roos and Swetnam 2011; Whitehair et al. 2018). Spanish colonists had introduced sheep and other livestock to the region, but the effects of grazing on reducing fire spread were limited to small areas near Hispanic or Pueblo communities (Baisan and Swetnam 1997) and the Diné (Navajo) homeland where sheep grazing began to affect fires around 1830 (Guiterman et al. 2019). In an exceptionally long-term reconstruction of the fire regime from fire-scarred trees along with detailed archeological and cultural evidence, Swetnam et al. (2016) showed that fire regimes near villages in northern New Mexico ponderosa pine and mixed conifer forests were less frequent when Pueblo people were heavily using forest resources, which limited fuel buildup. Spanish colonization led to abandonment of most mountain sites leading to a period of “free-range” frequent fire, which was replaced by large grazing herds and organized fire control after the incorporation of the SWST in the USA (Swetnam et al. 2016).

Rapid changes affecting southwestern forests and fire regimes began in the late nineteenth century. As elsewhere in North America and around the world, a key impact of the industrial revolution was the spread of large-scale livestock grazing due to the construction of railroads that could ship animals and products like wool to distant markets. After the cession by Mexico of the territory of the SWST in the Treaty of Guadalupe Hidalgo (1848) and the Gadsden Purchase (1853), transcontinental railroads were completed across the SWST on northern (Albuquerque, Flagstaff) and southern (El Paso, Tucson, Yuma) routes by 1883. Large herds of sheep and cattle grazed heavily on understory grasses in southwestern woodlands and forests (Cooper 1960; Bahre 1991), resulting in a regional collapse in fire occurrence beginning around 1870–1890 due to the loss of contiguous fine fuels (Swetnam and Baisan 1996). Among the latest dates of fire exclusion in the SWST were the 1920s in West Texas (Sakulich and Taylor 2007) to as late as the 1950s in northern Mexico (Yocom Kent et al. 2017). Native Americans were forcibly restricted to reservations in the 1860s and 1870s with fire occurrence declining on most Native lands as well (Azpeleta Tarancón et al. 2018; Whitehair et al. 2018). However, a frequent surface-fire regime continued well into the twentieth century at some isolated sites such as Malay Gap on the San Carlos Apache lands in eastern Arizona (Cooper 1960) and much later in northern Mexico (Yocom Kent et al. 2017).

Timber resources were also opened for exploitation by the arrival of railroads. Logging railroads were constructed through thousands of miles of the relatively gentle topography of southwestern uplands, focusing on the high commercial value of large, old ponderosa pine trees (Baker et al. 1988). Logging railroads typically used narrow-gauge tracks that allowed the trains to make tighter turns and climb steeper grades than the mainline standard-gauge train. Early timber harvesting, predominantly of the valuable species ponderosa pine, was unregulated. To encourage railroad construction, the US government granted ownership of alternate square-mile "sections" to the railroad companies, which often promptly cut all the trees of commercial value. Loggers did not strictly respect land boundaries and many areas were not officially surveyed until the twentieth century. The Forest Reserve Act of 1891 set aside forests from other public lands due to concerns about resource loss, but effective management control was limited.

The US Forest Service under the US Department of Agriculture took over administration of lands that became the National Forest system under the Transfer Act of 1905. The US Forest Service aimed to conserve resources such as timber and water indefinitely under Hutcheson's (1729) philosophy of utilitarianism: "the greatest good to the greatest number of people for the longest time". Fire was viewed as the main threat to the forest (Baker et al. 1988) but across the West some, including an influential explorer of the Grand Canyon, John Wesley Powell, argued for the benefits of "light burning" to keep forests open (Pyne 1982). His view was not shared by US Forest Service leaders. Just 5 years after the Transfer Act, severe wildfires of 1910 in the northern Rockies pushed the new agency to adopt an assertive policy of fire suppression (Pyne 1982). Aldo Leopold, later renowned as a conservation biologist and restoration ecologist, began his career as a forester on the Arizona-New Mexico border in 1909. In an essay that captured the prevailing view about fire at the time, Leopold (1920) listed numerous reasons to oppose what he called "*Piute forestry*" or light burning: surface fires killed seedlings, consumed humus, scarred trees, etc. Other resource management agencies such as the Bureau of Indian Affairs, Bureau of Land Management, and the National Park Service, developed in the early twentieth century, followed the US Forest Service's lead on fire control. Pyne (1982) documents the extension of fire control to eventually cover virtually all forested lands; this was facilitated during the Great Depression of the 1930s by President Franklin Roosevelt's establishment of the Civilian Conservation Corps (CCC) to help protect national timber and grazing lands. In the SWST, CCC crews built roads and constructed lookout towers (Fig. 11.2).

Fig. 11.2 Fire towers were often quite tall for a clear view due to the relatively gentle terrain on many forested southwestern plateaus. The 25 m tall Kanabownitz tower on the North Rim of Grand Canyon National Park was constructed in 1940 by the Civilian Conservation Corps, a Federal program that greatly expanded fire control in the Southwest (photo NAU.PH.2013.36.1.142.5, Item number 162282. Special Collections, Cline Library, Northern Arizona University)

11.3 Southwest Forest Firefighters: A Unique History

Rural residents served as the main labor source for fire crews around the nation. In the SWST of the early twentieth century, Native American and Hispanic men and eventually, women, served as the skilled, willing firefighters who implemented the national policy. As large forested areas were opened by roads, reducing the time required to reach fires, and new equipment such as trucks and bulldozers became available after World War II (Pyne 1982), firefighting became an important seasonal employment and cash source for indigenous families in remote communities (Dejong 2004). On the Mescalero Apache Reservation in southern New Mexico, a new Apache firefighting team, the Red Hats, was organized in the spring of 1948 as part of the Southwest Forest Firefighters (SWFF) program. The first crew mostly consisted of war veterans, who maintained a high physical standard and a spiritual frame of mind that formed the legacy of the Indian fire warriors. Native crews practiced line-building routines and experimented with firefighting tools in a variety of terrain. In less than a decade, they became well known as a leading fire crew, in great demand particularly in the West. Their cohesion as a crew, family lineages, and respectful hierarchal structures, made them a very efficient team (Dejong 2004).

Indigenous men and women demonstrated a strong pride and purpose fighting fires. For their exemplary dedication, they became the elite among the wildland firefighting crews. By 1952, organized crews of Native Americans from the Mescalero and Jicarilla Apache and Navajo reservations, as well as the Pueblos of Acoma, Cochiti, Hopi, Jemez, Santo Domingo, San Juan, Taos, Zuni, and Zia, plus the first Hispanic unit from Peñasco, were part of the Red Hats (Fisher 2000). Due to their cultural perspective based on ancestral traditions connected to nature and seasonal processes, they were well prepared to work in the wilderness. Dejong (2004) argued that Native Americans´ familiarity with the dynamics of the landscape, as well as their traditional knowledge of natural processes and the use of fire, helped them understand intrinsic fire behavior, apply efficient techniques, and often led to success with their control lines. They also incorporated ceremonies, for example as related to rainfall, and traditional prayers and symbols. Increased mechanization during the second half of the twentieth century decreased the demand for crew members while many rural Native Americans found new sources of employment promoted by tourism, such as making and sharing traditional art, jewelry, and crafts.

Today, the SWST remains at the forefront of fire management professionalism, due in part to leading the nation in the number of lightning-caused fires (NIFC 2020; Chap. 1, Table 1.1). Hundreds of Native Americans are members of engine, hotshot and smokejumper crews (Fig. 11.3), among the most skilled professionals managing wildfires (Fisher 2000). In addition, the twenty-first century has seen broader recognition of the important value of Indigenous cultures and traditions (Lake et al. 2017). In combination with the promotion of relatively more integrated and ecologically based natural resource management, Indigenous knowledge is increasingly demonstrating sustainable management of natural resources (Raish et al. 2005). Indigenous communities such as the San Carlos Apache Tribe in eastern Arizona have become internationally recognized examples of the integration of the use of fire on tribal lands (Pyne 2014). This management promotes the conservation and maintenance of culture, traditions and ceremonies, as well as traditional food and medicinal plants (cultural fire management), while reducing the risk of uncharacteristically severe fires. Moreover, some of these communities have also become leaders in professional education in fire such as the Training Exchange program and in academic settings such as at Salish Kootenai College on the Flathead

Fig. 11.3 Wildland fire crew from the San Carlos Apache Nation. Indigenous fire crews make up a key component of USA fire management (photo M. Victor)

Indian reservation where Native students can gain a bachelor's degree in forestry with an emphasis in fire management. In summary, tribal communities were and are important leaders in fire management, developing opportunities and synergies that are bringing Indigenous knowledge into the policy and practice of adaptive management of natural resources.

11.4 Contemporary Forests Are Altered by Fire Exclusion

Fire exclusion, including intentional fire suppression, fuel removal through livestock grazing, and ignition removal through altered human presence—set in motion profound changes in southwestern forests that affect current and future management. In broad strokes, forests previously characterized by frequent, surface-fire regimes became dense because young trees were not thinned by fire, shifting these ecosystems toward infrequent but lethal crown fires (Covington and Moore 1994). Forests previously characterized by infrequent, severe fires were less affected by 1–1.5 centuries of fire exclusion, but the absence of severe fires across large landscapes during this period led to a greater homogenization of fuel as dense forests and woodlands filled in the places previously burned by stand-replacing fires (Cocke et al. 2005). In sum, across elevational gradients associated with ecologically distinct historical fire regimes, the fire exclusion period led to more total fuel, connectivity of fuels vertically within stands and horizontally across the landscape, and dead biomass accumulation in the form of forest floor and downed wood over time with forest succession (O'Connor et al. 2014). By the early twenty-first century, the maximum size of wildfires in the SWST as well as the area and proportion of severe fire all increased (Singleton et al. 2019).

Ponderosa and dry mixed conifer forests previously characterized by frequent, surface-fire regimes were quick to show structural changes associated with the loss of fire's ecological role and other impacts such as logging of large, old trees. Large cohorts of regeneration became established under favorable climate conditions such as occurred in 1919 in northern Arizona (Savage et al. 1996). The resulting "hyper-dense" forests began to support stand-replacing wildfires as early as the 1950s (Savage and Mast 2005). Forest structure at 33 sites across Arizona and New Mexico representing a range of soils shifted from open stands dominated by large trees at the time of fire exclusion *circa* 1880 (mean <150 trees/ha, <12m^2/ha of basal area (BA)) (Rodman et al. 2017). In contrast, the contemporary ponderosa forest in Arizona is 2–3 times denser, averaging 620 trees/ha and 25 m^2/ha of BA (Shaw et al. 2018). Canopy biomass more than doubled in dry forests of Grand Canyon National Park from 1880 to 2000 (Fulé et al. 2004). As tree biomass increased through the twentieth century, herbaceous and shrubby understory plants declined and species composition shifted toward shade-tolerant species (Laughlin et al. 2011).

The structure, composition, and disturbance regimes (notably fire) of southwestern forests shaped the habitat to which animals have evolved and persisted for thousands of years. The exclusion of fire and subsequent forest "densifiation" that occurred following Euro-American settlement altered wildlife habitat. Studies contrasting wildlife use of "controls" (current forest conditions with high tree density and exclusion of fire) with "restoration treatments" (use of mechanical thinning and prescribed fire to recreate reference conditions) help demonstrate how fire exclusion has affected wildlife (Kalies et al. 2010, 2012; Johnson and Chambers 2017). Most studies are short-term (≤3 years), but nonetheless show positive effects of forest restoration on wildlife (Chambers and Germaine 2003). For example, the breeding bird community in ponderosa pine forests changed after restoration treatments, with density of tree seed eaters, understory insectivores, and aerial insectivores increasing in treated stands. Bark insectivores and ground-foraging birds had a positive or neutral response to treatments. In general, breeding birds responded positively to decreased canopy cover and retention of mature trees and snags following restoration treatments and were negatively associated with medium-sized trees, quadratic mean diameter, and downed wood, elements associated with current dense forest conditions (Gaines et al. 2007; Kalies and Rosenstock 2013). Bats and rodents varied in their use of treated and untreated stands. Bat species adapted to fly in dense "cluttered" forest (*Myotis* species) used both treated and control stands but those physiologically and morphologically adapted (with low echolocation call characteristic frequency) to reference forest conditions (e.g., Mexican free-tailed bat (*Tadarida brasiliensis*)) were more active in restoration treatments (Considine and Chambers *in review*). Rodents followed a similar response pattern with generalists such as deer mouse (*Peromyscus maniculatus*) remaining common regardless of treatment, open-forest species such as golden-mantled ground squirrel (*Callospermophilus lateralis*) responding positively to treatment, and dense-forest species such as Abert's squirrel responding negatively to treatment (Kalies et al. 2012). These responses may be partly due to the change in understory vegetation following treatments. Plant species richness, biomass, graminoids, forbs, and shrubs increased in treated relative to control plots. Many arthropods, likely affected by increases in understory (grasses, forbs, shrubs), also responded positively, although bark beetles decreased (Noble 2015). Fewer patterns are evident with large, highly mobile animals such as bears, elk, and deer that can move easily among dense to open forest patches and across heterogeneous landscapes. In summary, a heterogeneous forest provides habitat for many species, with some species better adapted to open conditions and others to denser forest as defined by reference conditions. The current dense, high-severity fire-prone forests do not provide the historical structure most wildlife use and if they burn, are likely to take decades to hundreds of years to restore (Chambers and Germaine 2003; Considine and Chambers *in review*).

Although many animal species evolved with low-severity, frequent fire in the Southwest, uncharacteristically severe fires can have particularly negative effects on threatened or endangered species tied to mature forests. The Mount Graham red squirrel (*Tamiasciurus hudsonicus grahamensis*) occupies spruce-fir and mixed conifer forest in the Pinaleño Mountains in Arizona with a limited range extent of <250 km^2. The squirrel is a critically imperiled subspecies federally listed as Endangered, and believed to consist of fewer than 250 individuals. Most individuals survived the Nuttall Complex Fire in 2004, which burned a mosaic of ground and crown fires, with no detectable difference in body mass or reproductive condition between burned or unburned areas; red squirrels probably evolved with patchy, low-intensity fire (Koprowski et al. 2006). However, between 2015 and 2019, and in combination with the mixed-severity Frye Fire in 2017 that reburned much of the Nuttall Complex Fire (McGuire and Youberg 2019), the population was reduced by >75%, to about 35 individuals. The species is already at high risk of extinction because of its small geographic extent, declining population, effects of human disturbance, competition with Abert's squirrels, reduced genetic variation, and climate change (Koprowski et al. 2006; Leonard and Koprowski 2010; Blount and Koprowski 2012; Fitak et al. 2013; IUCN 2020; NatureServe 2020). The addition of uncharacteristically severe fires may prove to be the tipping point in cumulative anthropomorphic effects for this species.

A second species at risk is the Mexican spotted owl (MSO), associated with high canopy cover in late-seral ponderosa pine-Gambel oak and mixed conifer forest in Arizona, Colorado, New Mexico, and Utah. Although the species has a large range extent of 200,000–2,500,000 km^2, habitat is patchily distributed. This owl subspecies, federally listed as Threatened, has an estimated total population size of several thousand individuals. However, the uncertain population trend, habitat loss, degradation, and fragmentation, and threat of uncharacteristically severe fire continue to threaten this species. When first federally listed in 1993, the MSO was at greatest risk from even-aged forest management slated for a significant portion of their nesting habitat; uncharacteristically severe fires are now considered a greater threat. Stand-replacing fires tend to consume tree foliage that serves as important cover for MSOs from overhead predators, such as the northern goshawk (*Accipiter gentilis*) and great horned owl (*Bubo virginianus*) which also compete with MSOs for prey. The low wing aspect ratio and relative wing loading of the MSO allow it to navigate complex forest canopies but reduces its adaptive flight advantage in high-severity burned areas which become open-canopied forests. Climate change in combination with high tree densities and increased fuels may exacerbate wildfire effects on MSO habitat. Increased tree densities also reduce understory cover, important for nesting and a key factor influencing habitat for prey populations. The increase in extent and severity of wildfires could have a significant effect on MSO populations. Following the 2002 Rodeo-Chediski Fire, which burned 187,000 ha, occupancy declined inside the fire perimeter and has remained low through 2016. Mega fires can affect MSO populations and habitat selection for years to decades after a fire (Timm et al. 2016; Ganey et al. 2017; Lommler 2019).

11.5 Shifting Policy and Management Practice

Ecological and social legacies emerging from a century of fire suppression and exclusion in conjunction with climate change have made their mark on Southwestern landscapes, evidenced by forest overgrowth and catastrophic wildfires (Hurteau et al. 2014). Although policy-driven change in forest structure and fire regimes since the 1910 wildfires (Sect. 11.2) is not unique to the SWST, it has contributed to increased risk of larger, higher-severity wildfires that must be addressed through forest management. For example, in 2011 the Wallow Fire became the largest forest fire in recorded southwestern history, burning 217,741 ha in the White Mountains at the Arizona-New Mexico border. Limited fuel treatments had occurred in that area and most fires had been suppressed rapidly (Waltz et al. 2014). Flood risk has further complicated postfire management in varied topography across the SWST due to highly variable annual monsoon rains; flood events following the 2010 Schultz Fire near Flagstaff, Arizona caused substantial damage and loss of life (Combrink et al. 2013). These challenging ecological conditions surrounding wildfires in the SWST continue to create substantial social impacts through economic loss, changing relationships with the land, and the health and well-being of those affected (Covington and Vosick 2016). Recent trends documenting more frequent and severe wildfires in the SWST indicate that these challenges and impacts are unlikely to end without marked long-term changes in forest and fire management.

Numerous recent, notable wildfires have shifted public opinion and support of wildfire and prescribed fire management in the SWST. Complex public attitudes towards fire as a management tool emerged after a prescribed fire escaped near Los Alamos, New Mexico in 2000 to become the Cerro Grande Fire (Hill 2000; Brunson and Evans 2005). However, studies following this fire indicated that community involvement in postfire restoration improved citizen-agency relationships and established local support for future management efforts (Ryan and Hamin 2006). Support for active forest management has continued to grow in the years following large fire events; for example, the Rodeo-Chediski Fire in 2002 resulted in increased local awareness and interest in forest management to address wildfire risk (Carroll et al. 2011). Growing public interest and involvement in fire management and forest restoration has also resulted in new, innovative approaches to reduce wildfire risk in the

Southwest. The 2010 Schultz and Hardy Fires led the local government to establish a community bond setting aside $10 million for forest restoration efforts on public lands around Flagstaff, Arizona (Mottek-Lucas 2015). This effort, now known as the Flagstaff Watershed Protection Project, was built on two decades of positive relationship building and local collaboration around shared values for the surrounding landscape. One “silver lining” to wildfires may be improved community and stakeholder relations and broader public involvement in posfire restoration (Flores et al. 2018).

Other southwestern fires have been influential for advancing knowledge and practices surrounding wildfire management, particularly in Arizona. Both the 1990 Dude Fire and the 2013 Yarnell Hill Fire resulted in multiple firefighter fatalities. The fire safety acronym LCES (Lookouts, Communication, Escape Routes, Safety Zones) for identifying hazardous fire conditions to protect firefighters from entrapment was developed in response to investigations of the Dude Fire, and is still used in the Incident Response Pocket Guides for US firefighters (NWCG 2020). The Yarnell Hill Fire tragedy highlighted the need for better understanding of how firefighters process and retain information, and led to renewed conversations about preventing entrapment and prioritizing firefighter safety (Karels and Dudley 2013). Together, both fires have resulted in national and international reflection and improvements to wildland firefighter training and incident management (Hardy and Comfort 2015).

11.6 Future Scenarios: Adapting to Changing Society and Warming Climate

The trajectory of warming climate is altering vegetation (i.e., fuel) and fire regimes in the SWST in concert with increasing human stresses on forest ecosystems. Climate change scenarios for the twenty-first century and beyond suggest substantial change to vegetation and fire patterns even under relatively mild warming such as 1.5–2 °C (Chap. 12; Garfin et al. 2014). Higher warming implies unrecognizable levels of change. The climate of the SWST has already warmed by about 1 °C since the 1980s, with an associated increase in severe fires (Singleton et al. 2019). Mueller et al. (2020) reported the strongest links between severe fire behavior and vapor pressure deficit, a measure of atmospheric dryness also associated with drought stress and tree mortality (Williams et al. 2012). Managers and scientists share major concerns for species and habitat conservation, loss of ecosystem services, and interlinked cascading disturbances (e.g., fire-flood-soil loss-watershed impact) (Falk et al. 2019).

Adaptation of management strategies to the evolving role of fire is essential. Thoughtful, intentional adaptation is much better for human and ecological communities than reactive or outdated policies. Treatments aimed at restoring natural qualities and resilience of fire-excluded forests may offer near-term protection against severe fire behavior and current levels of climate change, but rapid action is needed (Stephens et al. 2020). Specific actions usually include mechanical thinning of dense stands of small-diameter trees, often in conjunction with prescribed fire, and sometimes other activities such as seeding of native understory species, restoration of seeps and springs, and road closures (Covington et al. 1997). As an example, since the onset of fire exclusion *circa* 1880, average forest BA had tripled across experimental sites covering an elevational gradient from pinyon-juniper to mixed conifer in the Apache-Sitgreaves National Forest. Thinning treatments based on the prefire-exclusion forest structure reduced BA by 52% and tree density by 85% (Roccaforte et al. 2015). The reduction in density was greater than that of BA because smaller trees were preferentially thinned. Applying fire behavior models to similar treatments across a landscape on the Arizona Strip, Roccaforte et al. (2008) estimated reductions around 50% in canopy biomass and canopy bulk density—key variables controlling crown fire spread—with a predicted effect of restoring fire behavior characteristics similar to those of the historical forest even under sustained high windspeeds (70 km/h).

The use of fire itself as a management tool is also of interest in the SWST, either by prescribed burning or by allowing lightning-ignited fires to burn for "resource objectives"[1] such as fuel reduction and thinning of small trees. Despite the early resistance to intentional burning by the US Forest Service and others, Aldo Leopold (1924) quickly came to realize the damage created by fire exclusion. Harold Weaver, a forester with the Indian Service (later, Bureau of Indian Affairs) wrote about the high fuel hazard created by dense conifer reproduction (Weaver 1951) and put his ideas into action by burning with the Colville, Apache, and Hualapai Tribes. Support from tribal members and managers led to repeated burning of the Hualapai forest in the western Grand Canyon region since the 1960s, essentially recreating historical fire patterns (Stan et al. 2014). Huffman et al. (2017) found little reduction in live fuels in low-severity portions, and excessive tree mortality and loss of large snags in high-severity portions of 10 "resource objective" fires in Arizona. They recommended managing fires toward the moderate-severity category for the best ecological outcomes, but recognized that this entailed a higher risk of escaped fires and negative social effects (Stoddard et al. 2020).

11.7 Future Fire in Southwestern Forest Social-Ecological Systems

Fire, forests, and people have always been linked, but the coupling of human-caused climate warming with growing populations in the dry SWST make the connection inextricable. Developing strategies for adaptation to rapidly warming climate

[1] The nomenclature for this type of fire management policy dates back to "light burning" and "prescribed natural fires", later "resource benefit" fires.

requires making forecasts of complex system behavior (Hurteau et al. 2016). Climate-sensitive simulation models of forest dynamics that incorporate fire behavior are valuable forecasting tools but there are tradeoffs between ease of use and complexity. At the most user-friendly analytical level, a vulnerability assessment allows managers to combine qualitative and quantitative estimates of climate effects for supporting practical planning (Friggins et al. 2019). For specialists accustomed to technical models, the venerable statistical models linked in the Forest Vegetation Simulator (FVS)—the most widely used modeling system in USA forests—were adjusted by Crookston et al. (2010) to incorporate likely effects of warming climate on tree survival and regeneration. The Climate-FVS model has been applied in the SWST to predict future forest carbon (Bagdon and Huang 2014) and susceptibility to wildfire (Azpeleta et al. 2014). Even more complexity is incorporated in models that simulate ecological processes, currently the most sophisticated and data-intensive modeling systems (Loehmann et al. 2020). Overall, modeling suggests reduced forest growth and limited postfire recovery in coming decades. Yazzie et al. (2019) reported that forest biomass and the occurrence of native tree species over the elevational gradient from ponderosa to spruce-fir are likely to shrink dramatically on the Navajo Nation before 2050 even under a low-moderate climate change scenario. Although the reintroduction of frequent surface fire regimes is widely advocated, simulation studies at the stand- (Shive et al. 2014) and landscape-scales (Flatley and Fulé 2016) suggest that reproducing the prefire-exclusion frequency of burning could lead to increasing mortality and forest decline under warming climate. In other words, while historical conditions remain important points of reference, restoration of previous disturbance patterns alone is unlikely to be sufficient for sustaining key forest ecosystem services.

One major future fire-wildlife interactions and management issue involves threatened or endangered species such as the MSO; forest restoration and thinning goals need to be balanced with providing habitat needs for species of conservation concern. The Research & Development and National Forest System (forest management) branches of the US Forest Service have partnered to monitor trends in habitat loss throughout the MSO's range by incorporating historical MSO occupancy data and new remote sensing technologies. The initiative's goal is to understand the degree of habitat loss and identify an approach that allows scientists to quantify landscape level changes. Others are looking into tribal forests as models for balancing the triple bottom line of land stewardship (environmental stewardship, economic performance, and community well-being), where moderate thinning around nest sites has been shown to have little to no negative impact on owl occupancy and reproduction rates (Hoagland et al. 2018). Linking habitat modeling with simulation of future projections of severe fire, Wan et al. (2019) seek to suggest priorities for fuel treatments aimed at protecting biodiversity. Bridging gaps between diverse landowners to protect and conserve wildlife species into the future is imperative given the complex, dynamic ecological conditions of our forests.

Social wildfire adaptation efforts that compliment ecological restoration in the SWST have become increasingly valued in conversations surrounding

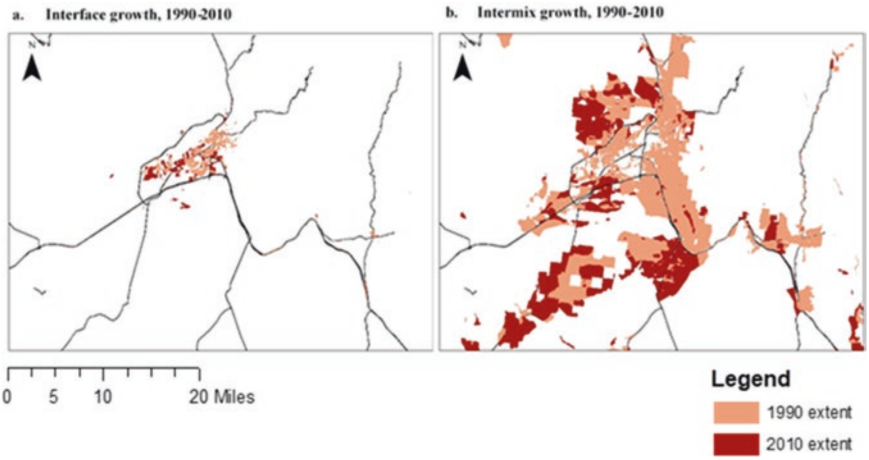

Fig. 11.4 Wildland-urban interface (WUI) maps show rapid expansion around Santa Fe, New Mexico 1990–2010. Interface WUI refers to areas where development is adjacent to but separate from wildland vegetation, whereas intermix WUI refer to areas where development and vegetation intermingle. The category called "intermix", representing mostly scattered, low-density housing, had the largest increase. Data retrieved from SILVIS (Radeloff et al. 2017)

landscape resilience as the wildland urban interface, populations, and risk continue to grow (Fig. 11.4). A growing interest in public education and homeowner involvement in landscape-level risk mitigation has cultivated emergence of diverse efforts to "live with fire" in the Southwest. Some of these approaches are more formal and intersect with national-level efforts; for example, two of the original 12 Firewise Community Program pilot sites established in 2002 are located in the Southwest: Timber Ridge in Prescott, Arizona and Greater Eastern Jemez WUI Corridor near Jemez Springs, New Mexico (NFPA 2016). Almost two decades later, there are now 114 certified Firewise sites in Arizona and 32 in New Mexico (NFPA 2020). Programs like Firewise have created new avenues for funding at the community level, ranging from small education-focused grants to support for fuel breaks on public-private land boundaries. Growing recognition that wildfire adaptation is a process rather than an end goal has led to increasing interest in the concept of Fire Adapted Communities (Paveglio and Edgeley 2020), leading to the creation of collaborative efforts like the Fire Adapted New Mexico Learning Network and the Arizona Fire Adapted Community Network. The emergence of collaborative structures to support cohesive fire management and risk mitigation is also present at the local level across the southwest, including groups like the Greater Flagstaff Forest Partnership, regional groups like the Santa Fe Watershed Association, and the FireScape initiative in the Arizona Sky Islands. These local and regional efforts align with recent national policy that calls for social adaptation to wildfire, including the National Cohesive Wildland Fire Management Strategy (WFEC 2014) and the development of Community Wildfire Protection Plans (Colavito 2019).

Other efforts to adapt to wildfire at the community level have been approached through more informal or grassroots channels, fostering opportunities for increased flexibility to tailor efforts that are best suited to that local context. Ruidoso, New Mexico has seen an evolution of locally-determined approaches to organized fire risk mitigation, ranging from a 1980s Village Council ordinance, to a Forest Health Coalition in 1995 that was later succeeded by the Ruidoso Wildland Urban Interface Group (Steelman and Kunkel 2004). Other local adaptation efforts might be as simple as hiring more fire- or emergency management-focused county employees to address local needs, as occurred after the 2011 Track Fire in Colfax County, New Mexico (Abrams et al. 2015). A critical next step for forest and fire management and policy is incorporating clear acknowledgement that communities in the SWST are diverse, and approaches to becoming "fire-adapted" can be widely variable but equally effective; this emphasis on flexibility is particularly important for locally-driven efforts to thrive.

Human community efforts to address wildfire risk and restore fire to the land increasingly acknowledge the need for proactive, tailored adaptation strategies that complement local social and ecological contexts (Paveglio et al. 2015, 2018). Looking forward, investment in and support of locally-driven forest management and fire mitigation efforts offer opportunities for more effective, cohesive ecological restoration and increase support for the natural role of fire in the SWST. Protecting and nurturing local and Indigenous knowledge about fire and the land has created unique opportunities for fire use in the SWST developing and adapting policies and management techniques at varying and nested scales to support that can benefit not only the southwestern states, but offer a template for other regions of the USA to follow. Recognizing and incorporating the strengths of social and ecological diversity in the SWST has, does, and will continue to create new opportunities for blending fire use and management with forest conditions.

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