

Montane Forests of the Southwest

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Introduction

The American Southwest is generally thought of as an arid region with expanses of deserts that are interrupted only by cities such as Phoenix, Tucson, and Albuquerque. This image of aridity has some truth, but the region also has cool, moist montane areas, namely the upper-elevation plateaus and mountains (fig. 1). These have forests of pines (*Pinus* spp.), Douglas-fir (*Pseudotsuga menziesii*), firs (*Abies* spp.), spruces (*Picea* spp.), and quaking aspen (*Populus tremuloides*)—trees more often associated with the mountains of Colorado, Wyoming, and Montana. The montane areas of the American Southwest also have grasslands, shrublands, and—on the highest peaks—alpine tundra.

Montane forests cover only about 8% of the combined areas of Arizona and New Mexico, but they are important in a variety of ways. Ecologically, they are part of the impressive biological diversity of the region, providing unique habitat in a generally arid region. Economically, they have been major sources of timber, livestock forage, and water, as well as sites for outdoor recreation and tourism. Aesthetically, they include some of the more impressive scenery of the Southwest.

Distribution

The montane forests of the American Southwest are limited to upper-elevation plateaus and mountains and therefore have a discontinuous distribution. Some areas are extensive, including the southernmost portions of the Rocky Mountains in northern New Mexico and a band ranging from west-central New Mexico to the region of Flagstaff, Arizona. Smaller areas are more numerous and include the Santa Catalina and Pinaleno Mountains in southern Arizona and the Animas Mountains of southwestern New Mexico, which are called “sky islands” because of the isolation of these upper-elevation areas in an expanse of lowland desert. The easternmost montane forest of the American Southwest occurs in the Guadalupe Mountains of western Texas and adjacent New Mexico.

The distributions of species that characterize today’s montane forests have changed numerous times in response to climate.

OVERVIEW



Figure 1. Montane forests and snow-covered alpine tundra on the San Francisco Peaks in northern Arizona.

Montane species were able to respond quickly and effectively to past climate changes because they generally moved only short distances up or down slope, depending on whether the climate was warming or cooling. In contrast, lowland species had to migrate long distances north or south, sometimes through areas interrupted by unfavorable habitat. Therefore, mountains provided refuges for species adversely affected by climate change and served as sources of species benefiting from climate change. Paleoecologists have determined that species migrated individually rather than in assemblages or communities (e.g., Cole 1985). Therefore, montane forests of the geologic past differed in species composition from today’s forests.

Ecosystem Drivers

Climate

The climate of the montane forests of the American Southwest is characterized by cold winters and warm to cool summers. Precipitation is bimodal with peaks in winter and mid-summer. Winter precipitation falls as snow, and January is usually the coldest, snowiest month. A substantial snowpack develops, especially in the subalpine zone, and lasts through March and often into April, depending on elevation and accumulation during winter. As the region becomes influenced by high pressure in April, the temperatures warm and precipitation de-



creases, causing April through mid-June to be the driest time of the year. The monsoon season, which is characterized by scattered afternoon thunderstorms, starts in late June or early July as warm, moist air masses move into the region from the Gulf of Mexico and Gulf of California. July is the warmest month; August is typically the wettest. Precipitation declines in September, but increases again in October-November with the beginning of the snow season. Lightning, which ignites many forest fires, occurs frequently in the Southwest, especially during the dry months of May and June.

The climate varies both spatially and temporally. Spatially, temperature and length of the growing season decrease with increasing elevation, but precipitation increases up to the sub-alpine zone and decreases above that point. Temporally, annual weather conditions are influenced by the El Niño-Southern Oscillation. El Niño events occur on an average of once every 3-4 years and typically last 12-18 months. They bring cooler, wetter winters to the Southwest, and rainfall during the monsoon season tends to be normal or above normal. In contrast, El Niño's counterpart, La Niña, tends to bring drier winters. These spatial and temporal variations markedly affect the frequency, duration, and intensity of forest disturbances such as fires.

Topography

Topography is a key factor influencing montane forests of the Southwest. The importance of large-scale variation in topography is illustrated by the restriction of montane forests to upper-elevation plateaus and mountains. Montane forests occur at elevations of 1,850 to 2,900 meters (approximately 6,000 to 9,500 feet), but it depends on latitude, with southern forests being at somewhat higher elevations than northern forests. Immediately below this elevational range is pinyon-juniper vegetation and in some areas, interior chaparral shrubland. Alpine tundra occurs at elevations higher than 2,900 m (~9,500 ft.) on mountains such as northern New Mexico's Wheeler Peak (4,011 meters; 13,161 feet) and northern Arizona's San Francisco Peaks (3,852 meters; 12,637 feet), as shown in figure 1.

On a smaller spatial scale, the topography of drainages, slopes, and ridgetops within the upper-elevation plateaus and mountains affects forest stand structure, species composition, and fire regime. This occurs because topographic position and slope exposure (aspect) affect site moisture. For example, moist drainages and moist north-facing slopes may have denser forests and burn less frequently but ultimately more intensively than the forests on drier ridgetops or on drier south-facing slopes.

Soil

Soils of montane forests in the Southwest are highly variable because they are products of diverse climate, topography, and vegetation. Soils have formed from volcanic materials or sandstone, limestone, or igneous rocks; however, parent material tends to have less influence on montane soils than soils at lower elevations (Klemmedson and Smith 1979, Maker and Saugherty 1986). In general, upper-elevation soils tend to be leached, acidic, well-developed, well-drained, shallow to deep, and fine to moderately coarse-textured (Hendricks 1985, Maker and Saugherty 1986). Soil moisture varies greatly by topographic position and slope exposure, as well as the time of year.

Natural disturbance

Key natural disturbances in montane forests of the American Southwest include past climate variability, fire, and native insects, parasites, and pathogens. Understanding their independent and interactive effects is essential for interpreting the stand structure, species composition, and other characteristics of these forests.

Past climate variability

Climate is a driver of the general distribution of montane forests, but climate variability is a disturbance factor. Montane forests of the Southwest have been subject to shifts in climate throughout their existence (shifts that were independent of human influence are treated in this section; those related to humans are covered in a following section on recent climate change). Drought is an important aspect of climate variability that has dramatically affected montane forests. It not only affects vegetation directly, but also indirectly by altering other disturbance factors. For example, drier periods have been characterized by a higher frequency of forest fires (Grissino-Mayer and Swetnam 2000) and more extensive fires (Margois et al. 2007), and drought years have been associated with insect-caused mortality (e.g., Worrall et al. 2008).

Fire

Because both the dry climate and high frequency of lightning in the Southwest encourage fires, fire has been a major influence on the montane forests. Also, Native Americans historically set fires to aid in hunting and increasing wild food crops; however, these fires were only important in relatively small areas, not throughout southwestern montane forests (Allen 2002). Historically, there were surface, crown, and mixed-severity fire regimes. A surface fire regime is characterized by frequent, low-intensity, low-severity fires with short flame heights (fig. 2). In contrast, a crown fire regime has infrequent, high-intensity, high-severity fires that burn the tops (crowns)



FIRE AND AVIATION STAFF, GRAND CANYON NATIONAL PARK

Figure 2. Surface fire in Grand Canyon National Park, northern Arizona.



FIRE AND AVIATION STAFF, GRAND CANYON NATIONAL PARK

Figure 3. Crown fire in Grand Canyon National Park, northern Arizona.

of trees (fig. 3); such fires are also known as stand-replacing fires. A mixed-severity fire regime has both surface and crown fires, typically with surface fires being far more common and widespread than crown fires.

Native insects, parasites, and pathogens

The major insects, parasites, and pathogens impacting the montane forests of the Southwest are native species of bark beetles, defoliating insects, dwarf mistletoes, and root decay fungi (Dahms and Geils 1997). Several species of bark beetles are usually present in low numbers in different tree species, persisting in freshly fallen trees and in less productive living trees. These small populations only occasionally result in tree deaths, but outbreaks occur periodically, especially with drought, and cause high mortality rates among larger, older, stressed trees. Among the defoliating insects, western spruce budworm primarily impacts understory white fir and Douglas-fir in the Southwest, and western tent caterpillar affects aspen. Outbreaks lasting several years reduce tree vigor and

can cause mortality. Dwarf mistletoes occur on most conifers and increase the likelihood and impacts of insect outbreaks and fire. Root decay fungi are widespread, weakening trees and thereby increasing the chances of bark beetle infestation.

Vegetation dynamics

Vegetation dynamics are the responses of vegetation to environmental changes. Because the environment is always changing, from small changes in weather to large disturbances such as crown fire, vegetation dynamics occur continuously. They range from small shifts in species' population sizes and distributions to reforestation following disturbance. A specific type of vegetation dynamics is the process of succession. It often occurs after major disturbances such as logging and involves a series of species replacements over time that is independent of additional changes in the regional environment.

Table 1. Summary of montane forests of the American Southwest.

	Ponderosa pine forest	Mixed conifer forest	Spruce-fir forest	Quaking aspen forest
Site conditions	Relatively low elevation; generally flat to moderately steep topography.	Mid elevation; often moderately steep, sometimes dissected topography.	Upper elevation; usually steep topography.	Mid elevation; often moderately steep topography.
Tree species	Ponderosa pine, along with pinyon pine and junipers in understory at low elevation and Douglas-fir, white fir, and quaking aspen at high elevation.	Ponderosa pine, Douglas-fir, white fir, and quaking aspen on dry sites. Also subalpine fir, blue spruce, and Engelmann spruce on moist sites.	Similar to mixed conifer forest at low elevation, but primarily Engelmann spruce, subalpine fir, and blue spruce at high elevation.	Quaking aspen, with ingrowth of conifers beginning in mid-succession (see tree species for mixed conifer forest).
Historical stand structure	Open canopy with dense herbaceous layer.	Likely open to closed canopy with variable herbaceous layer.	Likely depended on successional age.	Likely open to closed deciduous canopy with dense herbaceous layer at young successional age, followed by ingrowth of conifers.
Historical fire regime	Frequent, low-severity surface fires.	Mixed-severity fire regime with frequent, low-severity fires and smaller areas of infrequent, high-severity crown fires.	Poorly known, but likely mixed-severity at low elevation (see mixed conifer forest) and possibly a crown fire regime of infrequent, high-severity fires at high elevation.	Initiated by crown fires and thereafter similar to adjacent coniferous forest but likely with lower frequency and intensity.
Major historical human impacts¹	Fire exclusion and logging.	Fire exclusion.	Fire exclusion at low elevations; unknown at high elevation.	Fire exclusion.
Historical changes in stand structure¹	Increased density of canopy and understory trees.	Increased density of canopy and understory trees followed by decreases in at least some areas.	Similar to mixed conifer forests at low elevation. Unknown at high elevation, but likely related to successional aging.	Likely related to successional aging.
Historical changes in tree species composition¹	Increases of white fir and decreases of quaking aspen at mid and high elevations.	Increases of white fir at low elevation and subalpine fir at high elevation, followed by decreases in these and quaking aspen.	Increases of subalpine fir followed by decreases in it and quaking aspen at low elevation. Unknown at high elevation, but likely related to successional aging.	Increases of conifers and decreases of quaking aspen with successional aging.
Current fire regime	Mixed-severity.	Mixed-severity (with extensive crown fire) or crown fire.	Same as mixed conifer forest at low elevation and possibly same as historical fire regime at high elevation.	Unknown, but changes are likely similar to those of adjacent coniferous forest.

¹Excludes recent impacts such as management fire, climate change, and air pollution because their effects are not well known in the American Southwest.

Vegetation

Montane forests of the American Southwest are generally divided into four forest types based on the dominant tree species (table 1). With increasing elevation, they include three coniferous forests: ponderosa pine forest, mixed conifer forest, and spruce-fir forest. The fourth forest type is quaking aspen forest, a deciduous forest that grows in areas of past disturbance, primarily at the elevation of mixed conifer forest. The stand structure of each forest consists of a canopy layer (overstory) of the tallest trees and an understory made up of herbaceous plants, shrubs, and shorter trees, including species with the genetic potential to grow into the canopy. Details of stand structure (height, density, etc.) and species composition vary by and within forest type. Stand structure and species composition are determined primarily by moisture and disturbance, which in turn are influenced by elevation, topographic position, and slope exposure.

Common canopy tree species are (in approximate order of increasing elevation) ponderosa pine, Douglas-fir, southwestern white pine (*Pinus strobiformis*), quaking aspen, white fir (*Ab-*

ies concolor), limber pine (*Pinus flexilis*), blue spruce (*Picea pungens*), subalpine fir (*Abies lasiocarpa*), corkbark fir (*Abies lasiocarpa* var. *arizonica*), Engelmann spruce (*Picea engelmannii*), and bristlecone pine (*Pinus aristata*).

Understory tree species include junipers (e.g., Utah juniper: *Juniperus osteosperma*), pinyon (piñon) pines (e.g., Colorado pinyon: *Pinus edulis*), oaks (especially Gambel oak: *Quercus gambelii*), New Mexico locust (*Robinia neomexicana*), and Rocky Mountain maple (*Acer glabrum*).

Common shrubs include sages (*Artemisia* spp.), Gambel oak (which may be shrubby or tree-like), buckbrush (*Ceanothus fendleri*), manzanitas (*Arctostaphylos* spp.), creeping mahonia (*Mahonia repens*), honeysuckles (*Lonicera* spp.), currants (*Ribes* spp.), myrtleleaf huckleberry (*Vaccinium myrtillus*), ninebark (*Physocarpus monogynus*), dwarf or common juniper (*Juniperus communis*), and snowberry (*Symphoricarpus oreophilus*).

Herbaceous plants include graminoids (grasses and grass-like plants) such as bluegrasses (*Poa* spp.), bromes (*Bromus*

spp.), fescues (*Festuca* spp.), muhlys (*Muhlenbergii* spp.), and sedges (*Carex* spp.) as well as forbs (broad-leaved herbs) such as paintbrushes (*Castilleja* spp.), *Geraniums* (*Geranium* spp.), strawberries (*Frageria* spp.), fleabanes (*Erigeron* spp.), lupines (*Lupinus* spp.), groundsels (*Senecio* spp.), goldenrods (*Solidago* spp.), and bracken fern (*Pteridium aquilinum*).

Ponderosa pine forest

Ponderosa pine forest makes up 80% of the montane forests in the Southwest. It includes the largest contiguous ponderosa pine forest in North America, extending from west-central New Mexico to the region of Flagstaff, Arizona. Other large areas occur in the southern Rocky Mountains and Jemez Mountains in northern New Mexico and the Kaibab Plateau in northern Arizona.

Prior to settlement by non-indigenous peoples, ponderosa pine forest was generally characterized by relatively open stand structure with large, widely spaced ponderosa pines and a dense, grass-dominated herbaceous layer. Written descriptions from the time include:

We came to a glorious forest of lofty pines...every foot being covered with the finest grass, and beautiful broad grassy vales extended in every direction. The forest was perfectly open... (Beale 1858)

Descriptions of open forest are supported by historical photographs (fig. 4), historical data (e.g., Lang and Stewart 1910), reference sites relatively unaffected by non-indigenous peoples (Fulé et al. 2002), and research that reconstructed past forest structure and composition based on tree rings of current living and dead trees (e.g., Fulé et al. 1997). The open stand structure was maintained by a fire regime of frequent, low-severity surface fires that thinned tree populations; research on

fire history indicates that stands burned approximately every decade (Swetnam and Baisan 1996).

Stand structure and species composition depended on soil moisture. At lower, drier elevations, the canopy of ponderosa pines was very open and the understory had pinyon pines and junipers, reflecting proximity to pinyon-juniper vegetation. With more moisture at mid-elevations, ponderosa pine formed a denser but still open canopy (fig. 4) with ponderosa pine and sometimes Gambel oak dominating the understory. At higher elevations, the canopy was more diverse with ponderosa pine joined by Douglas-fir, quaking aspen, and white fir in forming the transition to mixed conifer forest.

Succession in ponderosa pine forest before the influence of non-indigenous peoples is best considered on an individual-tree scale, because stand- and landscape-scale disturbances such as crown fire were uncommon. Following the death of a large tree, fire eventually consumed it, creating a microsite relatively rich in nutrients and free of competitors. Although tree regeneration was uncommon (White 1985), ponderosa pine seedlings established in years when seeds and sufficient moisture were available; otherwise the microsite was colonized by herbs. Where ponderosa pine regeneration occurred, clusters of seedlings and saplings were thinned by surface fires, but eventually canopy trees were replaced.

Mixed conifer forest

Mixed conifer forest makes up 13% of the montane forest in the Southwest. All areas are relatively small, widely separated and surrounded by much larger areas of ponderosa pine forest. The largest areas of mixed conifer forest include the Kai-



Figure 4. Open structure of ponderosa pine forest in 1909 near Grandview Point, Grand Canyon National Park, northern Arizona. Photograph courtesy of Arizona Historical Society, Flagstaff, Ray Housley Collection.



Figure 5. Mixed conifer forest in 1909-1910 on the Kaibab Plateau, northern Arizona. Photographs from Lang and Stewart (1910).

bab Plateau and the San Francisco Peaks in northern Arizona, the White Mountains in east-central Arizona, and the southern Rocky Mountains and Jemez Mountains in northern New Mexico.

Stand structure prior to settlement by non-indigenous peoples is not well known because there are no descriptions or reference sites, and forest reconstruction studies are subject to greater error than the studies of ponderosa pine forest (but see Fulé et al. 2003a). However, with more moisture at higher elevations, most mixed conifer stands were likely denser than ponderosa pine forests, a conclusion suggested by historical photographs (fig. 5) and historical data on canopy-sized trees (Lang and Stewart 1910). Mixed conifer forest had a mixed-severity fire regime (e.g., Fulé 2003a). Most sites burned in high-frequency, low-severity surface fires similarly but somewhat less frequently than ponderosa pine forest (Swetnam and Baisan 1996). These fires occasionally crowned, especially in dense stands in dry years (cf. Margolis et al. 2007). The result was a patchy landscape mosaic that reflected the diversity and interaction of topography, vegetation, and fire (e.g., Moir 1993, White and Vankat 1993, Fulé 2003a).

As implied by the name mixed conifer forest, species composition was variable, depending primarily on moisture, which is influenced by elevation, topographic position, and slope exposure. The mix of canopy species included ponderosa pine, Douglas-fir, quaking aspen, white fir, limber pine, blue spruce, subalpine fir, corkbark fir, and Engelmann spruce. Individual stands typically had three to five of these species in the canopy, although less diverse stands were present, especially of Douglas-fir. Relatively dry stands were generally dominated by a mix of ponderosa pine, Douglas-fir, quaking aspen, and white fir. Such stands were widespread at low elevations (where they were transitional with moist ponderosa pine forest). At higher elevations, these stands were more restricted to dry sites, such as ridgetops and south and west slope exposures. Moist stands had a greater abundance of subalpine fir or corkbark fir and Engelmann and blue spruce in the canopy. Such stands were widespread at high elevations (where they were transitional with spruce-fir forest) and more restricted to valley bottoms and north and east slope exposures at lower elevations.

Succession in mixed conifer forest (and low-elevation spruce-fir forest) occurred at both the single tree and stand scales, reflecting the mixed-severity fire regime that included surface and crown fires. In areas where fires remained on the surface, succession occurred at the single tree scale, similar to ponderosa pine forest. In stands where fires crowned, succession often involved the initiation and growth of dense patches of young quaking aspen forest.



Figure 6. Spruce-fir forest ca. 1910 on San Francisco Peaks, northern Arizona. Photograph courtesy of Arizona Historical Society, Flagstaff, William H. Switzer Collection.

Spruce-fir forest

Spruce-fir forest makes up only 4% of the montane forest in the Southwest. All areas are small, widely separated, and surrounded by larger areas of mixed conifer forest. The largest areas of spruce-fir forest occur on the San Francisco Peaks in northern Arizona, the White Mountains of east-central Arizona, and the southern Rocky Mountains and Jemez Mountains of northern New Mexico.

Stand structure prior to settlement by non-indigenous peoples has not been well studied. Structure likely depended on successional age and therefore may be similar to today's structure (fig. 6). The fire regime is poorly known for the Southwest, but at relatively low elevations it was likely a mixed-severity regime similar to mixed conifer forest (Fulé et al. 2003a) and at higher elevations it may have been a crown fire regime characterized by high-severity, stand-replacing fires at intervals of one or more centuries. Succession following crown fire is unstudied for the Southwest, but tree density may have increased early in succession and decreased in older stands. Structure also depended on elevation, as stands were more open and had shorter canopies closer to treeline.

Stand composition was dominated by Engelmann or blue spruce, often with subalpine or corkbark fir and some quaking aspen. Low elevation stands had occasional ponderosa pines and Douglas-firs indicative of transition with mixed conifer forest. Some treeline stands were dominated by bristlecone pine. Tree species composition also depended on successional age, with younger stands dominated by Engelmann spruce, quaking aspen, or both. Subalpine or corkbark fir may have co-established with Engelmann spruce or followed several decades later.



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Figure 7. Patches of quaking aspen forest (light green) in mixed conifer forest (dark green) along the New Mexico-Colorado border.

Quaking aspen forest

Quaking aspen forest makes up only 4% of the montane forest in the Southwest. It typically occurs in small to large patches where crown fire had burned mixed conifer forest, or where other stand-replacing disturbance had occurred (fig. 7). Even distant patches are easily visible because aspens are lighter green than conifers in summer, yellow in fall, and leafless in winter. Extensive areas of quaking aspen forest occur on the San Francisco Peaks in northern Arizona, the White Mountains in east-central Arizona, and the southern Rocky Mountains and Jemez Mountains of northern New Mexico.

Stand structure prior to settlement by non-indigenous peoples is poorly understood. However, because structure depends on successional age and stand-initiating disturbances occurred in the past and present, the range of stand structures was likely similar to today (although there are likely proportionately fewer young and more old stands today). The fire regime of quaking aspen forest generally mimicked that of adjacent stands of coniferous forest; however, aspen stands are less flammable and therefore had lower fire frequency and severity.

In terms of species composition, aspen dominated the canopy of all stands and conifers were present in the understory in all except very young or semi-permanent stands. Conifers included ponderosa pine, white fir, subalpine or corkbark fir, and blue or Engelmann spruce, depending on site characteristics and composition of adjacent conifer stands.

Succession following crown fire (or other stand-replacing disturbance) began with aspen resprouting from root systems of trees whose trunks were killed. Fire stimulated sprouting. A

dense, even-aged canopy formed in a few decades. At some point in succession, depending on the availability of seed sources, conifers usually invaded (fig. 8). Mature stands, therefore, had a well-developed canopy of aspen and an understory with a mixture of aspen and conifers. The understory conifers, if present, had the potential to overtop and replace the relatively short-lived (100-150 years) aspen in succession, converting stands into mixed conifer forest. However, large stands where sources of conifer seeds were distant may have had little ingrowth of conifers and were semi-permanent.

Human Impacts (Stressors)

Before settlement by non-indigenous peoples

Prior to settlement by non-indigenous peoples, Native American impacts such as burning and cutting of southwestern montane forests were highly localized (Allen 2002) and generally focused on ponderosa pine forest. Clearing for agriculture occurred mostly in pinyon-juniper vegetation at lower elevations.

After settlement by non-indigenous peoples

Initial impacts of non-indigenous peoples on montane forests were also small, but grew in the second half of the 19th century when railroads linked the American Southwest to large commercial markets and made livestock grazing and timber harvesting profitable.

Livestock grazing

The major impact of 19th-century grazing of domestic sheep and cattle on the montane forests of the Southwest remained



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Figure 8. Quaking aspen forest with in-growth of young conifers on the San Francisco Peaks in northern Arizona.

little recognized until ecological research in the second half of the 20th-century linked it to the end of surface fires. In brief, the livestock grazed understory grasses and forbs, which reduced the contiguity of surface fuels in forests. This prevented the spread of surface fires, abruptly altering fire regimes. Without the thinning effects of frequent surface fires, more seedlings, saplings, and trees survived, and montane forests dramatically increased in density.

Timber harvesting

Logging was another historical factor that greatly affected the structure of montane forests. Following extensive clear-cutting in the late 19th and 20th centuries (primarily in ponderosa pine forest), regeneration resulted in dense stands of tree seedlings. Without the thinning effects of frequent surface fires, these stands matured into much denser, more even-aged forests than had been present before logging.

Fire suppression

Fires initially were unintentionally excluded from montane forests of the American Southwest by livestock grazing, but soon after the turn of the 20th century land management agencies such as the newly created U.S. Forest Service began to intentionally put out fires in an attempt to protect forest resources. Fire suppression became a focus of management practices in the Forest Service and later in other agencies like the National Park Service, and it was increasingly effective in stopping fires through most of the 20th century. With the exclusion of fire, the structure and species composition of southwestern forests dramatically changed, as did their fire regimes.

Management fire

As the adverse effects of excluding fires became widely recognized in the second half of the 20th century, forest management practices changed to include reintroducing fire. Initially this was done through prescribed burning, i.e., fires set under prescribed conditions of temperature, humidity, wind speed, fuel moisture, etc. The intent was to ensure that prescribed burns remain surface fires, be restricted in area, and accomplish specific goals such as reduced tree densities and fuels (e.g., dead trees and forest floor litter such as needles and downed branches). Research findings on historical forest conditions were used as a reference point for management. Later, selected lightning-ignited fires began to be used for similar purposes. Fires were first reintroduced into ponderosa pine forest because of the relatively low risk of surface fires becoming crown fires. Reintroduction into mixed conifer forest has proven more challenging because of greater risk of undesirably large crown fires.

Exotic invasive plants

Exotic plants can alter ecosystem structure, composition, and function and can be a threat to biodiversity. Invasives generally are not as abundant in the Southwest as in other regions of the United States, primarily because extensive, intensive land use began later in this region (Rejmánek and Randall 1994); however, invasives are of growing concern in the region. The abundance of invasives in montane forests is highly variable. In general, they increase with disturbance (e.g., Laughlin et al. 2004, Crawford 2008) and decrease with increasing elevation (Vankat 2005).

Recent climate change

Climate has always changed, but this paragraph deals with recent climate change induced by human actions. Effects on montane forests of the Southwest have not been well-studied. Nevertheless, there are strong indications of links between recent climate change and forest changes. For example, climate change is likely involved in increased insect-caused tree mortality, an effect well-documented for pinyon pine in pinyon-juniper vegetation (Breshears et al. 2005) and apparently also present in montane forests (e.g., Worrall et al. 2008; cf. Vankat 2011b). Also, recent climate change has been linked to increased large wildfire activity in the western U.S. (Westerling et al. 2006).

Air pollution

Air pollution is a cause of recent climate change, but air pollutants can have direct effects on forest trees as well. Such effects have been little studied in the Southwest; however, the current atmospheric levels of ozone in some areas of the Southwest exceed the levels that have affected trees in montane forests of other regions (Vankat 2005).

Fragmentation

Fragmentation is a natural factor for montane forests of the Southwest because of their distribution on plateaus and mountains separated by lowlands. However, human-caused fragmentation occurs with clear-cut logging and increased landscape-scale crown fires. Such fragmentation has not been studied, although it may affect species' abilities to migrate to favorable areas in response to climate change.

Effects on montane forests

Ponderosa pine forest

Ponderosa pine forest has been more impacted than other montane forests of the American Southwest. Nearly all of it was grazed by livestock (much is grazed today), logged (some



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Figure 9. Dense stand of ponderosa pine forest after more than a century of fire exclusion in northern Arizona.

continues today), altered by fire exclusion, affected by recent climate change, and invaded by exotic plants.

As the result of fire exclusion and past logging, forest stands are much denser today than before settlement by non-indigenous peoples (fig. 9). Mid and high elevation stands also have shifted in species composition as a result of fire exclusion, with large increases in white fir, which is fire-intolerant and shade-tolerant, and decreases in aspen, which regenerates primarily by fire-stimulated root sprouting. In addition, forest fuels accumulated over the century without fire and have been augmented by widespread tree mortality caused by bark-beetle outbreaks, which in turn are related to recent climate change. With increased density and fuels, stands of ponderosa pine forest have become much more susceptible to crown fire, in effect shifting the fire regime from surface fire to mixed-severity fire. Where crown fire or clear-cut logging have oc-

curred, succession has changed in scale from single trees to stands or landscapes. In some lower-elevation areas, forest has been replaced by semi-permanent pinyon-juniper vegetation. In other areas, forest has been replaced by grasslands (fig. 10) or shrublands (Savage and Mast 2005). Fire regimes have the potential to be affected by cheatgrass (*Bromus tectorum*), an exotic invasive annual whose yearly production of biomass may literally fuel an unnaturally high frequency of surface fires.

In some areas, forest managers used mechanical thinning of small trees and management fires to address the increases in forest density and fuels and changes in forest composition. Nevertheless, much of the ponderosa pine forest needs restoration.

Mixed conifer forest

Nearly all of the mixed conifer forest was grazed by livestock (some continues today), altered by fire exclusion, and apparently affected by recent climate change. In comparison to ponderosa pine forest, there has been little logging, primarily because many stands are inaccessible and have few ponderosa pines, the most valuable timber species of the American Southwest. Exotic invasive plants are uncommon except in early stages of succession following crown fire (cf. Crawford 2008).

As a result of fire exclusion, mixed conifer forest increased in density, at least until the mid-20th century (Vankat 2011b), as well as in fuels (fig. 11). Species composition also changed, with increases in shade-tolerant, fire-intolerant species such as white fir and subalpine or corkbark fir. With increased density and fuels, the mixed-severity fire regime changed to include more crown fire, and today it may be a crown fire regime.



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Figure 10. Past crown fire replaced forest with grassland in northern Arizona.



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Figure 11. Stand of mixed conifer forest on San Francisco Peaks in northern Arizona.

For example, the mixed conifer forest of the topographically diverse North Rim region of Grand Canyon National Park in northern Arizona formerly had only small patches of crown fire (Fulé et al. 2003a,b), but experienced landscape-scale crown fires in the first decade of the 21st century. Post-fire succession in these areas produced extensive stands of quaking aspen forest. These had not been present historically but now have the potential to become semi-permanent where long distances to seed sources limit ingrowth of conifers. In addition, even unburned stands of mixed conifer forest of this area have changed. Recent research indicated tree density peaked in the mid-20th century and decreased to the early 21st century. Large decreases in aspen accounted for much of this decrease in tree density because of several factors including lack of surface fires, and the decreases in conifers appear to be related to unsustainably high tree density and recent climate change (Vankat 2011b).

Historical increases in forest density and fuels and changes in species composition have been addressed by forest managers in a few areas with mechanical thinning of small trees and with management fires. Thinning is difficult because of poor accessibility, and the use of management fires risks surface fires becoming crown fires. Most of the mixed conifer forest needs restoration.

Spruce-fir forest

Spruce-fir forest has been less impacted by human-caused stressors than either ponderosa pine forest or mixed conifer forest. There has been little logging (because of poor accessibility) or invasion by exotic plants. Livestock grazing (some continues today) and fire exclusion affected lower elevation stands, but their impacts on higher elevation stands are unclear. Recent climate change appears to have affected all elevations.

Changes in stand structure, species composition, and fire regime in low elevation spruce-fir forest have been similar to those described above for mixed conifer forest. In northern Arizona's Grand Canyon National Park, tree density appears to have increased with fire exclusion to the mid-20th century and then decreased (fig. 12). Large decreases in aspen were caused by several factors including lack of surface fires, and decreases in conifers were likely related to unsustainably high tree density and recent climate change (Vankat 2011b). In addition, the fire regime may have shifted to more crown fire, at least until canopies of some stands began to open after the mid-20th century. Forest managers have addressed increases in forest density in a few lower elevation stands by mechanically thinning small trees; however, this is difficult in many areas because of poor accessibility. Use of management fires



Figure 12. Spruce-fir forest in Grand Canyon National Park, northern Arizona. Downed dead trees in foreground illustrate recent decrease in density.

is also challenging because of the risk of surface fires becoming crown fires.

Changes in upper elevation stands are less well known. Fire exclusion, which has lasted a little more than a century, may not have affected these forests because historically, crown fires likely occurred at intervals of one or more centuries. In some high-elevation areas, the spruce and fir canopy has died as a result of insect outbreaks that are likely tied to recent climate change.

Quaking aspen forest

Quaking aspen forest has also had relatively few impacts. Livestock grazing occurred (some continues today), and fire exclusion and climate change may have reduced the health of stands. However, there has been little logging or invasion by exotic plants.

The effects of fire exclusion on quaking aspen forest are complex. As described above, landscape-scale crown fires following fire exclusion in mixed conifer forest have resulted in the establishment of large areas of quaking aspen forest. However, fire exclusion (by reducing aspen sprouting and mortality of conifers) may expedite the successional conversion of quaking aspen forest into mixed conifer forest. Fire exclusion is also one of many factors involved in the declining health of stands in many areas of the Southwest. Aspen is not regenerating well due to fire exclusion and grazing of sprouts by livestock and elk. "Sudden aspen decline," which refers to mortality caused by insects, bark beetles, and canker fungi in response to drought, high temperatures, late frosts, and

repeated defoliation by insects, is also affecting stand health (Worrall et al. 2008). The role of climate in affecting insects, bark beetles, and canker fungi suggests sudden aspen decline is related to recent climate change.

Forest managers have attempted restoration of quaking aspen forest on a limited scale. Approaches include prescribed burning and fencing to exclude livestock and elk. Prescribed fires pose a risk of crown fire in adjacent mixed conifer stands, and fencing is costly.

Conclusion

This overview of montane forests is based on the research of many scientists. However, the frequent, necessary inclusion of equivocating words such as “likely”, “may”, and “appears” indicates that additional research is needed. This is especially true in light of an uncertain future in which climate change, exotic invasive species, and other stressors may have increasingly large effects.

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