ASSESSMENT OF MIXED CONIFER FOREST CONDITIONS, NORTH KAIBAB RANGER DISTRICT, KAIBAB NATIONAL FOREST, ARIZONA, USA

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ABSTRACT

Southwest mixed conifer forest types maintain a diversity of tree species and structural conditions that contribute to desirable ecosystem services (e.g., higher biodiversity, watershed protection, forest carbon pools and aesthetic values). Less is known about mixed conifer forest and historical changes in composition and structure than for other Southwest forest types such as ponderosa pine. The U.S. Forest Service 2009 Kaibab Forest Health Focus initiative identified mixed conifer forest as a priority vegetation type requiring active forest restoration and hazardous fuel reduction in light of recent and severe fire activity. We evaluated contemporary changes in mixed conifer forest conditions on the North Kaibab Ranger District (NKRD) of Kaibab National Forest north of Grand Canyon National Park (GCNP), where other recent studies and historical forest inventories provided an excellent opportunity for comparative analyses. Inventory data from 1909, 1955 and the 1990s on the NKRD showed that average basal area had doubled by 1955. Basal area in 1990 was also double that of 1909, but had decreased by 28%, for trees ≥30 cm in diameter since 1955. Tree density for shade-tolerant species such as spruce and true fir showed a >600% increase between 1909 and 1990, whereas ponderosa pine showed little increase. Inventory data indicated a pattern of high basal area accretion prior to 1955 as fire was excluded from MC forest and increased tree recruitment of shade tolerant species following selective logging and insect caused tree mortality during the 1970s and 80s. Separate analyses of elevation and annual solar radiation gradients indicated that tree species composition was significantly different from low to high elevation sites in 1990, as was average canopy height. Densities of shade-tolerant trees were high on all sites. Forest structural attributes associated with fire behavior did not differ significantly across gradients with the exception of relatively mesic sites at high elevations or in shaded areas (i.e., drainages) that showed 18% greater canopy bulk density and 11% lower canopy base height. Restoration activities in mixed conifer forest should be focused on reducing a historically high density of shade-tolerant understory trees while providing opportunities for the regeneration of fire-adapted species, such as ponderosa pine and Douglas fir. Tree thinning and burning activities should seek to restore mixed severity fire regimes that historically maintained tree species and structural diversity, while reducing overall hazardous fuel accumulations that have developed for most site conditions in the absence of fire.

INTRODUCTION

Mixed conifer (MC) forest on the Kaibab Plateau in northern Arizona is typically characterized by tree species that include ponderosa pine (*Pinus ponderosa*), white fir (*Abies concolor*), Douglas fir (*Pseudotsuga menziesii*), and aspen (*Populus tremuloides*), but also intermixes with spruce-fir forest on more mesic sites with blue spruce (*Picea pungens*), Engelmann spruce (*Picea engelmannii*), and sub-alpine fir (*Abies lasiocarpa*) (White and Vankat 1993). This mixed composition facilitates structural complexity and species diversity, which in turn provide a variety of ecosystem services, such as maintaining watershed values, forest carbon pools and wildlife species habitat (North et al. 2009). The 2009 U.S. Forest Service (USFS) Kaibab Forest Health Focus (Sisk et al. 2009) was a stakeholder-driven initiative and process that identified ponderosa pine and MC forest as priority forest types in need of restoration treatments critical to the maintenance of values and conditions resilient to ecosystem stressors. Stakeholders included local, state and federal land management agencies and non-government environmental organizations.

Studies focused on the condition of western MC forests suggest that many areas are susceptible to increased tree mortality and insect outbreaks as a result of past fire suppression, climate-induced drought and water stress (Guarín and Taylor 2005, Vankat et al. 2005, North et al. 2009, Fulé et al. 2009, van Mantgem et al. 2009). Historically, fires burned with low to mixed severity in MC forest on the Kaibab Plateau (Fulé et al. 2003). Recent wildfires in ponderosa pine and MC forest on USFS land north of Grand Canyon National Park (GCNP), such as the Outlet (2000) and Warm (2006) fires, have shown uncharacteristically extensive and severe fire behavior, particularly in areas of dense and contiguous tree canopy (Wimberly et al. 2009).

While forest conditions in ponderosa pine-dominated sites are well studied, quantitative characterizations of past and present mixed conifer forest composition and structure are relatively few in number (but see White and Vankat 1993, Fulé et al. 2003, Heinlein et al. 2005, Cocke et al. 2005, Fulé et al. 2009, Vankat 2011). Forest reconstruction and dendrochronology studies for GCNP have demonstrated striking changes in forest composition and structure since historical fire suppression activities began c. 1879 (Fulé et al. 2003, Fulé et al. 2004). However, a loss of historical evidence on more mesic MC forest sites can increase uncertainty about forest conditions and change because of loss of evidence, particularly for small diameter trees, which can be consumed by fire or decay rapidly after mortality (Allen et al. 2002). Forest inventories can provide an added source of information about forest conditions for identifying historical forest structure, composition and dynamics over time to enhance reconstruction data (Sesnie and Bailey 2003, Fulé et al. 2003, Fulé et al. 2004, Vankat 2011).

Less is known about MC forest conditions occurring in forests to the north of GCNP on USFS land, which has been subject to numerous forest management regimes and policy changes over the last century. Our analysis of MC forest structure and composition on the North Kaibab Range District (NKRD) of the Kaibab National Forest (KNF) was undertaken to inform land-use planning and stakeholder discussions about historical changes in MC forest conditions, and to develop restoration treatment recommendations for broad spatial extents. In order to establish an improved understanding of existing MC forest conditions on the NKRD, our study objectives were to: 1) compare historical and contemporary mixed conifer forest structure and composition; 2) characterize environmental conditions that contain MC forest types and determine current forest structure and composition differences across elevation and solar radiation gradients associated with site moisture regimes; and 3) provide a quantitative framework for developing restoration criteria and a desired future condition for MC forest types.

Despite a century of active forest management on USFS lands, which included fire suppression, tree thinning and selective logging, shade-tolerant species have become an increasingly dominant component of MC forest types in the absence of fire (Stein 1988, Fulé et al. 2009, White and Vankat 1993). In addition, forest composition and structure within the MC forest types potentially differ along elevation and topographic gradients associated with site moisture regimes (White and Vankat 1993, Fulé et al. 2003). Kaibab National Forest staff distinguishes between dry and wet site MC forest types, and have developed a set of desired conditions for each type to guide forest management planning. However, site-scale biophysical conditions have not been quantitatively assessed to contrast forest conditions across moisture gradients. We hypothesized that site biophysical variables influence niche factors and disturbance patterns that can drive MC forest structural differences known to influence fire behavior, such as canopy bulk density and canopy base height. Canopy bulk density (kg/m^3) and canopy base height (m) are two important forest structural parameters commonly used to assess forest fuel conditions and model wildland fire behavior (Chuvieco et al. 2003). Historical and contemporary forest inventory data can help to characterize potential differences in MC forest structure and composition prior to developing restoration and hazardous fuels mitigation recommendations within MC forest types on the NKRD.

METHODS AND MATERIALS

Study Area

The study area includes MC forest on the NKRD in northern Arizona (Figure 2.1). A 65,700-ha area was initially defined as containing MC forest based on the extent of the LANDFIRE program's (http://www.landfire.gov/) existing vegetation map and MC forest categorizations. This area ranges in elevation from 1,700 to 2,800 m. However, only MC forest at elevations above ≥2,550 m (total area = 49,300 ha) was examined due to the 2006 Warm Fire that burned some MC forest below this elevation. In addition, MC and spruce-fir forest principally exist on sites above 2,500 m (White and Vankat 1993). Kaibab National Forest staff typically considers forests above 2,900 m as the spruce-fir forest type, although MC forest on mesic sites below this elevation may closely resemble spruce-fir species composition. Average annual precipitation and temperature can vary considerably across the Kaibab Plateau according to meteorological data recorded from years 1925 to 2009 (http://www.wrcc.dri.edu/). The Jacob Lake (2,414 m) weather station that is within the ponderosa pine forest type, at the northern end of the Kaibab Plateau, has an annual average of 53 cm of rainfall and 268 cm of snowfall, whereas the Bright Angel Ranger Station (2,560 m) to the south in GCNP shows an annual average of 64 cm of rainfall and 347 cm of snowfall. Temperatures associated with MC forest are generally cooler in the upper elevations and range between a maximum of 25° C in July to a minimum of -9° C in January at the Bright Angel Ranger Station.

Topography in the study area is comprised of low, forested plateaus and ridge tops divided by valley bottoms and more continuous areas of even terrain toward the center of the Kaibab Plateau. Soils underlying MC forest generally are Utric Glossoboralfs and Typic Cryoboralfs and Paleboralfs with a mixture of fine sandy and gravely loam textures (Brewer et al. 1991).

Available Datasets

No new data were collected with this study as historical and contemporary forest inventory data were available for the NKRD (Sesnie and Bailey 2003). Three principal datasets were consolidated and used to perform comparative analyses:

- Historical inventory data from 1909 and a stand table for the MC forest type on the

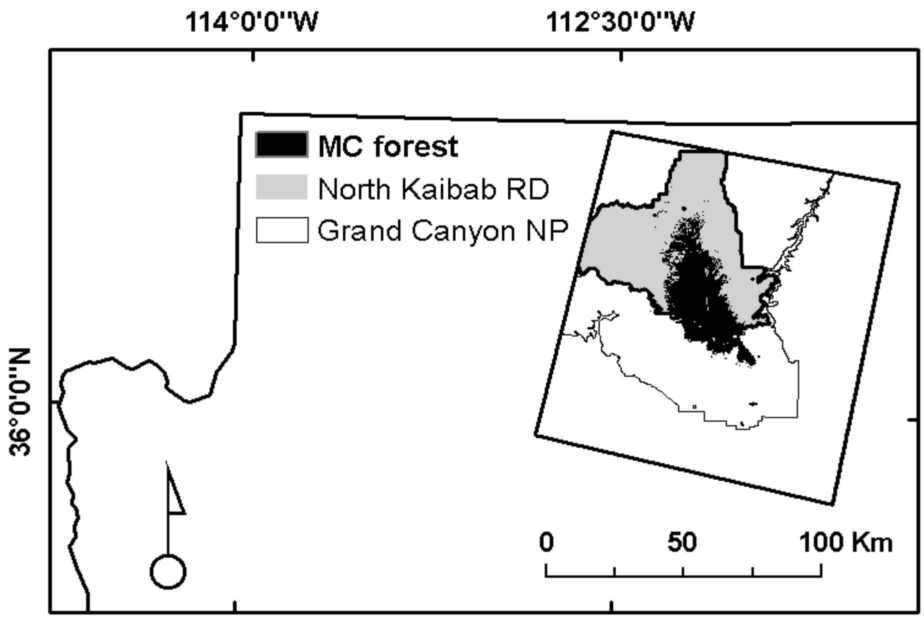


Figure 2.1 Mixed conifer study area on the Kaibab National Forest, North Kaibab Ranger District in northern Arizona.

Table 2.1 The number and area of mixed conifer forest stand polygons analyzed according to elevation and solar radiation categories.

Elevation Categories	Descriptor	No. Stands	Area (ha)	% of Area Sampled[a]
1 (2,550 – 2,627 m)	Dry	50	930	10.2
2 (2,627 – 2,693)	Moist	118	4,100	52.5
3 (2,693 – 2,807)	Mesic	134	4,692	81.5
Solar radiation categories[b] 1 (268,695 – 1,727,604 w/m^2/yr)	Mesic	42	1,113	49.8
2 (1,727,604 – 1,810,183)	Moist	124	4,495	40.1
3 (1,810,183 – 1,865,237)	Dry	77	2,803	41.0
4 (1,865,237- 2,023,515)	Very Dry	40	1,208	46.6

[a] Percent of area sampled indicates the proportion of area inventoried that was in a mixed conifer forest type rather than aspen, ponderosa pine or other hardwood forest types.
[b] Solar radiation categories are associated with slopes of increased exposure to sunlight throughout the year.

NKRD summarizing tree density (trees/ha) for conifer species were compared to the most recent forest inventory data described below. The 1909 inventory data are from a 52-ha "strip cruise" which measured diameter at breast height (d.b.h, 1.37-m above the ground) for all conifer trees ≥15.2 cm d.b.h, in addition to seedlings ranging in height from 0 to 1 m and saplings that ranged from 1m in height to <15.2 cm d.b.h (Lang and Steward 1910). Basal area (m^2/ha) was calculated for each tree species within 2.5 cm diameter classes for trees >15.2 cm and <50.8 cm d.b.h and 5 cm diameter classes for trees ≥50.8 cm d.b.h.using the equation for English units (d^2*0.005454)* the number of trees per acre in a class, where d^2 is the squared d.b.h class. An assumed mid-point d.b.h of 7.6 cm was used to estimate sapling basal area for all tally trees in this size class. Basal area was then converted to m^2/ha. In previous studies, Lang and Stewart (1910) stand table data have compared favorably to tables developed Southwest forest types in the early 1900s (Woolsey 1911, Sesnie and Bailey 2003) and forest reconstruction data (Fulé et al. 2003, Fule et al. 2004). These data represent early MC forest structure and composition prior to more extensive USFS timber management and active fire suppression, although fire regime disruption likely occurred prior to 1909 because of heavy livestock grazing beginning c. 1885 (Russo 1964). A second pair of stand tables for open and dense forest conditions developed from 1955 Continuous Forest Inventory (CFI) 10th ha plots (n = 54) in unlogged MC forest was also compared with the 1909 inventory. The 1955 stand tables tallied saplings in diameter categories between 9.1 cm and 19.2 cm d.b.h and 19.3 cm and 29.4 cm d.b.h and no seedlings were accounted for in tables. The mid-point for each diameter class was used to estimate basal area for saplings in addition to 2.5 cm diameter classes for trees ≥29.4 cm.

• Recent inventory data for MC forest types were collected between 1980 and 2000 (USFS Stand Exam inventories) and used for comparison with the 1909 MC stand table. This recent dataset is referred to as the "1990 inventory" (average year measured) and cover site biophysical conditions representative of the NKRD MC forest stands. Tree measurements were collected using variable-radius plots for trees ≥12.7 cm d.b.h and nested fixed-radius plots (typically 1/300 ac or 2 m radius plots size) for smaller trees <12.7 cm d.b.h. A diameter was recorded for all trees greater than 2.5 cm d.b.h (1" d.b.h) and all other seedlings and saplings were counted. Approximately one plot per hectare was established within stand polygons, which were drawn over orthorectified aerial photographs to discriminate different forest types and site conditions. Small tree counts and diameter measurements differed between 1909, 1955 and 1990 inventories as diameters were measured with greater precision in 1990. Basal area calculations for 1909 and 1955 were more uncertain, particularly for saplings, since trees were tallied within a diameter range that can over or underestimate these values. Nevertheless, saplings typically constituted a small proportion of the overall tree basal area on a site.

• Environmental data were evaluated in a geographic information system (GIS), along with 30-m digital elevation models (DEMs) from the National Elevation Dataset (NED, http://seamless.usgs.gov/). DEMs were used to estimate average elevation and annual solar radiation values within 1990 forest inventory units (mapped stand polygons). Terrain features were used to develop biophysical categories for stratifying and comparing MC forest inventories according to low-, mid- and high-elevation sites across the NKRD.

Analyses

To compare contemporary and historical forest conditions, MC 1990 inventory data (n = 528 stands) were summarized using average tree species density and basal area regardless of geographic location or biophysical setting. Tree density and basal area for conifers were also summarized according five d.b.h classes (<10cm, 10-29.9cm, 30-45.9cm, 46-60.9cm, >61cm) for comparison between inventory dates and tree species. In the KNF inventory database, stand polygons were classified by dominant tree species. For this analysis, only MC forest types dominated by a combination of ponderosa pine, spruce, true fir or Douglas fir trees were summarized and compared with 1909 MC inventory data. 1990 MC stands had a maximum of 50 percent of the basal area comprised by ponderosa pine. Average tree density and basal area for each coniferous tree species were used to compare the two forest inventories since only a summarized stand table for MC forest was available from 1909.

We also evaluated average tree species density and basal area from 1990 MC forest inventories within elevation categories above 2,550 m. These categories are related to precipitation gradients at a macro-scale, according to interpolated mean annual precipitation data (not shown, http://www.worldclim.org/). Elevation categories were selected using three quantile groups, with elevation values ranging from the 25th to 50th percentile (Dry), 50th to 75th percentile (Moist) and values >75th percentile (Mesic) for existing MC forest mapped by LANDFIRE (Table 2.1; Figure 2.2). MC forest polygons below the 25th percentile were <2,550 m, which excluded some lower elevation MC forests that transition from ponderosa pine. MC forest structure and composition within stand polygons for each elevation category were assumed to follow a gradient of increasing annual precipitation and temperature based on weather station records from the Kaibab Plateau and interpolated climate data. The elevation category of an MC stand inventory polygon was determined using the average value calculated with the Spatial Analyst extension to ArcGIS (v.9.3; Environmental Systems Research Institute, Redlands, CA).

To determine if MC forest composition differed between elevation categories, multivariate comparisons were made using Multi-Response Permutation Procedures (MRPP; McCune and Grace 2002) implemented in PC-ORD (v.5; McCune and Medford 1999). MRPP provided a non-parametric multivariate statistical comparison capable of using non-Euclidean distance measures to compare tree species data within elevation categories. MRPP also is a robust means of analyzing data of unequal and small sample sizes (McCune and Grace 2002). Comparisons among elevation categories were made using Sorensen (Bray-Curtis) similarity values derived from the average basal area for each tree species. Average stand tree basal area, density, canopy bulk density, canopy base height and canopy height in each elevation category were compared using two-sample t-tests (test statistic = t, $\alpha = 0.05$).

We also analyzed total annual solar radiation categories to compare forest composition and structure along moisture gradients associated with topography. Solar radiation is a function of local-scale topography and likely interacts with elevation. However, for this study, observations were made without accounting for differences in elevation to avoid limitations associated with a large number of categories and a small number of representative samples. Global solar radiation values (w/m^2/year) were derived from the DEM using the Solar Analyst v. 1.0 extension to ArcView (v.3.3; Environmental Systems Research Institute, Redlands, CA). As with elevation, annual solar radiation was divided into four quantile categories (Table 2.1; Figure 2.3). Radiation categories represent an increasing amount of annual sunlight incident upon land surfaces as a function of slope conditions, surrounding terrain, and aspect. The amount of solar radiation on a site drives important ecosystem processes, such as photosynthesis, transpiration and evaporation, plant growth, and species composition in addition to soil and plant moisture conditions (Pocewicz et al. 2004). Only MC forest inventories above 2,550 m were used to evaluate changes in tree density, basal area, canopy bulk density, canopy base height and canopy height according to radiation categories. The multivariate (MRPP) and univariate (t-tests) analyses detailed above were also used for these comparisons. The radiation category of each MC stand inventory polygon was determined using the average value calculated in ArcGIS.

All 1990 forest inventory data were summarized using the Forest Vegetation Simulator (FVS) Central Rockies variant for Southwest tree species (http://www.fs.fed.us/fmsc/fvs/). Canopy bulk density and canopy base height estimates were calculated with the FVS Fire and Fuels Extension (Reinhardt and Crookston 2003), which uses empirical methods described in Scott and Reinhardt (2001).

Most MC forest on the NKRD has undergone selective harvesting in the past three decades, according to post hoc forest change comparisons made using spectral data Landsat Multispectral Spectral Scanner (MSS) imagery from 1973, 1983, and 1993 (data not shown). However, forest disturbances were not accounted for in our comparative analyses of stands, with the exception of relatively small areas that have experienced clear cutting or other severe disturbances (e.g., wind-throw or fire). These stand polygons were typically <6 ha in size and were removed from all analyses because they represented a small proportion of MC stands in the study area with principally early successional forest characteristics.

RESULTS AND DISCUSSION

Mixed Conifer Inventories

The 1909 stand table and 1990 forest inventory data indicated that large changes have occurred in MC forest composition and structure over the 20th century (Table 2.2). Tree density for shade-tolerant species, such as spruce and true fir, increased >600% between years 1909 and 1990. Density and basal area increases were primarily from recruitment of shade-tolerant saplings and trees 10 cm to 46 cm d.b.h (Table 2.3). A relatively small increase in tree density (53%) and basal area (24%) was observed for ponderosa pine. Ponderosa pine and Douglas fir were favored for timber harvest on the NKRD, which is a potential explanation for minor increases in basal area that have been observed for these species in other parts of the Southwest (Fulé et al. 2009). For all conifer species combined, tree density was over three times higher in 1990 than was documented in the 1909 inventory, and basal area increased by 83%. High tree density and basal area from 1990 inventories were similar to values reported in previous studies excluding aspen (White and Vankat 1993, Fulé et al. 2003, Cocke et al. 2005). Further analyses of 1990 MC forest conditions within elevation and solar radiation categories below included aspen for comparison with other studies.

Comparisons between 1909 and 1990 inventories should be considered with some discretion, as sampling protocols were different and only a stand table summary is available from 1909. In addition, the specific geographic location of the 52 ha plot reported in the 1909 inventory is unknown. Fulé et al. (2003, 2004) found that the 1909 stand table summary data matched well with reconstructed forest composition and structure data derived from studies in GCNP. The 1909 inventory and contemporary data likely provide a useful reference for identifying general changes in MC forest

Table 2.2 Differences in mean tree density and basal area for all conifer tree species including seedling and saplings between 1909 and 1990. Species are ponderosa pine (PP), Douglas fir (DF), true-fir (TF, sub-alpine fir and white fir) and spruce (SP, Engelmann and blue spruce) to matching 1990 inventory data with the 1909 MC table.

	Average density (trees/ha)			Average basal area (m^2/ha)		
Species	**1909**	**1990**	**Increase (%)**	**1909**	**1990**	**Increase (%)**
PP	17.4	26.7	53	5.1	6.3	24
DF	6.9	36.9	435	2.0	3.1	55
TF	37.8	304.2	705	3.6	7.7	114
SP	12.6	88.3	601	2.1	6.2	195
SUM	74.7	456.2	-	12.8	23.4	-

Table 2.3 Differences in mean tree density and basal area for all conifer tree species between 1909 and 1990 within five diameter classes.

1909 average density (trees/ha)						1909 average basal area (m^2/ha)				
DBH Class	**PP**	**DF**	**TF**	**SP**	**Sum**	**PP**	**DF**	**TF**	**SP**	**Sum**
Saplings	9.9	4.1	32.8	9.0	55.9	0.3	0.1	0.8	0.3	1.5
15.2-29.9[1] cm	3.7	1.4	2.8	1.9	9.8	0.8	0.3	0.6	0.4	2.1
30-45.9	2.2	0.5	1.3	1.5	5.2	1.4	0.3	0.8	0.7	3.2
46-60.9	0.9	0.6	0.6	0.5	2.6	1.1	0.7	0.7	0.5	3.1
>=61	0.6	0.3	0.3	0.1	1.3	1.5	0.6	0.7	0.2	3.0
				Sum	74.7				**Sum**	12.8

1990 average density (trees/ha)						1990 average basal area (m^2/ha)				
DBH Class	**PP**	**DF**	**TF**	**SP**	**Sum**	**PP**	**DF**	**TF**	**SP**	**Sum**
Saplings	16.0	29.2	280.0	69.7	394.9	0.1	0.1	0.3	0.2	0.7
10-29.9 cm	6.5	5.7	19.5	14.3	45.9	1.3	1.1	3.5	2.6	8.5
30-45.9	2.2	1.5	3.6	3.5	10.8	1.5	1.0	2.3	2.2	7.0
46-60.9	1.3	0.5	0.8	0.7	3.3	1.7	0.6	1.1	0.9	4.3
>=61	0.7	0.2	0.2	0.1	1.2	1.7	0.4	0.5	0.2	2.9
				Sum	456.2				**Sum**	23.4

[1]The breakpoint between sapling and larger trees is 15.2 cm for the 1909 inventory, as these data are derived from a stand table summary.

composition and structure over the last century on the NKRD. In addition, CFI stand tables indicate that tree density and basal had nearly doubled by 1955 on the NKRD. A 1955 stand table derived from 49, 10th ha plots in unlogged MC forest showed an average of 34 trees/ha and basal area of 23.2 m^2/ha, in comparison with 35 trees/ha and 12.8 m^2/ha in 1909 for all conifer trees with a measurable d.b.h. A second stand table from 1955 also showed an average basal area and tree density of 29.4 m^2/ha and 69 trees/ha, respectively, but were derived from only five plots in unlogged MC forest. The 1955 stand tables were comparable to total basal area in 1990 (23.4 m^2/ha), however, 91% of the basal area in 1955 was from trees ≥30 cm d.b.h., compared to 63% in 1990. Only a single CFI plot in MC forest was reported as logged in the 1955 inventory.

These inventory data reflect changes in forest structure and composition that likely occurred as a result of fire suppression between 1909 and 1955 and increased selective logging in MC forest prior to 1990. A doubling of tree basal area between 1909 and 1955 was consistent with simulated biomass accretion reported for the north rim of GCNP by Fulé et al. (2004). Tree biomass, which is highly correlated with basal area, increased by an average of 122% when simulated at 20-year time intervals between 1880 and 2040, increasing as much as 279% on higher elevation sites (Fulé et al. 2004). Reduced basal area for trees ≥30 cm between 1955 and 1990 is likely the result of selective logging of large trees in MC forest during this period. Historical tree harvest records from the NKRD and CFI plots show that selective logging in MC forest began shortly after 1955 and increased in subsequent years due to an increase in spruce budworm (*Choristoneura occidentalis* Freeman) activity and tree mortality during the mid-1970s and 80s (Wahlfeld 1993, Sesnie and Bailey 2003).

Changes in forest structure over time are consistent with those reported by Vankat (2011) in GCNP, which showed extraordinarily high average tree basal area (65 m^2/ha) for MC forest in 1935, followed by much lower basal (35 m^2/ha) recorded at these sites in 2004. Increased tree mortality was recorded in MC forest on the NKRD during the 1970s and 1980s because of high tree density and spruce budworm defoliation (Wahlfeld 1993). However, average values for basal area reported for MC forest in 1935 are questionable (Vankat 2011), as these values greatly exceeded those estimated in stand tables developed from unlogged CFI plots in 1955 for the NKRD. An average basal area of 65 m^3/ha in 1935 would closely match those of old-growth MC forest recorded on highly productive sites in the southern Sierra Nevada of California (68.5 m^2/ha), where fire was excluded for 135 years (North et al. 2004). Nevertheless, patterns of high biomass accretion, inflection and recession between 1935 and 2004 in GCNP reported by Vankat et al. (2005) and Vankat (2011) likely reflect forest dynamics in areas of high tree density and basal area where no logging had occurred.

Elevation Gradient

Inventory data and tree measurements summarized over stand polygons were not suitable for discerning fine-scale site differences and relationships between spatial heterogeneity in forest composition and structure. However, these polygons were delineated to encompass a similar site biophysical condition, forest type and successional stage. As such, these data and analyses are best interpreted as distinguishing vegetation differences and site-scale biophysical conditions at a scale of 6-100 ha.

Differences in MC forest observed within the three elevation categories were principally due to dissimilarities in tree species composition (Figure 2.4a, Figure 2.4b). Multivariate comparisons among the elevation categories using MRPP demonstrated that MC forest in elevation categories 1 (dry) and 2 (moist) were not significantly different in tree species composition (Table 2.4). Inventory data indicated that a transition in tree species composition occurred above 2,700 m between MC forest and increasingly spruce- and true fir-dominated forest. A large decrease in basal area was also observed for ponderosa pine above this elevation in category 3 (mesic), but the species was co-dominant in the other two categories (Figure 2.4a, Figure 2.4b). Ponderosa pine was represented by a lower number of trees/acre in all elevation categories, but was proportionally high in basal area, indicating that fewer large trees were typically present. A higher density and basal area of white fir at lower elevations was compensated for by more abundant subalpine fir at higher elevations (Figure 2.4a, Figure 2.4b). Aspen showed very little difference among elevation categories.

Overall, forest structure data indicated a gradual decrease in tree density with increased elevation, but similar basal area across all three elevation categories (Table 2.5). Nevertheless, univariate comparisons of average tree density, basal area, and canopy bulk density among all three elevation categories were not significantly different (Appendix 2-A). Forest structural conditions were generally similar across categories (Table 2.5). An exception was average canopy height, where MC forest in elevation category 1 (22.3 m, dry) was statistically significantly different from categories 2 (21.0 m, moist; $t = 2.045$, $p = 0.022$) and 3 (20.6 m, mesic; $t = 2.81$, $p = 0.003$). This result likely is due to a shift in species composition or the successional status of MC forest favoring a greater abundance of shorter-stature trees at higher elevations. Average canopy bulk density was also significantly different between elevation categories 2 (2.06 m, moist) and 3 (1.60 m, mesic; $t = 1.65$, $p = 0.007$); however, both average tree height and canopy base height exhibit relatively minor differences among categories.

Our results indicate that a change in tree species composition occurs with increased elevation, as do small changes in canopy height. With respect to overall MC forest structural conditions, density, basal area and canopy bulk density were similar across elevation categories. Shade-tolerant trees, although different in species composition, were a substantial component of MC forest at all elevations. These results suggest that that a large number of understory shade-tolerant trees have developed in the absence of disturbance factors (e.g., fire), regardless of potential site differences among elevation categories. Moreover, average tree density and basal area were similar to MC forest conditions observed in GCNP. Fulé et al. (2003) showed average MC tree density was 873 trees/ha and basal area was 38.8 m^2/ha for the Little Park area of GCNP. These data are also comparable to forest structure estimates from Thompson Canyon in GCNP by White and Vankat (1993) that ranged from 720 to 1,394 trees/ha and 29.0 m^2/ha to 48.3 m^2/ha basal area. These tree densities were quite similar to MC forest on USFS land quantified from 1990 inventory data (Table 2.5). Basal area was also similar, but somewhat lower ($\leq$31 m^2/ha, Table 2.5), which was expected given the diffeective timber harvests prior to 1990 inventories.

Solar radiation gradient

Tree species composition differed at increasing levels of annual solar radiation , which can moderate site moisture conditions according to local hillslope topography (e.g., foot slope to ridge-top; Pocewicz et al. 2004). Notably, subalpine fir and spruce decrease in density and basal area with increased annual solar radiation in a consistent fashion (Figure 2.5a, Figure 2.5b).

These differences likely explain significant differences in tree species

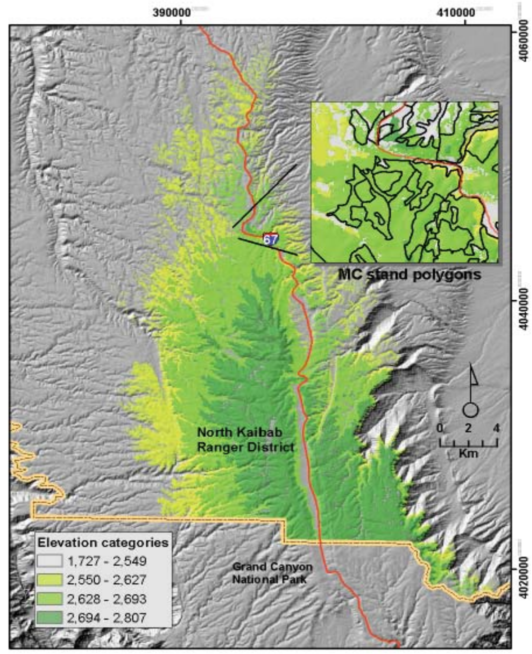


Figure 2.2 Map of elevation categories used to select mixed conifer stand polygons and inventory data.

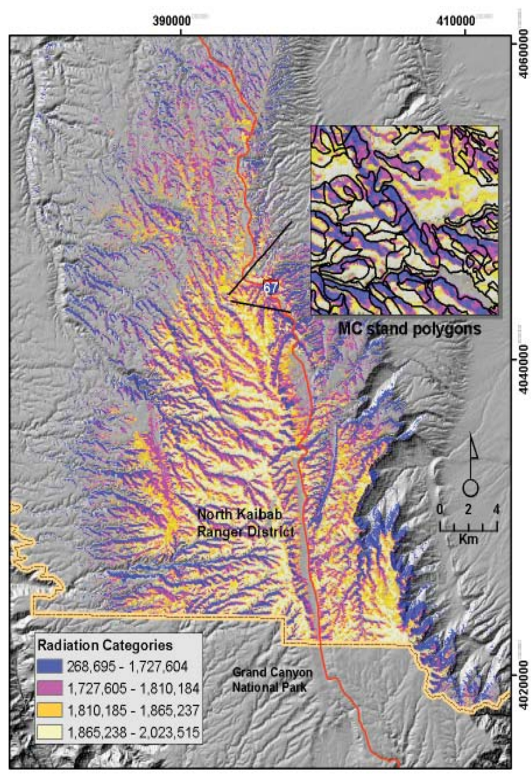


Figure 2.3 Map of annual solar radiation (w/m^2/yr) categories used to select mixed conifer stand polygons and inventory data.

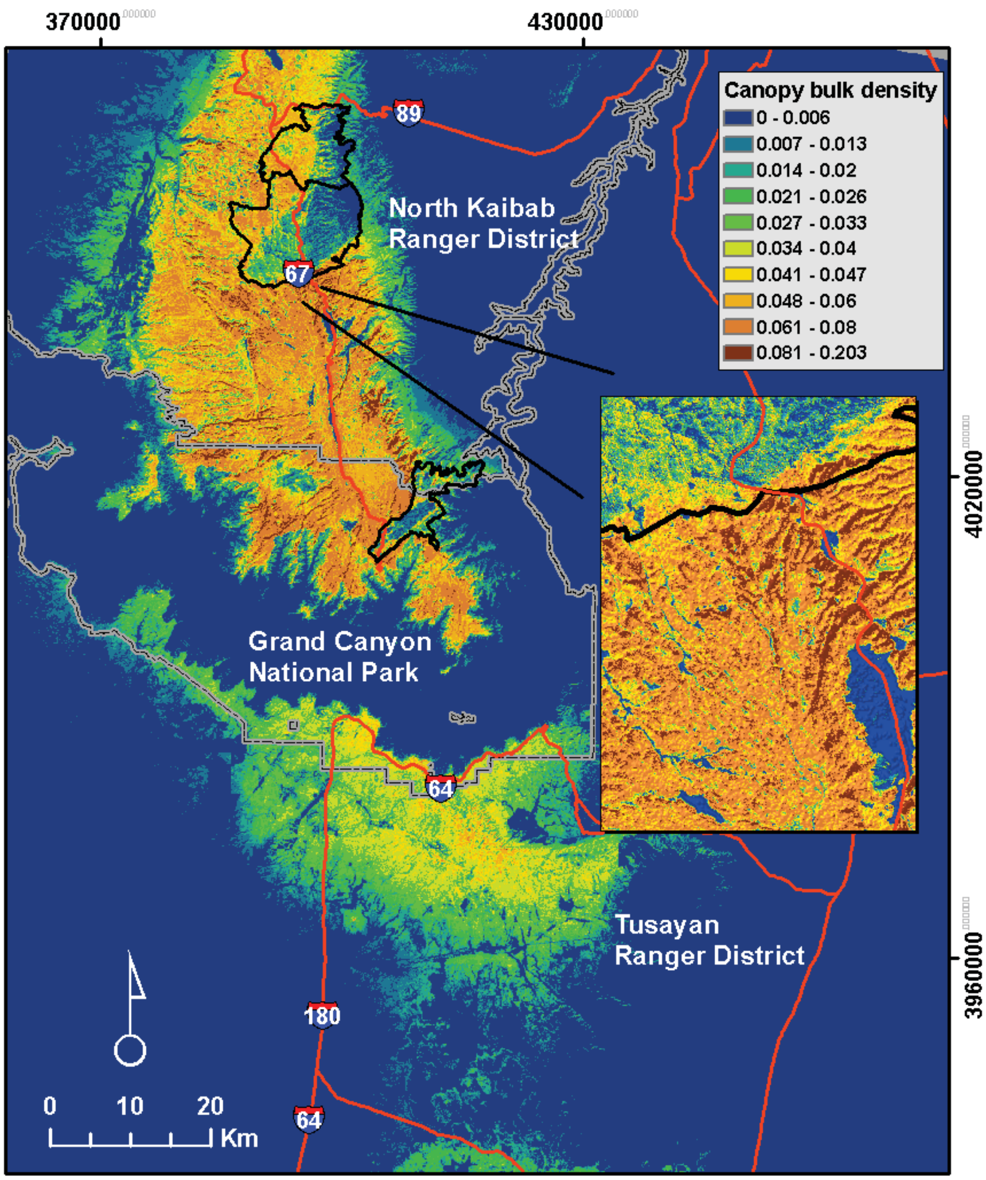


Figure 2.6 Digital map of canopy bulk density (kg/m3) derived for the Kaibab National Forest and GCNP (grey outline) from 2006 Landsat Thematic Mapper (TM) imagery and US Forest Service Inventory and Analysis plots. Large changes in canopy bulk density within map polygons (black) are a result of the Warm (north) and Outlet (south) fires. Validation information for canopy bulk density were derived from 271 validation plots and bootstrapped error estimates (Mean/Median residual error = 0.013/0.006 kg/m^3 and 73.4% of the variance was explained by the regression tree model used).

Elevation comparisons	T	A	*p*-value
1 vs. 2	-0.37	0.001	0.278
1 vs. 3	-17.23	0.037	<0.001
2 vs. 3	-23.05	0.036	<0.001

Table 2.4 Results from MC forest comparisons by tree species basal area and elevation categories using multivariate MRPP statistical tests. T is the test statistic and A is the chance corrected agreement statistic that describes within group homogeneity compared to randomized data.

Elevation category	TD	BA	CBD	CBH
1 (2,550 – 2,627 m)	1,006 (115.1)	31.32 (3.2)	0.105 (0.008)	1.76 (0.163)
2 (2,627 – 2,693	898 (117.3)	30.92 (2.0)	0.104 (0.004)	2.06 (0.163)
3 (2,693 – 2,807)	788 (56.5)	31.45 (1.9)	0.109 (0.003)	1.60 (0.004)

Table 2.5 Information on forest structure along an elevation gradient in the Kaibab Ranger District, Kaibab National Forest, Arizona. Data are from a 1990 inventory for mixed conifer stands at three elevations. In the table TD = tree density given as trees/ha. BA – basal area given as m^2/ha. CBD = canopy bulk density expressed as kg/m^3. CBH = crown-base height given in meters. All numbers in brackets are standard errors [SE] of the average.

Solar radiation comparisons	T	A	*p-values*
1 vs. 2	-0.40	0.0010	0.2579
1 vs. 3	-2.52	0.0087	0.0268
1 vs. 4	-2.68	0.0134	0.0226
2 vs. 3	-2.07	0.0041	0.0446
2 vs. 4	-2.52	0.0061	0.0273
3 vs. 4	-2.67	0.0089	0.0216

Table 2.6 Results from MC forest basal area comparisons by tree species between each of the radiation categories described as mesic, moist, dry and very dry using multivariate MRPP statistical tests.

Radiation categories	TD	BA	CBD	CBH
1 (268,695 – 1,727,604 w/m^2/yr)	981(126.6.)	34.1 (3.5)	0.127 (0.009)	1.61 (0.147)
2 (1,727,604 – 1,810,183)	903 (68.8)	30.3 (1.9)	0.104 (0.004)	1.753 (0.101)
3 (1,810,183 – 1,865,237)	938 (75.1)	33.3 (2.6)	0.106 (0.005)	1.924 (0.180)
4 (1,865,237- 2,023,515)	908 (95.5)	29.2 (3.7)	0.101 (0.101)	1.771 (0.169)

Table 2.7 Average (SE) tree density (TD; trees/ha), basal area (BA; m^2/ha), canopy bulk density (CBD; kg/m^3), and crown-base height (CBH; m) for mixed conifer stands and summarized by solar radiation category using the 1990 inventory data.

composition observed for all but the first two solar radiation categories (Table 2.6). Other species differed less consistently across radiation categories, although Douglas fir and aspen showed somewhat higher tree densities and basal area on sites receiving greater solar radiation. These results were similar to elevation comparisons that show species specific responses along presumed site moisture gradients related to different amounts of annual solar radiation, annual precipitation and turnover in tree species composition and abundance. Results did show somewhat more complex relationships between solar radiation categories and tree species dominance on a site. For example, ponderosa pine basal area increased and then decreased on sites from low to high solar radiation and tended to be replaced by, or was co-dominant with, Douglas fir on potentially drier sites (Figure 2.5b). These species occurred in low numbers according to tree density data, but were proportionally high in basal area, suggesting that a few large individual ponderosa pine and Douglas fir trees were typically present in MC forest. White and Vankat (1993) have suggested that a large increase in shade-tolerant species density and dominance on these sites poses a potential threat to mixed conifer forest diversity as low numbers of relict overstory ponderosa pine and Douglas fir are replaced by spruce and true fir.

On average, forest structure was more varied among solar radiation categories in terms of basal area than tree density (Table 2.7). Average canopy height also decreased from 22.0 m on mesic sites to 19.5 m on very dry sites. Both basal area and canopy height were significantly different between most solar radiation categories (Appendix 2-A). These data suggest that, in addition to site moisture, other factors such as land use practices may influence forest structural characteristics. For example, sites with low annual solar radiation (mesic) were generally on steeper north-facing slopes (>25% slope) or within narrow canyon areas (Figure 2.2). It is possible that these sites were less favorable for selective tree harvesting or less susceptible to other disturbances, such as frequent fire. Based on fire-scar data from GCNP, Fulé et al. (2003) observed that north facing slopes exhibited less frequent fires than did south and east facing slopes.

Sites with very low solar radiation (mesic) showed significantly higher canopy bulk density than all other categories, in addition to having the lowest average canopy base height (Table 2.7, Appendix 2-A). Wimberley et al. (2009) showed that un-thinned drainages, associated with the lowest solar radiation values, experienced the greatest burn severity during the 2006 Warm Fire. Canopy bulk density from this study was slightly higher than that estimated in GCNP mixed conifer sites (0.08 kg/m^3) by Fule et al. (2004), likely due to different canopy bulk density equations used. Nevertheless, values were consistent with canopy fuels modeled from USFS Forest Inventory and Analysis plots (Figure 2.6, unpublished data). Extensive areas of moderate to high canopy bulk density (0.061 to 0.20 kg/m^3) and low canopy base height (<2 m on average) are evidence that contiguous canopy fuels exist for MC and ponderosa pine forest types that dominate the NKRD. When combined with extreme fire weather, these conditions have the potential to promote both passive and active canopy fire activity (Fulé et al. 2001, Wimberly et al 2009).

CONCLUSIONS

Historically, site biophysical conditions and mixed severity fires created heterogeneous MC forest structure and composition in stands within close proximity to one another (Fulé et al. 2003). Today's MC forests on the NKRD are dramatically different from when forest inventory data were first collected in 1909. On average, 1990 MC tree density is six times greater than shown in 1909 inventory records and

Figure 2.4 Mixed conifer average (A) tree density and (B) basal area and standard error for tree species within three elevation categories.

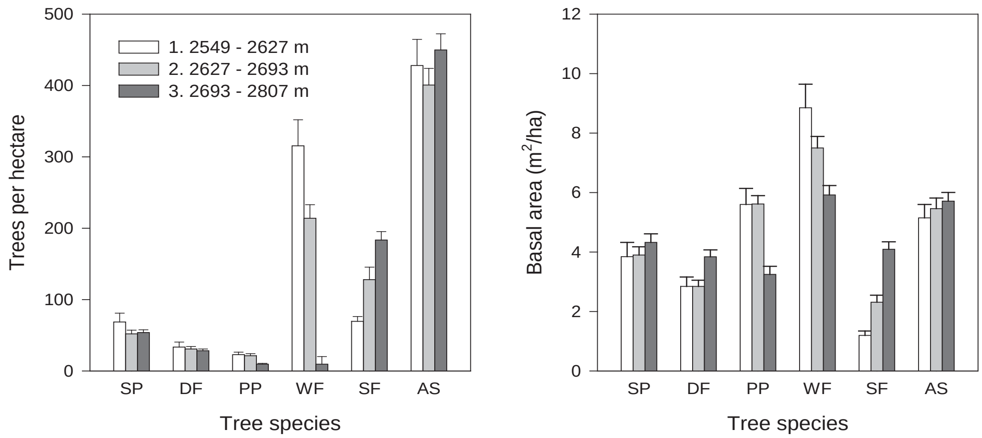
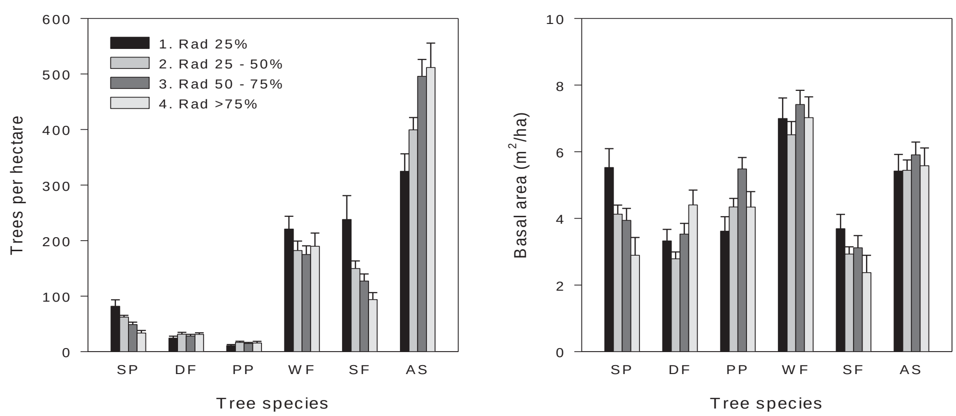


Figure 2.5 Mixed conifer average (A) tree density and (B) basal area and standard error for tree species within four solar radiation categories.



basal area has doubled on average over this same period. Perhaps most notable is that current forest inventory data on USFS land showed nearly equal tree densities and only moderately less basal area in comparison with tree data reported from studies in GCNP mixed conifer forest given their different land management histories. Forest management on the NKRD historically resulted in selective logging practices that removed a small proportion of trees and were focused on harvesting primarily overstory ponderosa pine and Douglas fir trees with commercial value (Sesnie and Bailey 2003). In addition, reduced fire frequency has facilitated a large cohort of shade-tolerant tree species resulting in more contiguous vertical and horizontal canopy structure in MC forest. Tree species composition differed within the MC forest type along the elevation and solar radiation gradients studied, but showed little or no significant difference in forest structural conditions. This was contrary to our expectation that overall tree density and basal area would differ significantly along elevation and solar radiation gradients that are linked to site moisture regimes. High tree densities and canopy bulk density have become increasingly contiguous across sites where fire has been mostly absent over the last several decades, increasing the likelihood of landscape-scale canopy fire events (White and Vankat 1993, Fulé et al. 2004, Wimberly et al. 2009).

Prior studies indicate that Southwest MC conditions are less likely to be resistant to tree mortality factors, such as periodic drought, climate change (hotter drier conditions) and other associated environmental stresses (North et al. 2009, Fulé et al. 2009), and suggest important implications for implementing restoration treatments. First, fire undoubtedly played an important role in maintaining lower shade-tolerant tree densities prior to fire suppression activities, particularly on dry sites. True fir species are sensitive to bole scorch and low intensity fires that would likely have maintained historically lower numbers of established trees (Fulé and Laughlin 2007). Mixed severity fire was a periodic disturbance in MC forest that likely maintained a more spatially heterogeneous distribution of tree species, a diversity of structural conditions, and lower tree densities (Stein 1988, White and Vankat 1993, Fulé et al. 2003, Fulé et al. 2009, North et al. 2009). Returning more frequent and low-intensity fires to contemporary MC forest conditions is essential to achieving forest restoration goals, but could initially increase ground fuel accumulations via understory tree mortality in post-treatment areas, or present fire control risks (Stephens 1998, Agee 2003, but see Fulé and Laughlin 2007). To address uncertainty regarding the role of prescribed fire in MC forest restoration, recent fire monitoring plots established within GCNP can provide information on pre-treatment conditions and post-fire effects on MC forest composition and structure (Fulé and Laughlin 2007). Similarities between USFS land and GCNP forest conditions also provide a potential analog from which to develop methods for achieving desired outcomes using prescribed fire. However, Wimberly et al. (2009) found that forest thinning, followed by prescribed burning, was a significant factor in reducing burn severity in areas experiencing recent and extensive wildfire on the NKRD, in contrast to using these treatments types independent of each other. Greater interagency collaboration may also improve forest stewardship activities across USFS and GCNP lands on the Kaibab Plateau (see also Holcomb et al. this volume). Stakeholder-driven planning efforts, such has the Kaibab Forest Health Focus, can also facilitate socially viable forest restorations recommendations and environmental decision making (Sisk et al. 2009).

Second, silvicultural treatments such as thinning, prescribed burning or other selective tree harvest practices should be aimed at reducing overall tree density and basal area to restore species and size class distributions that support mixed-severity fire regimes. In this context, North et al. (2009) present recommendations for utilizing biophysical gradients associated with differing site moisture and disturbance regimes, which could be used to help guide silvicultural treatments, in conjunction with USFS desired conditions for MC forest types. Additionally, hazardous fuels reduction can likely be accomplished by restoring forest resiliency to natural fire events in areas of high fire risk. Results from Vaillant et al. (2009) indicate that understory thinning treatments prior to applying prescribed fire can be effective when targeted in areas with hazardous canopy fuels conditions for reducing high canopy fire risk in MC forest. Restoration activities should also create opportunities to regenerate fire resistant species, such as ponderosa pine and Douglas fir, and reduce contiguous areas of high canopy bulk density on the NKRD (Figure. 2.6). Historically, dry MC sites were likely dominated by fire resistant tree species, in contrast to mesic or higher elevation sites dominated by spruce and true fir species. Creating canopy-gaps in close proximity to residual ponderosa pine and Douglas fir, and reducing competitive interactions with shade-tolerant species, may promote regeneration for these species. Silvicultural practices that encourage natural stand dynamics and mixed severity fire behavior are needed to restore mixed conifer forest conditions which are less susceptible to extreme disturbance.

Some elements of this study and assessment of MC forest and landscape conditions can be expanded to other southwestern locations where forest inventory data are available. However, historical data of similar quality to the 1909 forest inventory data are relatively rare. USFS Forest Inventory and Analysis plots for MC forest types and other historical forest inventories (e.g., CFI plots) can also be used in combination with multi-temporal remotely sensed data to estimate existing forest structural conditions and changes that have occurred in recent decades. Available forest inventory data, coupled with published studies and historical syntheses provide an important and efficient means of informing collaborative land-use planning efforts, forest restoration goals, and hazardous fuels reduction objectives in southwestern MC forest types.

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	BA			D			HT			CBD			CBH		
Elev. class	**df**	**t**	***p***	**df**	**t**	***p***	**df**	**t**	***p***	**df**	**t**	***p***	**df**	**t**	***P***
1 vs. 2	97	0.1990	0.4213	166	1.3652	0.0870	81	2.0458	**0.0220**	76	0.0932	0.4630	143	-1.266	0.1038
1 vs. 3	73	-0.079	0.4684	182	1.4384	0.0760	64	2.8105	**0.0033**	65	-0.448	0.3276	73	0.8751	0.1922
2 vs. 3	214	-0.394	0.3469	250	-0.106	0.4575	213	0.9780	0.1646	227	-0.901	0.1842	165	2.4384	**0.0079**
	BA			**D**			**HT**			**CBD**			**CBH**		
Rad. class	**df**	**t**	***p***	**df**	**t**	***p***	**df**	**t**	***p***	**df**	**t**	***p***	**df**	**t**	***P***
1 vs. 2	164	2.2044	**0.0144**	164	1.0127	0.1563	109	2.4526	**0.0079**	59	2.31742	**0.01198**	78	-0.745	0.2290
1 vs. 3	117	0.4259	0.3355	117	0.6368	0.2627	106	1.2000	0.1164	63	2.02850	**0.02337**	117	-1.155	0.1251
1 vs. 4	81	2.7850	**0.0033**	81	0.9596	0.1700	66	3.9768	**0.0001**	72	2.33187	**0.01125**	77	-0.638	0.2625
2 vs. 3	199	-2.141	**0.0167**	199	-0.506	0.3064	176	-1.185	0.1188	176	-0.3863	0.34987	111	-0.705	0.2410
2 vs. 4	163	1.0349	0.1511	163	0.2185	0.4136	64	2.3509	**0.0109**	77	0.33897	0.36778	63	-0.081	0.4677
3 vs. 4	116	2.6364	**0.0048**	116	0.6055	0.2730	69	3.1025	**0.0014**	82	0.63654	0.26310	110	0.5230	0.3010

Appendix 2-A Elevation and solar radiation class comparisons of forest structure parameters using two sample *t*-tests. Degrees of freedom (df) differ for comparisons which assume an unequal variance as a result of F-test comparisons for two sample variances. Significant class differences ($p \leq 0.05$) are in bold. Basal area = BA, tree density = D, canopy height = HT, canopy bulk density = CBD and canopy base height = CBH.