DISSERTATION

FOREST STRUCTURE IN UNHARVESTED OLD-GROWTH: UNDERSTANDING THE INFLUENCE OF SOILS ON VARIABILITY OF LONG-TERM TREE DYNAMICS AND FIRE HISTORY

Submitted by

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ABSTRACT

FOREST STRUCTURE IN UNROADED OLD-GROWTH: UNDERSTANDING THE INFLUENCE OF SOILS ON VARIABILITY OF LONG-TERM VEGETATION DYNAMICS AND FIRE HISTORY

Western North American forests adapted to frequent fires have been fundamentally altered and fragmented as a result of fire exclusion, the transportation infrastructure, development patterns, and other landscape level changes. In order to enhance the resiliency, diversity, and productivity of forest ecosystems it is essential to encourage collaborative, science-based restoration of forest landscapes and to develop a public understanding of the dynamic nature of forests. The USDA's Collaborative Forest Landscape Restoration Program (CFLRP) provides guidelines for community stakeholders and private advocacy groups to engage with federal, state, and local agency stewards to develop monitoring and assessment goals for forest restoration projects. The Uncompahgre Plateau (UP) was identified as one of ten initial CFLRP locations nationwide and has very large, old heritage trees scattered across never-harvested areas within the National Forest boundaries. Understanding how soil depth influences fire behavior and canopy development and determining the nature of historical fire regime on the UP are key elements for the development of local forest restoration prescriptions.

Heritage trees appeared to occur more often on rocky soils, and I expected this could result from different fire behavior in landscape patches where soils are too thin to support dense forest cover and fuels. I tested the influence of soil depth on forest composition and the fire history of the study area in three phases. First, I recorded soil depth and site characteristics for 80 randomly selected plots and included targeted site sampling of all heritage trees ($\geq$ 80 cm diameter) on two unroaded, never-harvested mesas to examine the relationship between soil depth, stand basal area, and the presence of heritage trees. The development of forest canopies (which influence fire regimes and tree survival) appeared to relate to soil characteristics (particularly rock cover). Single factor analysis revealed that soil depth alone only accounts for about 10% of stand basal area variation, but locations with soil > 30 cm deep had almost twice the basal area of locations with < 15 cm of soil depth. Comparing the observed to expected occurrence of heritage trees in four soil depth categories revealed a disproportionately greater presence of old-growth heritage trees on the locations with shallow soils. These results indicate that simple soil depth measurements can be used by restoration planners to develop stand-level spatial patterns. In the second phase, I used standard dendrochronology techniques to age trees from random plots, targeted heritage trees, and aspen transects to determine if historical stand structure patterns revealed forest age caps in concert with known landscape level historical fires. The spatial pattern of pre-1880 trees revealed that landscape level fires in the 1800s were likely not intense enough to kill all conifers over large areas, but were intense enough to kill most aspen stems on two of four sampled mesas. The mixed-severity nature of historical fires indicates that forest managers should have the leeway to plan for a spectrum of low to high severity fire effects within their restoration treatments. The third phase of my research tested the validity of my age-cap sampling methodology. I applied my sampling protocols to results from thirty systematic grid sampling locations composed of mixed conifer and spruce fir forests on the Kaibab Plateau, located on the North Rim of the Grand Canyon. My methodology targeted the largest trees and identified the oldest trees in the mixed conifer plots 97% of the time (in all but one plot). While a complete census of all trees would provide perfect information on the presence of an age cap, the validation of my targeted sampling approach provides a high confidence method to characterize the oldest trees in sampling locations with a substantial savings in the amount of time and resources expended. The subsequent ability to characterize the historical fire regime at the scale of the sampling design provides forest managers with another tool to inform restoration prescriptions. Applying the knowledge gained from the unroaded, never-harvested mesas to similar forest types on the Uncompahgre Plateau will guide landscape-scale treatment planning designed to restore ecosystem structure, composition, and function while reintegrating and managing wildfire as a natural component to reduce the risk of unnaturally severe crown fires.

ACKNOWLEDGMENTS

There are many individuals and organizations I would like to thank for generously supporting my research. First and foremost is Dr. Dan Binkley. I was stationed at Lajes Field (on the Azores archipelago island of Terceira) when I first contacted Dan. Dan reached a welcoming hand across the Atlantic and agreed to be my faculty sponsor for the Graduate Degree Program in Ecology at CSU. He shared ideas for a handful of potential research projects that could be addressed in a three year timeframe, and his low-key but professional and productive style is intertwined with an unending curiosity and contagious good humor that made him the ideal mentor and friend. Some of the most enjoyable and educational opportunities along this journey were spent in the forest, listening to Dan and Bill Romme “ecologize”. Gentlemen and scholars both, the comfortable and confident exchange of ideas between them shaped how I think and taught me that true insight is most often revealed in the nature of our questions. Peter Brown was exceptionally generous with his time, tools, and expertise as he opened my eyes to the world of dendrochronology.

This research was supported by the United States Air Force Academy, Department of Biology, and the Uncompahgre Plateau Collaborative Forest Landscape Restoration Project. I thank Colonel John Putnam for helping me pursue my passion to teach and the Uncompahgre Project community for allowing me to work in such a breathtaking venue with a cast of caring characters. Megan Matonis was a stalwart and uncomplaining partner during demanding field work on the unroaded mesas, and her inquisitive nature helped shape my initial research goals.

This endeavor would have ended before it ever began without the love and support from my wife and our daughters. Raising a family in a military-to-military marriage is trying enough, but adding in the uncertainty and heartache of more than three years of deployment separations

makes the challenge herculean. The strength of the trust and faith we share as a family enabled us to make it through some challenging times, and I look forward to being under the same roof as we write the future chapters of our lives together.

TABLE OF CONTENTS

CHAPTER 1

THE INFLUENCE OF SOIL DEPTH ON MIXED CONIFER BASAL AREA AND LONG-TERM FOREST STRUCTURE

Summary

Soil characteristics, particularly rock cover, influence the development of forest canopies which influence fire regimes and tree survival. I studied the relationship between soil depth, basal area, and tree species composition in mixed conifer forests on unroaded, never-harvested mesas on the Uncompahgre Plateau in southwestern Colorado. I sampled soil depth and measured basal area from a network of 80 randomly selected plots on adjacent mesas to assess an expected correlation between deeper soils and higher basal area. Forest basal area from prism plots averaged 55 $\mathrm{m^2/ha}$, distributed across quartiles of 32 $\mathrm{m^2/ha}$, 41 $\mathrm{m^2/ha}$, 57 $\mathrm{m^2/ha}$, and 87 $\mathrm{m^2/ha}$. Across the study sites about 10% of the variation in basal area was related to soil depth. Locations with greater than 30 cm soil depth had almost twice the basal area of locations with less than 15 cm soil depth. Counterintuitively, the infrequent locations with very shallow soil contained a disproportionately greater presence of very large (heritage) trees that measured more than 80 cm diameter at breast height (dbh). Stand-scale forest restoration prescriptions (such as restoration thinning) should be informed by within-stand soil depth patterns to restore historical forest spatial patterns on the Uncompahgre Plateau.

Introduction

Congress established the Collaborative Forest Landscape Restoration Program (CFLRP) with Title IV of the Omnibus Public Land Management Act of 2009. The purpose of the CFLRP is to encourage the collaborative, science-based ecosystem restoration of priority forest landscapes. Through collaboration between federal, state, and local agencies as well as interested groups and private citizens, the program encourages close coordination between foresters, scientists, and landowners to develop collaborative solutions for landscape-scale operations. This model encourages foresters and scientists to bridge the gap between entrenched bureaucracies like federal agencies and environmental groups (Egan 2007), and successful restoration is achieved by balancing ecological and economic interests.

The Uncompahgre Plateau in southwestern Colorado experienced frequent fires before Euro-American settlement (Brown and Shepperd, 2003), followed by very few fires in the 20th Century as a result of overarching federal fire suppression policies. Collaborative forest restoration efforts under the Uncompahgre Plateau CFLRP seek to reduce the risk of severe wildfires by shifting forest structure away from high densities of trees and low densities of meadows. In support of this effort, I examined two unroaded, never-harvested mesas with mixed conifer old-growth stands to establish presettlement reference conditions and determine how soil characteristics (particularly rock cover) influenced the development of forest canopies and fire regimes.

Initial reconnaissance on the mesas appeared to reveal a pattern where shallow, rocky soils had fewer trees in total, but supported more heritage trees (≥ 80 cm diameter) of ponderosa pine and Douglas-fir. I expected these shallow, rocky soils to have a lower basal area that supported lower fire severity. In contrast, deeper soils with less rock cover were expected to support a more traditional cool/moist mixed conifer structure with more spruce and fir, greater canopy contiguity, higher basal area, and therefore greater risk of stand-replacing fires. The nature of these sites presents the opportunity to examine presettlement spatial patterns that include a number of rare old-growth stands and individual heritage trees. Understanding how soil/rock cover influences canopy development and fire regimes will allow us to inform stand-scale treatments (such as restoration thinning) that account for within-stand variations in soil depth.

The connection between rockiness, fire behavior, and tree survivorship has been studied across a range of fire-adapted forests. On the one hand, deeper soils are expected to lead to increased forest productivity due to increased availability of soil moisture and nutrients. Within stands, seedling establishment depends on adequate seed production and precipitation, exposed mineral soils, and a release from competition with understory species (White 1985). Local water supply is strongly influenced by soil texture, with implications for species composition and production (Abella and Covington, 2006). In southwestern forests adapted to frequent fires, large trees are often more reliant on winter precipitation and deep soil water than small trees, so restoration thinning that targets low-density stands of larger trees can improve stand resilience to warmer and drier climate conditions (Kerhoulas et al., 2013).

On the other hand, the presence of rocky or poor soils is often linked to higher survival of presettlement trees. Geomorphology and soils create a complex forest landscape mosaic based on differing productivity and capability to support plant communities (Abella and Covington, 2006). Since forest communities vary at local, landscape, and regional levels (Allen et al., 2002), understanding the influence of soil depth and rockiness on stand characteristics and within-stand patterns may help inform restoration prescriptions. In Appalachian *Quercus* forests where low intensity surface fires were thought to be common prior to Euro-American settlement, surviving trees on rocky patches had fewer fire scars and these same patches supported a greater density of fire-sensitive species, suggesting rocky patches mitigate fire severity (Signell and

Abrams, 2006). Presettlement trees in piñon-juniper (*Pinus edulis – Juniperus osteosperma*) woodlands are more common in stands with greater surface rock cover (Johnson and Miller, 2008) since the rocky sites support low levels of surface fuels which leads to low intensity fires and higher rates of survival (Baker and Shinneman, 2004).

Low water availability in coarse, rocky soils produced sparse understory vegetation and low fire intensity in never-harvested ponderosa pine (*Pinus ponderosa*) forests (Kaufmann et al., 2003), and fire return intervals are longer on lower quality soils (Brown et al., 1999). Rock outcrops on ridges, in meadows, and at the edge of meadows are havens for old ponderosa pines due to protection from intense fires, and the scarce water and nutrient availability in these environmentally stressed locations leads to slower growth and increased tree longevity than where resources are abundant (Huckaby et al., 2003; Abella and Denton 2009). In a remnant old-growth forest in Arizona, soil moisture, organic C, and total N contents were low due to extremely low soil bulk density, but this poor soil area characterized by unusually slow tree growth rates contained an exceptionally high presettlement ponderosa pine density (183/ha) (Abella, 2008). This study will examine how these alternate forces play out on the unroaded, never-harvested mesas of the Uncompahgre Plateau.

A map (Appendix 1.A) of a geographical information system (GIS) query of forest cover occurring in a similar mixed conifer elevation gradient to the study sites (2600 – 2800 m) indicates the historical structure of forests on these mesas could provide confidence in restoration planning for approximately 60,000 ha on the Uncompahgre Plateau. I evaluated the hypothesis that shallow, rocky soils have a lower basal area associated with lower fire severity and longer fire return interval while deeper, less rocky soils are associated with a higher basal area and a greater risk of stand-replacing fires. I also measured soil depths surrounding all presettlement heritage trees (≥ 80 cm dbh) to evaluate the perceived relationship between shallow, rocky soils and the survival of presettlement trees.

Methods

Study area

The Uncompahgre Plateau in southwestern Colorado stretches approximately 200 km from northwest to southeast (from the Colorado-Utah border to the San Juan Mountains) and more than 230,000 ha are encompassed in the Uncompahgre National Forest (Fig. 1.1). Geologic formations of granite, Morrison, and Dakota sandstones and Mancos shale dominate this high, long uplift of sedimentary rocks. Erosion resistant sandstones characterize the topographic pattern of isolated finger mesas surrounding a domed upland; numerous sharp and rugged canyons dissect the Plateau borders (Hughes et al., 1995). Upland areas on the Plateau range from 2400 – 3050 m, and canyon bottoms can extend down to elevations below 1800 m. The mixed conifer forests of the study area (scientific names in Table 1.1) occur along a continuum from warm/dry (montane) to cool/moist (subalpine) climatic zones (Romme et al, 2009).

After Euro-American settlement, both the structure and function of mixed conifer forests adapted to frequent fires were altered by practices such as livestock grazing which removed fine fuels (Brown and Wu, 2005), logging, and the active suppression of fire (Cooper, 1960; Covington and Moore, 1994; Romme et al., 2009). Due to a reduction in fire-frequency, contemporary mixed conifer forests on the Uncompahgre Plateau and throughout southwestern Colorado have been altered to the point where current forests often have two to four times more basal area and tree density than was common prior to 1870. Current forest structure supports higher severity and more destructive wildfires and, coupled with the preferential harvesting of large trees, have left few examples of old-growth in areas formerly characterized by frequent fires (Brown et al., 2001; Brown and Wu, 2005; Fulé et al., 2009; Korb et al., 2012). These structural changes are accompanied by composition changes, with substantial increases in fire-susceptible species like aspen, Engelmann spruce, and subalpine fir, and corresponding decreases in ponderosa pine (Figs. 1.2 and 1.3).

Winter monthly temperatures on upper portions of the Plateau average -3° to -6° C while summer months average 12° to 14° C. The upper portions of the Plateau receive about 85 cm of precipitation each year (mostly snowfall) with only 20% falling during the growing season (Columbine Pass SNOTEL site#409, 2900 m elevation, 38° 25' N, 108° 23' W http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=409&state=co). Lower portions of the Plateau are warmer (winter monthly temperatures averaging -2° to -4° C and summer months averaging 16° to 18° C) and receive less precipitation with an average of 55 cm each year, with 25% falling during the growing season (Sanborrn Park RAWS, 2450 m elevation, 38° 11' N, 108° 13' W, http://www.raws.dri.edu/cgi-bin/rawMAIN.pl?coCSAN).

The Mountain Utes used the Uncompahgre Plateau for hunting and foraging for almost a millennium before they were evicted in 1881. Very intensive livestock grazing began the following year (Hughes et al., 1995; Shinneman and Baker, 2009). Presettlement fires occurred within the ponderosa pine and mixed conifer forests on the plateau at least every 10 - 15 years. Major landscape-level fires occurred in 1842 and 1879, well-known regional fire years on the Western Slope of Colorado. Age data from higher elevation forests suggests many stands regenerated after crown-opening fires in 1879 (Brown and Shepperd, 2003). Evidence of the large fires in 1842 and 1879 was detected in widely separated locations, though fire behavior and impacts probably varied greatly across the Plateau.

Two adjacent, unroaded, never-harvested mesas were studied (Fig. 1.1). Motley (about 90 ha, 38˚ 27' N, 108˚ 23' W) and Goodtimes Mesas (about 60 ha, 38˚ 27' N, 108˚ 24' W) were likely not harvested following Euro-American settlement due to their relatively small size combined with steep and difficult access to the mesa tops. Elevation on the mesas ranges from 2730 - 2775 m, and similar forests are found from elevations of about 2600 - 2800 m. The forests are a heterogeneous mixture of warm/dry and cool/moist mixed conifer forest types. Very large (≥ 80 cm diameter) ponderosa pine and Douglas-fir heritage trees occur as individuals across the mesas, though rare clusters of two ponderosa heritage trees occurred on Motley Mesa. The shallow and well drained Olathe family of soils on these mesas was formed from interbedded sandstone and shale. The depth to underlying Dakota sandstone bedrock is generally 10 – 50 cm (Hughes et al., 1995). Small areas of rock outcrops occur across the mesas, and these are often associated with heritage trees (Fig. 1.4).

Sampling methods and data collection

Three approaches were used to evaluate the spatial patterns within stands (Fig. 1.5). First, I used a GIS to overlay a 50 m x 50 m grid on each mesa to provide unbiased mesa-scale sampling where each gridline intersection was numbered and designated as a possible plot. Sampling locations were determined by using a random number generator to select 80 plot locations (40 plots on each mesa). I used a 20 BAF (4.5 m^2 ha^{-1}) prism held over the plot center to sample trees and record species, diameter, and live/dead status for all "in" trees as well as other stand composition observations (e.g., visible fire scars, beetle infestation). The number of trees included in each prism plot sample is dependent on tree diameter and distance from plot center (e.g., small diameter trees must be very near to the plot center while very large diameter trees can be some distance from plot center and still be included). Since prism plots vary in size, soil depth was sampled at 5 m from the plot center in each of the four cardinal directions, with the four measurements averaged to create a standardized depth for each random location.

Second, I used targeted sampling to map the location of all heritage trees, then recorded the species, dbh, and soil depth around each tree and took cores for aging. Targeted sampling of the heritage trees allowed me to examine how soil depth in the immediate vicinity possibly influenced the survival of these presettlement trees. Eight soil depth measurements were taken for each heritage tree, sampling at both 1 m and 5 m from the perimeter of the trunk in the four cardinal directions. Soil depth was sampled at 1 m and 5 m from heritage tree trunks to account for the physical alteration of the abiotic environment by large, lateral roots from both ponderosa pines and Douglas-firs. These eight measurements were used to record a single average soil depth value around each heritage tree.

Third, soil transects were used to investigate soil depth spatial patterns in concert with the random plots and targeted sampling of heritage trees. The soil transect locations on both mesas were selected to intersect a mosaic of forest vegetation types. Motley Mesa is long and narrow, so the two 1-km transects ran parallel on the north end of the mesa where there was a more heterogeneous warm/dry and cool/moist mixed conifer mosaic. The southern end of Motley Mesa was a more homogenous cool/moist mixed conifer composition. Due to the smaller size of Goodtimes Mesa, one transect was 1-km in length and the other was 700 m and crossed the full width of the mesa. Soil depth to rock was measured at 20 m intervals along each transect.

Soil depth measurements were consistently applied across the three soil depth sampling methods by first measuring the organic horizon depth and then plunging a standard screwdriver (probe) with a 30 cm long shaft into the soil until it either hit rock or penetrated to the hilt. It required very little practice to determine the different feel and sound of hitting rock versus hitting a root, and in drier soils, a rubber mallet was used to ensure compaction did not stop penetration before hitting underlying bedrock. In areas where the plunge penetrated to the full length of the screwdriver, the location was recorded as ≥ 30 cm.

This type of simple, speedy, non-destructive rod penetration method was first described by Viro (1952) to record mineral soil depth to bedrock. Variations of this method have been used to assess soil rockiness based on a proportion of sampleable points along transects (Sasser and Binkley, 1989) as well as within plots (Stohlgren and Bachand, 1997). The rod penetration method has been extensively cross-referenced with soil pits and soil sifting at a landscape scale in Sweden (Stendahl et al., 2009), and a comparison of models designed to estimate stone and boulder content in forest soils found that the most useful model consisted of a single independent variable – mean penetration depth (Erikkson and Holmgren, 1996).

Data analysis

The relationship between soil depth and basal area was examined with the curve fitting routines in *CurveExpert Professional* (www.curveexpert.net). Soils deeper than 30 cm were assigned a depth of 30 cm. The relationship between soil depth and heritage tree locations was examined by using a ratio of the observed versus expected occurrence of heritage trees in the 80 random plots based on soil depth categories (< 15 cm, 15 – 19.9 cm, 20 – 29.9 cm, ≥ 30 cm). The proportion of plots in each soil depth category where heritage trees occurred (observed) was divided by the proportion of plots in each soil depth category from the total sample of random plots (expected: n/80). Soil depth was divided into discrete categories to facilitate the use of this technique (if validated) by seasonal crews for marking treatments like restoration thinning.

To further examine the rocky, shallow soil relationship with heritage trees, I used a combination of soil depth measurements from all three approaches (i.e., random plots, heritage trees, and soil transects) to develop a GIS-based soil map comparing soil depths on the mesas to the presence of heritage trees. Using the map to examine soil depth in proximity to heritage trees provided a secondary method to assess how soil depth can influence canopy development and fire behavior. I used inverse distance weighting (IDW) to assign soil depth values based on the distance from the nearest neighbor of a known point (Swetnam et al., 2011; Raty and Kangas, 2012). This approach assigns greater weight to nearby sample points than to those that are more distant. This probabilistic approach is an application of the first law of geography according to Waldo Tobler (1970) that everything is related to everything else, but near things are more related than distant things.

Results

Soil depth and stand structure

Forest basal area from prism plots averaged 55 m^2/ha, distributed across quartiles of 32 m^2/ha , 41 m^2/ha, 57 m^2/ha, and a fourth quartile maximum basal area of 87 m^2/ha. Due to the variable plot nature associated with prism sampling, the high basal areas are likely an artifact of the methodology. Soil depth accounted for 10% of the variation in stand basal area, and current basal area almost doubled with increasing soil depth from 15 cm to 30 cm (Fig. 1.6). A single outlier plot with shallow soil and very high basal area was omitted. The outlier plot center was located within 10 m of a heritage tree where the soil depth was shallow, but the prism included a number of nearby trees where soil depth was greater than 30 cm. Soil depth also related to stand composition; 84% of the plots with soil depth > 25 cm were dominated by cool/moist mixed conifer species including Engelmann spruce, Blue spruce, subalpine fir, Douglas-fir, and aspen. The basal area and spatial patterns associated with cool/moist mixed conifer composition stands on the study sites can vary widely (Fig. 1.3).

The targeted sampling of heritage trees revealed the average soil depth for all 45 trees was less than 30 cm. Within the random survey, very shallow soils (< 20 cm) accounted for only 21% of the random plots, yet these locations had 41% of the heritage trees (Fig. 1.7). Where heritage trees occurred on deeper soils, they were always bounded on other exposures by shallower soil depths (Fig. 1.8).

Discussion

Soil depth, basal area, and stand composition

Soil depth only accounted for 10% of the basal area variation in the random plots. The relationship may be stronger than my sampling indicates, because the trees within the field of the prism were often beyond the distance of the soil depth measurements. Soil depth measurements were limited to the upper 30 cm, so the relationship with basal area might have been stronger if soil deeper than 30 cm influences basal area. While the random plot sampling methodology did not account for the scale of shallow soil patches, the hypothesis that shallow, rocky soils have a lower basal area associated with lower fire severity while deeper, less rocky soils are associated with a higher basal area and a greater risk of stand-replacing fires is supported by evidence from the other two approaches. The strong association of heritage tree sites and shallow soils supports the idea that shallow and rocky soils influence tree survivorship, likely as a result of low connectedness among tree crowns and lower risk of active canopy fires, also reported by Huckaby et al., 2003, Kaufmann et al., 2003, and Abella, 2008. On these mesas, evidence indicates that low surrounding basal area and low crown bulk density does not have to occur around the full circumference of a tree in order to shelter it from fire mortality. Many of the heritage trees with multiple fire-scars had extremely shallow, rocky soils on only one exposure, but that was apparently enough to shelter them from historical fire mortality.

The species composition of the random plots generally followed expectations where deeper soils were comprised of more densely growing, cool/moist mixed conifer species (i.e., Douglas-fir, Engelmann spruce, blue spruce, subalpine fir, aspen) and shallower soils had a higher representation of large Douglas-firs and particularly more ponderosa pines. There were no pure aspen stands either on top of the mesas or in the drainage between them. Across the Plateau, the composition of mixed stands of aspen and conifers are changing with increases in conifer overstory basal area and decreases in aspen overstory basal area. The absence of fire is causing the overstory replacement of aspen by conifers in some stands, leaving a distinct older class of aspens with few aspen suckers growing into the overstory (Smith and Smith, 2005).

Fire regimes and restoration planning

A fire that burns with a severity sufficient to kill most living overstory trees in a specified area is considered a stand-replacing fire. The patchiness, stand composition and size of tree cohorts surrounding charred snags and logs, and the presence of many heritage trees in the randomly selected plot locations indicates that past landscape-level fires likely burned in a heterogeneous, mixed-severity manner at the scale of these mesas (50 – 100 ha). Some areas seem to have experienced crown-opening fires while other areas experienced low-severity surface fires and evidence of the heterogeneous pattern of fire-mortality on these relatively small mesas intimates the complexity of the overarching landscape mosaic in frequent-fire forests (Bormann and Likens, 1979; White and Pickett, 1985; Turner and Romme, 1994).

Soil depth measurements may indicate a scale of spatial variation in factors driving forest structure. In forests adapted to frequent fires, stand structure influences both spatial and temporal regeneration and mortality, and stand-level spatial patterns influence forest processes (e.g., disturbance behavior, regeneration, snow retention, habitat quality) that can lead to improved resiliency from low- and mixed-severity fires (Boyden et al., 2005). Expanding from the stand to the landscape perspective, when fire returns to a landscape, restoration treatments that thinned and accounted for within-stand spatial variation resulted in greater tree survival and reduced fire intensity (Strom and Fulé, 2007; Roccaforte et al., 2010). The high occurrence of presettlement heritage trees in shallow and rocky soils reveals that the rod soil plunge technique is a viable option for developing within-stand spatial patterns. Fewer, larger trees tend to occur in shallow soil sites while denser clumps of trees occur in deeper soils. In a shallow soil, mixed conifer environment, the easy, speedy, and non-destructive soil probe technique (Viro 1952) can be utilized today as a guide for seasonal crews when marking individuals, clumps, and openings within larger restoration treatments to prepare for the return of fire to the landscape.

Current forest structure and fuel conditions would support stand-replacing fires at landscape scales and this appears to be a significant departure from historical reference conditions. Restoration treatments and planning are well underway through the community of the Uncompahgre Plateau CFLRP, and stand-scale forest treatments (such as restoration thinning) should account for within-stand variations in soil depth to develop appropriate spatial patterns. In particular, restoration treatments should aim to retain ponderosa pine (and some

Douglas-fir) on shallow soils within stands, and perhaps a richer mixture of conifers on deeper soils.

Table 1.1. Mixed conifer forest species composition on the Uncompahgre Plateau, Colorado. Unlike other mixed conifer forests in southwestern Colorado, white fir (*Abies concolor*) was not observed in the study area on the Uncompahgre Plateau.

Species	Common Name
Abies lasiocarpa	Subalpine fir
Picea engelmannii	Engelmann spruce
Picea pungens	Blue spruce
Pinus ponderosa	Ponderosa pine
Populus tremuloides	Quaking aspen
Pseudotsuga menziesii	Douglas-fir
Quercus gambelli	Gambel oak

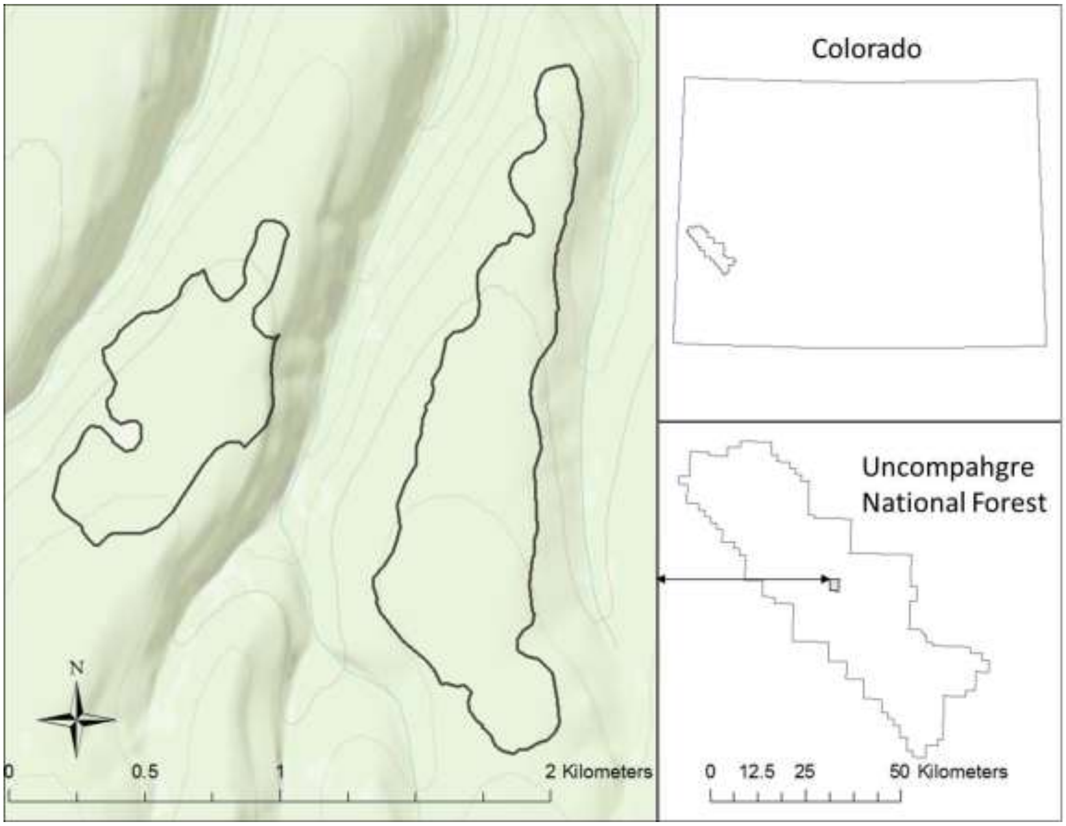


Figure 1.1. Unroaded, never-harvested study sites in the Uncompahgre National Forest, Colorado. Goodtimes Mesa (left, about 60 ha) and Motley Mesa (right, about 90 ha). Contours are at 25 m intervals.

Figure 1.2. Characteristic heritage tree locations. Clockwise from left.
(1) Ponderosa pine (107.7 cm dbh, breast height in 1564) with two visible ground level fire scars surrounded by other pines, spruce, fir, and aspen. From the vantage point of the photographer, exposed rocks are visible in the upper soil layer for approximately 20 m.
(2) Ponderosa pine (84.6 cm dbh, breast height in 1687) with aspen and Gambel oak. Exposed rocks adjacent to the heritage tree are visible in the upper soil layer throughout the surrounding understory.
(3) Douglas-fir (111.3 cm dbh, breast height in 1723) located amidst aspen, Engelmann spruce, and Douglas-fir just below the eastern rim of Motley Mesa.

Figure 1.3. Two characteristic mixed conifer stands in the study area. Both stands have similar cool/moist mixed conifer species composition (i.e., Engelmann spruce, blue spruce, subalpine fir, Douglas-fir, and aspen) but the stand on the left has high basal area and high canopy bulk density while the stand on the right has lower basal area and a more open canopy.

Figure 1.4. Left: platy rocks and low surrounding canopy bulk density around a fallen presettlement ponderosa pine exhibit the relationship between rocky soils and heritage trees. Right: an extreme example of a ponderosa pine heritage tree (96.5 cm dbh, breast height in 1626) surrounded by shallow, platy sandstone. Soil depth increases in the background with the denser trees.

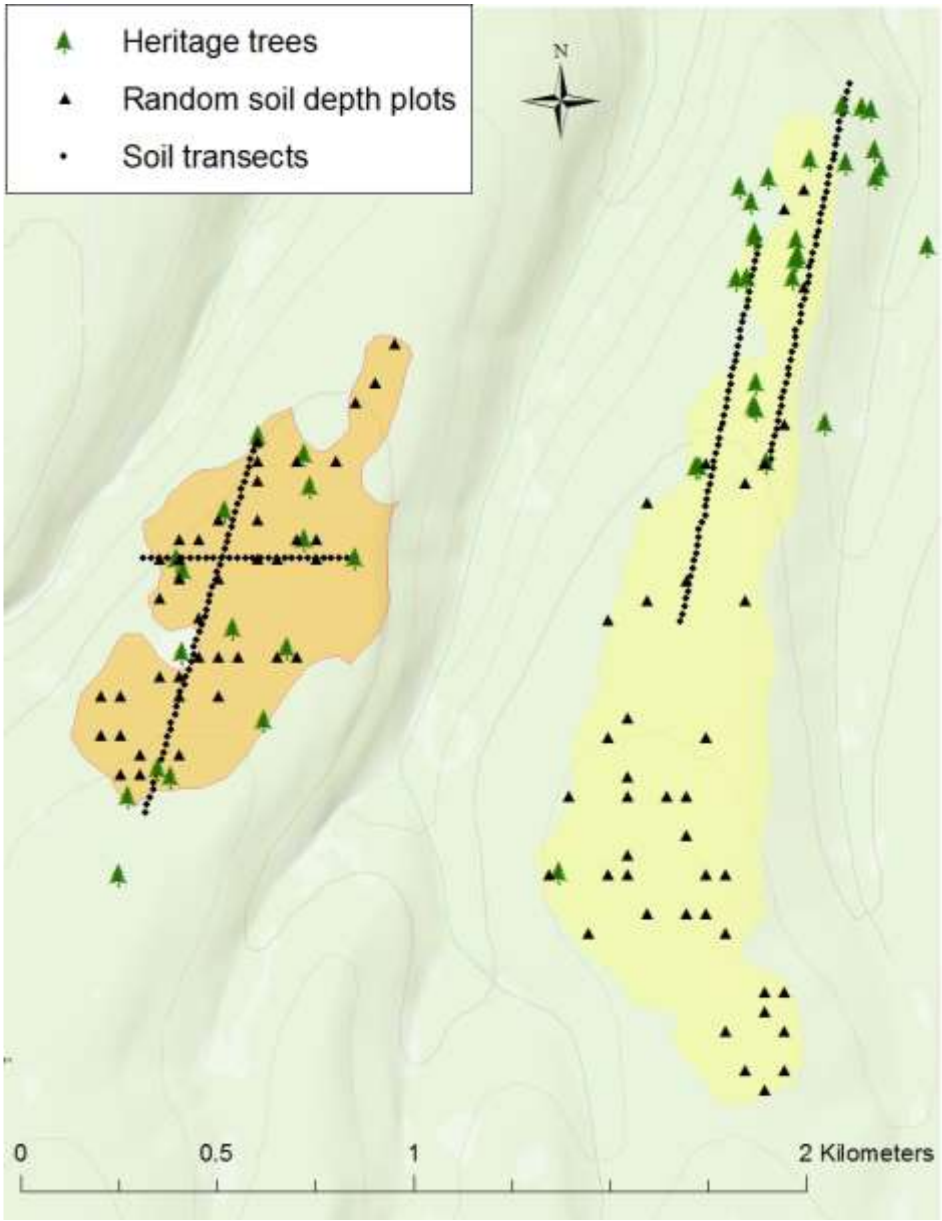


Figure 1.5. Soil depth sampling locations for Goodtimes Mesa (left) and Motley Mesa (right). Three sampling methods were used to examine the influence of soil depth and rockiness on basal area and stand structure. Soil depth at the 80 random plot locations was an average of four depth measurements while eight depth measurements were averaged for the heritage tree locations. A single soil depth measurement was taken for each transect point. The Motley transects are both on the northern end of the mesa because it has a heterogeneous mosaic of warm/dry and cool/moist mixed conifer stands, openings, and heritage trees. Contours are at 25 m intervals.

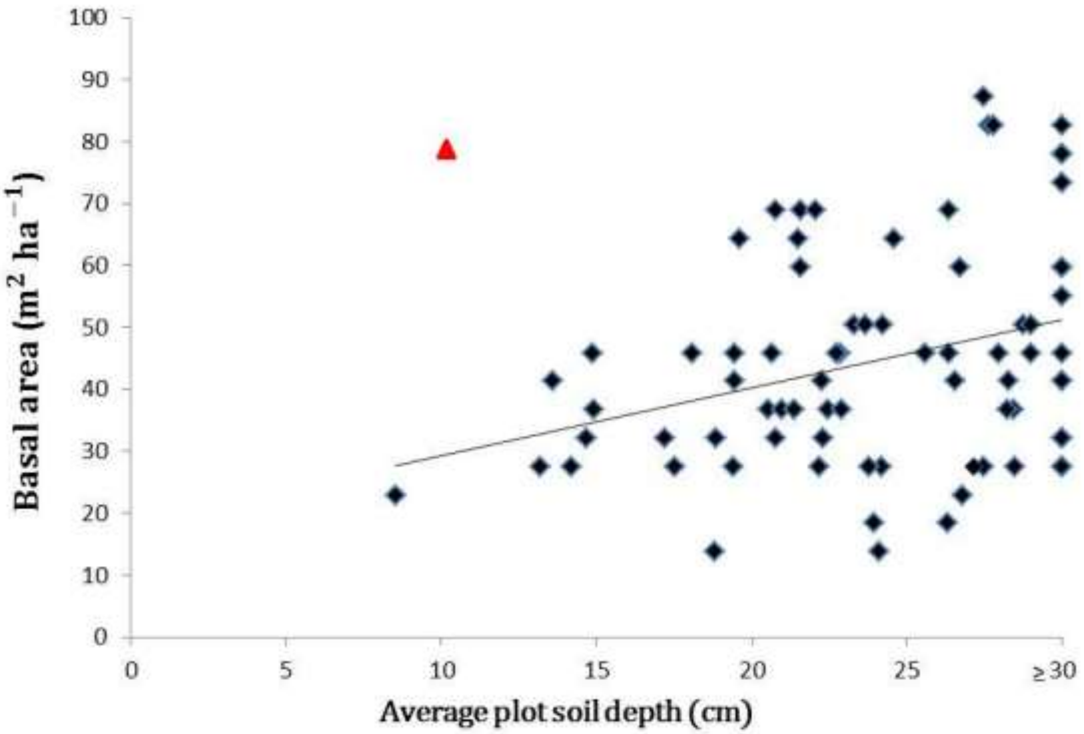


Figure 1.6. Sampling plot average soil depth (cm) vs. plot basal area (m^2 ha^{-1}). The outlying (triangle) plot had a heritage tree on a small patch of shallow soil surround by much deeper soil. Without the outlier, soil depth accounted for approximately 10% of variation in stand basal area. (r^2=0.10; p=.005; y=1.1x +18.3). Basal area increased by almost two-fold with a doubling of soil depth for 79 random plots.

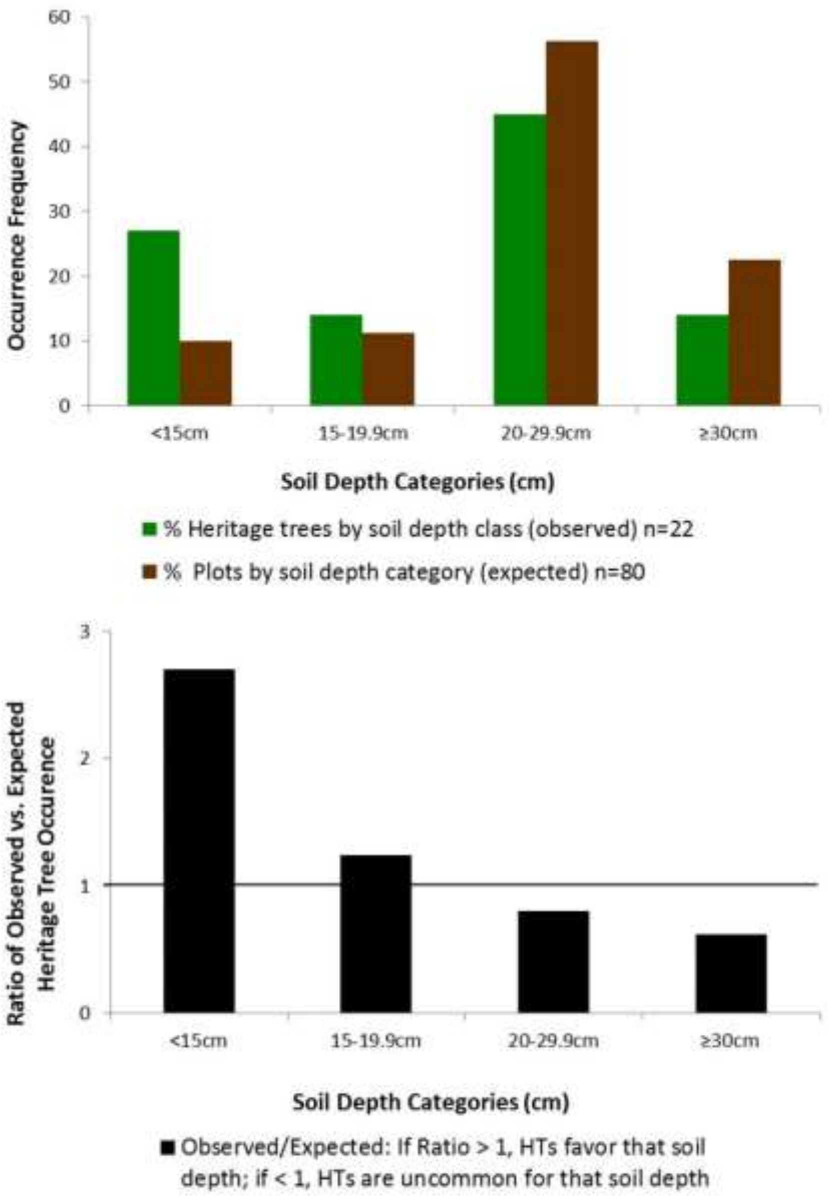


Figure 1.7. The top graph shows the proportion of the 80 random plots by soil depth category and the proportion of heritage trees that occurred in each soil depth category. The bottom graph shows the ratio of observed vs. expected heritage tree occurrence by soil depth category in 80 random plots. The infrequent shallow soil plots contained a much higher than expected proportion of heritage trees.

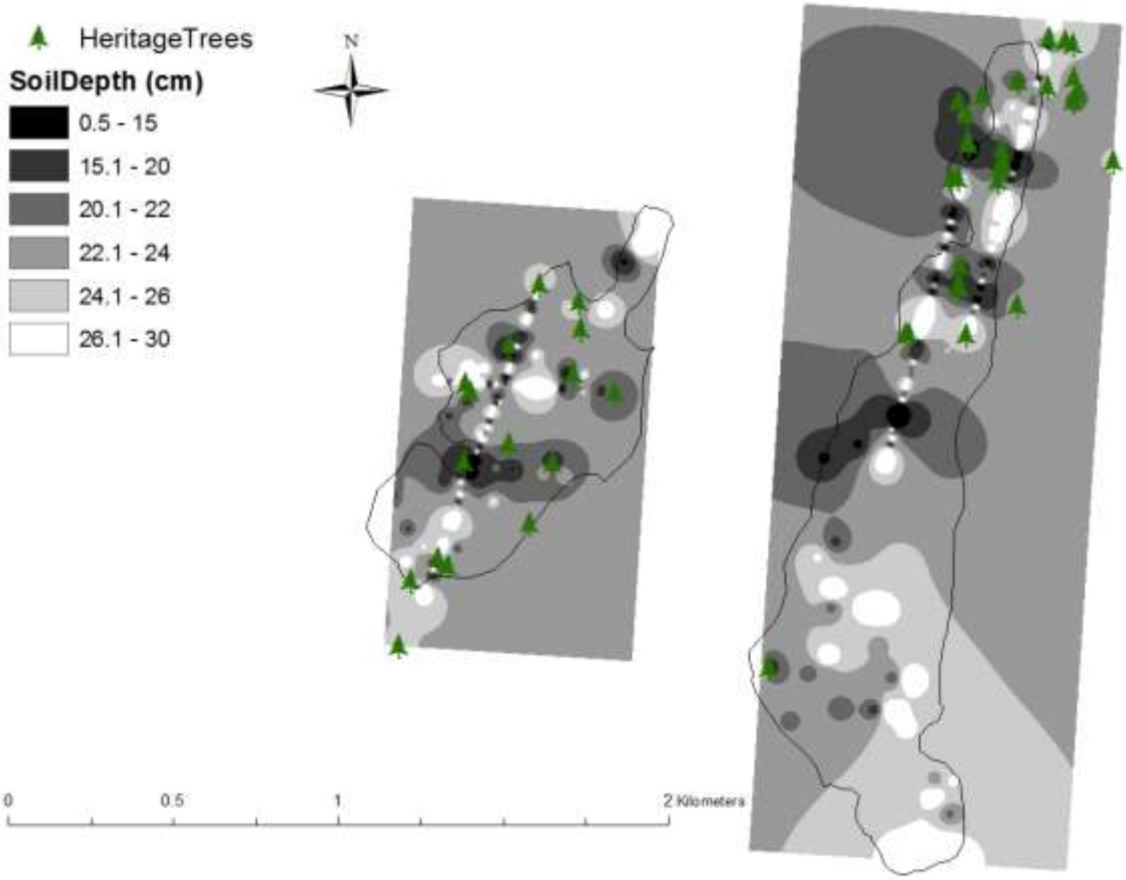


Figure 1.8. Inverse distance weighting (IDW) soil depth map of Goodtimes (left) and Motley (right) Mesas. Representative depths were derived from a combination of measured soil depths from all three sampling methods (random plots, targeted heritage trees, and soil depth transects). All heritage trees bounded by shallow/rocky soils on at least one side. Based on the data, the shaded rectangles represent the spatial extent of the IDW process for each mesa.

LITERATURE CITED

Abella, S.R., Covington, W.W., 2006. Forest ecosystems of an Arizona *Pinus ponderosa* landscape: multifactor classification and implications for ecological restoration. Journal of Biogeography 33, 1368-1383.

Abella, S.R. 2008. A unique old-growth ponderosa pine forest in northern Arizona. Journal of the Arizona-Nevada Academy of Science 40, 1-11.

Abella, S.R., Denton, C.W., 2009. Spatial variation in reference conditions: historical tree density and pattern on a *Pinus ponderosa* landscape. Canadian Journal of Forest Research 39(12), 2391-2403.

Allen, C.D., Savage, M., Falk, D.A., Suckling, K. F., Swetnam, T.W., Schulke, T., Stacey, P.B., Morgan, P., Hoffman, M., Klingel, J.T., 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecological Applications 12, 1418-1433.

Baker, W.L., Shinneman, D.J., 2004. Fire and restoration of pinon–juniper woodlands in the western United States: a review. Forest Ecology and Management 189, 1-21.

Bormann, F.H., Likens, G.E., 1979. Catastrophic Disturbance and the Steady State in Northern Hardwood Forests: A new look at the role of disturbance in the development of forest ecosystems suggests important implications for land-use policies. American Scientist 67, 660-669.

Boyden, S., Binkley, D., Shepperd, W., 2005. Spatial and temporal patterns in structure, regeneration, and mortality of an old-growth ponderosa pine forest in the Colorado Front Range. Forest Ecology and Management 219, 43-55.

Brown, P.M., Kaufmann, M.R., Shepperd, W.D., 1999. Long-term, landscape patterns of past fire events in a montane ponderosa pine forest of central Colorado. Landscape Ecology 14, 513-532.

Brown, P.M., Kaye, M.W., Huckaby, L.S., Baisan, C.H., 2001. Fire history along environmental gradients in the Sacramento Mountains, New Mexico: influences of local and regional processes. Ecoscience 8, 115-116.

Brown, P. M., Shepperd, W. D., 2003. Preliminary fire history in ponderosa pine forests of the Uncompahgre Plateau. Rocky Mountain Research Station, Fort Collins, CO.

Brown, P.M., Wu, R., 2005. Climatic and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. Ecology 86, 3030-3038.

Churchill, D.J., Larson, A.J., Dahlgreen, M.C. , Franklin, J.F., Hessburg, P.F., Lutz, J.A., 2013. Restoring forest resilience: From reference spatial patterns to silvicultural prescriptions and monitoring. Forest Ecology and Management 291, 442-457.

Cooper, C.F., 1960. Changes in vegetation, structure, and growth of southwestern pine forest since white settlement. Ecological Monographs 30, 129-164.

Covington, W.W., Moore, M.M., 1994. Southwestern ponderosa forest structure – changes since Euro-American settlement. Journal of Forestry 92, 39-47.

Egan, D., 2007. Conserving and restoring old growth in frequent-fire forests: cycles of disruption and recovery. Ecology and Society 12.

Eriksson, C.P., Holmgren, P., 1996. Estimating stone and boulder content in forest soils—evaluating the potential of surface penetration methods. Catena 28, 121-134.

Fulé, P.Z., Korb, J.E., Wu, R., 2009. Changes in forest structure of a mixed conifer forest, southwestern Colorado, USA. Forest Ecology and Management 258, 1200-1210.

Huckaby, L.S., Kaufmann, M.R., Fornwalt, P.J., Stoker, J.A., Dennis, C., 2003. Identification and ecology of old ponderosa pine trees in the Colorado Front Range. US Department of Agriculture, Forest Service, Rocky Mountain Research Station. USDA Forest Service General Technical Report RMRS-GTR-110.

Hughes, T., Kingston, R., Cencich, B., 1995. Soil survey of Uncompahgre National Forest Area, Colorado, parts of Mesa, Montrose, Ouray, and San Miguel counties. USDA Forest Service and Soil Conservation Service, in corporation with the Colorado Agricultural Experiment Station. Fort Collins, CO.

Johnson, D.D., Miller, R.F., 2008. Intermountain presettlement juniper: distribution, abundance, and influence on postsettlement expansion. Rangeland ecology & management 61, 82-92.

Kaufmann, M.R., Huckaby, L.S., Fornwalt, P.J., Stoker, J.M., Romme, W.H., 2003. Using tree recruitment patterns and fire history to guide restoration of an unlogged ponderosa pine/Douglas-fir landscape in the southern Rocky Mountains after a century of fire suppression. Forestry 76, 231-241.

Kerhoulas, L.P., Kolb, T.E., Koch, G.W., 2013. Tree size, stand density, and the source of water used across seasons by ponderosa pine in northern Arizona. Forest Ecology and Management 289, 425-433.

Korb, J.E., Fulé, P.Z., Stoddard, M.T., 2012. Forest restoration in a surface fire-dependent ecosystem: An example from a mixed conifer forest, southwestern Colorado, USA. Forest Ecology and Management 269, 10-18.

Raty, M., Kangas, A., 2012. Reprint of: Comparison of k-MSN and kriging in local prediction. Forest ecology and management 272, 51-60.

Roccaforte, J.P., Fulé, P.Z., Covington, W. W., 2010. Monitoring landscape-scale ponderosa pine restoration treatment implementation and effectiveness. Restoration Ecology 18, 820-833.

Romme, W.H., Floyd, M.L., Hanna, D., 2009. Historical Range of Variability and Current Landscape Condition Analysis: South Central Highlands Section, Southwestern Colorado & Northwestern New Mexico. Colorado Forest Restoration Institute, Fort Collins, CO, USA.

Sasser, C.L., Binkley, D., 1989. Nitrogen mineralization in high-elevation forests of the Appalachians. II. Patterns with stand development in fir waves. Biogeochemistry 7, 147-156.

Shinneman, D.J., Baker, W.L., 2009. Historical fire and multidecadal drought as context for pinon-juniper woodland restoration in western Colorado. Ecological applications 19, 1231-1245.

Signell, S.A., Abrams, M.D., 2006. Influence of rocky landscape features and fire regime on vegetation dynamics in Appalachian Quercus forests. Journal of Vegetation Science 17, 675-684.

Smith, A. E., Smith, F. W., 2005. Twenty-year change in aspen dominance in pure aspen and mixed aspen/conifer stands on the Uncompahgre Plateau, Colorado, USA. Forest Ecology and Management 213, 338-348.

Stendahl, J., Lundin, L., Nilsson, T., 2009. The stone and boulder content of Swedish forest soils. Catena 77, 285-291.

Stohlgren, T.J., Bachand, R.R., 1997. Lodgepole pine (Pinus contorta) ecotones in Rocky Mountain National Park, Colorado, USA. Ecology 78, 632-641.

Strom, B.A., Fulé, P.Z., 2007. Pre-wildfire fuel treatments affect long-term ponderosa pine forest dynamics. International Journal of Wildland Fire 16, 128-138.

Swetnam, T., Falk, D.A., Hessl, A.E., Farris, C., 2011. Reconstructing Landscape Pattern of Historical Fires and Fire Regimes. In The Landscape Ecology of Fire (pp. 165-192). Springer, Netherlands.

Tobler, W., 1970. A computer movie simulating urban growth in the Detroit region. Economic Geography 46, 234-240.

Turner, M.G., Romme, W.H., 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecology 9, 59-77.

White, A.S. 1985. Presettlement regeneration patterns in a southwestern ponderosa pine stand. Ecology 66, 589-594.

White, P.S., Pickett, S.T.A., 1985. Natural disturbance and patch dynamics: an introduction. In: White, P.S., Pickett, S.T.A. (Eds.), The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, Orlando, FL.

Viro, P.J., 1952. On the determination of stoniness. Communicationes Instituti Forestalis Fenniae 40 (3).

CHAPTER 2

HISTORICAL MIXED CONIFER STAND STRUCTURE REVEALS MIXED-SEVERITY FIRE INTENSITY

Summary

Treatments to restore forest structure in fire-adapted forests of western North America are often guided by reference conditions of historical forest structure, composition, and fire regime. I assessed four mesas (two were never-harvested) composed of warm/dry and cool/moist mixed conifer forests on the Uncompahgre Plateau in southwestern Colorado to determine the severity of presettlement landscape-level fires in the 1800s. The presence of an age cap (with few if any older trees present) has been used to indicate a severe, stand-replacing fire. I used standard dendrochronology techniques to search for age caps and thereby determine whether fires in the 1800s could be classified as surface, mixed-severity, or stand-replacing fires at the scale of the mesas (50 – 100 hectares). I applied a combination of three approaches to evaluate age caps and spatial patterns within stands: 80 randomly selected locations for old conifers, targeted sampling of all heritage-tree conifers (≥ 80 cm diameter), and five long transects for old aspen. The spatial pattern of trees that predate 1880 indicated that landscape-level fires in the 1800s were not intense enough to kill all conifers over areas as large as the mesas. In contrast, a fire in 1879 appeared intense enough to kill most aspen stems on two of the four mesas. Current forest structure and fuel conditions would support stand-replacing fires for both conifers and aspens, revealing a substantial departure from historical reference conditions. Applying this information to similar areas on the Uncompahgre Plateau will guide landscape-level treatment planning to

restore forest structure, composition, and function while reintegrating and managing wildfire as a natural component to reduce the risk of unnaturally severe crown fires.

Introduction

Effective forest restoration is built on a clear understanding of current and historical forest reference conditions, and how natural disturbances maintained the structure and composition that promoted vegetation and wildlife habitat diversity (Covington and Moore, 1994; Fulé et al., 1997; Allen et al., 2002; Churchill et al., 2013). Reference conditions do not refer only to forest conditions in a particular place and time, but encompass processes (such as fire) that provided the selective force driving evolutionary adaptations over thousands of years (Fulé 2008). In western North American forests adapted to frequent fires, current forest structures are not compatible with the types of fire regimes that characterized historical forest structures. Any warming or drying with future climates would accentuate this difference and the structure of contemporary forests that has created the potential for a higher incidence of wildland fires makes the use of the historical range of variability (HRV) or presettlement historical reference conditions a suitable target for restoration goals (Korb et al., 2012). In spite of active fire suppression efforts, fire will return to forests adapted to frequent fires, and management focus should be on how to prepare for the return of fire. Reference conditions provide the best target to build consensus on restoration goals while mitigating the risk of catastrophic loss of these forest systems.

Understanding fire as an inherently complex landscape process is essential for assessing reference conditions, and these conditions are specific to particular locales or forest types (Turner and Romme, 1994). Mixed conifer forests are characterized by a mixed-severity fire regime where the size and distribution of stand-replacing patches and other patches that burned with different severities create a heterogeneous mosaic of forest structure and composition (Collins and Stephens, 2010). Prior to Euro-American settlement, mixed conifer forest composition (scientific names given in Table 2.1) and structure were directly affected by climatic conditions through recruitment pulses where high seed production years were followed by warm, wet weather that favored seedling establishment (Cooper 1960; Covington and Moore, 1994; Stone et al., 1999; Mast et al., 1999) and indirectly affected through major fire years with accumulated fine fuels and dry conditions (Brown et al., 2001; Brown and Wu, 2005). High recruitment periods followed low-intensity fires when mineral soils were exposed and seedling competition for resources with understory species was greatly reduced (White and Pickett, 1985; Kaufman et al., 2000; Boyden et al., 2005).

Large, fire-resistant ponderosa pines and Douglas-firs dominated relatively open warm/dry mixed conifer stands in historical forests that also included Engelmann spruce, subalpine fir, quaking aspen, and Gambel oak (Romme et al., 2009). Mixed-severity fires in the warm/dry mixed conifer forests were marked by recurrent, non-lethal fires at 10-20 year intervals, and rare landscape-level lethal fires that occurred at greater than 100 year intervals. The cool/moist mixed conifer forest occured at higher elevations and on northerly aspects, and was characterized by the absence of ponderosa pine with a greater representation of Douglas-fir. Cool/moist mixed conifer forests were also typified by a mixed-severity fire regime with non-lethal fires at 10-20 year intervals, but with regular stand-replacing fires that killed most overstory trees at intervals of greater than 100 years (Romme et al., 2009; Fulé et al., 2009; Korb et al., 2012).

After Euro-American settlement, both the structure and function of forests adapted to frequent fires were altered by practices such as livestock grazing which removed fine fuels

(Brown and Wu, 2005), logging, and the active suppression of fire (Cooper, 1960; Covington and Moore, 1994; Romme et al., 2009). Due to a reduction in fire-frequency, contemporary mixed conifer forests on the Uncompahgre Plateau (Fig. 2.1) and throughout southwestern Colorado have been altered to the point where current forests often have two to four times more basal area and tree density than were common prior to 1870. Current forest structure supports higher severity and more destructive wildfires and, coupled with the preferential harvesting of large trees, there are few examples of old-growth in areas formerly characterized by frequent fires (Brown et al., 2001; Brown and Wu, 2005; Fulé et al., 2009; Korb et al., 2012). These structural changes are accompanied by composition changes, with substantial increases in fire-susceptible species like aspen, Engelmann spruce, and subalpine fir, and corresponding decreases in ponderosa pine (Figs. 2.2 and 2.3).

Even without preferential harvesting of the largest trees, continued fire suppression leads to the eventual destruction of all old-growth. The irruption of small, densely aggregated trees decrease spatial heterogeneity by filling in parks and mini-meadows while increasing fuel loading and vertical structure, making forests more susceptible to high-intensity crown fires (Fulé and Covington, 1995; Binkley et al., 2007). Old-growth trees that do not burn may experience higher mortality rates through increased competition with younger trees, which may increase susceptibility to bark beetles.

Determining the spatial scale and severity of historical disturbances presents a substantial challenge for managers preparing restoration prescriptions for forests adapted to frequent fires. The Uncompahgre Plateau in southwestern Colorado experienced frequent fires before Euro-American settlement (Brown and Shepperd, 2003; Smith and Smith, 2005) followed by very few fires in the 20th Century. Stand-replacing fires are high-severity surface or crown fires that kill most of the canopy trees or shrubs in an area (Baker, 2009), and collaborative forest restoration efforts seek to reduce the risk of severe wildfires by shifting forest structure away from high densities of trees and low densities of meadows. In support of restoration efforts on the Plateau, I assessed two unroaded, never-harvested mesas composed of warm/dry and cool/moist mixed-conifer forests. The primary goals were to determine how forest structure has changed since 1880 by assessing the severity of presettlement landscape-level fires in the 1800s, and to establish a method that provided a spatial scale baseline of historical disturbances to assist in restoration planning.

Initial reconnaissance on the mesas appeared to reveal a pattern where shallow, rocky soils had fewer trees in total, but supported more heritage trees (≥ 80 cm diameter) of ponderosa pine and Douglas-fir. I expected these shallow, rocky soils to have a lower basal area that supported lower fire severity. In contrast, deeper soils with less rock cover were expected to support a more traditional cool/moist mixed conifer structure with more spruce and fir, greater canopy contiguity, higher basal area, and therefore greater risk of stand-replacing fires. Long aspen transects on two additional mesas assessed largest tree establishment patterns to examine the spatial scale of known historical fires on aspen and conifer age caps in mixed conifer. All together, these mesas are representative of about 60,000 ha of the Plateau, between 2600 – 2800 m elevation (Appendix 2).

Methods

Study area

The Uncompahgre Plateau in southwestern Colorado stretches approximately 200 km from northwest to southeast (from the Colorado-Utah border to the San Juan Mountains) and more than 230,000 ha are encompassed in the Uncompahgre National Forest (Fig. 2.1).

Geologic formations of granite, Morrison, and Dakota sandstones and Mancos shale dominate this high, long uplift of sedimentary rocks. Erosion resistant sandstones characterize the topographic pattern of isolated finger mesas surrounding a domed upland; numerous sharp and rugged canyons dissect the Plateau borders (Hughes et al., 1995). Upland areas on the Plateau range from 2400 – 3050 m, and canyon bottoms can extend down to elevations below 1800 m. The mixed conifer forests of the study area occur along a continuum from warm/dry (montane) to cool/moist (subalpine) climatic zones (Romme et al, 2009).

Winter monthly temperatures on upper portions of the Plateau average -3˚ to -6˚ C while summer months average 12˚ to 14˚ C. The upper portions of the Plateau receive about 85 cm of precipitation each year (mostly snowfall) with only 20% falling during the growing season (Columbine Pass SNOTEL site#409, 2900 m elevation, 38˚ 25' N, 108˚ 23' W http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=409&state=co). Lower portions of the Plateau are warmer (winter monthly temperatures averaging -2˚ to -4˚ C and summer months averaging 16˚ to 18˚ C) and receive less precipitation with an average of 55 cm each year, with 25% falling during the growing season (Sanborrn Park RAWS, 2450 m elevation, 38˚ 11' N, 108˚ 13' W, http://www.raws.dri.edu/cgi-bin/rawMAIN.pl?coCSAN).

The Mountain Utes used the Uncompahgre Plateau for hunting and foraging for almost a millennium before they were evicted in 1881. Very intensive livestock grazing began the following year (Hughes et al., 1995; Shinneman and Baker, 2009). Presettlement fires occurred within the ponderosa pine and mixed conifer forests on the plateau at least every 10 - 15 years. Major landscape-level fires occurred in 1842 and 1879, well-known regional fire years on the Western Slope of Colorado. Age data from higher elevation forests suggests many stands regenerated after crown-opening fires in 1879 (Brown and Shepperd, 2003). Evidence of the large fires in 1842 and 1879 was detected in widely separated locations, though fire behavior and impacts probably varied greatly across the Plateau.

Two adjacent, unroaded, never-harvested mesas were studied (Fig. 2.1). Motley (90 ha, 38˚ 27' N, 108˚ 23' W) and Goodtimes Mesas (60 ha, 38˚ 27' N, 108˚ 24' W) were likely not harvested following Euro-American settlement due to their relatively small size combined with steep and difficult access to the mesa tops. Elevation on the mesas ranges from 2730 - 2775 m, and similar forests are found from elevations of about 2600 - 2800 m. The forests are a heterogeneous mixture of warm/dry and cool/moist mixed conifer forest types. Very large (≥ 80 cm diameter) ponderosa pine and Douglas-fir heritage trees occur as individuals across the mesas, though rare clusters of two ponderosa heritage trees occurred on Motley Mesa. The shallow and well drained Olathe family of soils on these mesas was formed from interbedded sandstone and shale. The depth to underlying Dakota sandstone bedrock is generally 10 – 50 cm (Hughes et al., 1995). Small areas of rock outcrops occur across the mesas.

Three sampling approaches

I used a combination of three sampling approaches to assess the severity of 19th century fires and the spatial patterns within stands (Fig. 2.4). First, a random sampling approach provided an unbiased representation of the mesas. The random plot approach was not sufficient to capture the largest and oldest trees, so I used targeted sampling (Baker and Ehle, 2001) to census all heritage trees on the never-harvested mesas. A third survey was used to expand the characterization of the oldest aspen on two nearby mesas, which had been selectively logged for conifers but not for aspen.

For an unbiased random sampling of the mesas, I used a GIS to overlay a 50 m x 50 m grid on each mesa (Goodtimes-58 ha and Motley-87 ha) where each gridline intersection was numbered and designated as a possible plot. Sampling locations were determined by using a random number generator to select 80 plot locations (40 plots on each mesa). I used a 20 BAF ($4.5\ \mathrm{m}^2\ \mathrm{ha}^{-1}$) prism held over the plot center to sample trees and record species, diameter, and live/dead status for all "in" trees as well as other stand composition observations (e.g., visible fire scars, beetle infestation). I cored the three largest diameter trees in each plot to investigate the presence of stand-initiation age caps. If the three largest trees were all of the same species, I also cored the next largest tree of a different species. If a tree with a significantly larger diameter was visible from the plot center but not contained within the plot, it was added to the sampling. The targeted sampling of heritage trees recorded the species and diameter for each tree and I also collected cores to determine their ages. The initial assessment of random plot aspen cores on the never-harvested mesas revealed that all aspen initiated after 1880, so the third approach sampled five long (1-km) aspen transects running through contiguous aspen stands to see if conifer and aspen age caps (or lack thereof) differ. I wanted to see if aspen transects supported the initial impression that all current aspen on the never-harvested mesas initiated after the regional fire year of 1879, and I expanded the sampling to see if the same pattern could be observed on nearby mesas. I used the same prism plot approach to collect cores from 3 - 5 of the largest "in" aspen at 100 m intervals in contiguous aspen stands, or whenever there was a change in the stature, density, or apparent aspen age.

One aspen transect was located on each of the never-harvested mesas, and a third was located on the drainage slope between them. The fourth aspen transect was on the rim of Sawmill Mesa (adjacent to and northwest of Goodtimes Mesa). The fifth aspen transect was approximately 8 km northwest of the primary study area on Love Mesa. Similar to the never-harvested mesas, the aspen transects on Sawmill and Love Mesa were in heterogeneous mixed conifer forests that contained occasional presettlement trees. Selective harvesting of conifers occurred on these mesas but stumps were uncommon along the transects. All tree core samples were collected, mounted, sanded until the cellular structure of the xylem was clearly visible under magnification, and aged according to standard dendrochronological methods (Stokes and Smiley, 1968; Grissino-Mayer, 2003).

Data analysis

After aging all trees collected from the random plots and heritage trees, I created age distributions to display the pattern of largest tree establishment on each mesa. Comparing these age distributions to null forest structure expectations for high-severity, mixed-severity, and low-severity fires revealed the severity of historical fire regimes at the scale of the mesas. This same approach was applied to the aspen transects, enabling a direct comparison between the establishment patterns of conifers and aspens at the same spatial scale.

Widespread evidence indicates the presence of fires near the never-harvested mesas in 1818, as well as the notable regional fire years on the Plateau of 1842 and 1879 (Brown and Shepperd, 2003). I mapped all sampled presettlement trees (a combination of presettlement trees in the random plots and targeted heritage trees) to compare their establishment dates against known historical fire years. I used a GIS to measure the distance from known living trees to other known living trees on the mesas in the major fire years of 1818, 1842, and 1879. I used an expanding radius around each living tree to map the inter-tree distances from known living trees to other known living trees. After mapping the inter-tree distances from trees that established prior to or in the specified historical fire year, I quantified the area of each mesa that was within a particular distance from a known tree using 50m radius increments. Quantifying the area allowed me to develop cumulative frequency distributions that characterized the proportion of each never-harvested mesa that was located at various distances from known surviving trees.

Results

Age structure and fire history

The initiation dates of the large trees in the random plots indicated that presettlement fires burned in a heterogeneous, mixed-severity manner at the scale of these mesas (Fig. 2.5). Goodtimes and Motley Mesa both displayed multi-decadal gaps where no known-surviving trees reached sapling height in the randomly sampled locations. Using the two major, regional fire years of 1842 and 1879 as benchmarks, about 20% of the largest trees in the random plots reached sapling height prior to the 1840s, and about 60% of the largest trees reached sapling height prior to the 1870s. These results display a mosaic of fire-severity and effects at the mesa-scale. Goodtimes Mesa displayed conifer recruitment pulses in the 1840s and the 1870s, which may relate to fires or climate patterns. Motley Mesa displayed evidence of event-driven conifer recruitment pulses in the 1840s and the 1860s (Fig. 2.5). Neither Goodtimes nor Motley Mesa had clear age caps that would indicate large, crown-opening fires at the scale of the mesas.

A total of 45 heritage trees were present on the two mesas, giving an average density of one heritage tree for each 3 ha. All heritage trees on both mesas established before the known fire year of 1879, but five heritage trees on Motley Mesa (three Ponderosa pines, one Douglas-fir, and one Blue spruce) and one on Goodtimes Mesa (Engelmann spruce) established after the known fire year of 1842 (Fig. 2.6). Many of the heritage trees had multiple fire scars and, coupled with the high number of random plot trees predating known major fire years, this further indicates that fire intensity did not reach stand-replacing levels for conifers at the scale of these never-harvested mesas.

In contrast to conifers, stand-replacing severity appeared likely for aspen on two of the four mesas surveyed (Fig. 2.7). In addition to the major fire years of 1842 and 1879, fire-scar evidence indicates widespread fires on the Uncompahgre Plateau in 1863 (Brown and Shepperd, 2003). On the never-harvested mesas, major recruitment pulses in the 1870s and 1880s likely coincided with historical fires in 1863 and 1879, but the high number of aspens that reached breast height in the late 1870s indicates that any fires in 1879 were not stand-replacing for aspen. In contrast, establishment patterns for aspen transects in similar mixed conifer forest on Sawmill and Love Mesas show clear age caps consistent with stand-replacing fire-severity for aspens in 1879. Sawmill and Love Mesas were selectively harvested for conifers, but not for aspen, and individual aspen stems more than 250 years old have been observed on the Uncompahgre Plateau (Smith and Smith, 2005). The potential longevity of aspen on the Plateau coupled with largest tree data from aspen transects on all four sampled mesas indicated establishment patterns that are likely coupled to fire events.

Discussion

Mixed conifer studies in other areas reveal similar mean fire return intervals and mixed-severity fire regimes to historical patterns on the Uncompahgre Plateau. Mixed conifer forests in southwestern Colorado had an increase of two to four times the basal area and tree density in contemporary forests when compared to the historical structure in 1870. Similar changes occurred in mixed conifer forests of the Grand Canyon, where basal area more than doubled and tree density was almost four times as high when compared to presettlement patterns (Fulé et al., 2009). The dramatically altered structure and composition of contemporary mixed conifer forests belies the heterogeneous pattern of historical fire-mortality and recruitment that characterizes an overarching landscape mosaic in frequent-fire forests (White and Pickett, 1985; Turner and Romme, 1994).

Fire severity and tree establishment patterns

If a stand-replacing fire occurred at the scale of the never-harvested mesas, the patterns of largest tree establishment across the study areas would reveal a pulse of post-fire recruitment with very few trees surviving that pre-date the fire. High-severity, stand-replacing patches (< 4 ha) are relatively common in mixed conifer fires from California, through the Central and Southern Rockies, and into the Southwest while large stand-replacing patches (> 60 ha) are less common (Collins and Stephens, 2010; Evans et al., 2011). At the small mesa-scale (50 – 100 ha), large fires could yield a mixed-severity structure where there is an age cap for aspen (not fire-resistant), but there is no age cap for fire-resistant conifers. This type of pattern was evident in individual permanent plots (0.1 ha) in mixed conifer on the North Rim of the Grand Canyon, where the age and species composition of plots was used to determine if trees in the plot established after stand-replacing fire (fire-initiated) or if individual trees or cohorts established under an overstory of fire-resistant trees (non-fire-initiated) (Fulé et al., 2003). In contrast, aspen groups in mixed conifer in a low-severity regime might have reduced or extinguished fires (Dietrich, 1983), resulting in a surface-fire structure where there is no age cap for either conifers or aspens.

The age distributions based on establishment date from the random plots (Fig. 2.5) and the heritage trees (Fig. 2.6) clearly show that presettlement fires in the 19th century were not stand-replacing at the scale of an entire mesa, because there are numerous trees pre-dating the known large fires. The oldest tree establishment dates do indicate that historical fires were stand-replacing at the smaller scale of some of the plots (variable sized plots due to prism sampling method). Evidence on the Uncompahgre Plateau indicates a presettlement history of widespread, recurring fires around the never-harvested mesas, so I selected 1818 (another known fire year) to display tree retention patterns over time.

A map of actual tree retention (Fig. 2.8) over time moves managers away from the quandary of trying to determine a specific scale of historical disturbances when developing restoration prescriptions. Instead, a tree retention map enables rapid analysis of patterns and could allow managers to quantify restoration planning factors (e.g., size of openings, spacing between tree clusters) via straightforward cumulative frequency distributions (Fig. 2.9). In preparation for the return of fire as a natural and integral forest process to restore a landscape mosaic, this capability allows managers to use historical guidelines developed from local reference conditions vs. struggling with arbitrary decisions regarding the size of high-severity patches.

The tree retention map and the cumulative frequency distributions indicate the distance from living trees today that were already established prior to the reference fire years. In 1818, about 64% of Goodtimes and 30% of Motley Mesa was within 100 m of a known-living tree. In 1879, about 89% of Goodtimes and 70% of Motley Mesa was within 100 m of a known-living tree. There could have been surviving trees that were killed in later fires or other mortality, but these comparisons reveal current conditions are substantially different from the more open presettlement forest structure.

Most of the heritage trees predate 1842, and their survival (Fig. 2.6) may have been fostered by shallow or rocky soil microsites that led to low accumulations of biomass and fuel

(Brown et al., 1999; Huckaby et al., 2003; Kaufmann et al., 2003). The Motley Mesa aspen transect revealed the presence of a few aspen trees that initiated in the 1850s and 1860s in the vicinity of ponderosa heritage trees. The survival of these small diameter, presettlement aspen adjacent to heritage trees seems to indicate that the protective properties of shallow/rocky soil microsites can extend to aspen as well as large, fire-adapted ponderosa pine and Douglas-fir trees.

While the age distributions reveal that 19th century fires were not stand-replacing at the scale of the never-harvested mesas, only about 20% of the random plot trees pre-dated 1842, and the distribution drops off rather sharply before 1840 rather than gradually tapering off into the early 1800s. The age structure of old trees from the random plots suggests that the large fires of the mid and late 1800s were not stand-replacing at the scale of the mesas but were still moderately severe and either killed a lot of the conifers or there was not substantial conifer recruitment during that period.

The spatial analysis of surviving trees may provide clearer insights than common categories of stand-replacing or mixed-severity fire. The pattern of surviving trees provides a minimum representation of all trees that would have survived a given fire. Forest composition and structure has changed dramatically since active fire-suppression began in the 1880s, and the changes are consistent with other fire-excluded mixed conifer forests where landscapes are now dominated by dense stands of young trees, heavy, contiguous canopies, and an accumulation of surface fuels (Fulé and Covington, 1997). The contemporary management implication of this pattern is that, without treatments like restoration thinning in preparation for the return of fire to the forest, we should expect considerable conifer mortality in future large fires and a potential transition to novel systems under a warmer, drier climate (Korb et al., 2012).

Fire severity and spatial scale

Across the Plateau, the composition of mixed stands of aspen and conifers are changing, with conifer overstory basal area increasing and aspen overstory basal area decreasing. Overstory replacement of aspen by conifers due to the absence of fire in these mixed stands is obvious in some locations, with a distinct older class of aspens and few aspen suckers growing into the overstory (Smith and Smith, 2005). Comparing conifer establishment patterns to aspen establishment patterns over the same area could yield insights for restoration prescriptions.

In the same spatial area, can a fire be stand-replacing for one tree species and not stand-replacing for another? The fire of 1879 was not stand-replacing for conifers since random plot conifer initiation dates reveal that about 60% of the largest trees were established prior to the fire (Fig. 2.5). Aspen initiation dates for the three transects on Motley and Goodtimes Mesas revealed that the 1879 fire was also not stand-replacing for aspen, since more than 20% of sampled aspens were established prior to the fire (Fig. 2.7). The never-harvested mesa aspen recruitment pulses in the 1870s and 1880s coincided with the known fire years of 1863 and 1879. Less than 5% of aspen dated to the 1860s and the only aspen that dated to the 1850s were small diameter stems co-located with heritage trees on rocky soil sites. The 1863 fire was clearly not stand-replacing for conifers on the never-harvested mesas, but it’s possible the 1863 fire was stand-replacing for aspen.

The aspen transects on Sawmill and Love Mesas occurred in areas that were selectively harvested for conifers (not for aspen), but still contained many presettlement ponderosa pines characterized by smooth, platy yellow or orange bark, flattened crowns, and some with fire scars. In contrast to the never-harvested mesas, aspen initiation dates indicate the fire of 1879 was stand-replacing for aspen since no aspen pre-dated the fire on Sawmill Mesa and less than 4% of the aspen on Love Mesa established prior to 1879 (Fig. 2.7). This evidence indicates that fires can be of sufficient severity to be a stand-replacing for aspens but not for conifers in the same stand. This type of pattern is common across the Uncompahgre Plateau, where overstory conifers can be hundreds of years older than overstory aspen in the same mixed species stand (Smith and Smith, 2005).

Based on an understanding of historical reference conditions and a range of historical variability, we have an opportunity to restore our forests and return to a structure and composition that supports vegetation and wildlife diversity while increasing resilience to low- and moderate-intensity fire. Examination of the study areas revealed that fires of the 1800s were not stand-replacing for conifers at the scale of 50 – 100 ha, but in some cases they were severe enough to kill most aspen. Current forest structure and fuel loads would support stand-replacing fires for both aspen and conifers. Forest restoration goals that aimed to shift likely fire behavior from stand-replacing to mixed-severity may match historical conditions, and tree retention maps based on local conditions and known historical fires can help inform restoration treatments. Conversion of forest structure to low-fuel levels that would largely foster surface fires would not be consistent with evidence from the 1800s for mixed conifer forests on the Uncompahgre Plateau.

Table 2.1. Mixed conifer forest species composition on the Uncompahgre Plateau, Colorado. Unlike other mixed conifer forests in southwestern Colorado, white fir (*Abies concolor*) was not observed in the study area on the Uncompahgre Plateau.

Species	Common Name
Abies lasiocarpa	Subalpine fir
Picea engelmannii	Engelmann spruce
Picea pungens	Blue spruce
Pinus ponderosa	Ponderosa pine
Populus tremuloides	Quaking aspen
Pseudotsuga menziesii	Douglas-fir
Quercus gambelli	Gambel oak

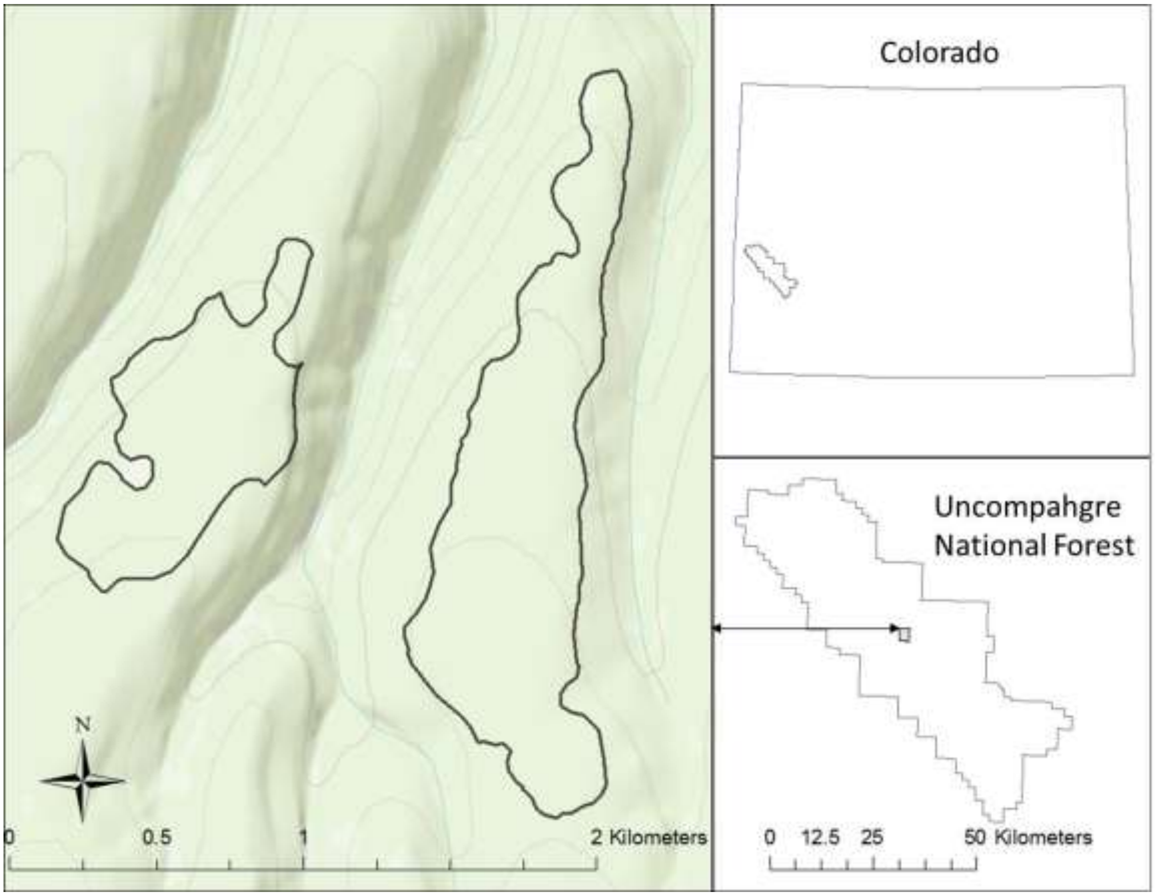


Figure 2.1. Unroaded, never-harvested study sites in the Uncompahgre National Forest, Colorado. Goodtimes Mesa (left, 60 ha) and Motley Mesa (right, 90 ha). Contours are at 25 m intervals.

Figure 2.2. Characteristic heritage tree locations. Clockwise from left.
(1) Ponderosa pine (107.7 cm dbh, breast height in 1564) with two visible ground level fire scars surrounded by other pines, spruce, fir, and aspen. From the vantage point of the photographer, exposed rocks are visible in the upper soil layer for approximately 20 m.
(2) Ponderosa pine (84.6 cm dbh, breast height in 1687) with aspen and Gambel oak. Exposed rocks adjacent to the heritage tree are visible in the upper soil layer throughout the surrounding understory.
(3) Douglas-fir (111.3 cm dbh, breast height in 1723) located amidst aspen, Engelmann spruce, and Douglas-fir just below the eastern rim of Motley Mesa.

Figure 2.3. Two characteristic mixed conifer stands in the study area. Both stands have similar cool/moist mixed conifer species composition (i.e., Engelmann spruce, blue spruce, subalpine fir, Douglas-fir, and aspen) but the stand on the left has high basal area and high canopy bulk density while the stand on the right has lower basal area and a more open canopy.

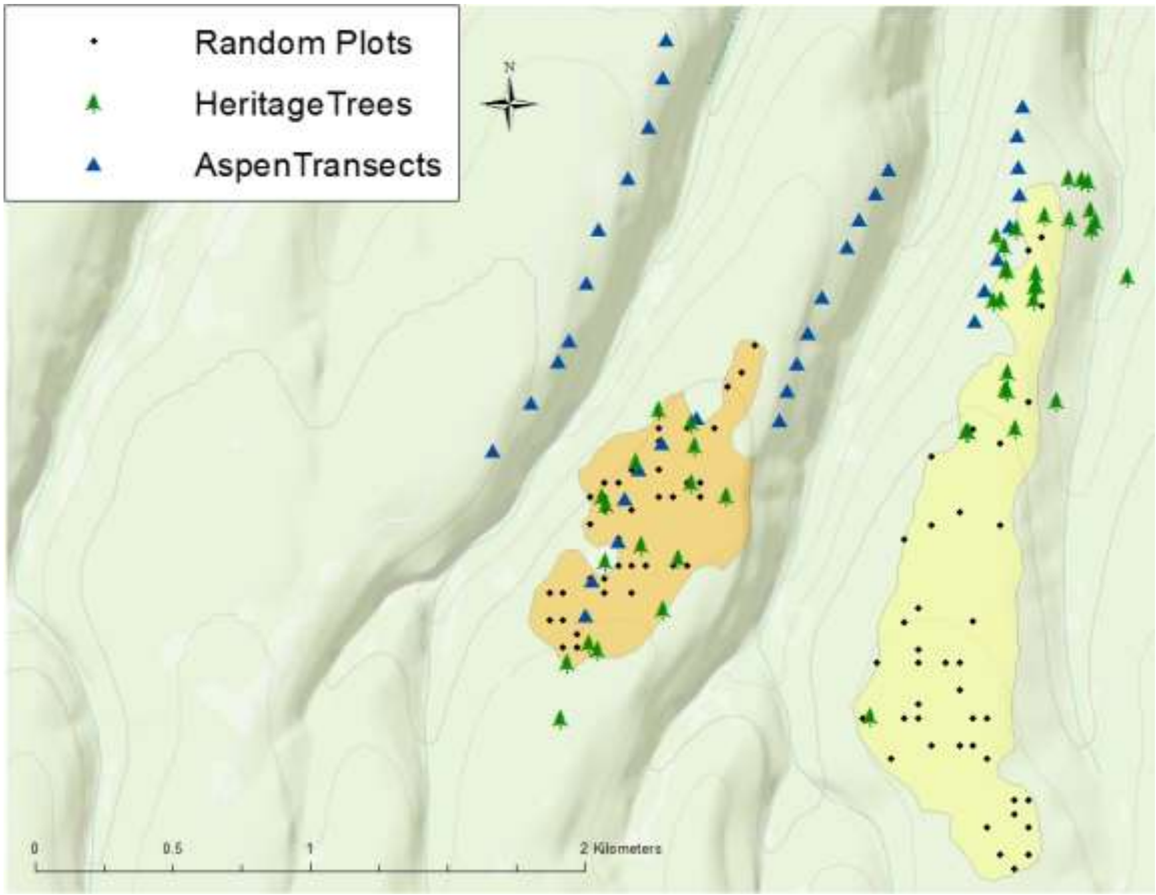


Figure 2.4. Tree establishment sampling locations for Goodtimes Mesa (left) and Motley Mesa (right). Three sampling methods were used to examine stand structure including: (1) 80 random plots, (2) targeted heritage tree sampling, and (3) five aspen transects (fifth aspen transect is northwest approximately 8 km on Love Mesa). Contours are at 25 m intervals.

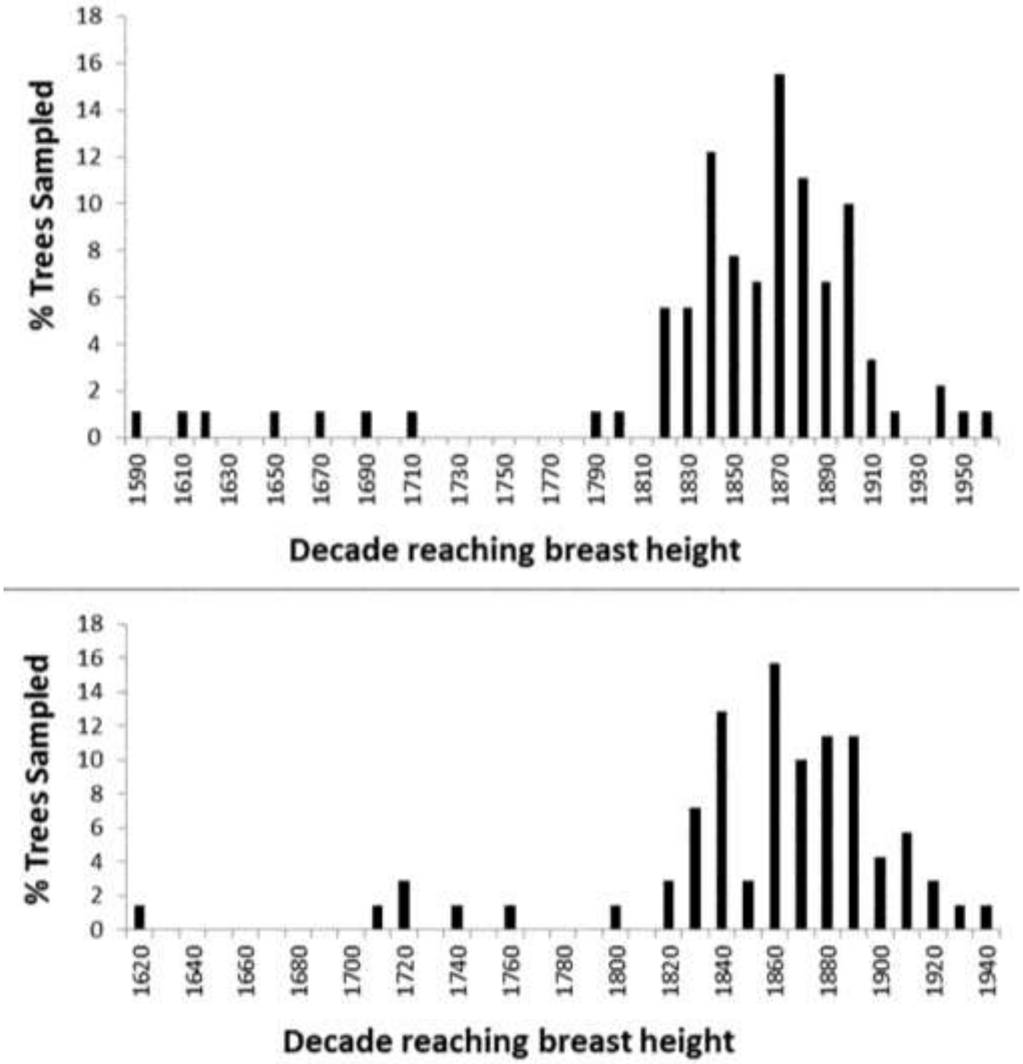


Figure 2.5. Patterns of largest tree establishment on Goodtimes (top) and Motley (bottom) Mesa reveal that presettlement fires were not stand-replacing at the scale of the mesas because many trees today pre-date the known major fire years of 1842 and 1879.

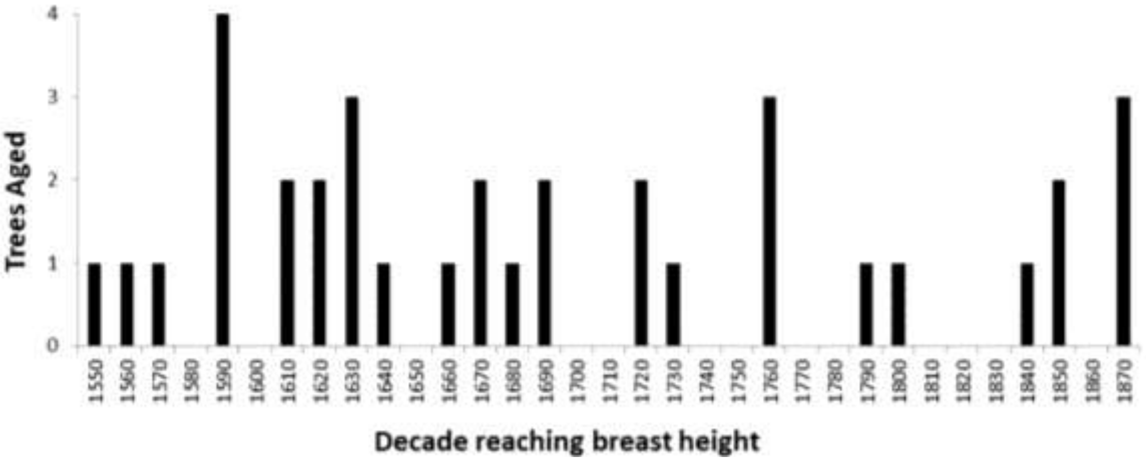


Figure 2.6. The 45 heritage trees (≥ 80 cm dbh) on the never-harvested mesas all predate the known regional fire year of 1879. The decade of establishment was impossible to determine from cores for ten trees due to substantial core rot. Heritage tree survival may have been fostered by shallow or rocky soil microsites that led to low accumulations of biomass and fuel, limiting fire-induced mortality.

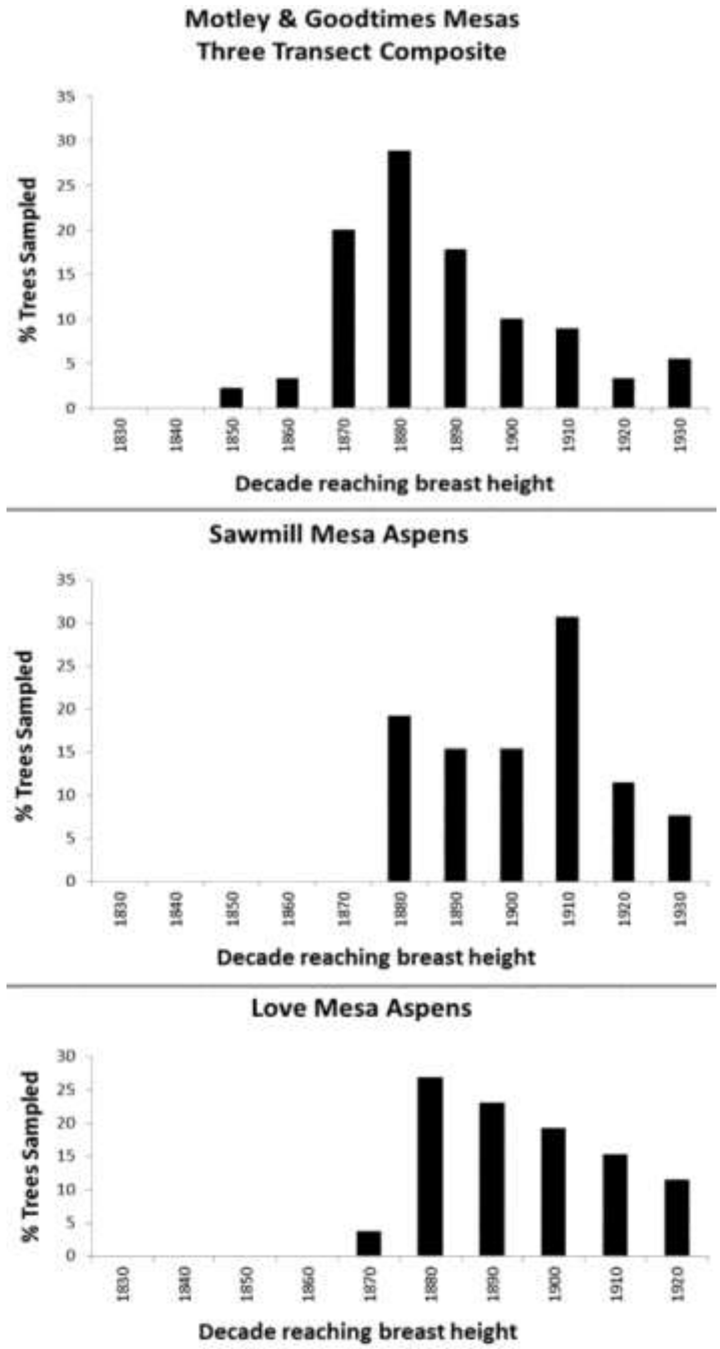


Figure 2.7. Aspen initiation dates for the three aspen transects on Motley and Goodtimes Mesas (top) reveal the regional fire year of 1879 was not stand-replacing for aspens at the level of these mesas, but the 1879 fire likely caused the recruitment spike in the 1880s. The aspen transects on Sawmill Mesa and Love Mesa occurred in similar mixed conifer forest with many presettlement ponderosas, and indicate the fires of 1879 were stand-replacing for aspen but not for conifers.

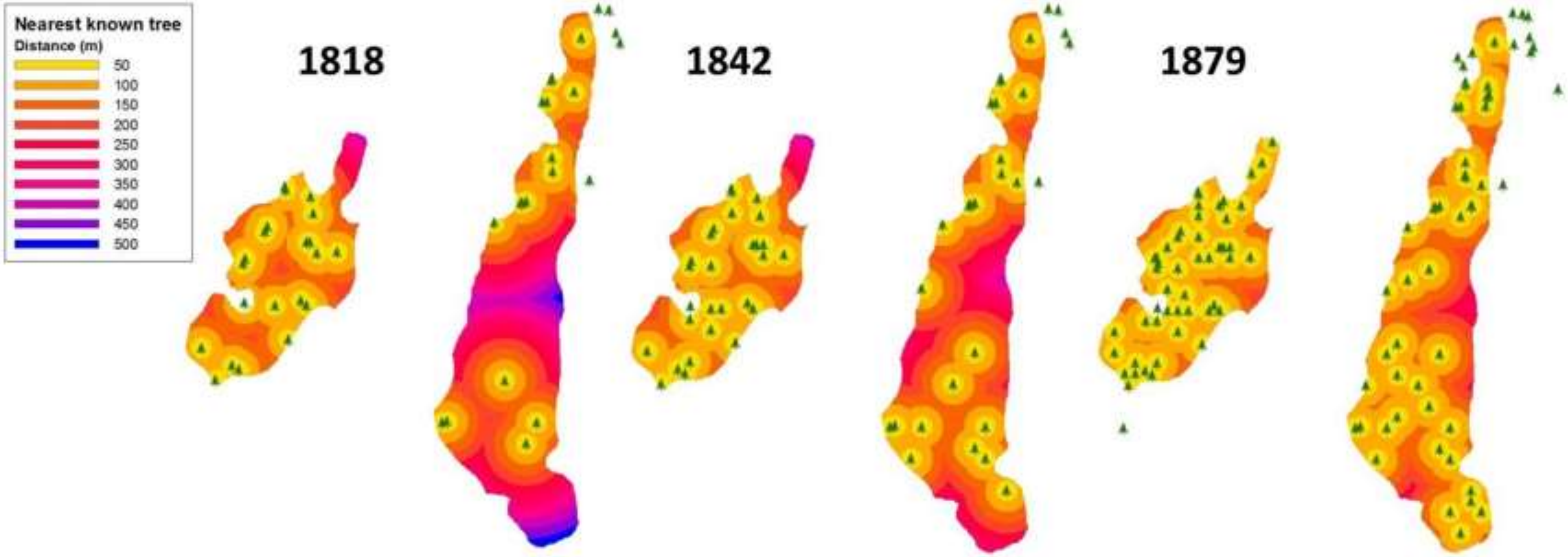
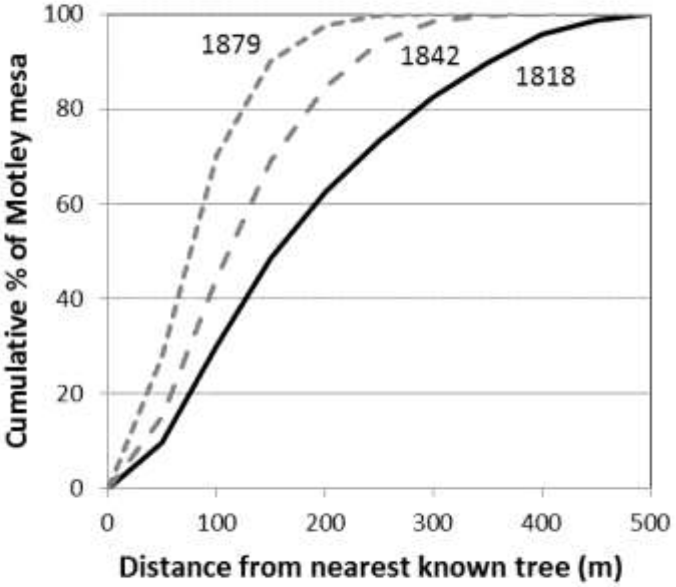


Figure 2.8. Tree retention patterns over time are revealed by combining the largest tree establishment patterns from the random plots with targeted heritage tree sampling. Historical patterns of establishment during known fire years eliminate the need to define categories of stand-replacing or mixed-severity fire regimes at the mesa scale, and instead simply show restoration planners the real scale of tree retention.



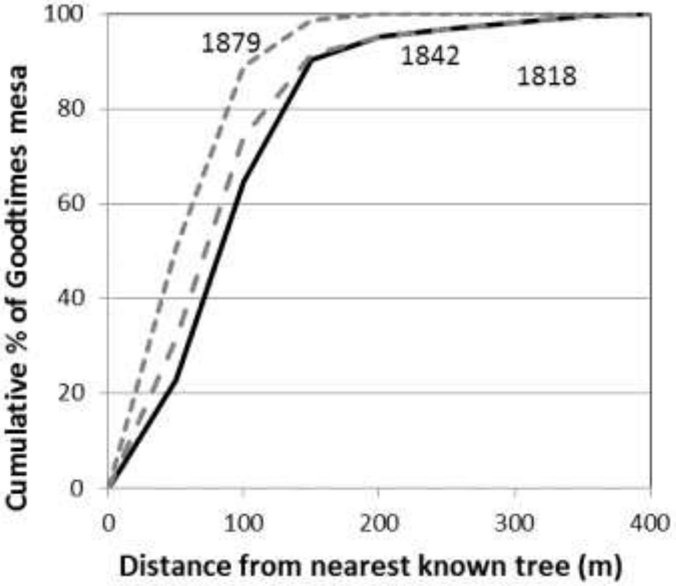


Figure 2.9. The cumulative frequency distributions derived from tree retention patterns on Motley Mesa (top) and Goodtimes Mesa (bottom) provide a useful tool to assist restoration planning by providing a spatial benchmark for forest openings during known fire years.

LITERATURE CITED

Allen, C.D., Savage, M., Falk, D.A., Suckling, K. F., Swetnam, T.W., Schulke, T., Stacey, P.B., Morgan, P., Hoffman, M., Klingel, J.T., 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecological Applications 12, 1418-1433.

Baker, W.L., Ehle, D., 2001. Uncertainty in surface-fire history: the case of ponderosa pine forests in the western United States. Canadian Journal of Forest Research 20, 1205-1226.

Baker, W.L., 2009. Fire ecology in Rocky Mountain landscapes. Island Press, Washington DC, USA.

Binkley, D., Sisk, T., Chambers, C., Springer, J., Block, W., 2007. The Role of old-growth forests in frequent-fire landscapes. Ecology and Society 12.

Boyden, S., Binkley, D., Shepperd, W., 2005. Spatial and temporal patterns in structure, regeneration, and mortality of an old-growth ponderosa pine forest in the Colorado Front Range. Forest Ecology and Management 219, 43-55.

Brown, P.M., Kaufmann, M.R., Shepperd, W.D., 1999. Long-term, landscape patterns of past fire events in a montane ponderosa pine forest of central Colorado. Landscape Ecology 14, 513-532.

Brown, P.M., Kaye, M.W., Huckaby, L.S., Baisan, C.H., 2001. Fire history along environmental gradients in the Sacramento Mountains, New Mexico: influences of local and regional processes. Ecoscience 8, 115-116.

Brown, P. M., Shepperd, W. D., 2003. Preliminary fire history in ponderosa pine forests of the Uncompahgre Plateau. Rocky Mountain Research Station, Fort Collins, CO.

Brown, P.M., Wu, R., 2005. Climatic and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. Ecology 86, 3030-3038.

Churchill, D.J., Larson, A.J., Dahlgreen, M.C. , Franklin, J.F., Hessburg, P.F., Lutz, J.A., 2013. Restoring forest resilience: From reference spatial patterns to silvicultural prescriptions and monitoring. Forest Ecology and Management 291, 442-457.

Collins, B.M., Stephens, S.L., 2010. Stand-replacing patches within a 'mixed severity'fire regime: quantitative characterization using recent fires in a long-established natural fire area. Landscape Ecology 25, 927-939.

Cooper, C.F., 1960. Changes in vegetation, structure, and growth of southwestern pine forest since white settlement. Ecological Monographs 30, 129-164.

Covington, W.W., Moore, M.M., 1994. Southwestern ponderosa forest structure – changes since Euro-American settlement. Journal of Forestry 92, 39-47.

Dieterich, J.H., 1983. Fire history of southwestern mixed conifer: a case study. Forest Ecology and Management 6, 13-31.

Evans, A.M., Everett, R.G., Stephens, S.L., Youtz, J.A., 2011. Comprehensive fuels treatment practices guide for mixed conifer forests: California, central and southern Rockies, and the Southwest. Joint Fire Science Program fuel treatment guide, The Forest Guild, Santa Fe, NM.

Fulé, P.Z., Covington, W.W., 1995. Changes in fire regimes and forest structures of unharvested Petran and Madrean pine forests.

Fulé, P.Z., Covington, W.W., Moore, M.M., 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. Ecological Applications 7, 895-908.

Fulé, P.Z., Crouse, J.E., Heinlein, T.A., Moore, M.M., Covington, W.W., Verkamp, G., 2003. Mixed-severity fire regime in a high-elevation forest of Grand Canyon, Arizona, USA. Landscape Ecology 18, 465-486.

Fulé, P.Z. 2008. Does it make sense to restore wildland fire in changing climate? Restoration Ecology 16(4):526-531.

Fulé, P.Z., Korb, J.E., Wu, R., 2009. Changes in forest structure of a mixed conifer forest, southwestern Colorado, USA. Forest Ecology and Management 258, 1200-1210.

Grissino-Mayer, H.D., 2003. A manual and tutorial for the proper use of an increment borer. Tree-Ring Research 59, 63-79.

Huckaby, L.S., Kaufmann, M.R., Fornwalt, P.J., Stoker, J.A., Dennis, C., 2003. Identification and ecology of old ponderosa pine trees in the Colorado Front Range. US Department of Agriculture, Forest Service, Rocky Mountain Research Station. USDA Forest Service General Technical Report RMRS-GTR-110.

Hughes, T., Kingston, R., Cencich, B., 1995. Soil survey of Uncompahgre National Forest Area, Colorado, parts of Mesa, Montrose, Ouray, and San Miguel counties. USDA Forest Service and Soil Conservation Service, in corporation with the Colorado Agricultural Experiment Station. Fort Collins, CO.

Kaufmann, M.R., Regan, C.M., Brown, P.M., 2000. Heterogeneity in ponderosa pine/Douglas-fir forests: age and size structure in unlogged and logged landscapes of central Colorado. Canadian Journal of Forest Research 30, 698-711.

Kaufmann, M.R., Huckaby, L.S., Fornwalt, P.J., Stoker, J.M., Romme, W.H., 2003. Using tree recruitment patterns and fire history to guide restoration of an unlogged ponderosa pine/Douglas-fir landscape in the southern Rocky Mountains after a century of fire suppression. Forestry 76, 231-241.

Korb, J.E., Fulé, P.Z., Stoddard, M.T., 2012. Forest restoration in a surface fire-dependent ecosystem: An example from a mixed conifer forest, southwestern Colorado, USA. Forest Ecology and Management 269, 10-18.

Mast, J.N., Fulé, P.Z., Moore, M.M., Covington, W.W., Waltz, A.E.M., 1999. Restoration of presettlement age structure of an Arizona ponderosa pine forest. Ecological Applications 9, 228-239.

Romme, W.H., Floyd, M.L., Hanna, D., 2009. Historical Range of Variability and Current Landscape Condition Analysis: South Central Highlands Section, Southwestern Colorado & Northwestern New Mexico. Colorado Forest Restoration Institute, Fort Collins, CO, USA.

Shinneman, D.J., Baker, W.L., 2009. Historical fire and multidecadal drought as context for pinon-juniper woodland restoration in western Colorado. Ecological applications 19, 1231-1245.

Smith, A. E., Smith, F. W., 2005. Twenty-year change in aspen dominance in pure aspen and mixed aspen/conifer stands on the Uncompahgre Plateau, Colorado, USA. Forest Ecology and Management 213, 338-348.

Stokes, M.A., Smiley, T.L., 1968. An Introduction to Tree-ring Dating. University of Chicago Press, Chicago, IL.

Stone, J.E., Kolb, T.E., Covington, W.W., 1999. Effects of restoration thinning on presettlement Pinus ponderosa in northern Arizona. Restoration Ecology 7, 172-182.

Turner, M.G., Romme, W.H., 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecology 9, 59-77.

White, P.S., Pickett, S.T.A., 1985. Natural disturbance and patch dynamics: an introduction. In: White, P.S., Pickett, S.T.A. (Eds.), The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, Orlando, FL.

CHAPTER 3

A COMPARISON OF TWO TECHNIQUES TO IDENTIFY THE OLDEST TREES IN MIXED CONIFER FORESTS

Summary

In western North American forests adapted to frequent fire, restoration prescriptions can be guided by reference conditions before Euro-American settlement. Determining historical forest structure in detail can require very intensive work, but some basic questions might be answered with relatively simple approaches. For example, historical fire intensity may be gauged by the presence of an age cap. If many trees date from a particular decade, and few if any predate that decade, then a very intense stand-replacing fire may be inferred. An age cap could be examined by aging all trees in a stand, only all trees that appear to be very old, or a subsample of all trees that may be sufficient to identify an age cap. In a large plot, a census of all trees provides high confidence in the age structure of a single location but would be very challenging to use at a landscape scale. In contrast, targeted sampling along transects or systematic grid locations across landscapes may provide age cap estimates for a much larger population but with lower confidence. On the North Rim of the Grand Canyon, Arizona, all large trees were censused in systematic grid of 0.1 ha sampling plots on the Little Park site in never-harvested mixed conifer forest to determine if severe fires could be identified by detecting fire-initiated tree groups based on tree age and species composition. I tested a time-saving method that targeted the largest trees in each plot and found that aging the three largest trees in each 0.1 ha plot identified the oldest trees in 73% of the 30 plots. In each case where aging the three largest trees failed to identify the oldest trees in the plot, the confounding trees were

smaller diameter, older aspen. A revised targeted sampling approach that aged the three largest diameter conifers and the three largest diameter aspen (when present) identified the oldest trees in almost all (97%) of plots with less than half the effort of a full census. The targeted sampling approach for identifying the oldest trees in a location is an efficient and accurate option to provide reliable age cap information to inform landscape-scale restoration programs.

Introduction

Effective forest restoration is built on a clear understanding of current and historical forest reference conditions and how natural disturbances maintained the structure and composition that promoted vegetation and wildlife habitat diversity (Covington and Moore, 1994; Fulé et al., 1997; Allen et al., 2002; Churchill et al., 2013). Reference conditions do not refer only to forest conditions in a particular place and time, but encompass processes (such as fire) that provided the selective force driving evolutionary adaptations over thousands of years (Fulé 2008). In western North American forests adapted to frequent fires, current forest structures are not compatible with the types of fire regimes that characterized historical forest structures. Any warming or drying with future climates would accentuate this difference, and the structure of contemporary forests that has created the potential for a higher incidence of wildland fires makes the use of the historical range of variability (HRV) or presettlement historical reference conditions a suitable target for restoration goals (Korb et al., 2012). In spite of active fire suppression efforts, fire will return to forests adapted to frequent fires, and management focus should be on how to prepare for the return of fire. Reference conditions provide the best target to build consensus on restoration goals while mitigating the risk of catastrophic loss of these forest systems.

Assessing reference conditions requires an understanding of fire as an inherently complex landscape process (Turner and Romme, 1994), and reference conditions are specific to particular forest types and locales. Mixed conifer forests are characterized by a mixed-severity fire regime where the size and distribution of stand-replacing patches and other patches that burned with different severities create a heterogeneous mosaic of forest structure and composition (Collins and Stephens, 2010). Prior to Euro-American settlement, forest composition and structure were directly affected by climatic conditions through recruitment pulses where high seed production years were followed by warm, wet weather that favored seedling establishment (Cooper 1960; Covington and Moore, 1994; Stone et al., 1999; Mast et al., 1999) and indirectly affected through major fire years with accumulated fine fuels and dry conditions (Brown et al., 2001; Brown and Wu, 2005). High recruitment periods followed low-intensity fires when mineral soils are exposed and seedling competition for resources with understory species is greatly reduced (White and Pickett, 1985; Kaufman et al., 2000; Boyden et al., 2005).

Throughout the southwestern United States, large, fire-resistant ponderosa pines and Douglas-firs dominated relatively open warm/dry mixed conifer stands in historical forests that also included Engelmann spruce, subalpine fir, white fir, quaking aspen, and Gambel oak (Romme et al., 2009). Mixed-severity fires in the warm/dry mixed conifer forests were marked by recurrent, non-lethal fires at 10-20 year intervals, and rare landscape-level lethal fires that occurred at greater than 100 year intervals. The cool/moist mixed conifer forests occurred at higher elevations and on northerly aspects and were characterized by the absence of ponderosa pine with a greater representation of Douglas-fir. Cool/moist mixed conifer forests were also typified by a mixed-severity fire regime with non-lethal fires at 10-20 year intervals but with regular stand-replacing fires that killed most overstory trees at intervals of greater than 100 years (Romme et al., 2009; Fulé et al., 2009; Korb et al., 2012).

After Euro-American settlement, both the structure and function of forests adapted to frequent fires were altered by practices such as livestock grazing which removed fine fuels (Brown and Wu, 2005), logging, and the active suppression of fire (Cooper, 1960; Covington and Moore, 1994; Romme et al., 2009). On the North Rim of the Grand Canyon, the mixed conifer forests on the Kaibab Plateau exhibit symptoms of fire exclusion with increases of two to five times the basal area and tree density in current forests than in presettlement forests (Fulé et al., 2002). Current forest structure and composition (Table 3.1) supports higher severity and more destructive wildfires and these structural changes are accompanied by composition changes, with substantial increases in fire-susceptible species like aspen, Engelmann spruce, white fir and subalpine fir, and corresponding decreases in ponderosa pine (Brown et al., 2001; Brown and Wu, 2005; Fulé et al., 2009; Korb et al., 2012).

Reference conditions inform discussions on restoration goals that include mitigating the risk of catastrophic loss of fire-adapted forest systems. Historical forest structures varied across time and space, so any single reference period (e.g., 1880 as pre Euro-American settlement date) captures only a snapshot in time of a dynamic landscape (Binkley et al., 2008), and any single plot captures only one location (Keane et al., 2009). Regional climate and land use changes can synchronize fire timing across large areas, but restoration prescriptions require local information about variations over time and space (Brown et al., 2001). Collecting this type of local data to inform restoration prescriptions in forests with a legacy of frequent fires can be challenging, because evidence of past events is often destroyed by subsequent disturbances.

The presence of an age cap (with few if any older trees present) has been used to indicate a severe, stand-replacing fire. Using this method, all cohorts in a sampled location are considered, but the oldest trees are given the greatest weight because their survival through known fire years in the area provides spatial context for the extent of high-severity fires. If fire-resistant species like ponderosa pine and Douglas-fir are the oldest trees in a plot with an uneven age structure, it can indicate that fire at that location was not severe enough to be stand-replacing. In concert with tree initiation dates, species composition can also be used to determine whether a stand originated after a stand-replacing fire. In contrast to locations where the oldest trees are fire resistant species, when the oldest trees in a plot are all fire-susceptible species like Engelmann spruce, aspen, or subalpine fir, there is often an even age structure and age cap that indicates a past fire was severe enough to be stand-replacing (Fulé et al., 2003).

I compared two landscape sampling approaches to characterize the presence or absence of age caps and fire regimes. In plots where a complete census of all trees was conducted, I assessed how effective targeted sampling (Baker and Ehle, 2001) of the largest trees was in identifying the oldest trees in each plot. The census plots were from the Kaibab Plateau (North Rim of the Grand Canyon, Arizona) where Fulé et al. (2003) sampled 0.1 ha (20 x 50 m) plots on a 600 x 1200 m systematic grid in the never-harvested, mixed conifer Little Park site. Their research sought to determine if severe fires could be identified by detecting fire-initiated tree groups based on tree age and species composition and the impact of elevation, aspect, and forest type on fire occurrence and frequency. The plots on the Kaibab Plateau were part of a comprehensive effort to evaluate historical fire regime characteristics and compare current forest conditions to historical data. The comprehensive approach coupled plot data with other methods that included: aerial photographs, vegetation maps, information from adjacent stands, multiple transect sampling methods, and targeted sampling of fire-scarred trees (Fulé et al., 2003). I expected the random plot/largest trees approach would provide a less resource intensive method to capture plot age caps with high confidence, thus validating its use at larger spatial scales with unbiased random sampling locations.

Methods

Study area

Grand Canyon National Park in northern Arizona (63˚ 03' N, 112˚ 07' W) was designated as an official national park in 1919 (Fig. 3.1). The primary public areas of the nearly 493,000 ha park are the North and South Rims of the Grand Canyon. The never-harvested forests of the Kaibab Plateau on the smaller, more remote North Rim are an ideal location to assess historical fire regime transitions from frequent, low-intensity surface fires to stand-replacing fires. The Grand Canyon is extremely geologically diverse and upland soils at the Little Park site were Cumulic Haplustolls, slopes were Oxyaquic Paleustalfs, and valley soils were Cumulic Haplustolls (Fulé et al., 2003).

Average annual precipitation at the North Rim ranger station (2542 m) is 58 cm, with annual snowfall of about 328 cm. Temperatures range from summer maximums of 26˚ C in July to winter minimum temperatures of 2˚ C in January. Forests at the Little Park site (4400 ha) were comprised of cool/moist mixed conifer trending to spruce-fir forests on the highest elevations of the Kaibab Plateau (Fig. 3.2). The majority of the Little Park sites occurred between about 2300 – 2500 m, following an increasing elevation gradient to compare elevational changes in fire regimes. Evidence from 132 fire-scarred trees at the Little Park site revealed a history of very high fire frequency prior to 1879, with an all-scars mean fire interval (MFI) of only 2.6 years. This pattern of frequent historical fires indicates many small-scale fires, but the

25% filtered frequency increased to a more typical mixed conifer MFI of 31 years (Fulé et al., 2003).

Sampling methods and data collection

Fulé et al. (2003) located 60 sampling plot centers on a 600 m (E-W) by 1200 m (N-S) grid and modified the National Park Service's Fire Monitoring plots to collect detailed tree condition and dendrochronological data. To permit future remeasurements, the 0.1 ha plots (20 x 50 m) were permanently marked with iron corner and center stakes and a large tree was tagged with distance and bearing to plot center. All trees in each plot were tagged and extensive tree attributes were recorded. Previous research in northern Arizona determined that ponderosa pines with a diameter (measured at breast height) greater than 37.5 cm or of any size with yellowed bark could be considered presettlement. All other conifer species with a diameter greater than 37.5 cm and all aspen with a diameter greater than 20 cm were also considered possible presettlement trees. All trees meeting possible presettlement criteria were cored as well as an additional 10% of trees within the plot that did not meet presettlement field criteria. I used 30 plots that had complete diameter and age data for all trees and "sampled" the three largest diameter trees in each plot to investigate the presence of stand-initiation age caps.

Data analysis

I compared the two sampling methods for identifying the oldest trees in a plot by targeted sampling of the largest trees in each plot from the Little Park data. All tree cores from the Little Park site were prepared and crossdated using standard dendrochronological techniques (Stokes and Smiley, 1968). After initial crossdating, ages were independently confirmed by another dendrochronologist, so there was complete confidence that the ages of the oldest trees in each Little Park plot were correctly identified. Correctly identifying the oldest trees in the Little Park plots via targeted sampling of the three largest trees would validate an efficient and accurate option to reliably identify the presence or absence of a stand initiation age cap to inform landscape-scale restoration programs in similar mixed conifer forests.

There was substantial species composition heterogeneity within the Little Park mixed conifer 0.1 ha plots, and Fulé et al. (2003) characterized the plot locations by dominant species composition (i.e., mixed conifer, ponderosa pine, spruce-fir, aspen). Focusing only on the ability to characterize sampling location age caps, I compared the amount of time required to characterize age caps via targeting the largest diameter trees versus the fixed plot method by re-categorizing the sampled plots into two composition groups: conifers and aspen. The average number of trees sampled in the census of conifer and aspen plots at the Little Park site was compared to the number of targeted sampling trees for an assessment of time/cost required to identify the oldest trees in mixed conifer plots.

Results

Targeted sampling of the three largest diameter trees in each Little Park plot identified the oldest tree establishment dates in 22 of 30 plots, or 73% of the time. In seven of the eight plots where aging the three largest trees did not correctly identify the oldest trees, smaller diameter, older aspen were the confounding factor. A modified targeted sampling approach that selected the three largest diameter conifers and the three largest diameter aspen (when present) in each plot identified the oldest trees in 29 of 30 plots, or 97% of the time. Targeted sampling of the largest diameter trees in the census plots provided a reliable method to identify the oldest trees with an average time/cost savings of 50-60%.

Discussion

The cost of reference conditions

Effective forest restoration is built on an understanding of current and historical forest conditions and how natural disturbances maintained forest structure and composition, but establishing reference conditions at a landscape scale can be a time consuming and expensive endeavor. Plot reconstructions provide exceptionally high quality results for the small populations represented within plots, but it requires a large number of plots to reliably extrapolate results to larger spatial scales. Achieving this level of effort can be difficult when securing funding for research and forest restoration is a substantial challenge (Evans et al., 2011). These results indicate that targeted sampling of the largest trees in plots will allow a high confidence characterization of the presence or absence of forest age caps, and the subsequent ability to characterize the historical fire regime at the scale of the sampling design. A landscape-scale assessment of oldest tree initiation dates and age caps would be essentially identical for the targeted sampling and full census approaches.

An average of eight trees in each Little Park conifer plot were cored to characterize the plot age cap. In conifer plots, sampling the three largest trees provides a high confidence estimate of the oldest trees in the location with an approximate 60% reduction in time/resources spent collecting samples in the field and mounting/sanding/cross-dating cores in the lab. In the Little Park aspen plots, an average of 11 trees were cored to characterize plot age cap. A hybrid “3+3” approach for stands with a substantial aspen component targeted the three largest diameter aspen and the three largest diameter conifers in each plot. Sampling this combination of six trees in all aspen plots successfully captured the oldest tree establishment dates 97% of the time. Similar to the conifer dominated plots, the “3+3” method results in a roughly 50% reduction in time and resources required to characterize the presence or absence of age caps in sampling locations.

Landscape-scale forest dynamics reveal a heterogeneous mosaic of structure and composition across a wide array of spatial and temporal scales (Turner and Romme, 1994). These inherently heterogeneous landscapes require multi-scale methods to characterize variation because plots and/or transects alone may artificially reduce variance due to spatial autocorrelation effects (Stohlgren et al., 1998). The 0.1 ha Little Park plots were only one component of an integrated, multi-scale forest assessment, but comparison revealed that the targeted sampling of the largest trees in a plot is a high confidence, cost effective technique to identify the oldest trees.

Targeted sampling of the largest trees that revealed a consistent age for the oldest trees in multiple locations would indicate stand-replacing fire severity. The targeted sampling of the largest trees from the Little Park site (three largest diameter trees for conifer plots; three largest diameter conifers and three largest aspen for aspen plots) revealed an uneven pattern of largest tree establishment (Fig. 3.3) that is indicative of the historical high frequency, mixed-severity regime documented by Fulé et al. (2003).

Forests adapted to frequent fires are substantially removed from reference conditions, and contemporary structure and composition would support high-severity fires at abnormally large spatial scales. Agencies and organizations that are working to restore forests and that enjoy strong community support and vibrant partnerships through collaboration have an edge in the battle for limited restoration resources (Evans et al., 2011). Targeted sampling of the largest trees to identify the oldest trees in a location can be easily taught to volunteers and could serve as a useful vehicle to encourage citizen-scientist and community involvement in the forest restoration process. Similar to the Kaibab Plateau, a reduction in fire-frequency has altered contemporary mixed conifer forests throughout southwestern Colorado to the point where forests have two to four times the basal area and tree density today compared to conditions that were common prior to 1870 (Fulé et al., 2009). In the Uncompahgre National Forest in Colorado (Fig. 3.1), this type of sampling has provided valuable local site information on previously unsampled areas at the landscape-scale to assist with the Collaborative Forest Landscape Restoration Program (CFLRP). This simple, efficient technique ultimately supports the goal of forest restoration through both data collection and community engagement.

Table 3.1. Mixed conifer forests on the Kaibab Plateau (North Rim of the Grand Canyon, Arizona).

Species	Common Name
Abies lasiocarpa	Subalpine fir
Abies concolor	White fir
Picea engelmannii	Engelmann spruce
Picea pungens	Blue spruce
Pinus ponderosa	Ponderosa pine
Populus tremuloides	Quaking aspen
Pseudotsuga menziesii	Douglas-fir
Quercus gambelli	Gambel oak
Robinia neomexicana	New Mexican locust

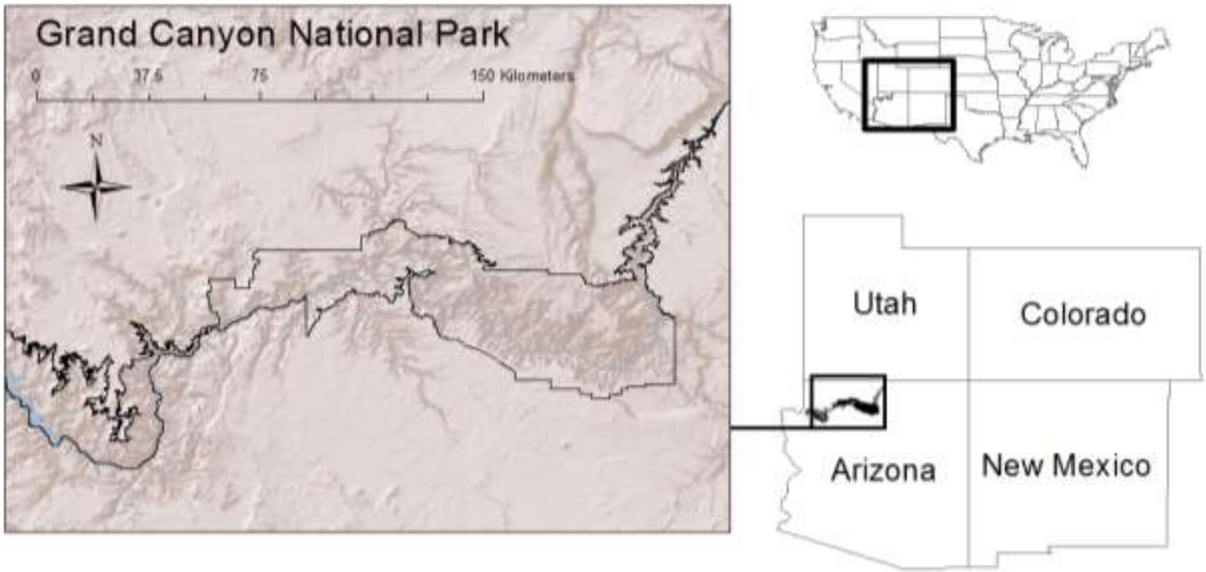


Figure 3.1. The targeted sampling of the largest trees in mixed conifer plots at the Little Park site on the Kaibab Plateau (Grand Canyon National Park, AZ) was validated as a cost-effective, reliable way to identify the oldest trees in plots.

Figure 3.2. Characteristic mixed conifer forest structural and composition heterogeneity from the Little Park site on the Kaibab Plateau, North Rim, Grand Canyon National Park. Clockwise from top left. (1) Yellow-bark presettlement ponderosa pines on a rocky slope amidst younger ponderosas with a presettlement Douglas-fir in the background. (2) Spruce-fir mix with aspens downslope and sapling ponderosa pines in the understory. (3) Predominantly spruce-fir forest with a few large aspen remaining in the overstory. (4) Vigorous understory recruitment in a cool/moist mixed conifer stand. Photos courtesy of Pete Fulé.

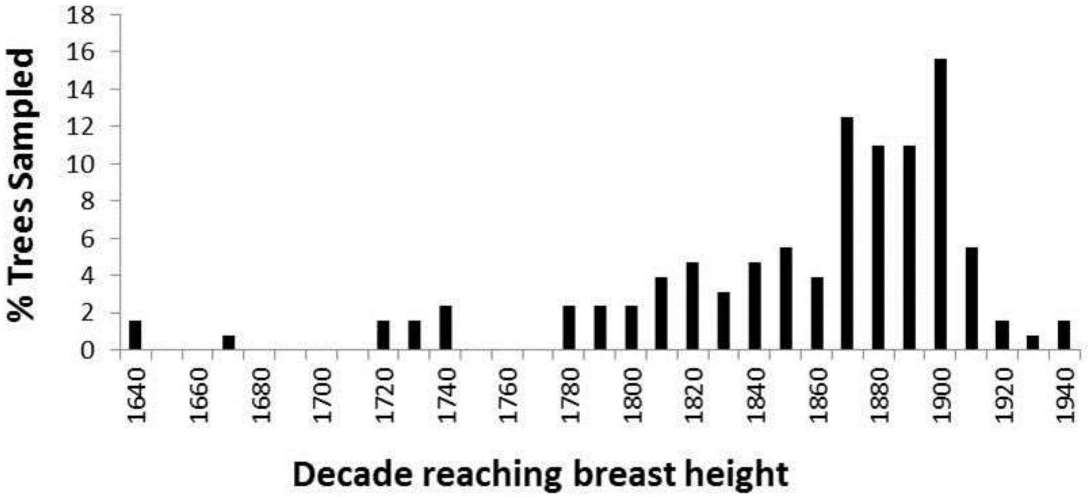


Figure 3.3. Patterns of largest tree establishment from the Little Park site on the Kaibab Plateau, Grand Canyon National Park, Arizona. Targeted sampling of the largest trees in the 0.1 ha plots revealed a mixed-severity regime at the scale of the sampling grid. Known major fire years in the area include 1785, 1806, 1847, 1873, and 1879.

LITERATURE CITED

Allen, C.D., Savage, M., Falk, D.A., Suckling, K. F., Swetnam, T.W., Schulke, T., Stacey, P.B., Morgan, P., Hoffman, M., Klingel, J.T., 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecological Applications 12, 1418-1433.

Baker, W.L., Ehle, D., 2001. Uncertainty in surface-fire history: the case of ponderosa pine forests in the western United States. Canadian Journal of Forest Research 20, 1205-1226.

Binkley, D., Romme, B., Cheng, T., 2008. Historical forest structure on the Uncompahgre Plateau: informing restoration prescriptions for mountainside stewardship. Colorado Forest Restoration Institute, Colorado State University.

Boyden, S., Binkley, D., Shepperd, W., 2005. Spatial and temporal patterns in structure, regeneration, and mortality of an old-growth ponderosa pine forest in the Colorado Front Range. Forest Ecology and Management 219, 43-55.

Brown, P.M., Kaye, M.W., Huckaby, L.S., Baisan, C.H., 2001. Fire history along environmental gradients in the Sacramento Mountains, New Mexico: influences of local and regional processes. Ecoscience 8, 115-116.

Brown, P. M., Shepperd, W. D., 2003. Preliminary fire history in ponderosa pine forests of the Uncompahgre Plateau. Rocky Mountain Research Station, Fort Collins, CO.

Brown, P.M., Wu, R., 2005. Climatic and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. Ecology 86, 3030-3038.

Churchill, D.J., Larson, A.J., Dahlgreen, M.C. , Franklin, J.F., Hessburg, P.F., Lutz, J.A., 2013. Restoring forest resilience: From reference spatial patterns to silvicultural prescriptions and monitoring. Forest Ecology and Management 291, 442-457.

Collins, B.M., Stephens, S.L., 2010. Stand-replacing patches within a ‘mixed severity’fire regime: quantitative characterization using recent fires in a long-established natural fire area. Landscape Ecology 25, 927-939.

Cooper, C.F., 1960. Changes in vegetation, structure, and growth of southwestern pine forest since white settlement. Ecological Monographs 30, 129-164.

Covington, W.W., Moore, M.M., 1994. Southwestern ponderosa forest structure – changes since Euro-American settlement. Journal of Forestry 92, 39-47.

Evans, A.M., Everett, R.G., Stephens, S.L., Youtz, J.A., 2011. Comprehensive fuels treatment practices guide for mixed conifer forests: California, central and southern Rockies, and the Southwest. Joint Fire Science Program fuel treatment guide, The Forest Guild, Santa Fe, NM.

Fulé, P.Z., Covington, W.W., Moore, M.M., Heinlein, T.A., Waltz, A.E.M., 2002. Natural variability in forests of Grand Canyon, USA. Journal of Biogeography 29, 31-47.

Fulé, P.Z., Crouse, J.E., Heinlein, T.A., Moore, M.M., Covington, W.W., Verkamp, G., 2003. Mixed-severity fire regime in a high-elevation forest of Grand Canyon, Arizona, USA. Landscape Ecology 18, 465-486.

Fulé, P.Z. 2008. Does it make sense to restore wildland fire in changing climate? Restoration Ecology 16(4):526-531.

Fulé, P.Z., Korb, J.E., Wu, R., 2009. Changes in forest structure of a mixed conifer forest, southwestern Colorado, USA. Forest Ecology and Management 258, 1200-1210.

Hughes, T., Kingston, R., Cencich, B., 1995. Soil survey of Uncompahgre National Forest Area, Colorado, parts of Mesa, Montrose, Ouray, and San Miguel counties. USDA Forest

Service and Soil Conservation Service, in corporation with the Colorado Agricultural Experiment Station. Fort Collins, CO.

Kaufmann, M.R., Regan, C.M., Brown, P.M., 2000. Heterogeneity in ponderosa pine/Douglas-fir forests: age and size structure in unlogged and logged landscapes of central Colorado. Canadian Journal of Forest Research 30, 698-711.

Keane, R.E., Hessburg, P.F., Landres, P.B., Swanson, F.J., 2009. The use of historical range and variability (HRV) in landscape management. Forest Ecology and Management 258, 1025-1037.

Korb, J.E., Fulé, P.Z., Stoddard, M.T., 2012. Forest restoration in a surface fire-dependent ecosystem: An example from a mixed conifer forest, southwestern Colorado, USA. Forest Ecology and Management 269, 10-18.

Mast, J.N., Fulé, P.Z., Moore, M.M., Covington, W.W., Waltz, A.E.M., 1999. Restoration of presettlement age structure of an Arizona ponderosa pine forest. Ecological Applications 9, 228-239.

Romme, W.H., Floyd, M.L., Hanna, D., 2009. Historical Range of Variability and Current Landscape Condition Analysis: South Central Highlands Section, Southwestern Colorado & Northwestern New Mexico. Colorado Forest Restoration Institute, Fort Collins, CO, USA.

Stohlgren, T.J., Bull, K.A., Otsuki, Y., 1998. Comparison of rangeland vegetation sampling techniques in the Central Grasslands. Journal of range management 51, 164-172.

Stokes, M.A., Smiley, T.L., 1968. An Introduction to Tree-ring Dating. University of Chicago Press, Chicago, IL.

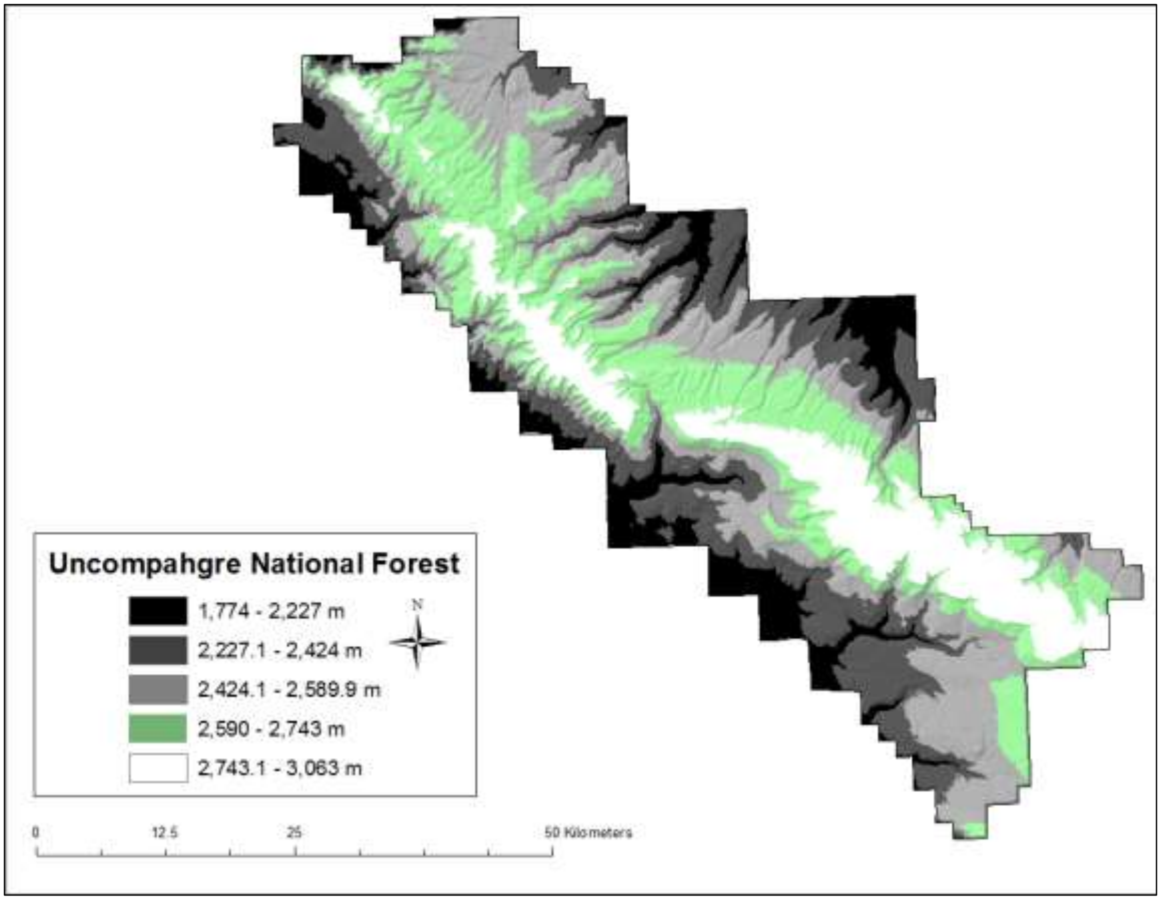
Stone, J.E., Kolb, T.E., Covington, W.W., 1999. Effects of restoration thinning on presettlement Pinus ponderosa in northern Arizona. Restoration Ecology 7, 172-182.

Turner, M.G., Romme, W.H., 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecology 9, 59-77.

White, P.S., Pickett, S.T.A., 1985. Natural disturbance and patch dynamics: an introduction. In: White, P.S., Pickett, S.T.A. (Eds.), The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, Orlando, FL.

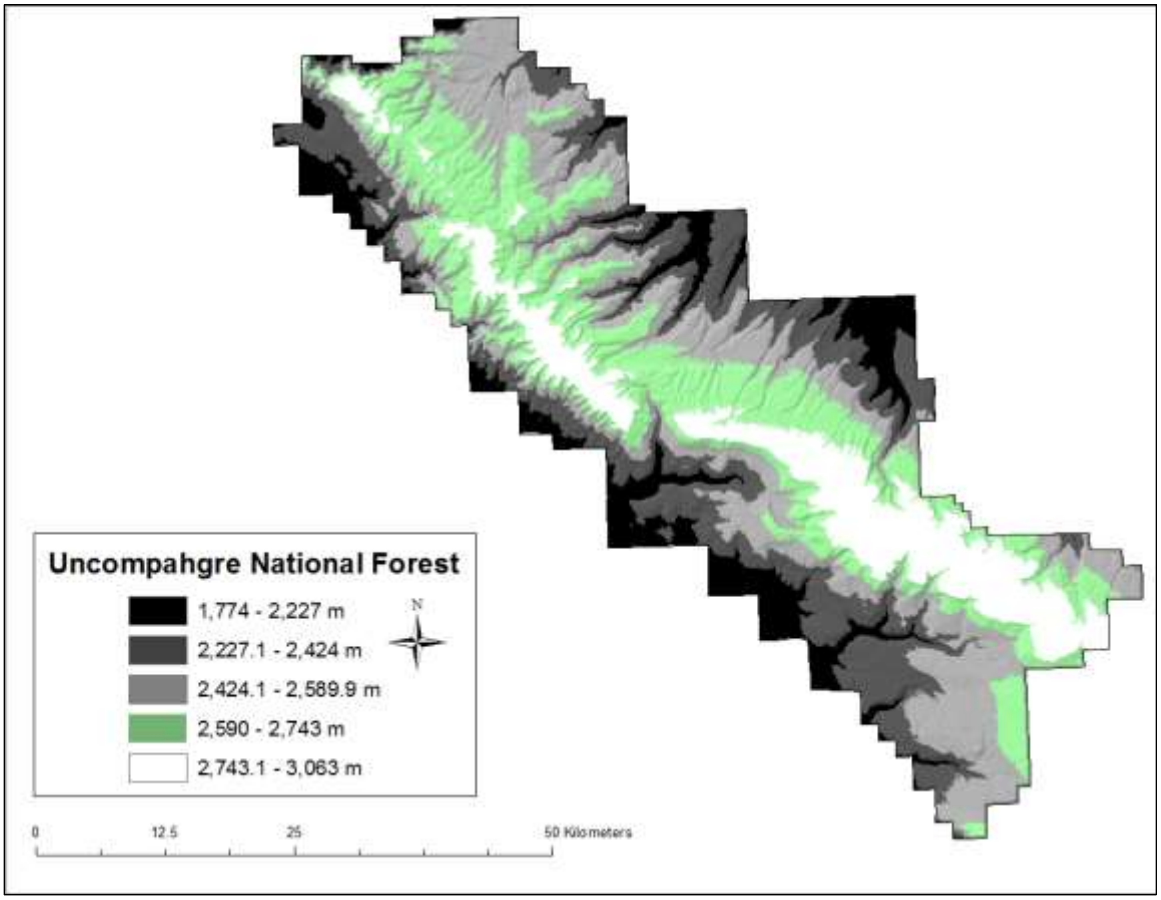
APPENDICIES

APPENDIX 1 FOR CHAPTER 1

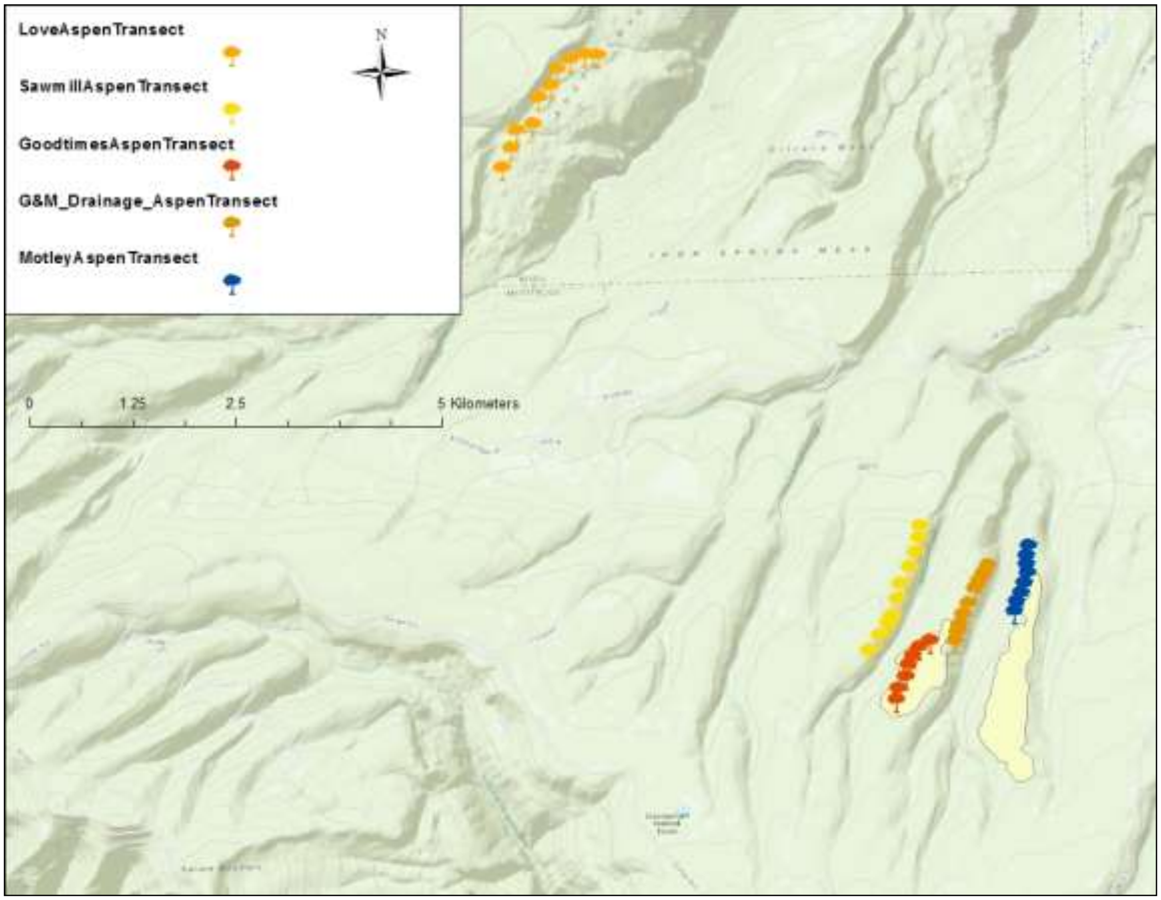


Appendix 1.A. Green-shaded portions of National Forest land on the Uncompahgre Plateau reflect areas where reference conditions from the unroaded, never-harvested mesas will support restoration planning in mixed conifer forest cover (approximately 60,000 ha).

APPENDIX 2 FOR CHAPTER 2



Appendix 2.A. Green-shaded portions of the Uncompahgre National Forest on the Uncompahgre Plateau reflect areas where reference conditions from the unroaded, never-harvested mesas will support restoration planning in mixed conifer forest cover (approximately 60,000 ha).



Appendix 2.B. The location of all five aspen transects with respect to the unroaded, never-harvested mesas. To examine the spatial scale of aspen mortality in the fire year of 1879, additional aspen transects were added on Sawmill Mesa (adjacent to Goodtimes Mesa) and approximately 8 km northwest on Love Mesa.