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Preliminary stratification and characterization of the mixed conifer forest type on the Kaibab National Forest, North Kaibab Ranger District

Final Report

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Table of Contents

Abstract

Less is known about mixed conifer forest types and historical changes in composition and structure than for other Southwest forest types such as ponderosa pine. The 2009 Kaibab Forest Health Focus initiative identified mixed conifer forest as a priority vegetation type requiring active forest restoration and hazardous fuels reduction. We evaluated contemporary changes in mixed conifer forest conditions on the Kaibab National Forest, North Kaibab Ranger District north of Grand Canyon National Park where other recent studies and historical forest inventories provided an excellent opportunity for comparative analyses. Inventory data from 1909 and the 1990s showed that tree densities were ten times greater and basal area has doubled in mixed conifer forest over the last century. Shade-tolerant species such as spruce and true-fir have increased dramatically whereas ponderosa pine and Douglas-fir were reduced or show very little increase. Two principal moisture gradients studied, elevation and annual solar radiation, indicated that tree species composition is significantly different from dry to wet sites as is mean canopy height, but shade-tolerant tree densities remained high on all sites. Restoration activities in mixed conifer forest should focus on reducing the extremely high density of shade-tolerant understory trees while providing opportunities for ponderosa pine and Douglas-fir regeneration on appropriate sites. Tree thinning and burning activities should seek to maintain tree species and structural diversity while reducing overall hazardous fuel accumulations that have developed in the absence of fire.

Key words: Mixed conifer forest, moisture gradient, elevation, solar radiation, GIS

1. Introduction

Mixed conifer forest on the Kaibab Plateau in northern Arizona is characterized by tree species that can include ponderosa pine (*Pinus ponderosa*), white fir (*Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*), and aspen (*Populus tremuloides*), but also intermix 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). The 2009 Kaibab Forest Health Focus was an initiative which identified ponderosa pine and mixed conifer (MC) forest as priority vegetation types in need of restoration treatments. While forest conditions on ponderosa pine-dominated sites are well researched, quantitative characterizations of past and present mixed conifer forest composition and structure are relatively few in number (*but see* Fulé et al. 2003, Cocke et al. 2005; Fulé et al. 2009). Forest reconstruction and dendrochronology studies for Grand Canyon National Park (GCNP) have demonstrated striking changes in forest composition and structure since fire suppression c. 1879 (Fulé et al. 2003). However, less is known about MC forest conditions occurring in forests to the north of GCNP on National Forest Service (NFS) land which have been subject to different forest management regimes and policy.

An analysis of MC forest structure and composition on the North Kaibab Range District (NKRD) 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 obtain greater clarity about existing MC forest conditions on NSF lands, our study objectives were to:

1. Compare historical and contemporary mixed conifer forest structure and composition.

2. Characterize environmental conditions that contain mixed conifer forest types and determine current forest structure and composition, stratified across moisture gradients (dry, moist, and relatively wet sites).
3. Provide a quantitative framework for developing restoration criteria and a desired future condition for mixed conifer forest types.

The objectives of this study consider that despite a century of active forest management on NSF lands, shade tolerant species have potentially become an increasingly dominant component of MC forest types in the absence of fire (Stein 1988, Fulé et al. 2009). In addition, forest composition and structure within the MC forest types will likely differ along moisture gradients associated with elevation and topography (White and Vankat 1993, Fulé et al. 2003). These factors can be evaluated with available data and information prior developing restoration and hazardous fuels mitigation recommendations within MC forest types on the North Kaibab Ranger District.

2. Methods and Materials

2.1 Study area

The study area includes mixed conifer forest on the Kaibab National Forest, North Kaibab Ranger District in northern Arizona (**Figure 1**). A 162,400-acre area was initially defined as containing the mixed conifer forest type based on the extent of the LANDFIRE program's existing vegetation map (http://www.landfire.gov/) and MC forest categories.

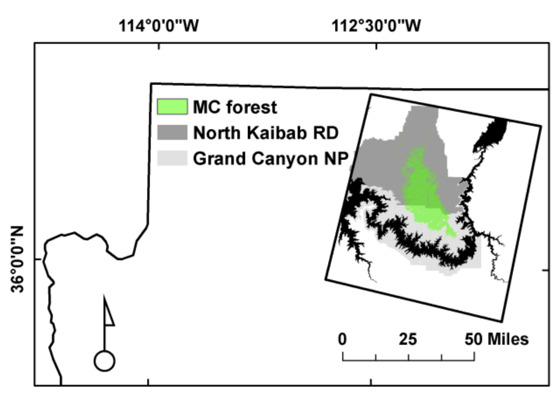

Figure 1. Mixed conifer study area on the Kaibab National Forest, North Kaibab Ranger District.

This area ranges in elevation from 1,700 m to 2,800 m. However, only MC forest above ≥2,550 m (121,900 acres) was examined due to a recent large fire (Warm Fire) burning through some MC forest below this elevation. In addition, MC and Spruce-Fir forest generally exists on sites above 2,500 m (White and Vankat 1993). Average annual precipitation varies considerably across the Kaibab Plateau according to weather station data (http://www.wrcc.dri.edu/). The Jacob Lake (2,414 m) weather station, to the north, has an annual average of 53 cm rainfall and 268 cm 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 347cm of snowfall. Temperatures are generally cooler in the upper elevations associated with MC forest and range between a maximum of 25° C in July to a minimum of -9° C in January.

Topography in the study area is comprised of low forested plateaus and ridge tops divided by valley bottoms and occasional dry meadows. Soils underlying MC forest generally consist of Utric Glossoboralfs and Typic Cryoboralfs and Paleboralfs with a mixture of fine sandy and gravely loam textures (Brewer et al. 1991).

2.2. Available datasets

No new data was collected with this study as historical and relatively recent forest inventory data were available for the North Kaibab Ranger District (Sesnie and Bailey 2003). Three principle datasets were consolidated and used to perform comparative analyses.

- **Historical inventory data** from 1909 and a stand table summary (tree density and basal area) for the MC forest type on the Kaibab Plateau were compared to the most recent forest inventory data. The 1909 inventory data are from a 128 acre "strip cruise", which measured all trees, including seedlings and saplings (Lang and Steward 1910). These data represent early MC forest structure and composition prior to US Forest Service timber management and active fire suppression.

- **Recent inventory data** for MC forest types were collected between 1980 and 2000 (Stand Exam forest inventories) and will be compared with the 1909 MC stand table. Recent data is referred to as the "1990 inventory" (average year measured).
- **Environmental data** contained in a geographic information system (GIS) were used to develop biophysical categories for stratifying and comparing MC inventories according to dry, moist and relatively wet sites. For this study, a 30-m digital elevation model (DEM) was use to estimate average elevation and annual solar radiation values within forest inventory units (mapped polygons).

2.3. Analyses

Available forest inventory data were analyzed in three ways to estimate changes in forest structure and composition over both time and space to the extent feasible. To accomplish this, past and present forest inventory data were used for comparative analyses.

First, all MC 1990 inventory data (n = 447) were summarized together using the weighted average for tree species density (trees per acre) and dominance (basal area; ft^2/ac) regardless geographic locations or biophysical setting. In the forest inventory database, polygons or "stands" are classified by dominant tree species composition. For this analysis, only MC forest types dominated by spruce, true-fir or Douglas-fir trees (i.e. non-ponderosa pine or aspen dominated forest) were summarized and then compared with the 1909 MC inventory data. Only descriptive statistics were used to compare the two forest inventories as only summarized stand table data were available for 1909.

A second comparison evaluated average tree species density and basal area from MC inventories within elevation categories above 2,550 m. Elevation categories were selected using three percentile groups with elevation values ranging from the 25^{th} to 50^{th} percentile, 50^{th} to 75%

percentile and values >75th percentile for existing MC forest mapped by LANDFIRE (**Table 1**; **Appendix A map**). MC forest below the 25th percentile was below 2,550 m and excluded from this analysis. Each of the three categories was assumed to follow a gradient of increasing annual moisture based on weather station records. The elevation category of each MC stand inventory polygon was determined using the mean elevation value calculated with zonal statistics in ArcGIS v. 9.3 (ESRI 2009). To determine if MC forest composition and structure statistically differed among elevation categories, multivariate comparisons were made using Multi-Response Permutation Procedures (MRPP; McCune and Grace 2002) in the PC-ORD v. 5 statistics package (McCune and Medford 1999). Multivariate MRPP comparisons among elevation categories were made using basal area by tree species as the principle explanatory variable. Elevation categories were also compared in separate statistical analyses according to average overall tree basal area, density and mean canopy height using two-sample t-tests.

A third and separate comparison was performed using total annual solar radiation categories to compare forest composition and structure along moisture gradients associated with aspect and topography. Global solar radiation values (w/m^2/year) were derived from the 30-m DEM using the Solar Analyst v. 1.0 (HEMI 2000) extension in ArcView v. 3.3 (ESRI 2002). Annual solar radiation was divided into four percentile categories similar to elevation (**Table 1; Appendix B map**). Radiation categories represent an increasing amount of annual sunlight incident upon land surfaces that is a function slope conditions, surrounding terrain and aspect (HEMI 2000). The amount of solar radiation on a site drives a number of important processes such as photosynthesis, transpiration and evaporation that impact site moisture, plant growth and species composition. Only MC forest inventories above 2,550 m were used to evaluate changes in tree species density and basal area according to radiation categories. Multi- and univariate statistical analyses (MRPP and t-tests) detailed above were also used for these comparisons. The radiation category of each MC stand inventory polygon was determined using the mean value calculated with zonal statistics in ArcGIS.

Table 1. The number of stand polygons and area covering mixed conifer forest by the 1990 forest inventory analyzed according to elevation and solar radiation categories. Categories were nominally characterized as being wet, mesic, dry or very dry based on assumed relationships reported from previous studies.

Elevation categories	**Desc.**	**No. stands**	**Acres**	**% of area sampled[1]**
1 (2,550 – 2,627 m)	Dry	50	2,298	10.2
2 (2,627 – 2,693)	Mesic	118	10,130	52.5
3 (2,693 – 2,807)	Wet	134	11,595	81.5
Solar radiation categories[2]				
1 (268,695 – 1,727,604 $w/m^2/yr$)	Wet	42	2,751	49.8
2 (1,727,604 – 1,810,183)	Mesic	124	11,107	40.1
3 (1,810,183 – 1,865,237)	Dry	77	6,925	41.0
4 (1,865,237- 2,023,515)	Very dry	40	2,985	46.6

[1]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.
[2]Ordinal solar radiation categories are associated with slopes of increased exposure to sunlight throughout the year.

All 1990 forest inventory data were summarized using the Forest Vegetation Simulator (FVS) Central Rockies variant for southwestern tree species (http://www.fs.fed.us/fmsc/fvs/).

Most MC forest on the North Kaibab Ranger District has undergone selective harvesting in the past three decades according to preliminary forest change comparisons with Landsat Multispectral Spectral Scanner (MSS) image data from 1973, 1983, and 1993 (data not shown). Therefore, forest disturbances were not accounted for with the exception of relatively small areas that have experienced clear cut harvesting or other severe disturbances (e.g., wind-throw or fire). These stand polygons were typically <15 acres in size which were removed from all analyses.

3. Results and Discussion

3.1 Mixed conifer inventories

A comparison of 1990 forest inventory data and the 1909 stand table indicated that large changes have occurred in MC forest composition and structure over that last century (**Table 2**). Tree densities for shade tolerant species such as spruce and true-fir have increased by several orders of magnitude from 1909 to 1990. Very little increase tree density and a small decrease in basal area were observed for ponderosa pine. Ponderosa pine is favored for timber harvest which is a potential explanation for reduced tree density and basal area or only a minor increase as observed for Douglas-fir (Fulé et al. 2009). Overall, tree density was ten times greater in 1990 than was documented the in 1909 inventory and basal area was twice as great. 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). Only conifer species were measured for the 1909 inventory. Therefore, aspen trees were not included with these comparisons although they were measured for the 1990 inventory. Further analyses of 1990 MC forest conditions within elevation and solar radiation categories below included aspen for comparison with other studies.

Table 2. Differences in tree density and basal area from 1909 mixed conifer stand table summary and 1990 forest inventory data. Aspen were not measured for the 1909 inventory. Summed data are shown in English units and the metric equivalent in parentheses (trees per hectare and m^2/hectare).

	Ave. trees per acre		**Ave. basal area (ft^2/ac)**	
Species	**1909**	**1990**	**1909**	**1990**
PP	43	50	22	20
DF	17	94	9	15
TF	93	1,024	17	41
SP	31	703	10	42
Sum	185 (75)	1,871 (755)	58 (13.3)	118 (27.1)

Comparisons between 1909 and 1990 inventories are somewhat tentative as sampling protocols were different and only stand table summaries are available from 1909. In addition, the geographic location of the 1909 inventory where all trees were measured for a 128 acre area is not known. Nevertheless, Fulé et al. (2003) found that the 1909 stand table summary data matched well with reconstructed forest composition and structure data derived from dendrochronology studies in GCNP. The 1909 inventory and comparisons with contemporary data likely provide a useful benchmark for determining general changes in MC forest composition and structure over the last century.

3.2 Elevation gradient

Only 1990 forest inventory data above 2,550 m were compared to analyze differences in MC forest composition and structure associated with increased elevation and moisture gradients. Differences in MC forest conditions within the three elevation categories observed were principally represented by changes in tree species composition (**Figure 2**). Multivariate comparisons among all three elevation categories using MRPP statistical tests demonstrated that MC forest in elevation categories 1 (dry) and 2 (mesic) were not significantly different in tree species composition (**Table 3**). Inventory data indicated that a transition in tree species composition occurred above 2,693 m between MC forest and increasingly spruce-fir dominated forest. A large decrease in basal area was also observed for ponderosa pine above this elevation in category 3 (wet), but was a co-dominant species in the other two categories (**Figure 2**). Ponderosa pine is represented by very few trees as tree density is lowest in all elevation categories, but is proportional high in basal area indicating that a few large individual trees are typically present on mixed conifer sites. A higher density and dominance of white-fir and blue spruce at lower elevations was replaced by more abundant subalpine-fir and Engelmann spruce at higher elevations. Aspen showed very little difference among categories.

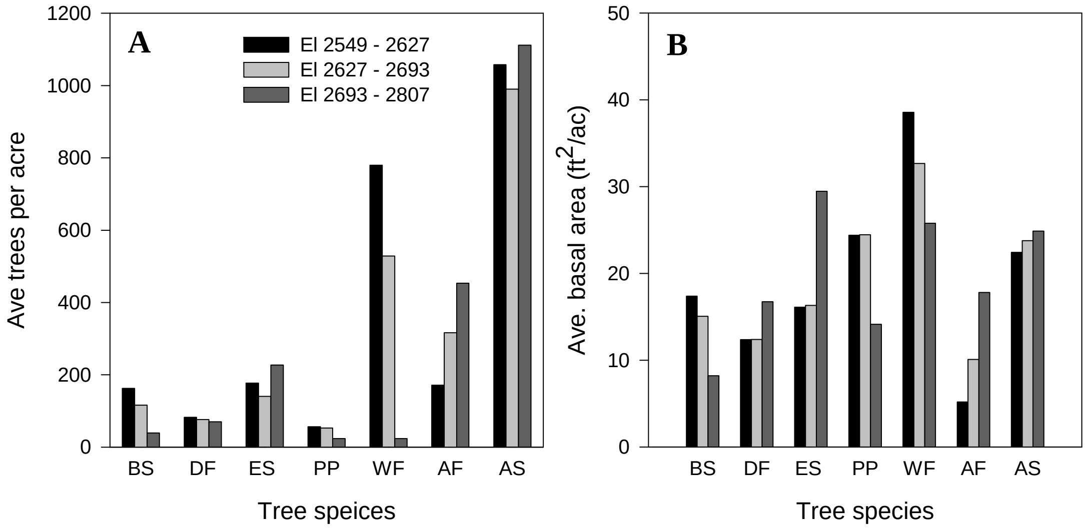

Figure 2. Mixed conifer average (A) tree density and (B) basal area for tree species within the three elevation categories. Tree species are blue spruce (BS), Douglas-fir (DF), Engelmann spruce (ES), ponderosa pine (PP), white-fire (WF), subalpine-fir (AF) and aspen (AS).

Table 3. 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 with-in group homogeneity compared to randomized data. For example, interpretation of these comparisons follows that MC forest composition in elevation categories 1 and 2 are similar and categories 2 and 3 are different for reasons greater than chance.

Elevation comparisons	**T**	**A**	***p*-value**
Dry vs. Mesic	-0.37	0.0008	0.2775
Dry vs. Wet	-17.23	0.0371	0.0000
Mesic vs. Wet	-23.05	0.0363	0.0000

Overall forest structure data also indicated a gradual decrease in tree density with increased elevation, but similar basal area across all three elevation categories (**Table 4**). Nevertheless, statistical comparisons (t-tests) of average tree density and basal area between all three elevation categories were not significantly different (data not shown). While tree species appear to be interchangeable along an elevation gradient, in general, forest structural conditions were found to be similar (**Table 4**). An exception was mean canopy height where MC forest in elevation category 1 (73.1’, dry) was significantly different from categories 2 (68.9’, mesic; t = 2.045, p = 0.022) and 3 (67.7’, wet; t = 2.810, p = 0.003). This is likely a result of decreased site productivity with increased elevation. According to statistical comparisons (t-tests), site index (SI) values, which are a measure of productivity, were significantly different among elevation categories and showed a decrease in mean SI from 74’ to 66’ to 65’ in each respective elevation category. Site index values from 1990 forest inventories indicate the average potential tree height growth over a 100 year period that is measured by tree core samples taken from the dominant trees on stand inventory plots.

Table 4. Mixed conifer tree density and basal area (BA) summarized by elevation category from the1990 inventory data. English (trees per acre, TPA) and metric units (trees per hectare, TPH) are shown for ease of comparison with other published studies.

Elevation categories	Ave. TPA	Ave. TPH	Ave. BA (ft^2/ac)	Ave. BA (m^2/ha)
Dry	2,486	1,006	136.4	31.32
Mesic	2,220	898	134.7	30.92
Wet	1,947	788	137.0	31.45

These data illustrate that a turnover in species composition occurs with increased elevation and as do moderate changes in canopy height structure in MC and spruce-fir forest. With respect to overall MC forest conditions, tree density and basal area show strong similarities across elevation categories. Shade tolerant trees, though different in species composition, were a large component of MC forest at all elevations. Implications of these data and that of the previous section are that a large number of understory shade-tolerant trees have developed in the absence of disturbance factors (e.g., fire), regardless of potential differences in site moisture regimes. Moreover, average tree density and basal area did not differ greatly from those observed in GCNP. Fulé et al. (2003) showed average MC tree densities were 873 trees per hectare (tph) and a basal area of 38.8 m^2/ha for the Little Park area of GCNP. These data are also comparable to forest structure estimates from Thompson Canyon GCNP by White and Vankat (1993) that ranged from 720 to 1,394 tph and 29.0 m^2/ha to 48.3 m^2/ha basal area. Basal area was somewhat lower from the 1990 inventory estimates reported for NFS land, which was not unexpected given the difference in forest management history and timber harvest prior to 1990 inventories.

3.3 Solar radiation gradient

Comparisons similar to those above were performed for solar radiation categories. Solar radiation is a function of local-scale topography that likely interacts with elevation. However, for this study, observations were made without accounting for differences in elevation to avoid statistical and other limitations associated with a large number of categories and comparisons. Nevertheless, tree species composition differed at increasing levels of annual solar radiation that typically moderate site moisture conditions in southwestern forests (**Figure 3**). Notably, subalpine-fir and Engelmann spruce decrease in density and basal area with increased annual solar radiation in a consistent fashion.

These differences likely explain significant changes in tree species composition observed for all but the first two solar radiation categories (**Table 5**). Other species were less consistent in the differences across radiation categories, although Douglas-fir and aspen showed somewhat higher tree densities and basal area on drier sites. These evaluations are not dissimilar to elevation comparisons which show species specific responses (e.g., species turnover or changes in beta-diversity) to potential changes in site moisture conditions. There were somewhat more complex relationships among species according local-scale differences in solar radiation with respect to tree species dominance on a site. For example, ponderosa pine basal area increased and then decreased from wet to very dry sites and tended to be replaced by or was co-dominant with Douglas-fir on the driest sites (**Figure 3**). These species occurred in low numbers according to tree density data, but were proportionally high in basal area suggesting that a few large individual trees were typically present in MC forest. White and Vankat (1993) noted 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.

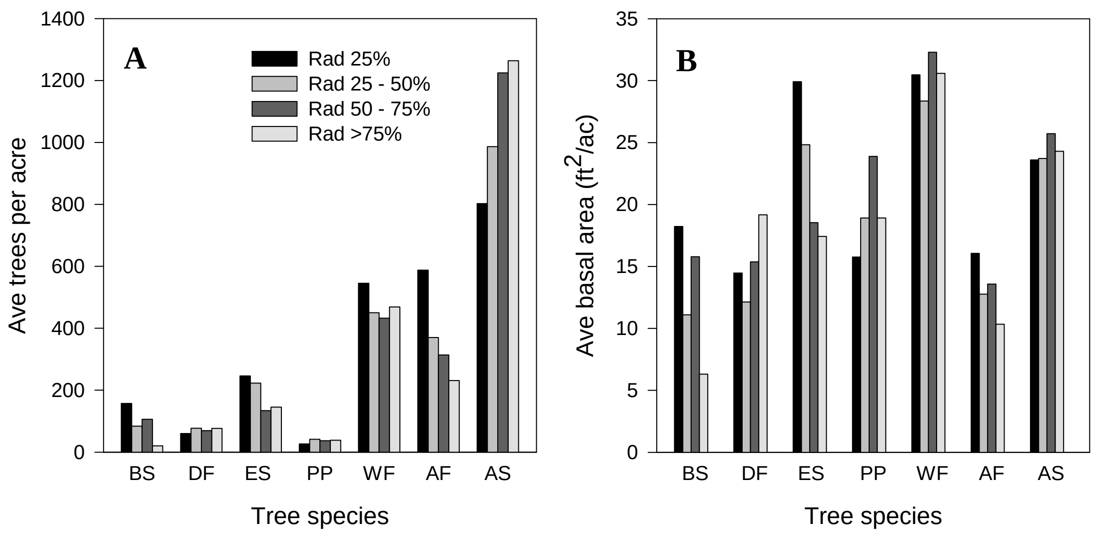

Figure 3. Mixed conifer average (A) tree density and (B) basal area for tree species within four solar radiation categories. The four radiation categories are defined as the 25th, 25th to 50th, 50th to 75th and >75th percentile groups for mixed conifer forest types.

Table 5. Results from MC forest basal area comparisons by tree species between each of the radiation categories using multivariate MRPP statistical tests.

Solar radiation comparisons	T	A	*p*-value
Wet vs. Mesic	-0.40	0.0010	0.2579
Wet vs. Dry	-2.52	0.0087	0.0268
Wet vs. Very dry	-2.68	0.0134	0.0226
Mesic vs. Dry	-2.07	0.0041	0.0446
Mesic vs. Very dry	-2.52	0.0061	0.0273
Dry vs. Very dry	-2.67	0.0089	0.0216

On average, forest structure was more varied among solar radiation categories in terms of basal area, but not tree densities (**Table 6**). Mean canopy height also decreased from 72.3’ on wet sites to 63.9’ on very dry sites. Both basal area and canopy height were significantly different forest comparisons between most solar radiation categories from t-tests (not shown). In contrast with elevation categories, no significant differences were found among average SI values for radiation categories, which ranged between 69’ on wet sites and 66’ of very dry sites. These data suggest, in addition to site moisture, other factors may exert control over forest structural features. For example, sites with low annual solar radiation (wet) were generally on steeper north-facing slopes (>25%) or within narrow canyon areas (**Appendix A map**). It is possible that these sites were less feasible for selective tree harvesting or less susceptible to other disturbances such as frequent fire. Fulé et al. (2003) noted that north facing slopes showed a far fewer number of fire intervals than did south and east facing slopes from fire-scare data in GCNP.

Table 6. Mixed conifer forest tree density and basal area summarized by radiation category from the 1990 inventory data.

Solar radiation categories	Ave. TPA	Ave. TPH	Ave. BA (ft^2/ac)	Ave. BA (m^2/ha)
Wet	2,425	981	148.5	34.1
Mesic	2,232	903	131.8	30.3
Dry	2,317	938	145.2	33.3
Very dry	2,245	908	127.0	29.2

4. Conclusions

Today’s mixed conifer forests on the North Kaibab Ranger District are dramatically different from when forest inventory data were first collected in 1909. In most cases examined with the present study, MC tree density is now 10 times greater than in 1909 and basal area has more than doubled. Perhaps most striking is that current forest inventory data on NSF land showed nearly equal tree densities and only a moderate decrease in basal area in comparison with tree data reported from studies in GCNP mixed conifer forest. Forest management histories on the NSF lands of the North Kaibab suggest that selective logging practices may have removed only a small fraction of trees with commercial value in previous years. In addition, reduced fire frequency has contributed to the development of a large cohort of shade-tolerant tree species that have created more contiguous vertical and horizontal canopy structure in MC and Spruce-Fir forest. We found no evidence to suggest that site biophysical differences have contributed observed differences in tree density and basal area between the 1909 and 1990 inventory data. Biophysical differences among mixed conifer sites mainly contributed to a turnover in tree species composition and an interchange shade-tolerant species from wet to dry sites, rather than large difference in general forest structural conditions.

Comparisons made with the present study suggest a few broader implications for restoration treatments within mixed conifer forest types. The first is that fire undoubtedly played an important role in controlling shade-tolerant tree densities prior to fire suppression. It has become more widely appreciated that fire was a periodic disturbance mechanism in mixed conifer forest that likely maintained a more even tree species distributions, a diversity of structural conditions and relatively low tree biomass on these sites (Stein 1988, White and Vankat 1993, Fulé et al. 2003, Fulé et al. 2009). True-fir species are sensitive to bole scorch and low intensity fires burning in the understory historically maintained low numbers of established individual trees. Returning more frequent low intensity fires to contemporary mixed conifer forest conditions is a necessary part of restoration, but could potentially add to ground fuel accumulations via understory tree mortality in post-treatment areas or present substantial fire control risks. To address uncertainty regarding the role fire in MC forest restoration, recent fire monitoring plots established within GCNP can provide information on post-treatment effects in mixed conifer forest. Given the similarities in forest structure and composition between NFS land and GCNP, this is a potentially representative analog.

Secondly, silvicultural treatments such as thinning, prescribed burning or other selective harvest practices should be aimed at reducing overall tree density and basal area to restore species and size class distributions similar to those observed in 1909. These activities should create regeneration opportunities for ponderosa pine and Douglas-fir regeneration where appropriate. Mixed conifer sites below ~2,700 m likely maintained higher densities of these species, in contrast to higher elevation Spruce-Fir dominated forest. This may include promoting advanced regeneration by reducing competitive interactions between these and shade-tolerant species or creating canopy-gaps in close proximity to residual ponderosa pine and Douglas-fir. Novel silvicultural practices that encourage site-scale seed dispersal and metapopulation dynamics for these species are likely needed to maintain composition and structural diversity for mixed conifer forest while reducing overall canopy and ground fuel accumulations.

Further study of MC forest conditions should be focused on comparison of forest fuel parameters such as crown bulk density, canopy cover, crown base height and live tree biomass among elevation and solar radiation categories as well as explore difference in height and diameter class distributions among species (e.g., vertical height structure and canopy strata). These analyses can also be expanded to other NFS lands in the southwestern US with the use USFS Forest Inventory and Analysis plots for mixed conifer forest types and other available historical forest inventories that potentially exist (e.g., Continuous Forest Inventory plots). Efficient use of available data and published studies, such as with the methods shown here, can suggest ways in which forest restoration goals and hazardous fuels reductions can be achieved for Southwest mixed conifer forest types.

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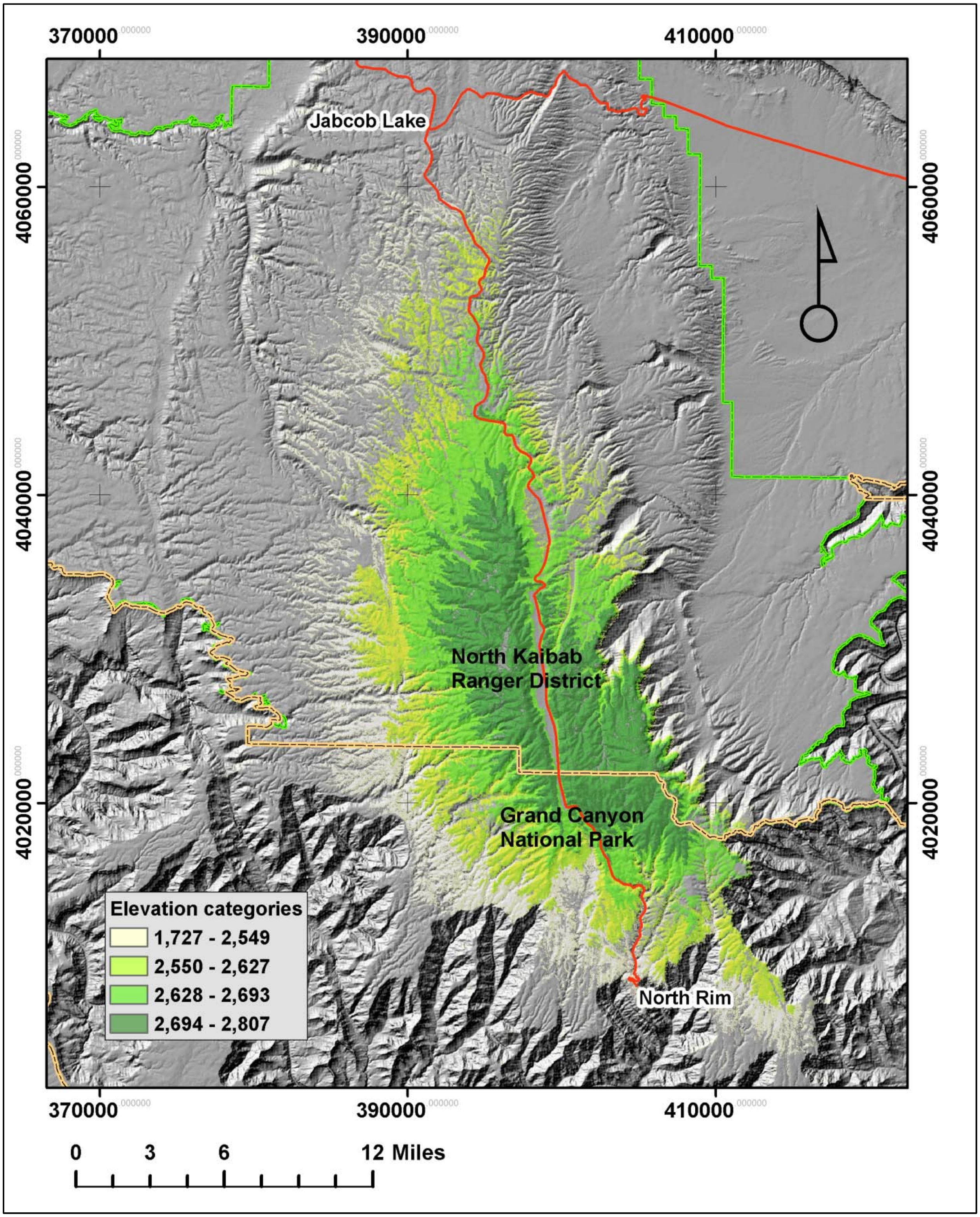
Appendix A. Elevation category map.



Appendix B. Solar radiation category map.