COMPARING ECOLOGICAL RESTORATION AND NORTHERN GOSHAWK MANAGEMENT GUIDELINES TREATMENTS IN A SOUTHWESTERN PONDEROSA PINE FOREST

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A Thesis

Submitted in Partial Fulfillment

of the Requirements for the Degree of

Master of Science

in Applied Geographic Information Systems

Northern Arizona University

December 2008

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ABSTRACT

COMPARING ECOLOGICAL RESTORATION AND NORTHERN GOSHAWK MANAGEMENT GUIDELINES TREATMENTS IN A SOUTHWESTERN PONDEROSA PINE FOREST

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We compared forest structure patterns resulting from application of revised Northern Goshawk Management Guidelines (GMG) and Ecological Restoration Guidelines (ERG)-based silvicultural thinning approaches in ponderosa pine (*Pinus ponderosa* C. Lawson var. *scopulorum* Engelm.) forests on replicated sites on the Kaibab Plateau in Northern Arizona. These management approaches have been proposed for wide application across tens of thousands of hectares of southwestern National Forests within Northern Goshawk (*Accipiter gentilis*) foraging areas. Both sets of guidelines use patterns and densities of presettlement forest evidences in the form of old forest remnants (pre Euro-American settlement era trees, stumps and snags) to guide their tree marking methodologies. Tree densities resulting from application of these treatment approaches and estimated presettlement densities were not significantly different. GMG-based treatments retained a larger proportion of trees in middle to large size classes, resulting in statistically significantly higher canopy cover and basal area. Tree spatial point patterns and tree patches (e.g., groups of trees with interlocking crowns) were analyzed. GMG-based treatments resulted in more consistent tree aggregation at fine-scales (<15 meters), than ERG-based treatments, a pattern similar to presettlement evidence patterns. GMG-based treatments

resulted in significantly fewer isolated individual trees, a higher mean density of trees within patches and more high density tree patches than ERG-based treatment results. No difference was observed in average diameter range of trees within groups. We conclude that with minimal modification, initial thinning approaches similar to those described in this study are highly compatible, both with each other and presettlement conditions, especially within forest landscapes where reintroduction of naturally ignited fires is a management goal. Despite this similarity, ERG and GMG-based stand management approaches will differ over the long term. The goal of ERG-based management is forests that can be regulated by natural processes, most notably surface fires similar to those common in the Southwest. The GMG approach, while allowing the use of fire, will require continual forest structure regulation and will inevitably result in future removal of large, old trees.

ACKNOWLEDGEMENTS

I would first like to thank District Ranger Tim Short and all staff of the North Kaibab Ranger District of the Kaibab National Forest for supporting these research efforts over the last three years. Without this support this project would not be possible. I would also like to thank Richard Reynolds, Allison Cofer and crew, and Dennis Lund, Charlie Denton, Dave Brewer and Michael Stoddard for generously donating days of time and effort to mark trees for retention with each treatment prescription. Integral to this study was the support of several enthusiastic crews of ERI staff members and student research assistants who worked to document over 7500 tree locations and attributes assessed in this study. I also thank Andrew Sánchez Meador for his generous spatial statistical advice and technical support. Finally, I would like to thank my committee members including co-advisors Dr. Pete Fulé and Dr. Christina Kennedy, and Dr. Margaret Moore, who helped to design this study and also reviewed the seemingly endless number of thesis drafts that I've sent to them for review over the course of my last semester as a graduate student.

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PREFACE

Some redundancy exists in the information presented in the five chapters comprising this thesis. The structure of this document follows a format intended to speed the preparation of the manuscript, presented in chapter 3, for submission to a scientific journal. Chapter 4, *Management Implications,* contains much of the same information in the discussion presented in Chapter 3, but contains more in-depth practical forest management topics than presented in the manuscript chapter. The conclusions of the thesis are contained in abbreviated form within Chapter 3 and are also repeated again in a separate conclusion chapter (Chapter 5). One literature cited section is presented at the end of the thesis, including references from throughout the entire thesis.

CHAPTER 1

Introduction

Background

Forest management approaches described in *Management recommendations for the Northern Goshawk in the Southwestern United States,* also known as the northern goshawk management guidelines (GMGs), mandate detailed forest spatial structure requirements and management activities to create habitat conditions for prey species that comprise the food web for the northern goshawk (Reynolds et al. 1992; 2006). The GMGs were developed in response to a growing body of research documenting population declines of this top avian predator in southwestern forests (Kennedy 2003). The stringent nature of the silvicultural requirements set forth in the GMGs and varying interpretations regarding their intent has made practical implementation of these guidelines in southwestern National Forests difficult and controversial (Kennedy 2003). This has led to abandonment of planned ecological restoration-based forest treatments within goshawk territories, incorrect application of GMGs at several project sites and overall uncertainty regarding the ecological basis for GMG-based forest treatments (Reynolds et al. 2006).

A regional review of the goshawk guidelines at several Forest Service (USFS) workshops in the fall of 2006 was initiated in order to clear up ambiguity and misunderstanding regarding application of the GMGs. At these workshops, ecological restoration guidelines (ERGs) were proposed by USFS southwestern region personnel as a compatible alternative to strict implementation of the GMGs (Reynolds et al. 2006). ERGs use the composition, density and location of presettlement forest remnants (stumps, snags, old trees and stump holes pre-dating settlement of the region) as a template for the spatial pattern of restored forests. The desired end result of ERG-based treatments at a particular site is a resilient, self-sustaining forest where ecosystem processes, structural patterns and species composition are similar to those present at the site prior to the influence of livestock grazing, fire suppression and logging (Moore et al. 1999; Society for Ecological Restoration 2004).

Goshawk Management Guidelines and Ecological Restoration -based forest treatment approaches have much in common when applied to southwestern ponderosa pine (*Pinus ponderosa* C. Lawson var. *scopulorum* Engelm.) forest types. Both treatment approaches involve retention of trees with old age characteristics (Moore 1999; Reynolds et al. 2006; Reynolds et al. 2007). Additionally, both attempt to emulate relatively open, park-like conditions known to exist across southwestern forests prior to Euro American settlement (Cooper 1960; Reynolds et al. 1992; Moore 1999). It is reasonable to assume that both approaches, when applied to typical contemporary ponderosa pine forests (typically high density, high canopy cover forests comprised of one to two cohorts), will result in reduced tree densities, reduced canopy cover, creation of forest openings, a reduction in crown fire hazard and overall un-even aged forest conditions.

It is possible that ecologically significant differences exist between forests treated with each technique. These potential differences may not only affect northern goshawk habitat, but also understory plant production, small mammal and bird habitat suitability, fire behavior and other ecological values and processes (Reynolds et al. 1992; Griffis et al. 2001; Fulé et. al 2001).

Thesis purpose and structure

This study was designed to quantify and compare impacts of these forest thinning approaches upon tree spatial structure. Therefore, this study required a unique approach for the assessment of treatment outcomes. First, this study is based upon stem-mapped tree and presettlement tree evidence location and attribute data collected within several mapped areas randomly located across a ponderosa pine dominated forest. This spatially explicit and relatively time consuming methodology was required because forest spatial structure characteristics are at the core of each treatment approach. An assessment of forest spatial structure conditions would be difficult, if not impossible, to quantify without spatially explicit mapping of tree locations. Second, thinning treatment outcomes were simulated from tree markings rather than measured in residual forest stands following implementation of each treatment.

This strategy, while not capable of providing results of practical treatment implementation, had two main benefits. It allowed both treatment guidelines to be marked and assessed within the same six mapped areas, thereby eliminating error associated with comparing treatment outcomes in separate forest stands having different initial forest structure. This was accomplished by applying prescriptions with removable tree marks (colored flagging), permitting application of a separate treatment prescription mark after trees marked with the initial prescription flagging were mapped and flagging was removed. A second benefit of this simulation approach was time and money savings associated with forgoing the expensive and often delay-prone process of implementing forest treatments on public forest lands.

The approach used in this study addressed the following study objectives:

1) Assess local presettlement forest densities and spatial patterns as evidenced by forest remnants (old living trees, snags, stumps, dead and downed trees).

2) Assess ERG and GMG-based treatments efficacy in restoring site-specific presettlement forest densities and spatial patterns.

3) Compare forest structure patterns of ERG and GMG-based treatments at sub-plot to plot-scales.

CHAPTER 2

Literature Review

The Development of Two Important Forest Thinning Approaches

The Ecological and Social Basis for Forest Thinning Treatments

Goshawk management guidelines and ecological restoration guidelines are forest management approaches that have been developed in response to changes in southwestern ponderosa pine forests since Euro-American settlement of the region in the late 1800s. Frequent surface fires, ignited by lightning or indigenous people, were a major regulator of ponderosa pine forest tree density, structural patterns and species composition prior to this time (Cooper 1960; White 1985; Covington and Moore 1994; Allen et al. 2002). A number of factors, including intense livestock grazing of herbaceous understory fuels, logging, railroad and road construction, and a policy of active fire suppression, rapidly changed the way fire interacted with forest structure after settlement (Cooper 1960; Dieterich 1980; Moore 1999; Allen et al. 2002). Associated results have been landscape-scale increases in tree biomass, changes in forest structural patterns, decreases in forest herbaceous understory productivity, as well as decreases in suitable habitat for several native vertebrate and invertebrate species (Reynolds et al. 1992; Covington and Moore 1994; Waltz 2003; Sánchez Meador 2006).

These structural changes are also, in large part, responsible for an ecosystem-wide transition from a low severity, frequent, surface fire regime to a less frequent, high severity, crown fire regime over the last century (Fulé et al. 1997; Swetnam et al. 1999). Such fires are often destructive to both human life and property and to forest ecosystems. These structural changes have also been linked to northern goshawk (*Accipiter gentilis*) population and prey base declines (Reynolds et al. 1992). In recent years, political pressure to reverse goshawk population declines and rising costs associated with the aftermath of destructive wildfires has drawn regional and national attention to ponderosa pine forest restoration efforts (Moir and Dieterich 1999). For these reasons, forest restoration approaches such as ecological restoration guidelines (ERG) and northern goshawk management guidelines (GMG) have been proposed for millions of hectares of public lands throughout the western United States (Allen et al. 2002).

Development and Purpose of Ecological Restoration Treatments

Ecological restoration has its roots in the field of restoration ecology. This branch of applied science developed through contributions from various fields ranging from conservation biology, geography, wetland management and disturbed land rehabilitation (Ehrenfeld 2000). As a result, ecological restoration project objectives and desired future conditions are not limited to a particular ecosystem type and are often highly variable. They may range from conservation or promotion of localized species populations or communities, rehabilitation of polluted or damaged sites, the recovery of ecosystem structure, to species composition or function across entire landscapes (Ehrenfeld 2000; Society for Ecological Restoration 2004).

In general, all ERG-based treatments are intended to "initiate or accelerate the recovery of an ecosystem with respect to its health, integrity and sustainability (Society for Ecological Restoration 2004)." To accomplish this goal, it is essential to have an understanding of an ecosystem's reference conditions, or conditions known to be within the range of healthy ecosystem variability, in order to guide ecosystems back to healthy conditions where ecosystem structure and processes can be maintained indefinitely (Moore et al. 1999; Society for Ecological Restoration 2004). For this reason, restorationists often must rely on presettlement ecosystem structure reconstructions, long-term ecological data and a variety of other anecdotal information sources to develop a coherent picture of ecosystem reference conditions (Covington and Moore 1994; Moore et al. 1999; Allen et al. 2002; Moore et al. 2004).

For decades, Southwestern restorationists have known that ponderosa pine forest structure within this lightning, drought and wind-prone region were shaped in large part by frequent surface fires (Weaver 1943; Weaver 1951; Cooper 1960). A well-established body of research has shown that prior to Euro-American settlement of the region (i.e, "presettlement" time periods) these landscapes burned frequently, with a fire-return intervals ranging from 2-20 years (Oliver and Larson 1996).

Early restoration attempts using fire alone were greeted with mixed success. An experiment in Northern Arizona in the 1970s had some beneficial effects--reducing tree densities, forest floor litter depths and recycling nutrients--but reintroduction of fire into dense, flammable forests was not only somewhat dangerous, but also resulted in mortality of large old trees, survival of many small diameter trees and little change in overall forest structure (Sackett et al. 1995). It was soon apparent that fire alone was not always capable of restoring ponderosa pine forests to presettlement forest structure conditions. In order to allow low severity surface fires to be reintroduced to contemporary ponderosa pine forests, some form of thinning was needed to create forest structure conditions similar to those present in presettlement forests (Sackett et al. 1995).

Due to the extremely dry climate of the Southwest and resulting slow decay rates, evidence of forest structure patterns existing prior to Euro-American settlement around 1879 (Fulé et al. 1997) can still be found in the form of stumps, snags, downed woody debris and old living trees. The location, density, and species composition of these forest remnants provide a source of evidence of presettlement forest structure and a guide for restoration thinning activities (Fulé et al. 1997; Moore et al 1999; Heinlein et al. 2002; Taylor 2002).

Ecological restoration practitioners have used these presettlement forest evidences to guide forest thinning projects in several areas. In the Sierra Nevada Mountains of California, practitioners have used stumps cut in the late 19th century to identify changes in forest density, species composition and spatial pattern over the last century (Taylor 2002). Several ecological restoration experiments making use of presettlement forest structures have been initiated in ponderosa pine forests of Northern Arizona; these include experiments at the Gus Pearson Natural Area, Apache-Sitgreaves National Forest, and Uinkaret Mountains in Northern Arizona (Covington et al. 1997; Fulé et al. 1997; Waltz et. al 2003).

Each of these studies features an Ecological Restoration Guidelines (ERG)-based thinning prescription developed from the composition, density and location of local presettlement forest remnants (stumps, snags, old trees, stump holes) to varying degrees in determining the desired character of restored forests. Using this approach, all trees established prior to Euro-American settlement, typically trees having old age characteristics (i.e., yellow bark, large branches, and/or large diameters) are retained. Non-living presettlement forest remnants (stumps, snags, stump holes) are replaced by one to several healthy trees that have established since Euro-American settlement within a fixed search radius (approximately 18 meters) surrounding each forest remnant (Covington et al. 1999). Replacement rates range from a ratio of 1.5 to 3 replacement trees to every presettlement evidence (Covington et al. 1999). The desired result of ERG-based treatments is forest structure patterns capable of developing into conditions comparable to those present at the site prior to the influence of industrial grazing, fire suppression and logging practices (Moore et al. 1999; Heinlein et al. 2002).

Choice of which specific trees are retained using ERGs depends upon the relative location of replacement trees to presettlement evidences and the choice of the tree marker and other site specific treatment objectives rather than predetermined diameter distribution targets. In general, a variable, but unregulated diameter distribution of healthy retained trees is sought (Covington et al. 1999). Specific spatial patterns created are determined by site-specific presettlement forest remnant patterns. Typically no forested patch sizes (i.e., groups of trees with interlocking crowns) are indicated (Covington et al. 1999).

ERG-based thinning treatments are designed to be completed in a single management entry. Ecological restoration-based management approaches rely on ecosystem processes such as fire to maintain forest stand structure over time (Society for Ecological Restoration 2004). Application of some form of prescribed or naturally ignited wildland fire is a cornerstone component of all ecological restoration guidelines in southwestern ponderosa pine forests. Restorationists advocate use of prescribed fire or naturally ignited wildfires to manage future forest structure development within restored areas (Moore et. al 1999).

Restoration of forest structural patterns using mechanical treatments is often the most conspicuous aspect of the ecological restoration process, and is often mistakenly confused as the entire ecological restoration process. Local ecological disturbance processes, such as fire, were primarily responsible for regulation and maintenance of presettlement forest structure patterns from microscopic to landscape spatial scales in southwestern forests. The restoration of dynamic, natural processes (e.g surface fires), not the creation of static forest structural patterns, is what allows forest management efforts to be considered ecological restoration (Falk 2006).

Development and Purpose of the Goshawk Management Guidelines

Ostensibly, goshawk management guidelines (GMG) were developed for use in southwestern National Forests to address twentieth century changes in forest structural patterns as they relate to northern goshawk habitat and prey-base availability. While this is true, GMG-based forest management represents a transition from a resource production-based strategy, to a much more complex, ecosystem-based strategy.

For a large part of the twentieth century, USFS land management policy was oriented toward resource production. This was officially outlined in policy contained within the *Multiple Use Sustained Yield (MUSY) Act* of 1960. The act declared that National Forests, should maintain, "a high-level regular output of the renewable resources of the national forest without impairment of the land's productivity (www.wildlifelaw.unm.edu/fedbook/multiu-.html)." The MUSY act allowed land management oriented toward timber production to proceed within southwestern National Forests, often at the expense of broader ecosystem sustainability.

As early as the 1970s, wildlife biologists from the Arizona Department Game and Fish began to acknowledge that contemporary forest management activities might be at odds with northern goshawk survival and reproduction (Peck 2000). During the mid 1970s to the mid 1980s, goshawk nest monitoring was implemented by southwestern National Forests. This monitoring resulted in placing the northern goshawk on USFS Region 3 Sensitive Species List and adding goshawk management recommendations to several southwestern National Forest Plans (Peck 2000; Kennedy 2003). Early goshawk management recommendations were primarily intended to limit forest harvesting near goshawk nesting areas (Reynolds et al. 2006).

In 1990, a seminal paper by Cole Crocker-Bedford published in the *Wildlife Society Bulletin* described effects of logging on goshawk survival and reproduction on the North Kaibab National Forest. Bedford concluded that both goshawk nest occupancy and reproduction success were negatively influenced by logging practices during the 1970s and 1980s (Bedford 1990; Reynolds et al. 2007).

Public outcry and a flurry of legal activities and agency policy development occurred following the 1990 publishing of the Crocker-Bedford paper (Peck 2000). Legal activities included several failed attempts to list goshawks as a federally endangered species, and an injunction halting forest cutting in all known goshawk territories in Arizona and New Mexico National Forests until forest plans were amended to address the goshawk issue (Peck 2000; Kennedy 2003). These activities prompted southwestern National Forests to form the Goshawk Scientific Committee (GSC) "to develop forest management recommendations based on the best science to protect goshawk populations" (Kennedy 2003; Reynolds et al. 2007). In 1992, the recommendations of the committee were released in the form of the research report RM-217: *Management Recommendations for the Northern Goshawk in the Southwestern United States* (Reynolds et al. 1992). The recommendations set forth in this document became part of an Environmental Impact Statement that eventually was included within Southwestern Region National Forest plans in a final record of decision issued in 1996 (USDA 1996).

Efforts to develop a broad northern goshawk conservation strategy were bolstered by a 1992 executive order directing the USFS to adopt ecosystem management policy (USFS 1992). This paradigm shifting policy directive quickly changed official national forest management priority from one based on short-term resource production, to one promoting long term ecological sustainability. While not entirely at odds with timber resource production, ecosystem management policy inherently restricts some timber management activities that are in conflict with sustainability of the broader ecosystem (Grumbine 1994). The GMGs could be considered one of the first coarse-scale Southwestern Region National Forest policies created to promote ecosystem management principles (Grumbine 1994; Peck 2003).

The fundamental premise of the GMGs is that goshawk and goshawk prey populations are limited by available food and suitable habitat (Reynolds et al. 1992). The goal of the GMGs is to create a range of forest habitats suitable for both goshawk nesting, hunting and diverse populations of goshawk prey. Such conditions are thought to allow goshawk populations the ability to withstand periodic decreases in any one prey species through reliance on other species comprising the broad food web of this top predator (Reynolds et al. 1992; Reynolds et al. 2006).

Under the GMGs, specific forest structure requirements apply to different portions of the 2428 hectare home range surrounding known goshawk nests. While the most stringent requirements apply to an approximately 73 hectare nesting area, the coarsest-scale requirements apply to a 2185 hectare area surrounding nesting areas comprised of goshawk post-fledgling areas and foraging areas (Reynolds et al. 1992). There are slight differences between foraging area and post-fledgling area management guidelines, but in general management recommendations for both of these areas are very similar (Reynolds et al. 1992; Richard Reynolds Personal Communication 2007).

GMGs employ Vegetation Structural Stages (VSS), a forest succession classification system first described in the late 1970s for use in western Oregon (Thomas et al. 1979) and adapted for the Southwest in RM-217. This system classifies 0.04 to 0.1 hectare clumps of trees of six forest structure development classes ranging from seedlings to old, large diameter trees (Reynolds et al. 1992). In this classification system diameter is used as a surrogate for age. A target distribution of these VSS classes is required for each component of the goshawk home range in order to provide habitat for several different prey species. Additionally, forested areas comprised of these VSS groups must meet certain criteria such as canopy cover, maximum opening size, snag and downed woody debris density and reserve trees (Reynolds et al. 1992). The objective of GMG-based treatments is a structurally regulated, uneven-aged forest composed of a mosaic of interspersed even aged tree groupings.

The GMGs are not a set of prescriptive forest management guidelines, but are instead a set of desired forest conditions for goshawk territories. These conditions are thought to be similar to forest conditions that existed prior to Euro-American settlement of the region (Reynolds et al. 1992; Reynolds et al. 2006; Youtz et al. 2008). To bring desired GMG-based forest structure requirements closer in line with pre-settlement conditions, recently regional USFS personnel have advocated use of presettlement forest remnants (old trees, old stumps and logs) to guide tree stocking levels and local vegetation patterns (Reynolds et al. 2006; Youtz et al. 2008). Beyond this recent change, GMG-based approaches do not prescribe any single specific silvicultural management action, but instead recognize that a variety of silvicultural approaches can be used to attain desired forest structure conditions (Reynolds et al. 1992).

Since attaining desired conditions prescribed in the GMGs is unlikely after only one treatment, it is assumed that, over time, multiple thinning entries into an area will be necessary to meet or maintain stated forest structure targets (Reynolds et al. 1992). A GMG-based forest management approach will inevitably result in southwestern forest structure patterns shaped primarily by silvicultural thinning. Since trees in smaller size classes will eventually grow into the largest size classes over time, a GMG-based management approach eventually will result in an over abundance of old, large diameter tree groups (VSS 5-6). These large tree cohorts will need to be harvested to maintain stated structural regulation requirements. The upper density limit of this VSS class within management areas is regulated by a set rotation age of approximately 200 to 250 years specified by regional USFS policy (Youtz et al. 2006). Perpetual regulation of large old age tree cohorts may be the most ecologically and socially important aspect of a GMG-based forest management approach (Long and Smith 2000).

The Development of Presettlement Forest Structure Patterns in Ponderosa Pine Forests

Presettlement forest spatial patterns

Several researchers have attempted to quantify spatial patterns in ponderosa pine forests located throughout the western United States. Perhaps most applicable to southwestern ponderosa pine forests are a small number of studies of presettlement forest spatial patterns. These include studies completed in Arizona by Cooper in 1960-61, White in 1985 and most recently Sánchez Meador (et al.) in 2006. Other studies completed in fire-adapted ponderosa pine forests in other areas of the western U. S. are also relevant. Spatial pattern metrics, spatial analysis techniques and the scale of spatial assessment employed in studies of forest spatial patterns have changed over time, and in some instances, the results of such studies are not always directly comparable. Taken together, all provide important information describing presettlement tree spatial patterns at sub-plot scales.

Cooper investigated spatial patterns within a ponderosa pine forest along the eastern Mogollon Rim in Arizona (1960). He used a contiguous quadrat analysis technique common to early spatial pattern studies (Grieg-Smith 1952). Cooper's results indicated that mature pines in this forest were aggregated in groups ranging in size from 0.06 to 0.13 hectares. In addition to this finding, in another nearby study Cooper (1961) used a metric of spatial point patterns, Clark and Evans R, developed by Clark and Evans in 1954 to further describe tree location patterns. Results of this analysis indicated that tree locations within 12 of the 14 mature stands (approximately 80 years old or older) that he assessed exhibited statistically random spatial arrangement at the stand-scale, with trees within the remaining two stands exhibiting statistically significant uniform (i.e.,, evenly spaced) patterns at the scale of his study sites. Cooper was one of the earliest Southwest researchers to quantify southwestern ponderosa pine forest patterns that previously had only been qualitatively described.

With the benefit of Cooper's research, White (1985) investigated spatial patterns of trees that predated Euro-American settlement (circa 1875) in a ponderosa pine forest near Flagstaff, Arizona. Pre-settlement era trees were observed in groups of trees with interlocking crowns ranging in size from 0.02 to 0.29 hectares (White 1985). Using Clark and Evans R assessed at the tree group-scale, White reported that overall tree location patterns within groups most commonly were statistically random, although one group exhibited a significantly aggregated pattern. Since the sample size of each tree group was quite small (ranging from 3 to 44 trees per group), it is not clear whether tree group-scale patterns were truly random or if findings indicating random patterns were a result of a low sample size (White 1985). White's study provides further quantitative evidence of the "grouped" (i.e., distinct groups of trees with interlocking crowns) structure of presettlement forests, evidence of a random pattern of trees within these groups and evidence indicating that tree groups are un-even, or multi-aged.

Early studies of forest spatial patterns were hindered by the scale of analysis. In Cooper's studies, the forest stand was the sole scale of spatial analysis; in White's, the tree group was the scale of analysis (Cooper 1961; White 1985). More recent studies of presettlement forest spatial patterns use advanced spatial statistical techniques such as K-function analysis, also known as Ripley's K analysis, to assess forest spatial patterns at multiple scales, ranging from fine-scales (<10 meters) to coarse-scales (up to half the minimum dimension of a mapped area) (Wong and Lee 2005). Ripley's K analysis allows comparison of measured forest patterns to Monte Carlo simulations of random patterns in order to assess statistically significant spatial randomness, aggregation or uniformity at a range of spatial scales (Wong and Lee 2005). Use of the K function, along with readily available advanced computing technology, has allowed contemporary researchers to assess forest spatial patterns in a way that was previously impossible.

The most relevant use of the K funcrion, with reference to presettlement southwestern ponderosa pine forests, is a study completed by Sánchez Meador (2006; Sánchez Meador et al. 2008). In this study, Sánchez Meador reconstructed presettlement forest conditions from permanent plots ranging in size from 1.2 to 4.1 hectares near Flagstaff, Arizona. Results indicate that presettlement forests exhibited significantly aggregated spatial patterns at all six sites assessed in the study, with the most significant aggregation occurring at 5-15 meter spatial scales.

Sánchez Meador also used a novel spatial modeling technique to assess presettlement forest spatial patterns as part of the same study (2006). In this portion of the study, he assessed forest patterns using groups of trees with interlocking crowns as the subject of analysis. He predicted crown radius for all mapped trees in this study using a regression equation of diameter versus crown radius (R^2=0.83), and then used a GIS buffering technique to create canopies for all mapped tree locations using these radii. This approach allowed identification of sub-plot scale tree groups, and tree group-scale characteristics, and indicted that prior to settlement, 75 to 83 percent of the trees within the six study areas were arranged in groups with interlocking crowns ranging in size from an average of approximately 45 to 90 m^2. These groups contained an average of 4.2 (range 3.6 to 5.4) trees per group (Sánchez Meador 2006).

In other regions of the western US, studies of presettlement ponderosa pine spatial patterns using Ripley's K analysis yield similar results. A reconstruction of presettlement stand patterns observed in forty-eight 0.5 hectare ponderosa pine stands in central Washington by Harrod (1999) indicated aggregation in presettlement stands at scales ranging from <1 meter to 15 meters. Youngblood and others (2004) reported variable spatial patterns within for old-growth ponderosa pine forests in eastern California and Oregon. In this study a significantly uniform pattern was observed within two of the three study areas at scales less than 1.0 and 1.4 meters respectively. Random tree patterns were observed at all sites. At one of the three areas, no deviation from a random pattern was observed at all scales (0 to 25 m). Random patterns were observed within the other two areas from 1.2 to 2.6 meters and 1.6 to 8.4 meters respectively. Significant aggregation was observed at both these sites at increasingly greater scales. Boyden et al. (2005) reported spatial patterns within a 9.3 hectare stand of old-growth ponderosa pine forest in the Front Range of the Colorado Rockies. Both random and uniform patterns were observed in the largest (i.e., oldest) diameter classes, with deviation from simulated random patterns observed at scales ranging from 5 to 7 meters (Boyden et al. 2005).

As discussed above, studies completed throughout the 20th century reveal several key patterns of presettlement ponderosa pine forest spatial structure. First, at the coarsest-scale of analysis, typically the plot or stand-scale, forest spatial patterns have been most commonly described as random. Secondly, while coarse-scale patterns are random, more sophisticated multi-scale analysis has revealed that at finer scales (25 meters or less), presettlement patterns were typically significantly aggregated. Lastly, fine-scale aggregated patterns are associated with a readily observable characteristic of presettlement or mature ponderosa pine forests: presettlement forests were comprised of groups or clumps of trees with interlocking crowns. Nearly seventy years of forest spatial pattern analysis provides quantitative evidence that supports the "patchy", "groupy" or "clumpy" descriptions of ponderosa pine forest spatial structure noted by many forest researchers and practitioners (*M. Tuten, personal observation*).

Forest structure development

Development of sub-plot scale aggregated forest patterns in presettlement ponderosa pine forests is a complex and not well understood process. It includes regeneration processes and patterns, the influence of disturbance processes such as fire and herbivory upon tree regeneration, competition between regeneration and understory plant species, as well as the interaction of climate and topography upon these processes. Assessment of these important factors offers insight into the development of ponderosa pine forest spatial patterns.

Mature forest spatial patterns are inherently related to tree regeneration processes and patterns. Ponderosa pine seeds are wind dispersed and rarely travel more than approximately 37 meters from the parent seed source (Larson 1961). Ponderosa pine seedling germination requires a mineral soil seed bed and warm and moist soil, conditions often limited by seasonal temperature and precipitation. Additionally, the bimodal precipitation regime common throughout the Southwest induces a high rate of seedling mortality, making regeneration establishment typically episodic (Larson 1961).

Other important influences on tree cohort establishment are elevation and associated changes in temperature and precipitation, soil type and texture, and biotic factors such as competition with understory vegetation and herbivory (Oliver and Larson 1996). On poor volcanic soils, seedling growth is typically slow and hindered by frost-heaving during winter months, and, regeneration patterns are less dense compared to areas with more productive limestone soils (Heidmann 1988; Covington et.al. 1997). Livestock grazing and wildlife browse also affect regeneration patterns. Pearson (1942) found that livestock grazing practices during early decades of the 20th century probably favored pine regeneration establishment by limiting seedling competition with grass. Other research indicates that elk and deer browse may contribute greatly to seedling and sapling mortality and limit height growth (Jones 1967). Consideration of all of these as well as other factors may be necessary to understand the processes driving regeneration structure and pattern at management-scales.

Under favorable conditions, ponderosa pine regeneration often forms dense thickets (Covington et al. 1997). These thickets have several important structural features. High canopy fuel loadings along with low live crown heights predispose these dense patches to mortality resulting from fire (Peterson et al. 2005). Regeneration patterns within regeneration patches has been described as random (Cooper 1961) in Arizona (trees less than 44 years old), but uniform (West 1969) in eastern Oregon (four of five sapling thickets ranging from 60 to 84 years old). Uniform or random regeneration patterns may be a product of intense root competition within the dense regeneration patch soon after seedling establishment (West 1969). This conclusion is supported by the finding that ponderosa pine allocates a greater proportion of carbon to root development versus height growth in the seedling phases (Grulke and Williams 2001). In montane ponderosa pine forests, during this phase of stand development, inter-tree resource competition may be more similar to levels common in the stem exclusion stand development phases described by Oliver and Larson (1996) in other North American forests.

Natural disturbance processes, such as fire, alter forest structure over time affecting mature forest spatial patterns (Oliver and Larson 1996). There is little, if any, evidence of stand-replacing crown fires in southwestern montane forests prior to the turn of the 20^{th} century (Moore 1999). Many photos from this time period indicate forest conditions were not consistent with conditions necessary to propagate crown fire under all but the most extreme fire weather conditions (Fulé et al. 2006). Typically forest cover was highly discontinuous, the bases of the live tree crowns typically were several meters high, surface fuel loadings were low, and fuel complexes capable of allowing fire to transition from the ground to live tree crowns were uncommon (Covington 2003).

There is, however, a great deal of evidence that high intensity, wind-driven fires, burning in light surface fuels were common across these landscapes (Arno 1996). Such fires have variable, yet somewhat predictable, effects upon ponderosa pines of different developmental stages and spatial patterns. Large old pines are very resistant to these fires and typically suffer little mortality (Mast 1993). Typically, crowns in these trees are high enough from surface fire heat to avoid crown scorch (i.e., damage to living foliage) and the thick bark is capable of insulating the cambium from heat damage (Wright et al. 1991).

In smaller age classes, fire effects are more variable. Pines in the pole to middle size tree diameters also have insulating bark and are capable of resisting heat damage to the cambium, but often experience crown scorching. This fire effect can lead to many outcomes including delayed mortality through crown scorch (Wright et al. 1991), increased susceptibility to insect attack or (Breece et al. 2007), or, if the tree survives, fire induced "pruning" of live crown foliage. In these classes, fire effects can range from causing direct mortality to increasing resistance to subsequent surface fires by raising the height to live crown (Biswell et al. 1973).

Surface fires interact perhaps most dynamically with pine seedlings and saplings. Fire is capable of spreading through the crowns of these individuals and can cause nearly complete mortality in seedling classes, depending upon the intensity and movement of the fire (Peterson et al. 2005). Surface fire effects on young pines changes rapidly as these trees grow. Six-year-old pines have been shown to survive in low intensity surface fire conditions (Bradley et al. 1992). Large sapling and pole size trees have been shown to survive all but the most intense fires as long as 50% of buds and at least 10% of the live crown remains intact following the fire (Zwolinski 1996).

Observations in southwestern montane forests throughout the 20th century indicate that, in the absence of fire, dense regeneration thickets do not typically develop into mature forests characteristic of presettlement forests. When dense conditions are maintained in an environment free of disturbance, growth stagnates (Oliver and Larson 1996; Peterson et. al 2005).

Two competing theories exist to explain how frequent surface fires interacted with forest structure to create the highly clumped patterns observed in many mature southwestern ponderosa pine forests. The first theory was proposed by Cooper in 1960. He proposed that aggregated, even-aged mature tree groups develop from the interaction of fire within even-aged ponderosa pine regeneration patches. This theory meshes nicely with the observation that ponderosa pine regeneration establishes in dense, single cohort thickets. Cooper concluded that mortality induced by frequent fire within young regeneration thickets resulted in a less dense, yet still aggregated tree spatial pattern.

Another theory was proposed by White (1985) after observations in ponderosa pine forests of northern Arizona. White observed that trees within groups of mature trees with interlocking crowns were two-aged to uneven aged, with tree ages ranging from 33-268 years. To explain this observation, White proposed that pine regeneration periodically established near the edges of existing mature pine clumps. He explained that this regeneration was capable of germinating in mineral soil seedbeds created when downed logs were completely consumed during frequent fires (White 1985).

Neither Cooper's nor White's spatial pattern development theories are entirely accurate. Both the Cooper and White pattern development theories are limited because evidence supporting each theory is limited in spatial extent. White's study was completed in a small area in northern Arizona and Cooper's in a small area in the White Mountains of eastern Arizona. Cooper's theory appears compatible with contemporary pine regeneration thicket patterns on seen on productive soils, while White's theory appears to be more compatible with regeneration patterns observed on less productive soils (Heidmann 1988; Covington et al. 1997). Contemporary regeneration patterns are also highly influenced by 20th century management practices such as grazing, harvesting and perhaps human activity induced changes in the regional climate (Sánchez Meador 2006). Additionally, topographic and climatic variation is known to affect fire regime parameters such as fire frequency, intensity and severity which may also affect ponderosa pine spatial patterns (Heyerdahl et al. 2001).

The development of presettlement spatial patterns across southwestern ponderosa pine forests is a complex and unresolved process involving many factors. What is clear is that such patterns developed in an environment prone to periodic surface fires. Given this reality, it is probable that whatever the exact mechanisms for the development of these patterns may be, understanding interactions between surface fires and ponderosa pine regeneration is fundamental to understanding the overall process that shaped presettlement forest spatial patterns.

Summary

Many contemporary southwestern ponderosa pine forests do not exhibit spatial patterns similar to presettlement spatial patterns described by Cooper (1960; 1961), White (1985) and others (Harrod 1999; Youngblood 2004; Boyce et al. 2005; Sánchez Meador 2006). Silvicultural thinning treatments are currently proposed to recreate these presettlement patterns in contemporary forests. A goshawk management guidelines-based approach relies heavily on Cooper's (1960) forest spatial pattern development model, while ecological restoration guidelines more closely follow the White (1985) model. Understanding the ability of these treatment approaches to recreate presettlement spatial patterns requires both quantification of local presettlement forest spatial patterns, and a rigorous comparison of patterns developed with each of these management approaches.

CHAPTER 3

Comparing Ecological Restoration and Northern Goshawk Management Guidelines Treatments in a Southwestern Ponderosa Pine Forest

Abstract

We compared forest structure patterns resulting from the application of revised Northern Goshawk Management Guidelines (GMG) and Ecological Restoration Guidelines (ERG)-based silvicultural thinning approaches in ponderosa pine (*Pinus ponderosa* C. Lawson var. *scopulorum* Engelm.) forests on replicated sites on the Kaibab Plateau in Northern Arizona. These management approaches have been proposed for wide application across tens of thousands of hectares of southwestern National Forests within Northern Goshawk (*Accipiter gentilis*) foraging areas. Both sets of guidelines use patterns and densities of presettlement forest evidences in the form of old forest remnants (pre Euro-American settlement era trees, stumps and snags) to guide their tree marking methodologies. Tree densities resulting from the application of these treatment approaches and estimated presettlement densities were not significantly different. GMG-based treatments retained a larger proportion of trees in the middle to large size classes, resulting in statistically significantly higher canopy cover and basal area. Tree spatial point patterns and tree patches (e.g., groups of trees with interlocking crowns) were analyzed. GMG-based treatments resulted in more consistent tree aggregation at fine-scales (<15 meters), than ERG-based treatments, a

pattern similar to presettlement evidence patterns. GMG-based treatments resulted in significantly fewer isolated individual trees, a higher mean density of trees within patches and more high density tree patches than ERG-based treatment results. No difference was observed in average diameter range of trees within groups. We conclude that with minimal modification, initial thinning approaches similar to those described in this study are highly compatible, both with each other and presettlement conditions, especially within forest landscapes where reintroduction of naturally ignited fires is a management goal. Despite this similarity, ERG and GMG-based stand management approaches will differ over the long term. The goal of ERG-based management is forests that can be regulated by natural processes, most notably surface fires similar to those common in the Southwest. The GMG approach, while allowing the use of fire, will require continual forest structure regulation and will inevitably result in future removal of large, old trees.

Introduction

A legacy of 20th century land management activities in southwestern ponderosa pine (*Pinus ponderosa* C. Lawson var. *scopulorum* Engelm.) forests has been gradual development of dense and contiguous forested landscapes, highly susceptible to expensive and destructive stand replacing wildfires (Dombeck et al. 2004). There is broad agreement that forest structure restoration activities are necessary across vast areas of ponderosa pine forest in the southwestern and western United States (Moore et al. 1999; Allen et al. 2002). Ecological restoration guidelines (ERG) and Goshawk Management Guidelines (GMG)-based thinning treatments have been proposed for use across thousands of national forest hectares in the southwestern United States to reduce tree densities to levels commensurate with those common in the region prior to Euro-American settlement of the region in the late 19th to early 20th centuries (Reynolds et al. 1992; Covington and Moore 1994; Allen et al. 2002).

Ecological Restoration and Goshawk Management Guidelines Fundamentals

Ecological restoration guidelines were recently proposed by USFS Southwestern Region personnel as a silvicultural thinning approach compatible with desired conditions advocated by the GMGs (Reynolds et al. 2006). While specific project objectives may be highly variable, all ecological restoration-based activities have the goal of "reestablishing to the extent possible the structure, function, and integrity of indigenous ecosystems and the sustaining habitats that they provide (Society for Ecological Restoration 2004)".

Ecological restoration efforts within ponderosa pine forests over the last half century have shown that restoration of presettlement forest structure using fire alone often results in unintended ecosystem changes such as large, old tree mortality and the risk of stand-replacing crown fires (Sackett et al. 1995). There is now widespread agreement among restorationists that forest thinning approaches are necessary to alter forest structure conditions in order to allow ecologically beneficial surface fires to be reintroduced to ponderosa pine forests to maintain ecological function and regulate forest structure over time (Moore et al. 1999; Allen et al. 2002).

Creation of forest structural patterns within the presettlement range of ecosystem variability is the goal of ERG-based thinning approaches (Moore et al. 1999). An ERG-based thinning approach draws upon insight gained from a study completed by White (1985) near Flagstaff, Arizona. White observed that trees within tree groups (i.e., two or more trees with interlocking crowns; Figure 3.1; Table 3.1) were uneven-aged, ranging in age from 33-268 years (White 1985). For this reason, ERG-based methods attempt to manage for uneven or multi-aged forests comprised of un-even or multi-aged tree groups (Moore et al. 1999). ERG thinning methodologies do not focus upon regulated diameter distributions, but instead use the location and density of presettlement forest remnants (old trees, stumps, snags, and stump holes predating settlement of the region) as a reference for the spatial pattern and density of the restored forest. Thinning guidelines comprise only a small part of an ERG-based approach within a degraded ponderosa pine forest. Other activities may include the restoration of understory plant community composition, control of exotic plant species and regulation of livestock grazing practices and importantly the restoration of natural disturbance processes such as frequent surface fire (Moore et al. 1999; Allen et al. 2002). A fundamental objective of ERG-based treatments is the reintroduction of periodic surface fires following initial thinning treatments in order to allow the structure and function of future forest ecosystems to be shaped by this important natural disturbance process (Moore et al. 1999; Allen et al. 2002).

While ERG-based management focuses on management for ecosystem structure, function and integrity, GMG-based approaches have a greater wildlife habitat conservation focus (Reynolds et. al. 1992, Long and Smith 2000, Society for Ecological Restoration 2004). A fundamental premise of the GMGs is that northern goshawk and prey populations are limited by available food and suitable habitat (Reynolds et al. 1992). The goal of the goshawk guidelines is to create a range of forest habitats similar to the range found in presettlement forests, suitable for both goshawk nesting and a wide variety of sustainable populations of goshawk prey species (Reynolds et al. 1992; Reynolds et al. 2006).

A GMG-based approach draws upon research completed by Charles Cooper in the central Arizona highlands indicating presettlement ponderosa pine forests were uneven or multi-aged at coarse-scales, but comprised of even-aged groups of trees with interlocking crowns at finer-scales (Cooper 1960). In order to manage for similar conditions, the GMG-based approach regulates forest structure within a 2185 hectare post-fledgling and foraging area surrounding known goshawk nests using a Vegetation Structural Stage (VSS) forest structure classification system. The VSS system was developed in the late 1970s for use in western Oregon (Thomas et al. 1979) and was adapted for the National Forest Service Southwestern Region (Reynolds et al. 1992). It classifies forest structure into 0.04 to 0.16 hectare tree groups (i.e., trees with interlocking crowns; Table 3.1) of six homogenous structural classes ranging from seedlings to old, large diameter trees (Reynolds et al. 1992). A GMG-based approach regulates forest structure by balancing the relative area occupied by forest structure within each of the six VSS classes using repeated management entries (i.e., harvesting) (Figure 3.2) Additionally, GMG foraging areas must meet certain criteria such as within group canopy cover, maximum opening size, snag and downed woody debris density and reserve trees (Reynolds et al. 1992). Lastly, in recent discussions regarding the implementation of the GMGs, regional USFS officials have highlighted the importance of using presettlement forest remnants (old trees, logs, stumps, snags) to guide site-specific tree stocking levels and spatial patterns (Youtz et al. 2006). While this activity is not specifically mentioned within the original GMGs, it is a recent effort intended to bring GMG desired future conditions closer into congruency with local presettlement forest densities and spatial patterns (Reynolds et al. 1992; Youtz et al. 2006).

Since tree groups in younger structural stages will eventually grow into the oldest and largest stages over time, a GMG-based management approach will eventually result in both an over abundance of old, large diameter tree groups (VSS 6), and the need to harvest these large tree cohorts to maintain the GMG structural regulation requirements. The upper density limit of this VSS class within management areas is regulated by the rotation age specified by regional National Forest policy, approximately 200 to 250 years old (Youtz et al. 2006).

Study Objectives

Since local evidence for both ERG and GMG stand development models exists, it is unclear which of these models is best suited to develop forest structural patterns similar to presettlement conditions (Cooper 1960; White 1985). What is becoming increasingly clear is the ecological importance of forest spatial patterns. Forest spatial patterns affect northern goshawk habitat and wildlife values (Reynolds et. al. 1992; Turner et al. 1997), but also influence tree regeneration and understory plant community structure (Griffis et. al. 2001), fire behavior (Agee 1998; Fulé et. al 2001) and other ecological values and processes.

The goal of this study is to quantify and compare presettlement forest structure patterns and patterns resulting from implementation of ERG and

GMG-based treatments in order to understand the compatibility of these management approaches. To accomplish this goal, the approach used in this study addressed the following the following three objectives:

1) Assess local presettlement forest densities and spatial patterns as evidenced by forest remnants (old living trees, snags, stumps, dead and downed trees).

2) Assess ERG and GMG-based treatments efficacy in restoring site-specific presettlement forest densities and spatial patterns.

3) Compare forest structure patterns of ERG and GMG-based treatments at sub-plot to plot-scales.

Methods

Study Site

The study area is an approximately 2000 hectare area located on the western edge of the Kaibab Plateau in the Kaibab National Forest, Arizona, USA (112° 30" W, 36° 30" N) ranging in elevation from 2260 to 2350 meters. Soils across the study area are derived from porous, Permian age Kaibab limestone rock layer which underlies the majority of the Kaibab Plateau (USFS 1991). Annual precipitation is bimodal, split between winter snowfall and late summer thunderstorms, averaging 59 centimeters annually between 1971 and 2000 (Western Regional Climate Center, www.wrcc.dri.edu). The majority of the study area is comprised of pure ponderosa pine stands, with scattered groups of Gambel oak (*Quercus gambelii* Nutt.) and aspen (*Populus tremuloides* Michx.) present sporadically. Since these species were relatively rare throughout the study area only ponderosa pine forest structure information is presented in this study.

Fulé et al. (2003) reported a range of presettlement mean fire return intervals ranging from 6-12 years from an area approximately 25 kilometers south of the study area. Removal of grassy fuels through livestock and large deer herds grazing during the 1920's to 1950's (Rasmussen 1941; Merkle 1962), as well as active fire suppression efforts beginning in the 1920s, reduced the frequency of fires within the region during the majority of the 20th century (Fulé et al. 2003). Current high densities of trees within the study area can be attributed in large part to the exclusion of tree density regulating surface fire from the landscape starting around the late 1800's (White and Vankat 1993; Fulé et al. 2002; Fulé et al. 2003).

Plot Selection

We randomly located six, two-hectare sites within stratified areas of the study area extent to provide examples of forest conditions present within ponderosa pine dominated forests of the North Kaibab Plateau. We chose a two-hectare plot size partly because of logistical limitations, but also to allow assessment of finer-scale tree groups and spatial point patterns (Figure 3.1), features reported elsewhere to exist at the scale of approximately 0.02 to 0.3 hectares (Cooper 1960; White 1985; Sánchez Meador 2006; Sánchez Meador et al. 2008). We stratified areas for plot selection within the study area extent before selecting plots according to the following criteria:

1.) *Areas between the elevations of 2210 and 2360 meters.* Locally, forests within this elevation band are predominantly of the ponderosa pine type.

2.) *Areas of less than 15% slope.* This was done to minimize variation in forest structure patterns due to the influence of aspect on forest species composition.

3.) *Areas with less than 75% of living presettlement-era trees remaining.* Unharvested or very lightly harvested forests were excluded from the study due to their relative rarity across the Kaibab Plateau and southwestern ponderosa pine forests.

Plot Marking and Mapping

Richard Reynolds, the senior author of *Management Recommendations for the Northern Goshawk in the Southwestern United States* (Reynolds et al. 1992), and several crew members marked trees to be retained with colored flagging using a Goshawk Management Guidelines-based foraging area thinning prescription (Reynolds et al. 1992) during mid-summer 2007. Because of the relatively small size of the stem-mapped plots relative to most silvicultural thinning projects, GMG tree markings were not adjusted to meet the stated area targets published within the guidelines; only Vegetation Structural Stage-based (VSS) tree groupings were marked. The approach used by Reynolds in this example was intended to serve as the initial management entry into the six stands observed in this study.

Following tree marking, we used a reference grid of survey tapes to map the locations of all live trees taller than 1.4 meters within each study plot using survey methods are similar to those used by Abella (2006) and

Covington et al. (1997). For each mapped tree and presettlement forest remnant within the plot boundary, we recorded species, diameter at breast height, condition (living or snag/log classes), bark color, and the presence or absence of flagging (indicating retention using a GMG-based prescription). We then removed all flagging from each marked tree after mapping.

During fall, 2007, an ERG-based prescription was marked within the same plots by staff from the Ecological Restoration Institute following an established ecological restoration marking protocol (Covington et al. 1999). ERG marking personnel used a 1 to 1.5 presettlement evidence to post-settlement tree replacement rate described by Covington et al. (1999) for this comparison. Field staff made a modification to the previously described methodology by employing a minimum 5-6 meter spacing of post-settlement trees in order to encourage growth of these individuals. Finally, to minimize potential measurement bias, no personnel involved with marking activities were involved with tree mapping activities.

Spatial Analysis

We combined all live presettlement trees as well as stumps, snags and downed trees present within study plots for presettlement (PRE) tree density and spatial pattern analyses. We considered all living trees of any size with yellow platy bark and other old-age characteristics (large diameter branches, dead tops, mature growth form) as presettlement forest evidences in this study. Field increment boring tests, reported by ERG marking personnel, indicated trees with diameters at breast height greater than 44.4 cm diameter germinated prior to the approximate settlement date of 1880 and were therefore included as presettlement trees (*D. Lund personal communication*). Further, this diameter cut-off is comparable to White's (1985) findings indicating presettlement era (<1880 establishment) trees could be conservatively identified as trees having a diameter at breast height of 37.5 cm or larger. Although the use of presettlement forest remnants as evidence of presettlement forest structure is imperfect, a recent study comparing presettlement remnants to long-term forest survey data (83 years or older) indicates that this technique is reliable within 10 percent of presettlement densities (Moore et al. 2004).

We investigated tree and presettlement evidence location point patterns to determine if patterns were uniform, random or aggregated (Table 3.1; Figure 3.1). This was accomplished through assessment of point data using the Ripley's K(t) function (Ripley 1976, 1977, 1981) with a square root, variance stabilizing transformation of K(t) to L(t)-t (Besag 1977). Significant aggregation or uniformity was tested by comparing observed L(t)-t values to a distribution of values from 99 simulated random point patterns (Upton and Fingleton 1985, Dale 1999). All Ripley's L(t)-t analyses were completed using a custom script written in R version 2.6.1 (R Development Core Team 2007) by Sánchez Meador (2006).

Since crown radii were not measured for individual trees we predicted a crown radius for each measured tree using the following regression of tree diameter and crown radius developed by Sánchez Meador (2006):

$$CrownRadius(m) = .1387(DBHcm)^{.7901}$$
$$n = 5075;\ r^2 = 0.83$$

We modeled canopies for all mapped trees using a vector GIS approach by buffering tree locations using crown radii estimated with this method.

Tree group-scale analyses were completed using trees with interlocking tree crowns to define individual tree groups (Table 3.1; Figure 3.1). Only tree groups entirely contained within plot boundaries were included in group analyses. All tree group analyses were completed using ArcGIS 9.2 vector data analysis capabilities.

Statistical Analysis

This study was designed as a replicated comparison of forest structure attributes resulting from the application of GMG and ERG-based treatments and to estimates of presettlement forest structure (PRE). Therefore, no statistical comparisons were made to contemporary forest structure conditions. However, contemporary information is presented for visual comparison with ERG and GMG-based treatment results. An alpha level of 0.05 was used for all tests. Assumptions of normality were assessed using the Shapiro-Wilk test. If assumptions of normality were met, paired parametric t-tests were used, otherwise the non-parametric Wilcoxon-signed rank test was used. Bonferroni correction was used to test for tree density differences in six diameter classes corresponding to the six VSS classes between treatment results. An exception to the use of paired t-tests was the use of a single factor ANOVA test to compare ERG and GMG-based treatment densities with estimated presettlement tree densities (PRE).

Results

Plot-scale metrics

Both GMG and ERG-based treatments resulted in tree densities that were not significantly different from presettlement forest densities (Table 3.2). GMG-based treatments resulted in a statistically significant, although only slightly higher, average basal area versus ERG-based treatment (21.8 m^2 ha^{-1} versus 18.0 m^2 ha^{-1}). Overall canopy cover, as determined by simulated tree canopy area as a percentage of the total plot area, was also significantly higher after GMG-based treatments than ERG treatments, although the absolute difference between these canopy cover estimates was quite small (24 versus 26 percent cover) (Table 3.2).

Diameter distributions resulting from GMG and ERG treatments were similar, although there were statistically significant differences in kurtosis and diameter classes. Although not statistically significant, on average, GMG diameter distributions were more negatively skewed (γ_1 = -0.07) toward larger diameter classes than ERG diameter distributions (γ_1 = 0.04). GMG-based treatment diameter distributions exhibited a peak in the middle to larger tree size classes (30 to 50 cm), while diameter distributions resulting from ERG-based treatments were more evenly distributed across all size classes. Average kurtosis values, a measure of distribution "peakedness," were negative for both GMG and ERG distributions, although diameter distributions resulting from GMG treatments were statistically significantly different than those resulting from ERG treatments (γ_2 = -0.42 versus -1.02).

Cumulative diameter distributions from all six mapped plots (8 hectares) illustrate the overall differences in diameter distributions between the two treatment approaches (Figure 3.3). ERG-based treatments resulted in higher densities of small diameter (<16 cm) and lower densities of medium diameter (24-48 cm) trees compared to GMG-based treatments. Both treatments resulted in nearly identical tree densities in the largest diameter classes (>56 cm). Of the six VSS classes, only tree densities in VSS class 4 differed significantly between treatment approaches, with GMG based treatments resulting in significantly higher densities (Table 3.3).

Point Pattern Analysis

Living presettlement era trees and non-living presettlement forest remnants were significantly aggregated at lag distances from 0 to 10 meters on all plots with the exception of plot 5 (Table 3.4). The mean minimum lag distance at which the fine-scale aggregation patterns were no longer discernable from a random pattern was approximately 23 m (S.E. = 6.5).

Significant aggregation of these structures was also observed at longer lag distances from 20-30 m on plots 2, 3 and 6 up to a 50 m lag distance on plot 1. This contrasts with contemporary forest conditions where live trees are aggregated at distances from 0 to approximately 20 to 40 meters on all plots and aggregated at all distances on plots 2, 3, and 6 (Table 3.4).

Both treatments dramatically affected tree spatial patterns. GMG-based treatments resulted in forest structure aggregation at lag distances of less than 10 meters on all measured plots. Aggregation patterns became indistinguishable from random patterns at lag distances of 14 meters or less on all plots with the exception of plots 2, 5 and 6 where significant aggregation either continued to greater lag distances (plots 2 and 5) or exhibited a additional aggregation greater lag distances (plot 6). Only one plot (plot 1) exhibited significant uniform spacing at any lag distance. On this plot, uniform spacing was observed at lag distances ranging from 8 to 16 meters. ERG-based treatments resulted in a peak of uniform spacing at distances less than 10 meters on plots 3, 4 and 5 and another peak in uniform spacing at distances beyond 40 meters on plot 5. Several peaks in significant aggregation were observed at distances ranging from 4 to 30 meters on plots 2, 4 and 5. Plot 6 exhibited significant aggregation from a lag distance of 16 meters to the maximum lag distance of 50 meters.

Tree group characteristics

Both treatments reduced the average number of tree groups per plot dramatically, from 43 to 79 percent overall. The number of tree groups per plot was very similar between treatment approaches, with GMG-based treatments resulting in a slightly higher, statistically insignificant, number of groups versus ERG-based treatments (Table 3.5).

GMG treatments yielded significantly more large groups per plot. GMG treatments resulted in an average of 11 groups with 5 or more trees per plot versus an average of about 4 groups of this size resulting from ERG-based treatments (Table 3.5). A similar difference was observed at larger group sizes, with GMG-based treatments resulting in an average of 3.3 groups comprised of 10 or more individuals, versus an average of 0.3 groups per plot resulting from ERG-based treatments (Table 3.5). ERG based treatments resulted in a significantly higher number of solitary trees than GMG-based treatments

While overall tree group numbers decreased, average group area (projected crown area) increased 52 percent on average after ERG-based treatments and 67 percent after application of GMG-based treatments. Average group area was reduced following these treatments only on plots 5 and 6 (Table 3.5). The two treatment approaches differed little in average tree group area, but GMG treatments resulted in larger average maximum group area versus ERG treatments, although this difference was not statistically significant (Table 3.5).

Average diameter range, a surrogate metric of tree group agedness, dropped an average of 16 and 17 percent following the application of ERG and GMG-based thinning treatments respectively (Table 3.5). This drop was not entirely consistent in all situations, as diameter range increased after treatment on some plots. Overall no statistical difference in average tree diameter range within groups was observed between ERG and GMG-based treatment approaches.

Discussion

What are the patterns of presettlement forest remnants used by practitioners of ERG and GMG-based treatments?

Average presettlement forest evidence densities of stands assessed in this study are slightly lower than presettlement forest structure studies reported in the literature for nearby areas. Fulé et al. (2002) used dendrochronological methods to reconstruct presettlement ponderosa pine densities in three areas along the North Rim within Grand Canyon National Park. Densities reported in these three sites averaged 152.7 pines ha^{-1} versus a mean of 141.2 pines ha^{-1} observed within the six plots assessed in this study. These lower density estimates may be related to the slightly lower elevation range of our study landscape relative to the sites assessed by Fulé et al. (2003).

Spatial patterns evident from analysis of the locations of presettlement forest structures indicates a high degree of aggregation at fine-scales (<10 meter lag distances). This finding is similar to other presettlement ponderosa pine forest spatial patterns observed in the Southwest. Sánchez Meador (2006) reported statistically significant aggregation patterns at lag distances less than 40 meters with a peak in aggregation at lag distances of 6 to 8 meters for presettlement forest structures on six plots near Flagstaff, Arizona. Other studies of presettlement forest spatial patterns in ponderosa pine forests of the western US report similar results (Harrod et al. 1999; Youngblood et al. 2004). Consistent fine-scale spatial aggregation of presettlement forest structures observed within all six plots may be due in part to the relatively small study landscape and stratification techniques employed in this study. It is possible that these presettlement patterns may differ with other patterns existing on other soil types, aspects and slopes (Heyerdahl et al. 2001).

At coarser-scales (>10m lag distances), there a fairly consistent gradual transition from an aggregated pattern to random spatial patterns, indicating a random arrangement of tree clusters throughout the study plots. This trend is also supported by other studies in western and southwestern ponderosa pine forests (Harrod et al. 1999; Youngblood et al. 2004; Sánchez Meador 2006). An important issue associated with this finding is the relatively small plot size used in this study to assess aggregation patterns at these coarse-scales. At the coarsest-scales, edge effects increase in importance, complicating spatial analysis results (Boots and Getis 1988).

Do Ecological Restoration and Goshawk Management Guidelines-based treatments restore presettlement forest density and spatial patterns?

Use of presettlement evidences by both ERG and GMG practitioners during tree marking was consistent with restoring presettlement densities. However, there appear to be important differences in the spatial arrangement of these trees with the implementation of each approach.

It is not realistic to assume ERG-based treatments are capable of restoring presettlement evidence patterns perfectly; but spatial patterns resulting from use of this treatment approach differed consistently with presettlement patterns in this study. Fine-scale ERG spatial patterns exhibited a much greater trend towards random and uniform spatial patterns than those resulting from GMG-based treatments. Several important factors are likely responsible for this inconsistency. First, is the use of a minimum tree spacing of approximately 6 meters, a modification to existing ecological restoration guidelines. Through use of this modification, marking personnel were unable to replicate the significantly aggregated presettlement forest spatial patterns observed on all of the six plots assessed. While at odds with presettlement evidence patterns, this modification may be useful for restoration of dry sites or sites with few large trees, as it may encourage tree growth by restricting intra-tree root competition. A second contributing explanation may be the maximum search radius employed in ERGs. The search radius is the distance between presettlement forest evidences and a post-settlement replacement trees. Since replacement trees are not necessarily adjacent to presettlement evidences, use of a search radius is often necessary. An approximately 18 meter maximum search distance was employed by ERG-marking personnel in this study. Because such a large search radius was used, the distance between presettlement evidences and a replacement trees may have been greater than presettlement forest evidence aggregation distances. Casual observations within study plots indicate this situation is fairly common. This situation is further compounded when a long distance search radius is used for selection of several replacement trees. Finally, some degree of error in application of the ecological restoration guideline methodology is also possible. Such errors could take the form of overlooking or missing presettlement evidences, or selecting replacement trees at a distance greater than the maximum search radius. While personnel involved in the ERG marking process have years of experience applying these guidelines, it is probable that such errors contributed to the observed discrepancies with presettlement patterns to some degree.

GMG-based treatments resulted in tree location aggregation patterns consistently similar to presettlement forest evidence aggregation patterns at fine-scales (<10 m lag distances). These fine-scale aggregation patterns are also intrinsically related to the method GMG-based treatment marking personnel used to assess presettlement evidence spatial patterns and the wildlife habitat management objectives described within the GMGs.

Although inclusion of site specific reference information recently has been promoted as a means to implement GMG-based treatments (Reynolds et al. 2006; Youtz et al. 2008), a specific methodology for doing so has not been outlined in published literature. The GMG-based approach used a "patch-scale" presettlement evidence to post-settlement tree patch replacement method. Whenever an aggregated patch of several dead presettlement evidences (most commonly cut stumps) was encountered by Reynolds or crew members, a patch of similar density and spatial pattern was selected from the surrounding post-settlement forest structure as a replacement for the presettlement evidence patch (*Richard Reynolds personal communication*). Further, GMG wildlife management perspective undoubtedly influenced selection of retained tree patches. Such fine-scale aggregation patterns are known to be beneficial to many small mammal and bird species that comprise the northern goshawk food web (Reynolds et al. 1992, Reynolds et al. 2006). This patch-scale approach, while obviously not capable of restoring patterns exactly, appeared to succeed in recreating presettlement patterns and initial wildlife habitat conditions better than ERG-based methods.

How do forest structure patterns of ERG and GMG-based treatments compare at sub-plot to plot-scales??

Despite statistically significant differences in basal area and canopy cover values (the latter being highly dependent upon the former) absolute differences were not large, with only 17 percent average difference in basal area and a 1.6 percent average difference in canopy cover. These differences are attributable to significantly different tree densities in the 30 to 46 cm diameter tree size class, corresponding to VSS class 4 (Figure 3.3).

Since ERGs specifically advocate retention of trees with old age characteristics, it is probable that the majority of this basal area difference is found in the large, but not necessarily old post-settlement tree classes. Density differences in these size classes may be related to two components of GMGs. First, trees in these size classes are preferred habitat for the tassel-eared squirrel (*Sciurus aberti*) and other closed-canopy dependent goshawk prey species. Second, the regulated diameter distribution required by GMGs necessitates greater numbers of trees in larger diameter classes than in smaller ones (Patton 1984, Reynolds et al. 1992). While density differences in smaller size classes were not observed, the more positively skewed and significantly higher average kurtosis values resulting from ERG-based treatments indicate that a broader range of tree diameters were retained throughout the entire diameter range than in GMG-based treatments. This difference is probably the result of an unregulated diameter distribution applied within forests containing large contemporary densities of small diameter trees (Table 3.2).

Sub-stand tree group differences and trends

Tree group-scale characteristics appear to be related to point patterns. The consistent fine-scale tree aggregation patterns created by GMG-based treatments resulted in significantly more groups of trees with interlocking crowns, fewer single trees, higher average group densities and higher densities of large tree groups (groups with 5 or 10 or more trees) per plot.

Spatial patterns *within* tree groups were not assessed in this study, but it is probable that trees within GMG groups are more closely aggregated than ERG-marked tree groups, as average group area and average maximum group area did not differ despite the previously mentioned differences. Since GMGs advocate retention of groups of large trees with interlocking crowns with high canopy cover to provide habitat for animals that form northern goshawk's prey base (Reynolds et al. 1992; Reynolds et al. 2006; Youtz et. al 2008), the high aggregation and patchiness associated with this treatment was a logical outcome.

A surprising finding is the lack of an observed difference in average diameter range of trees within groups resulting from ERG and GMG-based treatments. An uneven-aged forest comprised of well-interspersed, even-aged, or homogenous VSS groupings is a stated goal of GMG-based treatments. If diameter is used as a surrogate for age, as is often done, the range of diameters within even-aged groups should logically be narrower than the range of diameters within uneven-aged groups. Results of this study indicate that there is no consistent difference in the range of diameters within tree groups resulting from ERG or GMG-based thinning treatments. This lack of difference may be related to the finding that both treatments sought to retain nearly all of the oldest, largest diameter trees within all six plots, and, ERG-based treatments resulted in higher proportions of single trees unassociated with tree groups. The largest trees have the largest crown radii, and, therefore, are the most likely to be part of a group, regardless of their location relative to other trees. By the same rationale, small diameter trees are less likely to be included in a group and more likely to occur singly. Large trees drive both the formation of tree groups with interlocking crowns and contribute a large amount of group diameter variation. The retention of these trees with both treatment approaches is probably in large part responsible for the group diameter range results observed in this study. The significantly higher number of smaller, solitary trees retained by ERG-based treatments provides a further explanation for this trend.

GMG-based treatment results should be interpreted with caution, as this study represents only the initial management entry into these six stands. It is likely that many of the large diameter trees retained with the GMG-based treatment would be removed during the second management to regulate the abundance of VSS 5 and 6 group area to other VSS class groups.

Tree group metrics: limitations and presettlement context

Tree group-scale characteristics presented in this study are an inexact representation of actual patch structure characteristics existing within forest stands. Irregular tree crown shapes and bole lean were not assessed or incorporated into the tree patch model used in this study, thus restricting the accuracy of the results. Sánchez Meador (2006) has indicated that number of trees included within tree groups is highly sensitive to crown radii variation. Furthermore, tree group characteristics will change over time as crown radii increase with tree diameter growth. Despite these limitations, the tree patch identification technique employed in this study is useful for understanding the underlying effects of GMG and ERG-based treatments on tree group characteristics.

Since reconstruction of presettlement forest groups was not completed in this study, it is unclear how the results of GMG and ERG-based treatments compare with presettlement group characteristics at this site. A study that reconstructed presettlement (<1875) tree group characteristics at six sites located in the Coconino National Forest near Flagstaff, Arizona (Sánchez Meador 2006), reported tree group densities 40 to 60 percent higher than those reported in this study. While average group density was higher, average tree density within groups assessed by Sánchez Meador (2006) (4.2 trees per group) was consistent with GMG-based treatment results and 49 percent higher than ERG-based treatment results. Sánchez Meador's average maximum patch density (17.5) was more similar to GMG-based results (20.5) than ERG-based results (8.8) (Sánchez Meador 2006). Since little is known about variation in presettlement tree group characteristics within ponderosa pine forests of the Southwest, the similarities or differences between the results of these studies may or may not be coincidental.

Ecological Restoration and Goshawk Management Guidelines: Compatible Forest Restoration Solutions?

Overcoming fundamental differences

A fundamental difference between the forest management approaches assessed in this study is the means by which future forest structure patterns at these sites will be regulated. Ecological restoration clearly promote use of prescribed or natural fires as the primary means of regulating future tree regeneration and forest spatial patterns because much evidence indicates that interaction of surface fires with patches of young trees was responsible for regulating presettlement spatial patterns in Southwest ponderosa pine forests (Covington 2003). Conversely there is little evidence that fires interacted dynamically with mature or old ponderosa pine trees to shape presettlement forest structure patterns.

GMG-based forest management advocates consistent forest structure regulation through the use of repeated management thinning entries over time. Harvesting large, old, fire-resistant trees over time is a tacit assumption of these guidelines as they are applied over time. Since presettlement surface fires did not interact dynamically with trees in these structural classes there is no evolutionary or ecological basis for such a management approach. Furthermore, as trees in smaller size classes will eventually grow into the largest size classes over time, it is not a question of *whether* large old trees will be cut using the GMGs, but more a question of *when* they will be cut.

The level of large diameter harvesting associated with GMG-based forest approaches will depend, in large part, upon the rotation age employed throughout the region and the method used to assess VSS class regulation within Goshawk foraging areas. The former issue is essentially a question of whether society is ready to harvest large, old trees, both now and in the future. Unsustainable harvesting of large old trees in many portions of the Southwest is often cited as one of the major causes of forest health declines over the last century (Moore et al. 1999; Allen et al. 2002). While it is impossible to rule out future harvesting of large, old trees, today this approach may receive little public support given the relatively high ecological value and low density of these trees across Southwest forest landscapes, not to mention their social importance within the region. The latter issue, VSS class regulation, is a technical one, and will require a realistic approach to assessing and regulating VSS tree groupings throughout the region.

First, treatment implementation monitoring will be necessary to assess tree aggregation patterns. Monitoring approaches must evolve to be able to assess forest spatial patterns. Forest inventory approaches developed to assess tree density and volume are not suitable for assessment of sub-stand forest spatial patterns advocated by the GMGs. The mapping approach used in this study was time consuming and expensive, and may not be practical for forest treatment effectiveness monitoring purposes. A GIS based inventory approach utilizing high resolution imagery or LIDAR data (Lo and Yeung

2002) may be both more efficient and practical for assessing the success of silvicultural thinning treatment objectives.

Second, it will be difficult to regulate VSS groupings by area if trees are not aggregated at the required spatial scales. Even with improved, spatially explicit monitoring approaches, VSS group identification will always be a challenge. VSS structural stage distinctions vary with elevation, aspect, latitude and stand productivity. While many contemporary forests are essentially even-aged, many also contain uneven-aged tree groups. Given these challenges, agency budgetary limitations, and competing forest management priorities, it may not be possible to accurately assess and regulate VSS structures during a single management entry.

The approach used by Richard Reynolds in this study is a realistic first step to implementing GMGs in contemporary southwestern forest lands that often lack presettlement tree aggregation patterns. With initial treatments, managers can focus on recreating site-specific aggregated tree spatial patterns and densities before attempting to regulate VSS groups by area. Stands treated with a GMG-based management approach may not be reassessed for silvicultural treatments for many years, and during this time forest structure may change due to wildland fire impacts or other factors. The use of a similar approach may help managers to avoid "analysis paralysis" associated with VSS class regulation, while slowly moving towards the desired forest conditions described within the GMGs.

Finally, the realities of southwestern climate and regional USFS management will ultimately determine the degree to which fire plays a role in stand development within goshawk foraging areas. During this study, one of six the assessed stands was allowed to burn in a lightning-ignited wildfire under Wildland Fire Use guidelines (www.inciweb.org 2008). In landscapes where fires are allowed to burn, the question shifts from whether these management approaches are compatible with each other to whether these management strategies are compatible with fire. This question was not specifically assessed within this study, but it is clear that both approaches reduced many forest attributes (e.g.,, canopy cover, canopy biomass, tree density) associated with the threat of catastrophic crown fire (Peterson et al. 2005). In this regard, both approaches appear highly compatible.

If initial GMG-based silvicultural thinning treatments are applied in forests similar to the ones described in this study, results can be expected to be highly compatible with ERG-based objectives. Further, minimal modification of ERG-based treatment methodology appears capable of producing forest structural patterns with greater wildlife habitat values. While there is room for refinement of the methodologies used in both approaches, both appear capable of moving current forest structural conditions closer to presettlement forest structure patterns. Perhaps more importantly, both silvicultural approaches appear to result in forest structure conditions that are sustainable within landscapes managed with either natural or management ignited fires.

Acknowledgements:

The authors would first like to thank District Ranger Tim Short and all staff of the North Kaibab Ranger District of the Kaibab National Forest for supporting these research efforts over the last three years. We would also like to thank Richard Reynolds, Allison Cofer and crew, as well as Dennis Lund, Charlie Denton, Dave Brewer and Michael Stoddard for generously donating days of time and effort to mark trees for retention with each treatment prescription. We also thank Andrew Sánchez Meador for his generous spatial statistical advice and technical support. Finally, we would like to thank the enthusiastic crew of ERI staff members and student research assistants for their tireless efforts to document the over 7500 tree locations and attributes assessed in this study.

Table 3.1: Sub-plot scale forest pattern definitions.

Group	A sub-stand or plot patch consisting of two or more trees with interlocking crowns.
Aggregated	Indicates that at a certain scale (h), tree locations are significantly more aggregated than what would be expected from 99 simulated random point patterns.
Uniform	Indicates that at a certain scale (h), tree locations are significantly less aggregated than what would be expected from 99 simulated random point patterns.

Table 3.2: Density, basal area and canopy cover estimates. All contemporary trees (ALL), resulting Ecological Restoration Guidelines (ERG), and Goshawk Management Guidelines (GMG) and Presettlement Evidences (PRE†).

	Trees per Hectare					Basal Area (m^2 ha^{-1})			Canopy Cover (%)		
Plot	PRE	% Live	ALL	ERG	GMG	ALL	ERG	GMG	ALL	ERG	GMG
1	183.5	37	538.1	159.2	155.7	27.1	20.7	23.3	32.4	26.2	28.2
2	114.1	46	302.5	104.1	137.4	22.1	15.5	19.5	24.5	19.0	21.1
3	131.4	50	761.3	135.4	109.6	31.8	18.8	23.6	40.0	27.5	27.1
4	176.1	34	794.0	163.2	176.6	29.4	18.3	22.6	39.1	25.9	29.5
5	122.5	58	398.7	100.7	153.7	34.8	16.1	21.1	42.3	20.9	24.1
6	122.5	43	368.0	131.9	144.8	30.1	18.4	20.6	35.5	23.6	23.1
Mean	141.7	44.7	527.1	132.4	146.3	29.2	18.0*	21.8*	35.6	23.9*	25.5*
Standard Error	12.3	3.7	85.3	10.8	9.1	1.8	0.8	0.7	2.7	1.3	1.3

† where applicable; * statistically significant difference at 95% level

Table 3.3: Tree densities (per hectare) resulting from each treatment within six diameter classes (classes correspond to VSS diameter class cut-offs). Two-tailed paired t-test; alpha = .0083 with Bonferoni adjustment.

VSS Class	Diameter Range (cm at DBH)	Mean	
		ERG	GMG
1	0-4	9.7	5.3
2	4.1-16	18.5	8.0
3	16.1-32	27.9	34.4
4	32.1-46	26.3*	46.0*
5	46.1-62	34.0*	36.5*
6	62.1+	16.0	16.0

* Statistically significant difference at 95% level

Table 3.4: Spatial distribution [L(t)-t] of presettlement forest remnants and residual trees following simulation of ERG and GMG-based thinning treatments. Statistical significance at the 95% level is indicated by (+) for aggregated, (–) for uniform patterns; R represents forest structure patterns that do not differ significantly from a random (Poisson) pattern.

	Lag Distance (meters)																								
	2	*4*	*6*	*8*	*10*	*12*	*14*	*16*	*18*	*20*	*22*	*24*	*26*	*28*	*30*	*32*	*34*	*36*	*38*	*40*	*42*	*44*	*46*	*48*	*50*
Plot 1																									
PRE	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
ERG	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
GMG	R	+	+	R	R	--	--	--	--	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Plot 2																									
PRE	+	+	+	+	+	+	+	+	+	+	+	+	+	+	R	R	R	R	R	R	R	R	R	R	R
ERG	R	R	+	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
GMG	R	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Plot 3																									
PRE	+	+	+	+	+	+	+	+	+	+	+	R	R	R	R	R	R	R	R	R	R	R	R	R	R
ERG	R	--	--	--	R	R	R	R	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
GMG	R	R	+	+	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Plot 4																									
PRE	+	+	+	+	+	R	+	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
ERG	R	--	--	R	R	R	R	+	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
GMG	R	+	+	+	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Plot 5																									
PRE	+	+	R	R	R	+	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
ERG	R	R	R	R	R	R	R	+	+	+	+	+	+	+	R	R	R	R	R	R	--	--	--	--	--
GMG	R	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Plot 6																									
PRE	+	+	+	+	+	+	+	+	+	+	+	R	R	R	R	R	R	R	R	R	R	R	R	R	R
ERG	R	R	+	+	+	+	+	+	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
GMG	R	+	+	+	+	+	+	R	R	R	R	R	R	R	R	R	R	R	R	R	R	+	+	+	+

Table 3.5: Observed post-treatment tree group characteristics: Total Groups and Group Densities (asterisks indicate statistically significant differences at the 95% level).

	Plot Number						Descriptive Statistics	
	1	*2*	*3*	*4*	*5*	*6*	*Mean*	*SD*
Single Trees								
ALL	335	209	298	303	161	151	242.8	79.3
ERG	146	99	127	152	88	98	118.3*	27.1
GMG	83	57	50	73	51	45	59.8*	14.9
Total Groups								
ALL	150	58	181	198	99	80	127.7	57.0
ERG	50	29	39	65	35	43	43.5	12.7
GMG	62	28	38	72	49	46	49.2	15.9
Groups with 5 or more trees								
ALL	34	17	64	77	35	32	43.2	22.5
ERG	8	3	4	1	0	6	3.7	3.0
GMG	11	7	6	13	18	11	11.0	4.3
Groups with 10 or more trees								
ALL	16	6	24	29	12	14	16.8	8.4
ERG	0	0	1	0	0	1	0.3*	0.5
GMG	2	4	2	2	5	5	3.3*	1.5
Mean Group Density								
ALL	4.4	5.7	5.9	6.0	5.3	6.2	5.6	0.7
ERG	3.2	2.9	3.1	2.4	2.4	3.1	2.8*	0.4
GMG	3.3	6.4	3.6	3.4	4.6	4.1	4.2*	1.2
Max Group Density								
ALL	35.0	49.0	37.0	50.0	32.0	43.0	41.0	7.5
ERG	9.0	7.0	16.0	6.0	4.0	11.0	8.8	4.3
GMG	11.0	48.0	16.0	13.0	18.0	17.0	20.5	13.7

Table 3.5 (*continued*): Observed post-treatment tree group characteristics: Groups Area and Tree Diameter Range (asterisks indicate statistically significant differences at the 95% level

	Plot Number						Descriptive Statistics	
	1	*2*	*3*	*4*	*5*	*6*	*Mean*	*SD*
Mean Group Area (m^2)								
ALL	34.4	52.9	30.3	31.4	63.4	61.6	45.6	15.4
ERG	66.3	67.0	82.4	44.8	53.5	58.2	62.0	13.0
GMG	68.2	87.4	82.7	50.8	66.9	59.7	69.3	13.8
Max Group Area (m^2)								
ALL	254.3	587.2	400.3	411.8	381.1	343.6	396.4	109.4
ERG	221.6	160.9	373.3	138.6	153.2	168.0	202.6	88.3
GMG	242.3	587.2	359.7	197.4	193.5	228.3	301.4	152.5
Mean DBH Range within groups								
ALL	17.3	23.8	7.7	20.9	21.6	22.7	19.0	5.9
ERG	18.0	17.0	23.6	17.5	9.8	17.9	17.3	4.4
GMG	17.7	21.6	17.6	16.2	17.3	14.7	17.5	2.3

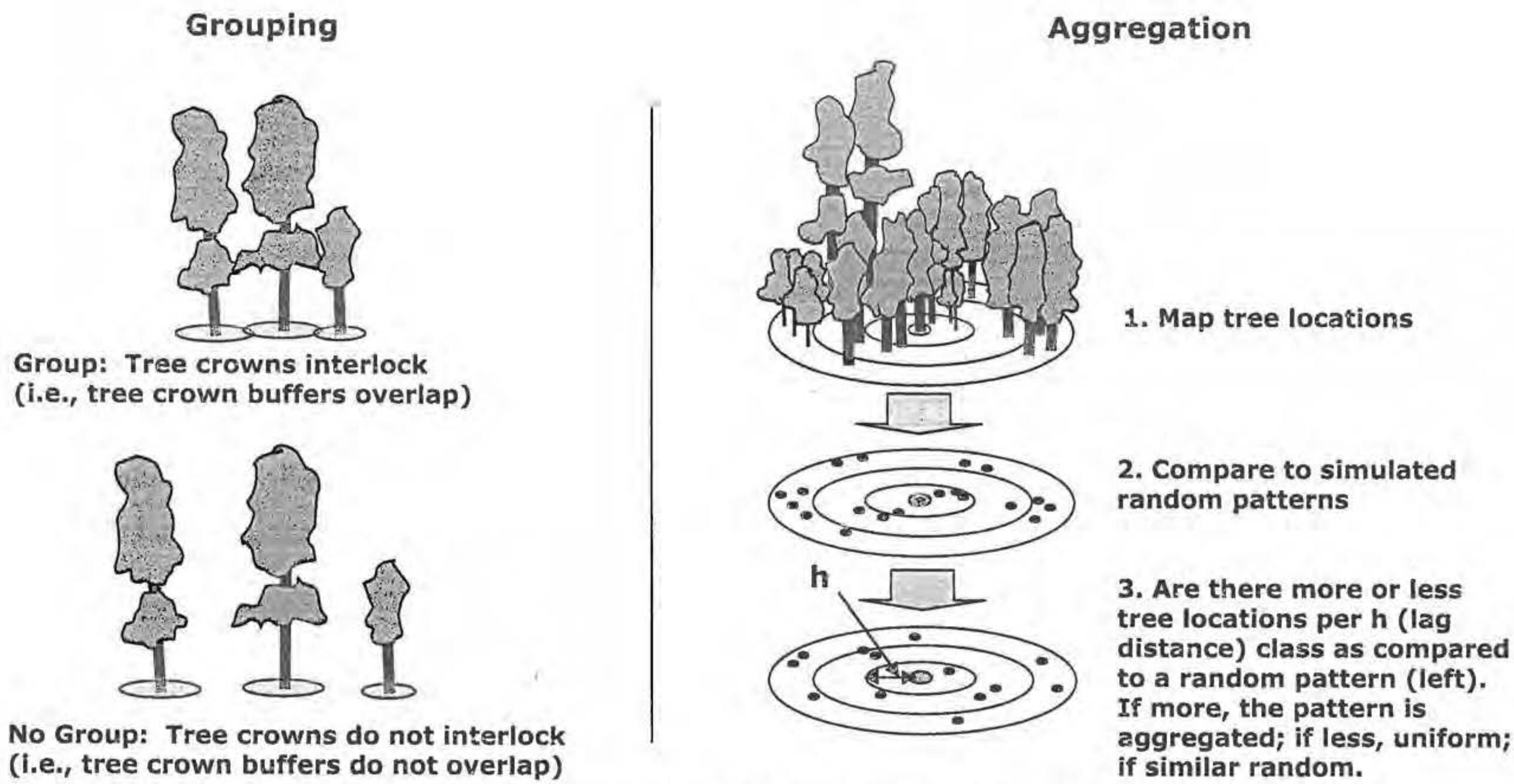

Figure 3.1: Discerning Sub-Plot Scale Groups and Spatial Point Patterns. Tree groups are discerned by the characteristics of individual trees (crown radius) comprising the group. Aggregation is determined by comparing the relative density of *n* tree centers within multiple concentric plots of increasing radii (h) to the relative density of *n* points generated by 99 simulated random point patterns within multiple concentric plots of increasing radii (h).

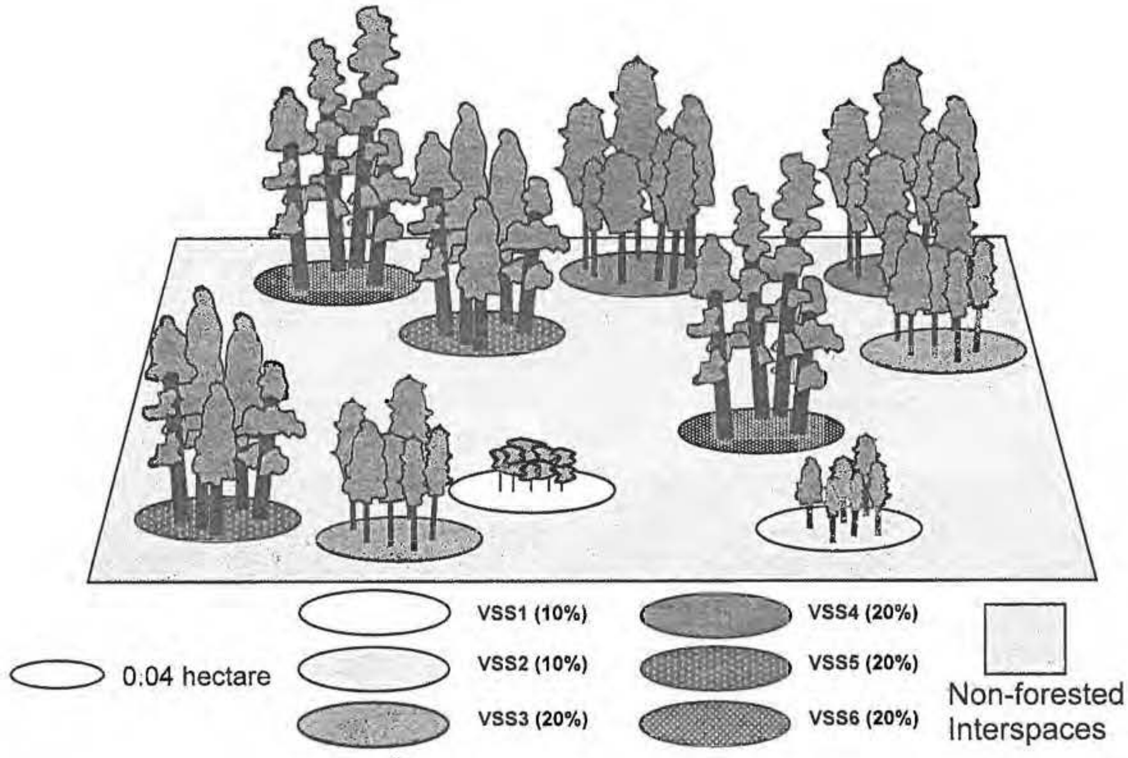

Figure 3.2: A hypothetical representation of Vegetation Structural Stage (VSS) group area targets and reserve trees for an approximately 1.2 hectare area within a northern goshawk foraging area.

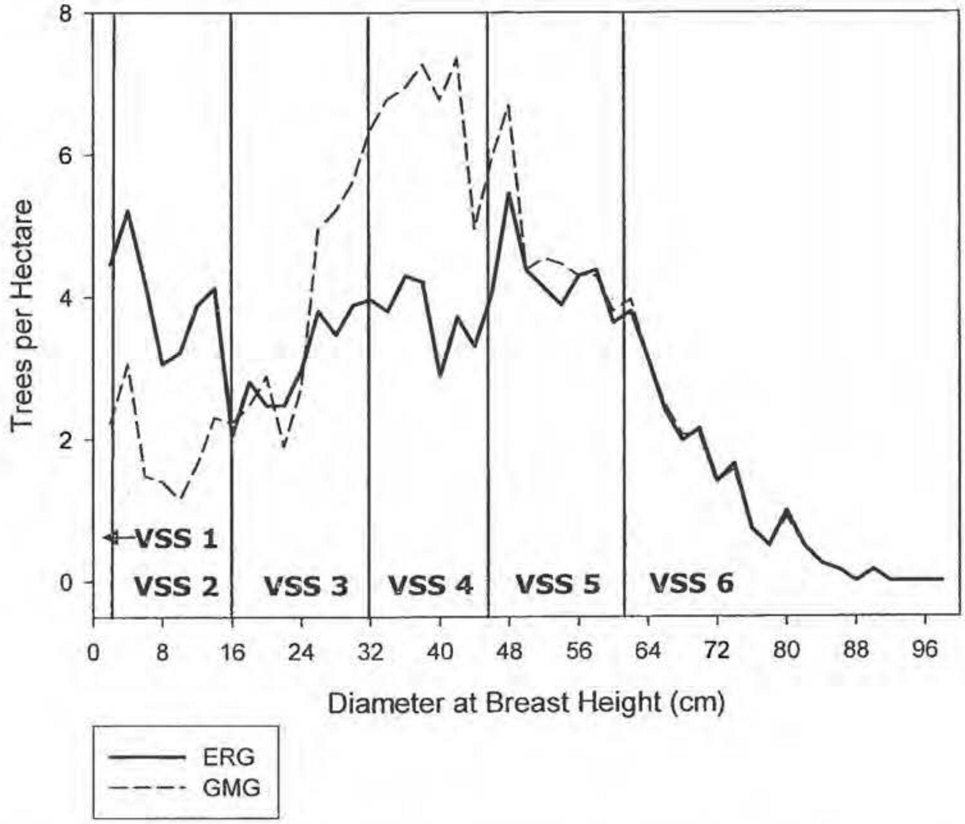

Figure 3.3: Cumulative residual tree diameter distribution and Vegetation Structural Stage (VSS) diameter class breaks for all six measured plots of each treatment approach. GMG = Goshawk Management Guidelines for Foraging Areas, ERG = Ecological Restoration Guidelines.

CHAPTER 4

Management Implications

Both ecological restoration (ERG) and goshawk management guidelines (GMG)-based forest management approaches have the broad goal of approximating presettlement forest spatial patterns through the use of forest management activities. To this end, practitioners of both approaches make use of presettlement forest remnant patterns (large old trees, snags and downed trees) to inform site-specific thinning treatment prescriptions. Use of these remnants to guide thinning processes has been described in ERG literature (Moore et al. 1999), but practical application of these guidelines is often complicated, and the efficacy of this approach in recreating site specific presettlement remnant patterns has not been tested. Given the ecological importance of forest spatial patterns, and the importance of specific spatial patterns to future VSS group regulation within goshawk foraging areas (Reynolds et al. 1992), it is important that forest spatial patterns resulting from both thinning and burning treatments are monitored and evaluated. Spatially explicit monitoring and assessment of forest spatial patterns is necessary to understand the effects of management approaches and natural processes that will ultimately shape future southwestern forests.

Using presettlement forest remnants to understand and create contemporary forest spatial patterns.

Forest researchers and policy makers have advocated using presettlement forest remnants to guide silvicultural thinning prescriptions (Moore et al. 1999; Taylor 2004; Reynolds et al. 2006; Youtz et al. 2008). These presettlement remnants or evidences are most commonly found within forests in the form of old living trees and old, non-living stumps, snags and downed trees. Non-living presettlement forest remnants often persist in ponderosa pine forests due to extremely slow rates endemic to the southwestern region. Locations of these remnants can be used to both inform and guide spatial pattern generation of forest restoration thinning projects (Covington and Moore 1994; Covington et al. 1999).

Despite widespread agreement among forest managers and researchers regarding the ecological importance of restoring presettlement spatial patterns, specific methods for using these structures in silvicultural thinning treatments either have not been thoroughly assessed for their efficacy in recreating presettlement patterns or remain unstated in technical terms (Reynolds et al. 2006; Youtz et al. 2008).

Three Approaches for Restoring Spatial Pattern

Three general methods exist for using site-specific presettlement forest evidence to guide forest spatial pattern generation in silvicultural thinning projects. The first involves a pretreatment assessment of presettlement remnant patterns and the latter two involve utilizing the locations of presettlement evidences during the tree marking (typically "leave-tree" marking) process:

1.) Assessment of presettlement forest structure patterns before treatment prescriptions are developed.

General forest spatial structure information such as tree aggregation patterns and tree group (i.e., groups of trees with interlocking crowns) sizes can be obtained through pre-treatment assessments. This information should be included in the development of site-specific silvicultural thinning prescriptions when restoration of presettlement spatial patterns is a project goal. This information can be used to assess the effectiveness of thinning treatments in recreating site specific spatial patterns. This approach requires substantial investment in pre-treatment presettlement spatial pattern assessment and analysis, and may be an expensive option not suitable for small "project-scale" thinning treatments.

2.) Individual tree-scale presettlement evidence replacement.

This approach uses the location, density and species composition of presettlement evidences to guide selection of trees for retention during ecological restoration marking activities (Figure 4.1). Such an approach has been widely researched and promoted at Northern Arizona University's Ecological Restoration Institute (Covington et al. 1994; Fulé et al. 2004). Typically all trees having old age characteristics, regardless of size, are retained. An additional 1.5 to 3 healthy trees that have established after settlement (settlement dates range from 1870s to after 1900 in some areas) are retained as close as possible to every non-living presettlement evidence (e.g., stumps, snags, dead and down trees) encountered during the tree marking phase of restoration activities. The goal of this approach is to recreate not only the spatial aggregation patterns (i.e., tree group sizes and patterns), but to also retain tree groups as near as possible to the location of presettlement evidence groups.

3.) Patch-scale presettlement evidence replacement

This approach is similar to individual tree-scale replacement described above, but differs in the scale at which presettlement evidences are replaced by post-settlement trees (Figure 4.1). Using patch-scale replacement, all old age trees are retained, but contemporary live tree patches are retained for every presettlement remnant patch. Using this approach, special effort is taken to select patches of similar size, density and aggregation patterns to non-living presettlement remnant patches. This approach is used by practitioners of Goshawk Management Guidelines (*Richard Reynolds, personal communication*). Key differences between this approach and individual tree replacement approach are: Patches are the unit of replacement versus individual trees, and the location of the retained post-settlement tree patches relative to presettlement remnant patch locations is not maintained.

Each of these three methods has utility for recreating and assessing presettlement forest spatial patterns. An understanding of site specific spatial patterns is useful to those designing site-specific, presettlement reference condition-based silvicultural thinning treatments. If management for local presettlement spatial patterns is a project objective, knowing the spatial pattern parameters will inform both the selection of activities needed to accomplish this objective and whether or not spatial pattern objectives have been accomplished. Ideally, spatial pattern information would be collected for every intensive thinning project to aid in development of local prescriptions. In practice, there is unlikely to be time or funds available for this purpose. In such situations, managers must rely on spatial pattern assessment and recreation techniques during the tree marking phase of forest thinning treatments.

An individual tree-scale presettlement evidence replacement approach is useful in situations where live post-settlement replacement trees are located within a short distance of non-living presettlement evidences within the stand (Figure 4.2c). This method can also be applied where presettlement evidences such as cut-stumps or downed trees exist within or among old, living trees (Figure 4.2b).

In forests where aggregated non-living presettlement evidence patches are located a long distance from live post-settlement replacement trees (Figure 4.2a) a patch-scale replacement method may be a more useful approach for replicating presettlement evidence patterns. The ratio of presettlement evidences to replacement trees can be used to guide the density of trees per replacement patch (i.e., using a 1:1.5 replacement ratio a presettlement evidence patch containing four stumps would yield a post-settlement replacement patch containing six trees).

The final location of aggregated tree patches relative to presettlement evidences is an attribute that will be determined from contemporary forest structure locations. If it is possible to retain aggregated tree patches near presettlement evidences an attempt should be made to do so, as the locations of presettlement forest remnants provide evidence that these areas were once forested in the past. Most importantly, both approaches should attempt to create post-settlement tree replacement patches of similar fine-scale spatial characteristics to presettlement evidences. Tree aggregation at scales less than 0.12 hectares is associated with small mammal and avian habitat suitability (Reynolds et al. 1992), and is a consistent pattern seen in several studies of presettlement ponderosa pine forest spatial patterns (Cooper 1960; White 1985; Sánchez Meador 2006; Tuten *this volume*).

Forest spatial patterns and GMG-based forest structure regulation.

Forest spatial patterns created through thinning treatments are permanent, and affect the ability of future managers to regulate forest structural development classes. Recreation of these patterns is an integral objective of both ERG and GMG-based forest restoration treatments (Reynolds et al. 1992, Moore et al. 1999). ERG-based, stand-scale tree diameter distributions are typically unregulated and future stand structure regulation will be accomplished through the use of fire. Inability to meet exact spatial pattern objectives using ERGs may have ecological ramifications, but this inability does not limit the ability to meet future stand management objectives. This is not necessarily true when implementing initial GMG-based thinning treatments.

Contemporary forest conditions amplify the importance of creating specific forest spatial patterns during initial GMG-based forest management entries. Throughout much of the Southwest, forests are essentially even-aged or two-aged, dominated by trees in VSS classes 3 and 4 due to 20th century land management practices (Allen et al. 2002; Reynolds et al. 2006). In order for future GMG-based VSS regulation to occur, it is essential that managers create distinct aggregated VSS group spatial patterns. If these patterns are not created during initial thinning treatments, it will be difficult, if not impossible, to regulate VSS 3 and 4 groups relative to younger VSS classes currently absent from the landscape in the future.

Influence of fire upon forest spatial patterns

It is especially important to monitor the effects of prescribed and naturally ignited wildfires upon contemporary forest patterns. Advocates of ERG-based forest management or, "natural process restoration," assume that contemporary fires are capable of maintaining future forest spatial patterns similar to presettlement spatial patterns. Currently little long-term evidence exists to support this assertion.

Presettlement fires typically burned in continuous abundant grassy fuels. Currently, much of the landscape once occupied by these fuels is dominated by pine litter and dissected by roads or other artificial firebreaks. Today, in many areas where grasses are present, much of this fuel is consumed annually through livestock grazing. Furthermore, presettlement fires often burned during windy hot, and dry conditions; a suite of conditions generally incompatible with practical contemporary fire management. Historical fires were likely capable of inducing a greater amount of tree mortality than contemporary fires. If severity differences between contemporary and presettlement fires are large, contemporary fires may be incapable of maintaining forest spatial patterns in a manner similar to that of presettlement fires. Therefore, it is essential to monitor effects of contemporary fires upon forest density and spatial patterns. Spatially explicit monitoring following fires will allow mangers to understand the long-term effects of fire on forest spatial pattern maintenance. This knowledge will be useful to both practitioners of ERG or GMG-based management approaches. Fires, either naturally or management ignited, are likely to burn within managed forests over time, affecting both the spatial pattern and density of tree regeneration and the future mature forests.

Spatial pattern assessment approaches

Unfortunately, typical forest treatment monitoring techniques are not capable of assessing spatial patterns. Also, most forest treatment monitoring techniques are not spatially explicit. Tree location information typically is not recorded together with tree attribute information (condition, diameter, height, etc...). Tree attribute information is sampled within management areas at several systematically or randomly placed plots. This approach is suitable for assessing average stand-scale tree attributes (e.g., tree density, basal area, canopy cover, etc...), but sampling tree information in this manner makes spatial pattern assessment inherently unreliable, if not impossible. Compounding this problem is the reality that tree attribute information is collected within variable or fixed-radius plots equal to or smaller in area than the scale of tree aggregation or tree groups (Avery and Burkhardt 1983). Even if spatially explicit tree attribute data were to be collected within these plots, the often systematic or random spacing of these plots and the small size of the plot would limit the ability to assess patterns that typically exist at scales often coarser than the plot-scale (Cooper 1960; White 1985; Sánchez Meador 2006).

Since management of sub-stand scale spatial patterns is a management objective, these patterns should be monitored and assessed using appropriate methods and experimental designs. Field surveys using planar mapping techniques are capable of capturing spatially explicit tree attribute data, but such approaches are likely too expensive and time consuming to be used in a treatment effectiveness monitoring scenario. Even if time and money were available, data collected using this approach would be inherently discontinuous, since mapping entire forested landscapes would likely be impossible.

Treatment monitoring approaches must evolve to be able to assess forest spatial pattern objectives. Geographic information systems (GIS) and remote sensing technology promise a technological solution to this monitoring shortfall. A GIS-based inventory approach utilizing high resolution imagery (Quickbird™), LIDAR or other remotely sensed continuous data may be a more efficient and practical approach for assessing the success of silvicultural thinning treatment spatial pattern objectives (Lo and Yeung 2002). In the near future, it is likely that spatially explicit, GIS-based approaches will gain importance in monitoring the ecological and future management implications of contemporary forest thinning and burning treatments.

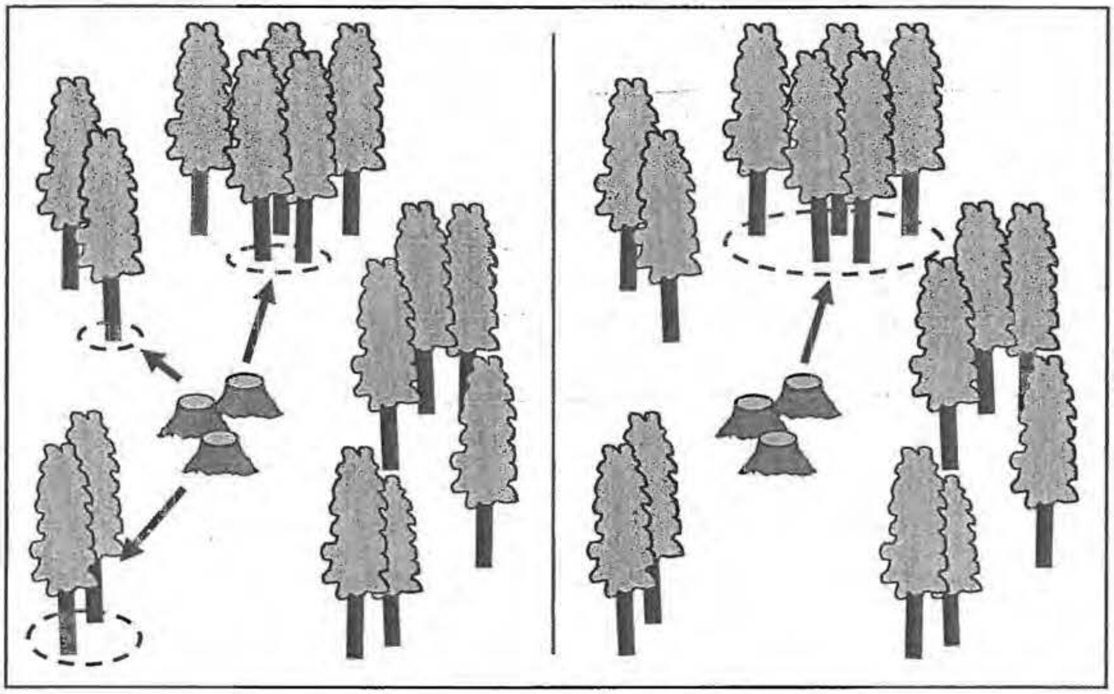

Figure 4.1: Individual tree-scale presettlement evidence replacement versus tree patch-scale presettlement evidence replacement. Individual tree-scale replacement (left) and patch-scale replacement (right). A 1:1.5 presettlement evidence to post-settlement tree replacement ratio was used in this example.

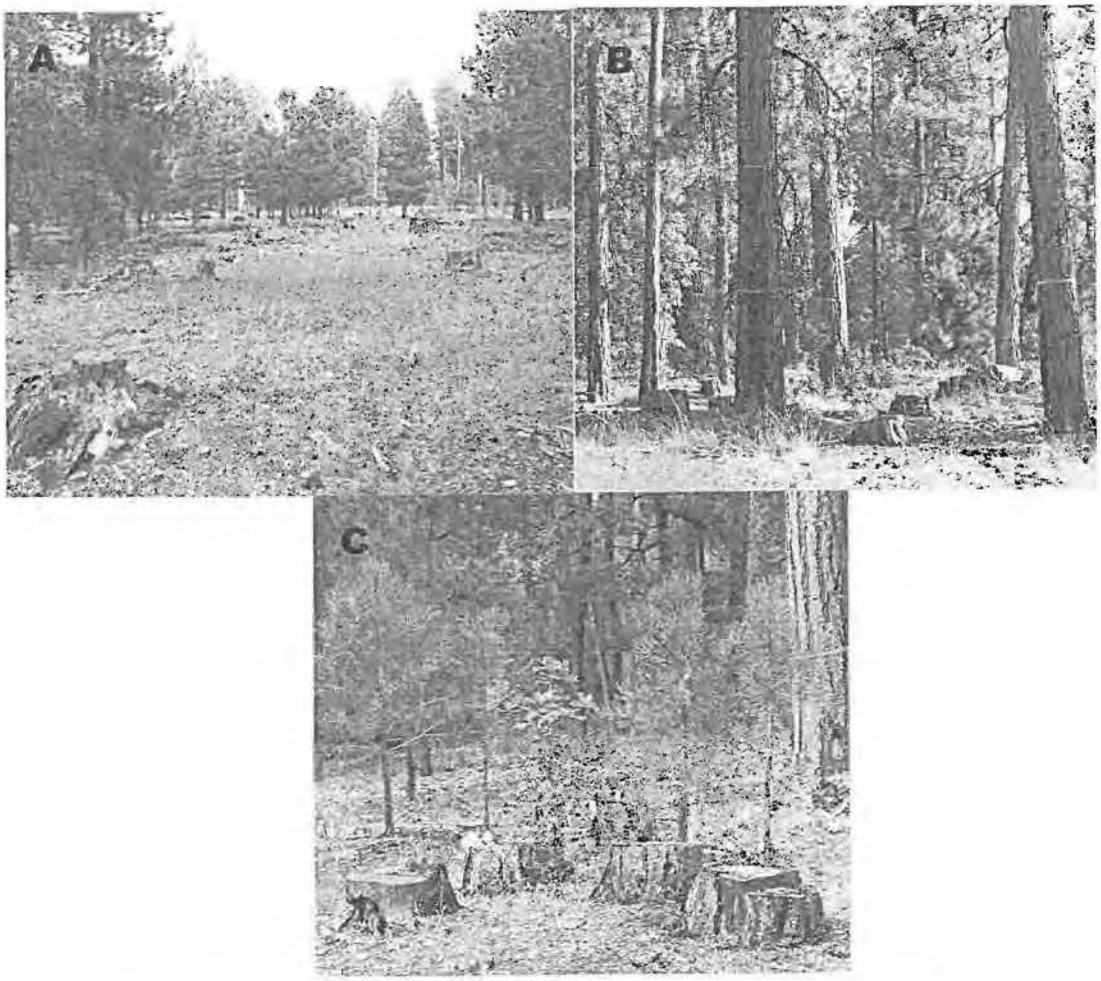

Figure 4.2: Presettlement forest evidence patterns (cut stumps and presettlement-era living trees) relative to contemporary forest structure. A) Stumps present within an intact forest opening a large distance from contemporary replacement trees; patch-scale replacement can be used to restore cut stump patterns using replacement trees from the forested areas surrounding the opening. B) Stumps are present within an existing presettlement era tree group; individual tree replacement can be used to replace these stumps. C) Nearby post-settlement trees in photo can be used to replace the cut stumps using individual tree replacement.

CHAPTER 5

Conclusion

Some inherent differences exist between ecological restoration guidelines and goshawk management guidelines-based forest management. An ERG approach is grounded in the idea that thinning activities should be used to create forest conditions where natural processes such as low to moderate intensity surface fires can be reintroduced to stimulate future forest pattern generation and other ecological functions. A GMG-based approach uses thinning to promote specific forest structural patterns that also allow the reintroduction of fire, but also create specific habitats for the prey base of the northern goshawk. Most importantly a GMG-based approach attempts to meet these first two objectives while attempting to provide a framework for sustainable management of economically valuable renewable forest resources.

Fire management in southwestern national forests is here to stay. Given the current trend of increasing fire use and agreement on the ecological benefits of fire, it is unlikely that future southwestern National Forest policy will restrict the use of fire in favor of purely silvicultural thinning approaches. Southwestern forest landscapes are simply too extensive, fire-prone and fire adapted to avoid the use of fire as a forest management tool in the future.

Ecological restorationists advocate using thinning to promote forest conditions amenable to the reintroduction of natural processes such as fire. It is also reasonable to assume that restorationists would advocate the use of thinning to regulate tree regeneration to promote locally appropriate spatial patterns if contemporary fires are proven unable to accomplish this goal. ERGs advocate thinning small diameter trees because scientific evidence indicates that natural processes (i.e., surface fires) endemic to southwestern forests regulated the structure of trees within these size classes and little evidence that such processes regulated the structure of trees in the largest size classes.

GMGs share many ecological objectives with ERG-based management approaches. This study indicates that the results of initial ERG and GMG-based thinning treatments differ significantly, but that absolute differences between these treatments are quite small and do not appear to prohibit use of ERG-based treatments within goshawk post-fledgling and foraging areas. While the importance of fire as a management tool is not highlighted within GMGs, use of fire within goshawk foraging areas is likely to become more prevalent in the future.

GMG-based forest management should be seen as a first-step toward accomplishing the lofty goal of ecosystem management in southwestern national forests. GMGs go one step further than ERG-based forest management in attempting to integrate both ecological and economic management objectives, recognizing and planning for harvesting needed renewable forest resources. Harvesting large old trees is often an anathema to restorationists, as these trees are both ecologically important and rare across southwestern landscapes. In the future, such trees may be more common and political and economic conditions may promote the harvesting of these trees. Successful and sustainable southwestern ponderosa pine forests management approaches in the future will undoubtedly require integration of both ecological and economic considerations.

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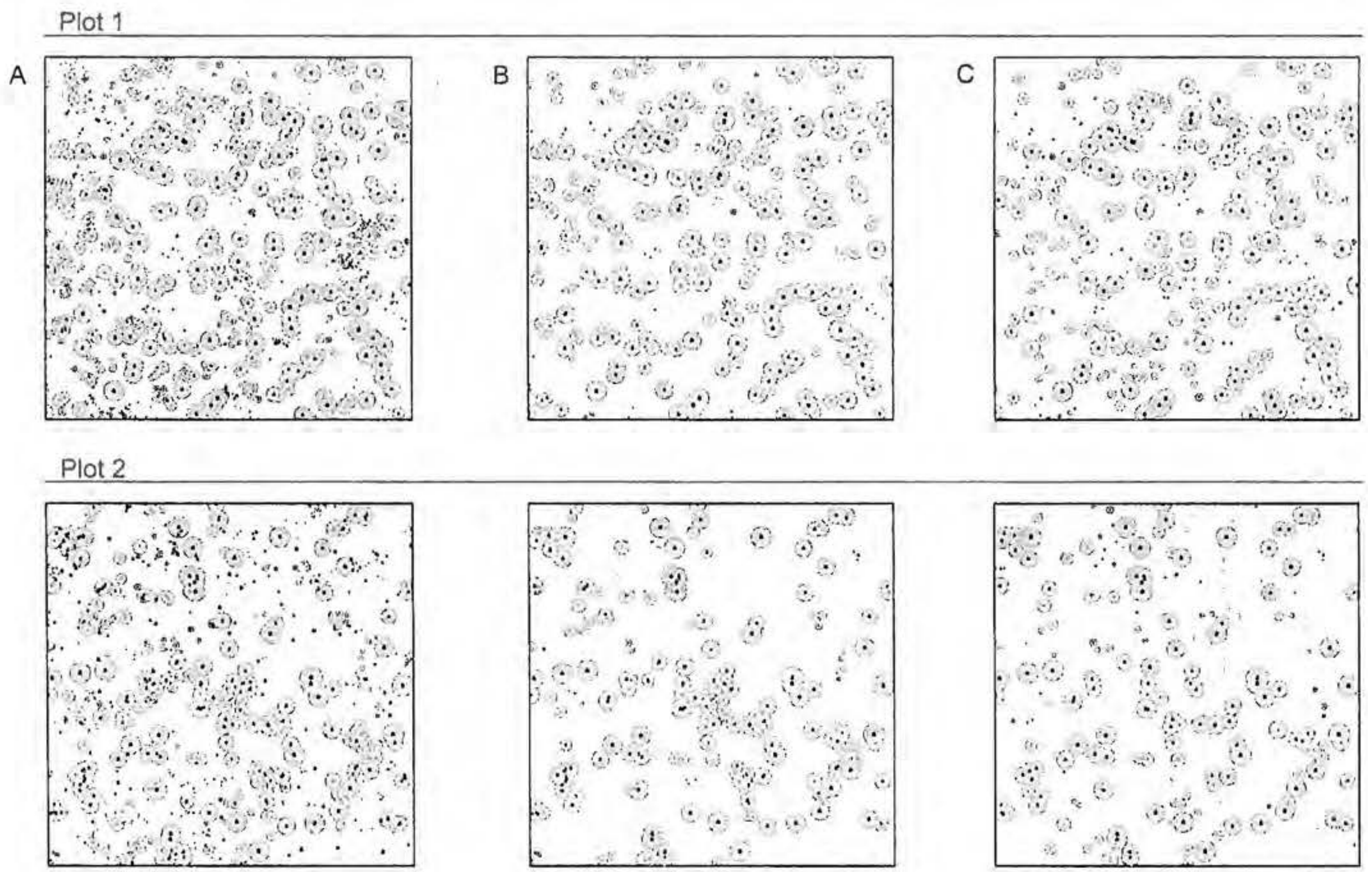
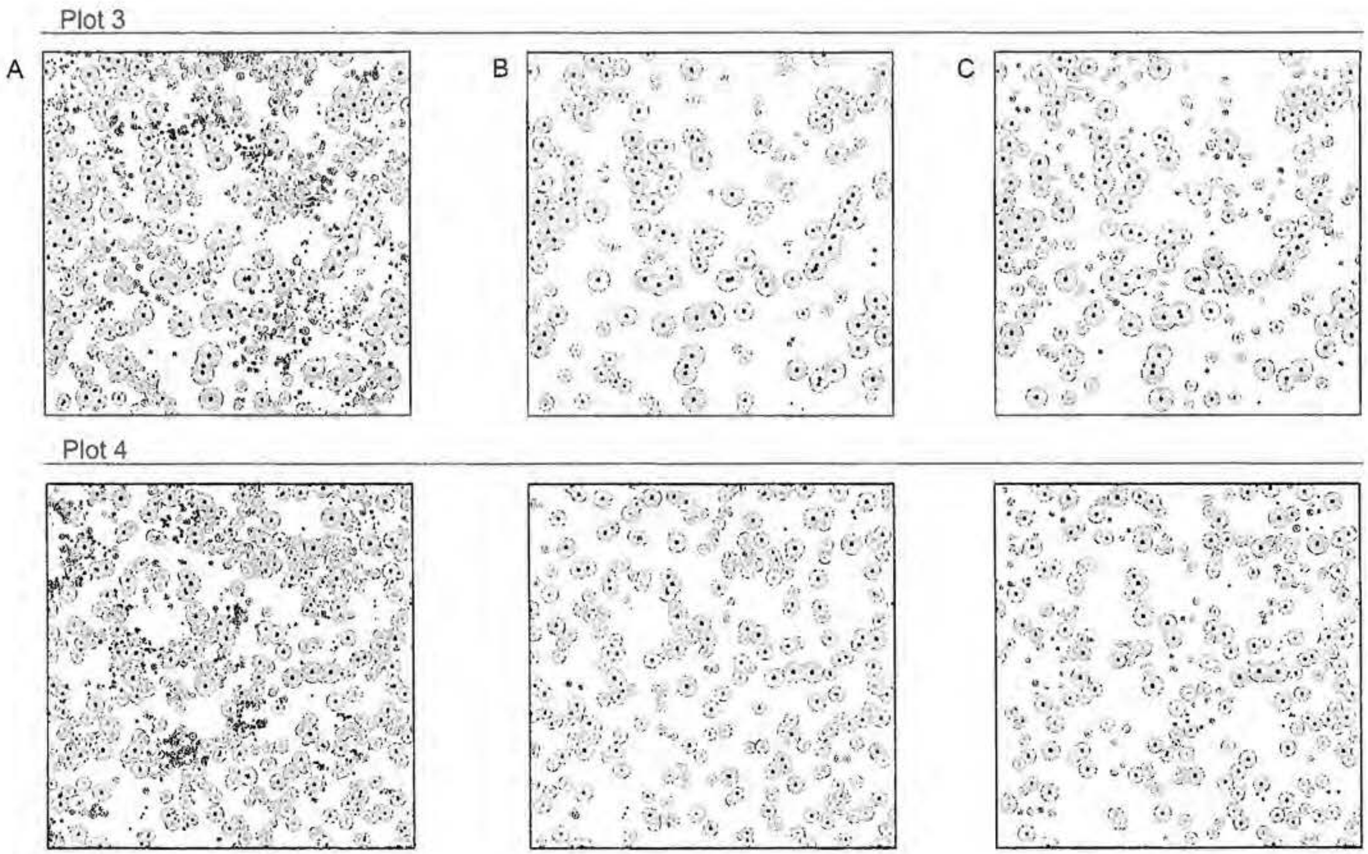
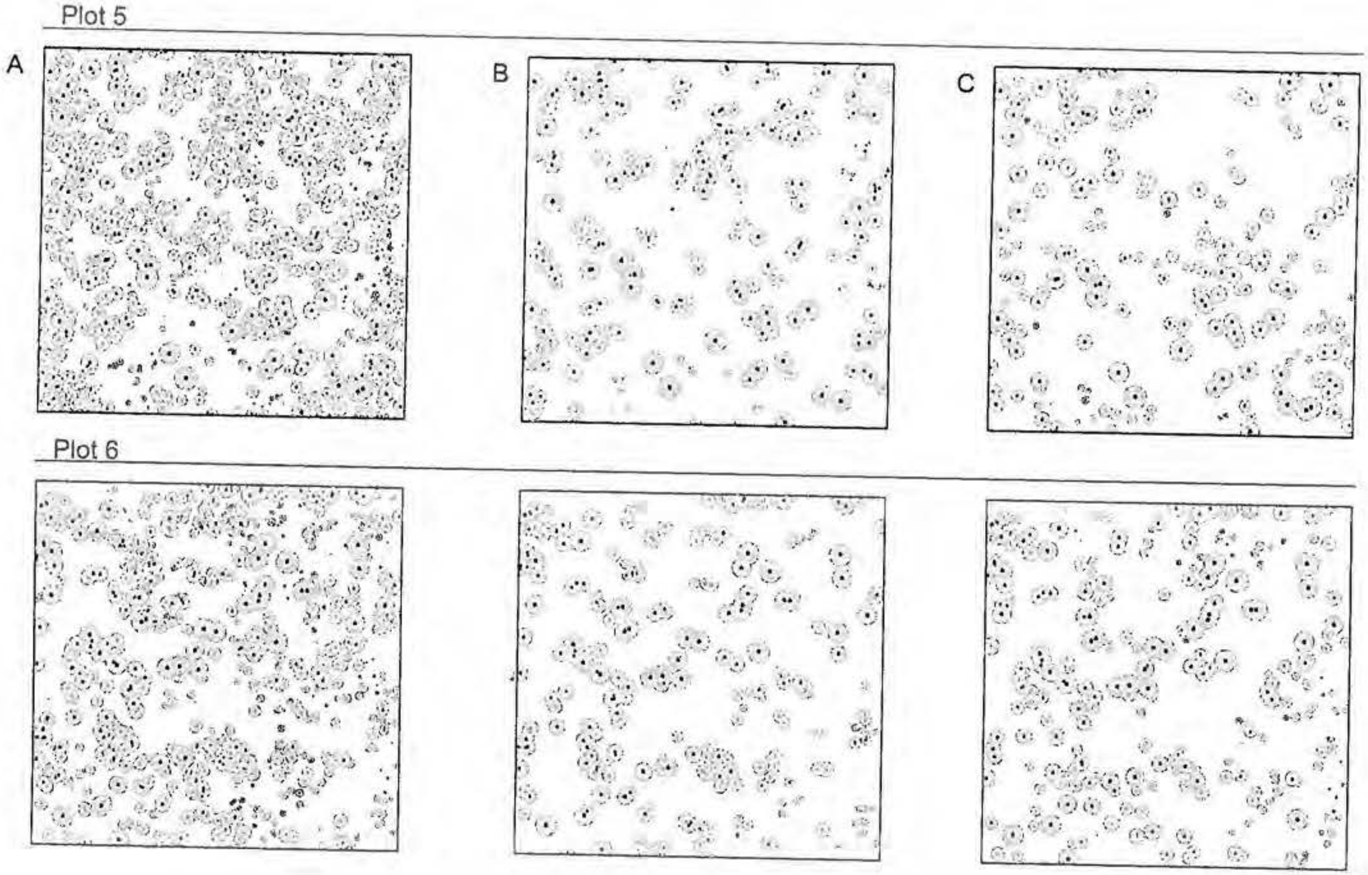
APPENDIX: Additional Figures



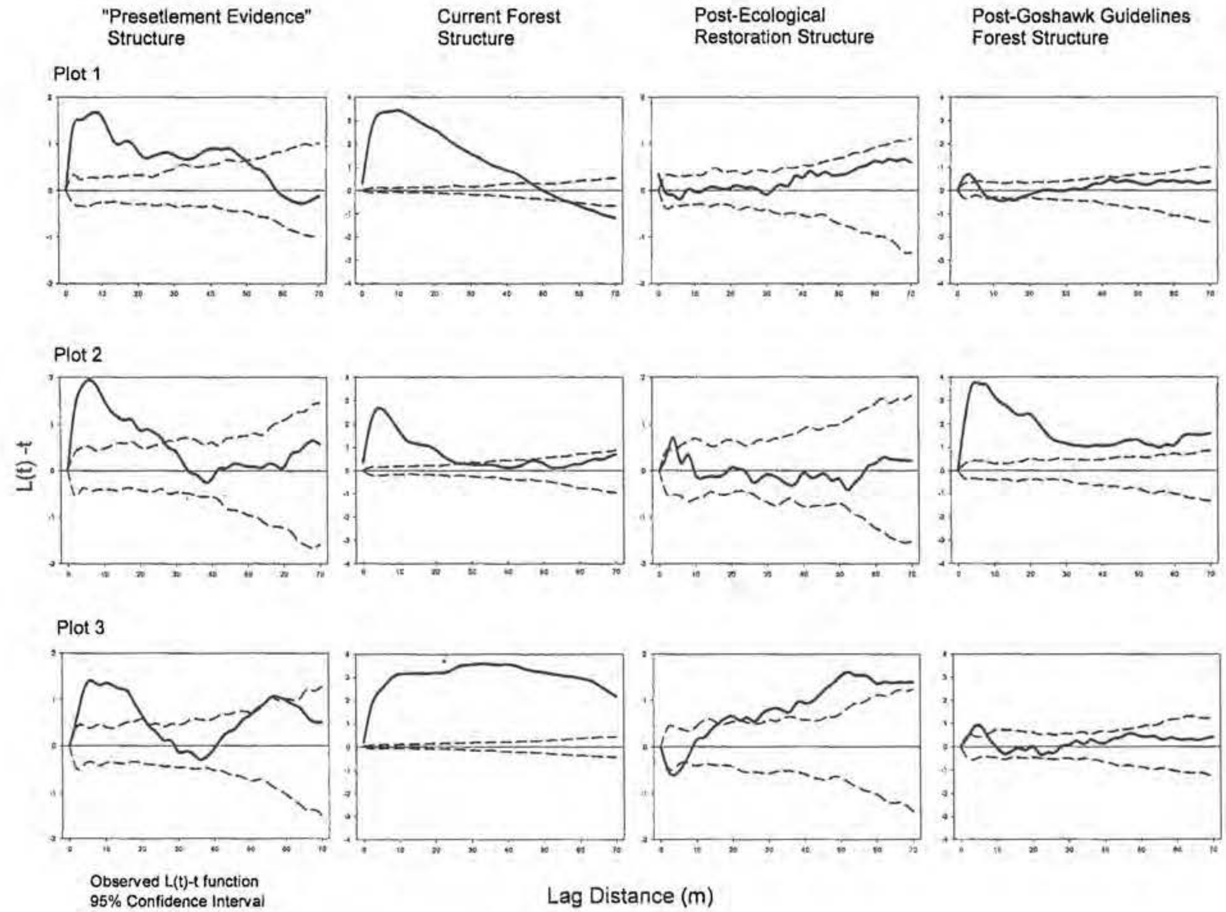
Appendix 1: Stem and canopy cover maps. All contemporary trees (A), post-treatment goshawk guidelines (B), and post-treatment ecological restoration guidelines (C).



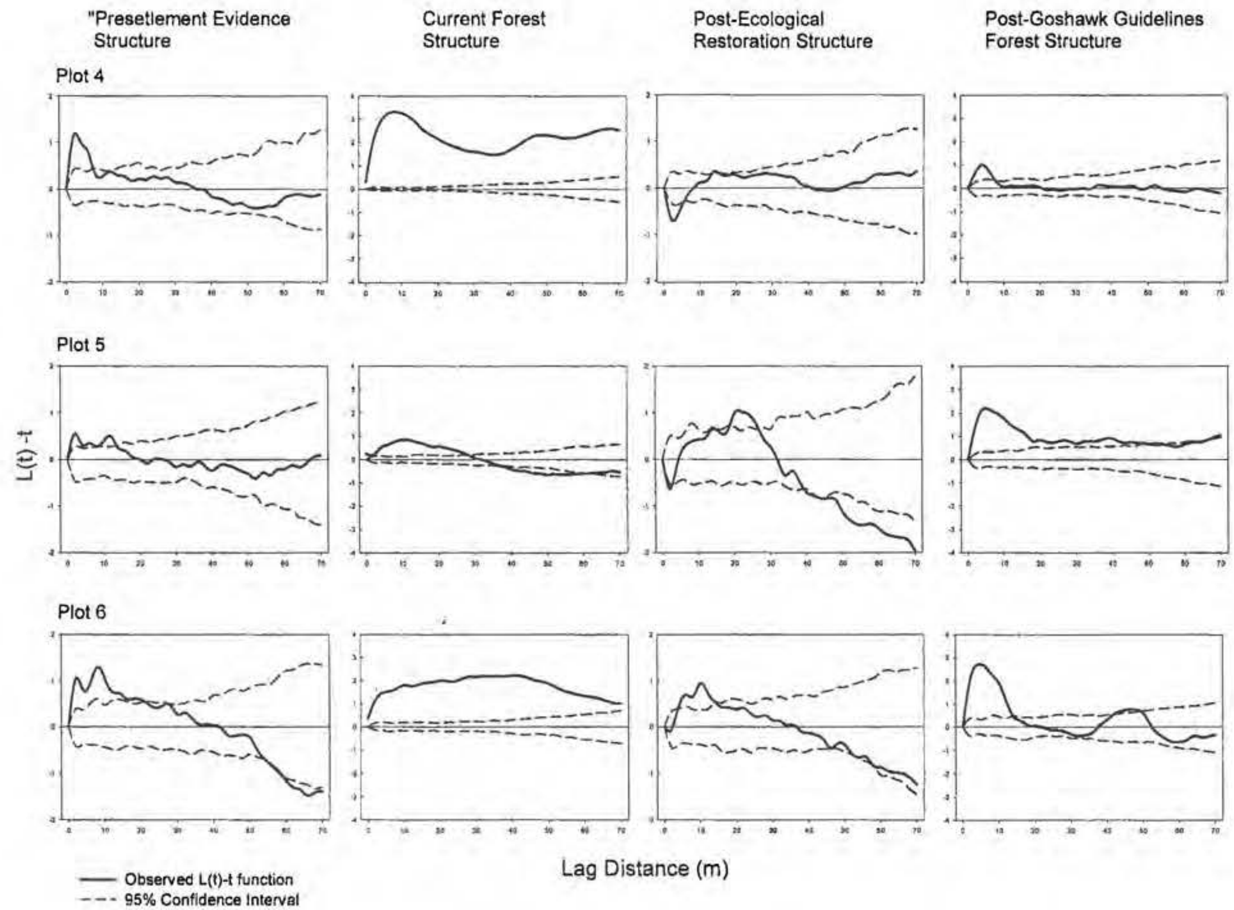
Appendix 1 (continued): Stem and canopy cover maps. All contemporary trees (A), post-treatment goshawk guidelines (B), and post-treatment ecological restoration guidelines (C).



Appendix 1 (continued): Stem and canopy cover maps. All contemporary trees (A), post-treatment goshawk guidelines (B), and post-treatment ecological restoration guidelines (C).



Appendix 2: Measured L (t) –t functions. Plots 1 through 3



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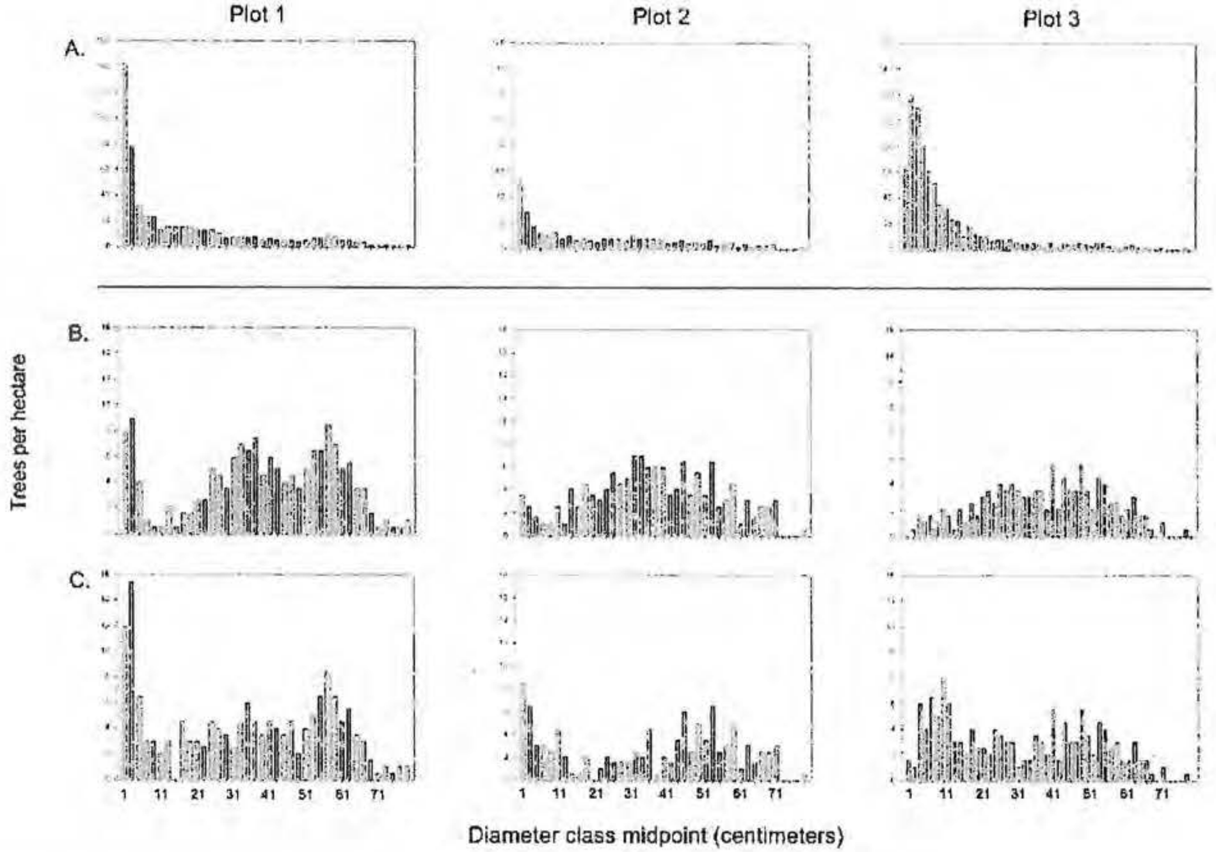
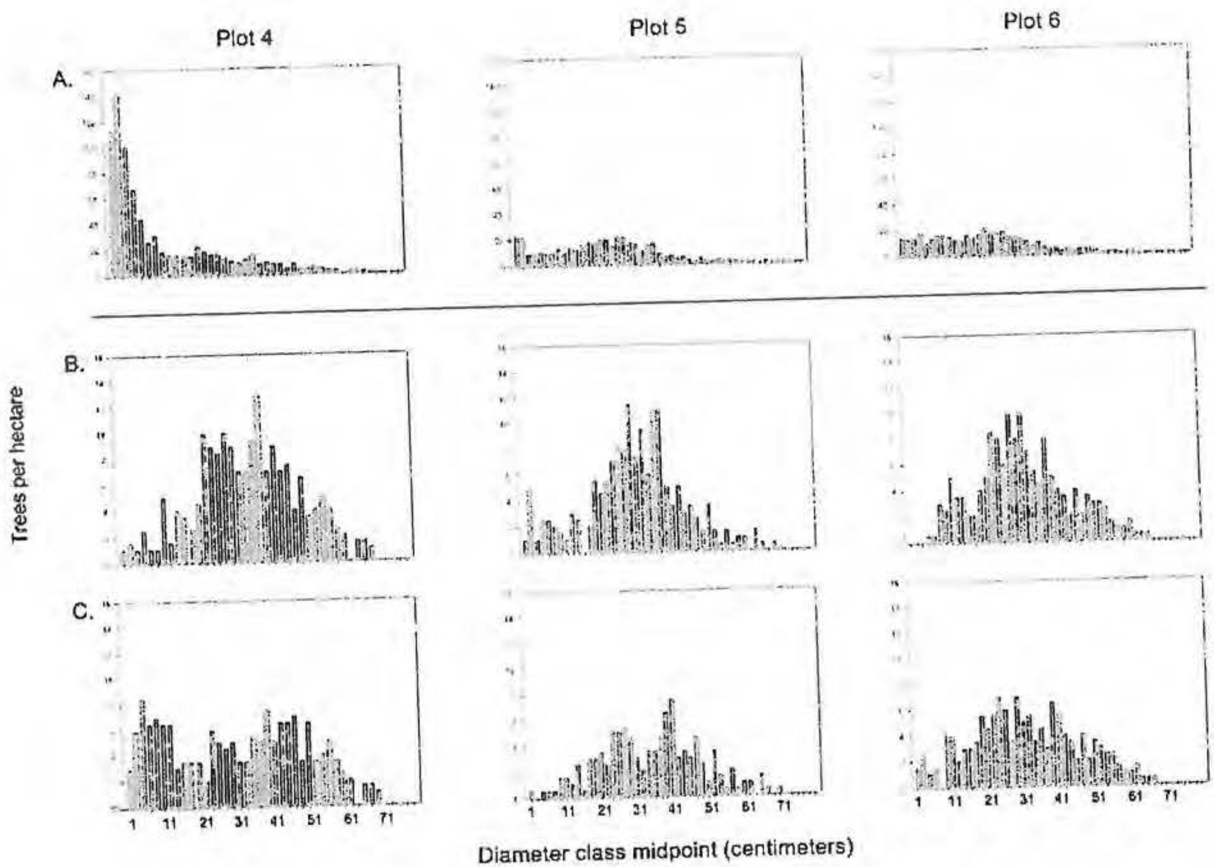


Appendix 3: Individual plot diameter distributions. Plots 1 through 3. All contemporary trees (A), post-treatment goshawk guidelines (B), and post-treatment ecological restoration guidelines (C).



Appendix 3 (continued): Individual plot diameter distributions. Plots 4 through 6. All contemporary trees (A), post-treatment goshawk guidelines (B), and post-treatment ecological restoration guidelines (C).