Analysis of Fire-related Vegetation Patterns in the Huachuca Mountains, Arizona, USA, and Sierra los Ajos, Sonora, Mexico

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ABSTRACT

There is general interest among fire ecologists to integrate observed fire regimes into long term fire management. The United States-Mexico borderlands provide unique research opportunities to study effects of contrasting forest management activities on forest structure and pattern. To increase understanding of the range of forest stand conditions in borderland ecosystems, we compared tree crown patterns from two forests near the US-Mexico border that are managed under contrasting fire policies and have contrasting fire histories. Locations of individual tree crowns in geographically and ecologically matched forest patches were detected and plotted from Digital Orthophoto Quarter Quadrangles (DOQ) using a semi-automated crown detection procedure. Spatial patterns of tree crowns were analyzed with point pattern methods. Results describe disparate spatial patterns and levels of crown density in fire-managed forests of the US and unmanaged forests of northern Mexico.

Keywords: aerial photography, canopy pattern analysis, fire history, fire policy, US-Mexico borderlands

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INTRODUCTION

United States fire policy in the era following western settlement emphasized fire suppression and exclusion, likely affecting formerly stable fire regimes. Rapid containment and suppression of wildfire, and large-scale grazing operations, produced overstocked forests that increased the risk of stand replacing fires (Arno 1996, Belsky and Blumenthal 1997, Allen *et al.* 2002). Fire ecologists and US land managers have in recent decades promoted periodic, low-intensity forest fires as a central ecological process in many North American ecosystems (Parsons and Landres 1998, Paysen *et al.* 2000). US land managers are accordingly investigating best treatment strategies to reduce fuel loads and to restore some stability in over-managed forests (Mutch 1994, Arno 1996, Mutch and Cook 1996, USDA Forest Service 2001). The appropriate level and type of treatments remain, however, open questions. We see the field of fire ecology helping to define reference conditions that inform fuel treatment activities.

Recent advances in geospatial technology and remote sensing enable low cost, detailed mapping and analysis of stand variation in forest ecosystems (Coulter *et al.* 2000, Franklin *et al.* 2001). We used remote sensing methods to determine if vegetation patterns differ between a fire-managed forest in the US and an unmanaged forest in Mexico and how Mexican forests could inform US forest restoration.

Nominally, Mexico supports a wildfire suppression policy, yet economic and social factors have prevented aggressive policy implementation in parts of northern Mexico (Gonzáles-Cabán and Sandberg 1989). Dendrochronology and fire ecology studies conducted in remote forests of northern Mexico report series of frequent low intensity surface fires that continued unaltered well into the 20th century and lower fuel loadings in Mexican forests when compared to fire-suppressed forests north of the border (Fulé and Covington 1996, Kaib 1998, Escobedo *et al.* 2001). Research in such unmanaged forests of northern Mexico may therefore provide important ecological information on fire-adapted communities and define reference conditions that inform forest restoration projects in the southwestern United States.

We investigated whether vegetation patterns differ between a fire-managed forest in the US and an unmanaged forest in Mexico. We explored methods that describe vegetation spatial patterns in areas with diverse fire and land use histories. Study sites in the Huachuca Mountains (HM) of southeastern Arizona and the Sierra los Ajos (SLA) of northern Mexico, each with recorded fire histories, were selected for comparative study based on location, shared geographic conditions, and climatic conditions.

The HM and SLA ranges are northern outliers of the Sierra Madre Occidental (both considered sky islands), and are separated by the US-Mexico international border. The ranges share Madrean vegetation community types, regional climatic processes, and similar topography and geology (Wallmo 1955, Brady and Bonham 1976, Wentworth 1985, Brown 1994, Fishbein *et al.* 1994, Stensrud *et al.* 1995, Escobedo 1998). Given their biophysical similarities, we investigated whether forest spatial patterns observed within the HM and the SLA reflect differences in fire management policy and fire history: unburned areas in the HM with a history of fire exclusion and extensive human land use, including lower elevation pine-oak patches and oak woodlands known as encinals, should exhibit greater stand density and local clustering than more recently and continuously burned areas of the SLA. The SLA has a history of repeated surface and small area fires and a history of less intensive human land use, so a heterogeneous canopy of live fuel should be present. We therefore hypothesize forest stands in the SLA will exhibit a more complex canopy pattern than forests in the HM. We hypothesized that fire exclusion in the HM contributed to greater stand density and homogeneity compared to the SLA.

We developed a set of methods to describe stand density and spatial characteristics related to fire exclusion and land use that employ high-resolution remote sensing and Geographic Information System (GIS) techniques.

Prior to settlement, Euro-American explorers in Arizona and New Mexico described ponderosa (*Pinus ponderosa*) pine stands as open and park-like, with grassy and herbaceous understory (Weaver 1951, Cooper 1961). In centuries preceding settlement, fire history reconstructions from the southwest region show that frequent and widespread fires typically occurred at least once per decade in ponderosa pine dominant stands (Weaver 1951; Swetnam and Baisan 1996, 2001). Elimination of periodic surface fire from southwestern forests encouraged expansion of pine-oak communities, increased tree density in ponderosa pine forests and oak woodlands, increased numbers of young pine and Douglas-fir (*Pseudotsuga menziesii*) in mixed conifer understory, and in general created forest conditions conducive to destructive fire (Bahre and Minnich 2002, Keane *et al.* 2002).

Untouched by fire for nearly a century, many pine and oak forests of the Southwest have been described as unhealthy and overcrowded (Marshall 1963, Mutch 1994, Belsky and Blumenthal 1997). Suppression activities have indirectly changed forest composition and structure from shade intolerant to shade tolerant, fire tolerant to fire sensitive, single layer canopy stands to multiple layer stands, and generally promoted greater density of biomass in forested ecosystems (Belsky and Blumenthal 1997, Barton 1999, Keane *et al.* 2002). Increased tree density and associated fuel loadings have reduced soil moisture and nutrient availability, leading to a decrease in species diversity of herbaceous plants (Clark 1990, Covington *et al.* 1997). Areas where fires have been suppressed and grazing has occurred show increases in stand density of young to medium aged trees in pine and mixed conifer stands, as well as recruitment of fire-sensitive species in lower elevation stands (Allen *et al.* 2002, Barton 2002).

Fire occurrence was reduced in the US during post-settlement times as a result of unchecked grazing practices and termination of burning by Native Americans (Manday and West 1983, Bahre 1991, Touchan *et al.* 1995). At the same time, wildfires occurring near rapidly expanding western settlements drew government attention to the consequences of unchecked fire on property and resources. Following a decade of extreme fires that caused substantial damage to human life and property, the United States instituted a policy of suppression and rapid elimination of ignitions (USDA Forest Service 2001). Recent policy adjustments implemented by the Forest Service call for an ecosystem management approach designed to sustain ecosystems integrity of wild lands (Jensen and Everett 1993). Ecosystem management relies on a set of reference conditions to aid restoration of altered ecosystems with the goal to return forests to their range of natural variability, reducing probability of catastrophic fires (Swetnam *et al.* 1999, Allen *et al.* 2002). The concept of "historical" or "natural" variability relies upon available information to determine composition, structure, and dynamics of fire-dependent forests prior to settlement (Swanson 1993). Federal, state and local management agencies support the use of prescribed burning and mechanical thinning to reduce fuels hazard and improve ecosystem health (Manday and West 1980, Keane *et al.* 2002). Restoration studies in the Southwest promote removal of surface fuels and thickets of young pines as an effective management approach (Covington *et al.* 1997, 2001).

Mexico and US fire policies are similar in many respects, but traditional slash-and-burn agricultural practices of Mexico's large indigenous population created a landscape where fire was commonplace (Bojórquez-Tapia 1988). As in the United States, indigenous populations in Mexico used fire as a tool long before European settlement, but where indigenous communities in the western US were mainly nomadic and used fire to hunt, many pre-Columbian Mexican populations were agrarian, using fire to clear fallow fields for crop rotation (Bojórquez-Tapia 1988, Rodríguez-Trejo 1996). This tradition of agricultural burning created unique problems for managers implementing Mexico's fire policy.

The complexity of Mexico's national fire policy is also related to ownership and management of forested lands. Prior to the Mexican Revolution (1910-1917), a large portion of Mexico's land consisted of haciendas, large tracts of private land owned by wealthy individuals (Sanderson 1984). Following the revolution, hacienda land was distributed through implementation of land reform laws (Article 27 of the 1917 Constitution) to groups of landless peasants or ejidos to grow and cultivate subsistence crops (Thoms and Betters 1998). Under this land reform, large portions of national forestland and associated timber came under jurisdiction of the ejido (Sanderson 1984).

In the 1960s, Mexico's forestry laws were amended to create "Comisiones Forestales" in 20 Mexican states, including Sonora (Zarraga-Muñoz 1963). At this time, it was required of all persons who were financially able to help the commissions fight wildfire, and strict fines were levied against "antisocial" persons who chose not to help. In addition to fines, Mexican law dictated prison sentences for persons causing forest fires greater than 10 ha (Zarraga-Muñoz 1963). Such penal motivations to participate in suppression and practice safe burning may have played some part in the observed reduction of recorded fires in northern Mexico from 1960-1990 (Fulé and Covington 1996, Kaib 1998) and influenced the severity of the 1998 fire season. While there remain few data on fire incidence between these years, it is of note that during the 1998 fire season, 97 % of total fire ignitions in Mexico were attributed to human causes (Cedillo and Sanchez 2000).

Although Mexico established strict laws to monitor and regulate burning, a question remains as to the extent to which these laws are enforced. While Mexico's constitution states all civil and military authorities as well as able-bodied citizens in the region are responsible for fighting fires, the extent to which this policy is enforced in northern Mexico is unclear. Evidence suggests that suppression and management activities have been neglected historically in Mexico due to cultural, economic, and social factors (Esquivas 1956, Bojórquez-Tapia 1988, Rodríguez-Trejo 1996).

In recent decades, the primary factor limiting wholesale fire suppression in Mexico is lack of funding for fire fighting and prevention programs. Differences between annual fire budgets of the US and Mexico may partially explain the discrepancy in Mexico between a hard-line fire policy and lax suppression and prevention activities (Table 1). While Mexico's budget generally increased during the 1980s, the country's fire program budget in US dollars remains at less than 1 % of the amount spent by the Forest Service.

Despite Mexico's recent move towards suppression, several mountain ranges in northern Mexico remain unaffected by heavy logging, grazing, and government management (Fulé and Covington 1996, 1999; Park 2001). Natural fire regimes in many of these ranges are believed to have continued to present, and local ecological conditions vary significantly from forests north of the border (Fulé and Covington 1996, 1999; Park 2001). Scientific study of forests with unaltered fire regimes in northern Mexico can be useful in establishing reference conditions as well as understanding ecosystem dynamics (Chou *et al.* 1993, Villanueva-Díaz and McPherson 1997, Fulé and Covington 1999, Minnich *et al.* 2000). Comparative landscape studies conducted in Baja California, Durango, and Sonora, Mexico, report substantial variations in fire regimes across the border and differences in landscape pattern of certain community types (Fulé and Covington 1996, 1998; Minnich *et al.* 2000). These cross-border fire studies emphasize differences in spatial pattern of fire regimes but little work has explicitly addressed relationships between fire regime pattern and canopy pattern in altered and unaltered sites across the border.

Current US fire policy stresses a need for forest management at the ecosystem level (USDA Forest Service 2001). In recent

Table 1. US and Mexico annual fire suppression budgets, 1983-1988.[1]

Year	United States[2]			Mexico[3]		
	Area burned (ha)	Cost (USD)	Cost ha^{-1} (USD ha^{-1})	Area burned (ha)	Cost (USD)	Cost ha^{-1} (USD ha^{-1})
1983	81 000	56 711 069	700.14	672 127	2 254 658	3.35
1984	187 000	102 491 769	548.08	583 248	3 194 175	5.48
1985	741 000	249 250 324	336.37	375 907	2 235 556	5.95
1986	406 000	167 696 327	413.05	718 620	1 314 004	1.83
1987	1 281 000	368 538 256	287.70	710 050	702 895	0.99
1988	1 556 000	204 357 759	388.40	1 280 638	1 629 630	1.27
Average	708 667	258 174 084	445.62	723 431	1 888 486	3.14

[1] Costs represent Forest Service expenditure for emergency fire suppression.
[2] Sources: US data from Fire Management Today, vol. 61 no. 3, 2001. United States Forest Service. Mexico data adapted from Gonzáles-Cabán and Sandberg (1989), with currency values converted from Mexican pesos to US dollars via Historical Exchange Rate Regime: [URL:http://intl.econ.cuhk.edu.hk/exchange_rate_regime/index.php?cid=17].
[3] It should be noted that the Mexican economy was stressed during the 1980s, experiencing currency depreciation throughout the decade. This is evident when noting the Fire Program's increase in spending (Mex. $) and the apparent decrease in spending when adjusted to US $. At either rate, as noted by Gonzáles-Cabán and Sandberg (1989), the increase in Mexico's fire spending barely keeps up with inflation.

decades, land managers acknowledged the role of fire for maintaining healthy ecosystems, but have only recently viewed fire as a management tool (Williams 2000). Ecosystem restoration by prescribed fire is a subject of debate; managers must consider various restoration techniques to suit a site-specific definition of a "healthy" ecosystem (Arno 1996, Mutch and Cook 1996). Ecological data providing historical reference conditions of fire-adapted ecosystems can aid management with forest restoration programs (Swetnam *et al.* 1999).

METHODS

Study Areas

Sierra los Ajos study site. The Sierra los Ajos (SLA), located east of Cananea, Sonora, are situated between Mexico's Sierra Madre Occidental and the Rocky Mountain region of the western United States. Elevation of the SLA ranges from 1050 m to 2625 m. Biological and floristic diversity is known to be high, related in part to its unique geographic location (Fishbein *et al.* 1994). Major forest community types include oak and mesquite grassland, oak woodland, riparian forest, pine-oak forest, and mixed conifer forest. A large portion of the range falls under protection of the 184 691 ha Ajos-Bavispe National Forest and Wildlife Refuge. The range was granted reserve status in Mexico in 1936 and refuge status in 1939.

Forests of the SLA escaped the fate of other heavily harvested areas of the Sierra Madre due to its National Forest and Reserve status. According to land use records, livestock grazing in upper elevations of the SLA was nonexistent until the middle of the 20th century (Marshall 1963, Bahre 1991). Light but non-uniform grazing occurred in areas of the range following establishment of ejidos in the area (Dieterich 1983). Local ejidos and SEMARNAP (Secretaría de Medio Ambiente, Recursos Naturales y Pesca) officials report small grazing operations, with as few as one dozen cattle grazing in 1997 (Escobedo 1998). It is believed that Apaches rarely occupied the SLA because fire scar records from the range do not reflect typical changes in fire variability associated with their removal in the 1800s (Swetnam *et al.* 2001). Presettlement fire frequencies recorded in the Canon Evans and Canon Oso areas of the SLA match fire scar records from southeastern Arizona, yet frequent fires beginning in the mid 1400s continued in some areas unaltered up until the 1970s (Table 2) (Kaib 1998). These fire-scar records make the SLA a useful model of a continuous natural fire regime unaffected by land use practices and fire suppression activities observed north of the border.

Huachuca Mountain study site. The Huachuca Mountains (HM) are located west of Sierra Vista, north of the US/Mexico border in southeastern Arizona. Elevation of the HM ranges from 1199 m to 2879 m. Plant community types and distribution in the HM generally mirror those in the SLA with the exception of greater distributions of Douglas-fir at higher elevations (Brady and Bonham 1976).

Table 2. Last widespread fire and mean fire intervals (MFI) for the Sierra los Ajos (Kaib 1998) and Huachuca Mountains (Danzer *et al.* 1996).

	Site	Last wide spread fire	MFI: all fires[1]	MFI: 10 %	MFI: 25 %
Sierra los Ajos	Canon Evans	1977	3.63	4.05	8.06
	Canon Oso	1972	3.18	3.92	5.23
Huachuca Mts.	Sawmill Canyon	1914	4.88	5.93	7.12
	Pat Scott Peak	1899	2.96	5.13	9.75

[1]Mean Fire Interval (MFI) for all fires is based on total fires recorded at the sites, MFI 10 % represents fires recorded on 10 % or more of sampled trees, and MFI 25 % represents fire recorded on 25 % or more of sampled trees.

The proximity of the Huachuca Mountains (HM) to the US/Mexico border and to the SLA (50 km SE) provides an ideal site for a cross-border landscape study (Figure 1). SLA and HM each consist of a continuous southeast-northwest ridge with considerable secondary faulting exposing several side canyons (Wallmo 1955, Fishbein *et al.* 1994). Similarities in local climate and geomorphology strengthen the argument for cross-border comparisons (Wallmo 1955, Fishbein *et al.* 1994, Stensrud *et al.* 1995, Escobedo 1998).

The HM have a distinct history of human land use associated with an operational military fort and significant timber harvesting activities (Wilson 1995). A surge in mining activities during the late 19th century created a demand for fuel wood, and sawmills were established in several areas of the HM (Wallmo 1955). By most accounts, logging in the HM lasted less than a decade but irrefutably changed forest structure. By the turn of the century, natural reforestation in logged areas was in progress (Wilson 1995).

Mean fire frequency of the Sawmill Canyon area between 1689 and 1889 was 4.88 yr to 7.12 yr (Table 2), and the last widespread fire occurred in 1914 (Danzer *et al.* 1996, Swetnam *et al.* 2001). For the Pat Scott Peak area, the mean fire frequency was 2.96 yr. Land use activities associated with timber harvesting and mining had profound effects on the structure of the forest. Absence of fire during all stages of the reforestation process may have also had a significant effect on current canopy structure of the range (Wilson 1995). Although fire history records show a decrease in fire frequency around the turn of the century, several large stand replacing fires were recorded in the HM during the mid to late 20th century (Taylor 1991).

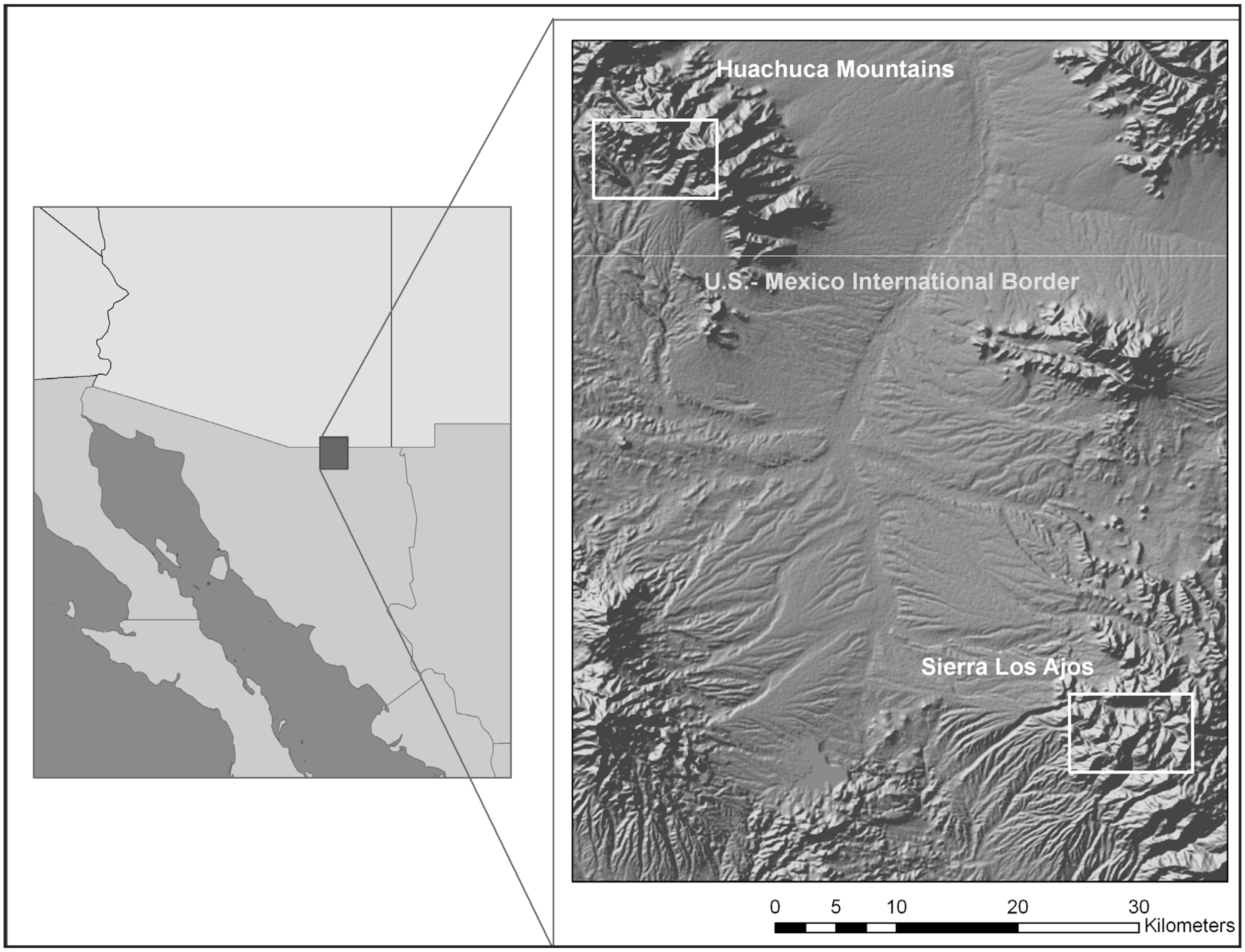

Figure 1. Map of study area.

Research Methods

The objective of our research was to increase understanding of the range of forest stand conditions in borderland ecosystems through comparison of spatial patterns from forests managed under contrasting fire policies. Spatial patterns observed in the Huachuca Mountains and Sierra los Ajos should reflect contrasting land use history and fire management strategies. Key fire ecology studies discuss thinning effects of frequent fire on forest stands and the relationship between fire suppression and increases of stand biomass (Dahm and Geils 1997). Pattern detection and spatial analysis techniques were selected to judge forest stand density and crown pattern. These techniques were used to describe stand homogeneity and heterogeneity and to test whether forest stands in the SLA exhibit a more complex overstory pattern resulting from a history of continued, frequent fires.

Spatial metrics. We used spatial metrics to analyze effects of fire suppression, non-suppression, and land use on canopy and stand pattern, quantifying patch character and pattern in pine-oak and oak woodland communities. High-resolution aerial images were processed to provide descriptions of canopy variation and individual tree patterns. The following remote sensing and statistical methods were used to compare canopy pattern:

1) Crown Detection. Semi-automated crown detection was implemented to

locate individual tree crowns based on spectral signature.

2) Point Pattern Analysis. Statistical methods are used to describe spatial patterns of tree crowns within a patch. Point pattern methods include: quadrat density, tests of Complete Spatial Randomness, and K-order Nearest Neighbor Analysis.

Requirements for high spatial resolution. Remote sensing techniques are used in many situations to measure fire related changes in landscape structure and pattern (Chuvieco 1999, Rogan and Yool 2001). Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) carry the fine temporal and spectral resolution suited for wildland fuel mapping and the study of fire related landscape change (Chou 1992, Keane *et al.* 2001). The 30 m spatial resolution of Landsat TM and ETM+ is practical for landscape generalizations, but fine resolution images reveal increased canopy detail (Hudak and Wessman 1998, Coops and Culvenor 2000).

High-resolution remote sensing platforms provide detailed spectral and spatial information of ecological processes occur at scales finer than the landscape level. In images where spatial resolution is smaller than the object of interest, spatial and biophyscial characteristics of the object can be assesed (Pastor and Broschart 1990, Coulter *et al.* 2000, Hay *et al.* 2002). One such example is the process of crown extraction from high resolution imagery using local maximum filtering or maximum likelihood classifier to separate crown from surface based on spectral response (Wulder *et al.* 2000, Leckie *et al.* 2003). At the patch level, detecting and modeling heterogeneous and homogenous canopy patterns in fire-dependent forests requires detailed aerial imagery (Keane *et al.* 2001).

Digital Orthophoto Quarter Quadrangles (DOQ). DOQs are high resolution (1 m to 1.5 m) digital files produced from scanned and orthorectified 1:40 000 (HM) or 1:20 000 (SLA) scale aerial photographs. Advantages to using DOQs over hardcopy aerial photography or satellite images include: fine spatial resolution, digital image enhancement, multi-scale viewing options, and easy production of GIS vector layers (Coulter *et al.* 2000). DOQs were the primary data source used for pattern analysis in this project. Remote sensing and GIS methods were based on three DOQs of the HM (Miller Peak, Montez, and Huachuca Mountain) and one of the SLA (Cuquiarichi).

GIS and Remote Sensing data. Satellite images, DOQs, digital elevation models (DEM), and digital raster graphics (DRG) of topographic features were incorporated into a GIS. One 60 m DEM of the SLA and three 30 m DEMs for the HM were acquired from the Arizona Regional Image Archive (ARIA: http://aria.arizona.edu). A polynomial geocorrection process was executed using Landsat TM scenes, DRGs and topographic maps as reference. Each DEM was registered with twenty ground control points (GCP) centered on prominent landscape features and areas common to both DEM and reference scenes and distributed evenly over the study area.

DOQ images for the HM and SLA study areas have consistent shadow direction indicating that the images were photographed at approximately the same time of day. Years for the US and Mexico photographs are relatively close: HM 1996 and SLA June 1997. Cloud cover is nonexistent in both images, but photographic procedures are for the most part unknown. After initial inspection, we found the data to be consistent (i.e., no major shadow effects or environmental haze) and comparable.

Radiometric inconsistencies not corrected during production of the DOQs were addressed prior to analysis through band reduction and histogram matching. Data discrepancy between color DOQs of the HM and the panchromatic DOQ of the SLA necessitated a band reduction of the 3 band CIR DOQs. To adequately compare data from the HM and SLA, histogram tests of digital number (DN) distribution in the color bands were compared to a panchromatic histogram. Histograms indicated band 2 of the CIR DOQ most resembled DN distribution of the panchromatic DOQ. To align DN values of the classes of interest, a histogram match was performed on band 2 and the panchromatic image. Because the band 2 and pan DN distributions shared a similar curve, this procedure matched minimum and maximum DN values representing the lightest (soil) and darkest (shadow) elements of each scene.

Polygon selection. Prior to analysis of study area sites, polygons were selected to represent encinal patches in areas with known fire history. The objective of patch selection was to match geographically similar areas in the HM and SLA for comparative analysis. At each fire history site, three polygons were digitized through visual interpretation of DOQs, each with different aspect and each digitized considering natural patch boundary. Three encinal polygons of the same fire history area in the HM southeast of Pat Scott Peak were delineated following the criteria. Polygons digitized from DOQs of SLA are located on slopes around the Canon Evans fire history area and chosen to replicate the topographic attributes (elevation, slope, aspect, and polygon area) of polygons from the HM fire history site (Figure 2). Three additional polygons were delineated at a second fire history site in the HM southeast of Pat Scott Peak. Site two polygons were extracted based on attributes shared with both site one and Cañon Evans of the SLA. Polygon attributes were aligned as closely as possible, but discrepancies occur in some cases where similar site characteristics could not be located within the study area.

Classifications of encinal patch polygons were verified with field reconnaissance and existing field data. Data points for some HM patches exist from previous studies (collected by Miller and Yool 2000) and were compared

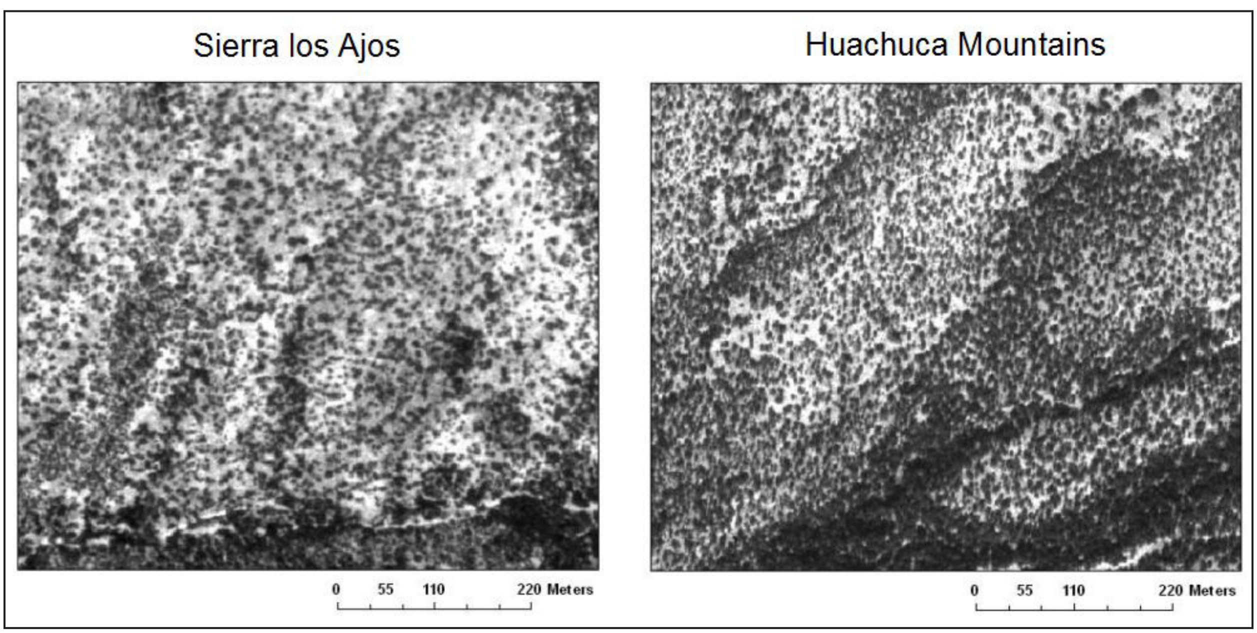

Figure 2. Details of DOQ illustrating canopy patterns from SLA and HM study sites.

to patch classification for verification. In areas with no existing field points, patch classification was verified *in situ* with topographic maps, DOQ and Global Positioning System (GPS) technology. Species composition of individual patches was noted, and GPS points were collected and imported into a GIS.

Point pattern analysis. Spatial analysis of fixed point locations can offer fundamental information on patch character and provide insight into processes driving pattern. Point pattern analysis can supply important information on patch density, spatial autocorrelation, clustering and dispersion. Methods involving statistical point analysis permit comparison of complex spatial patterns developed under various land use activities. The following spatial statistics were implemented to describe varying degrees of patch heterogeneity and homogeneity: Chi squared Poisson tests of complete spatial randomness, Nearest Neighbor Dispersion Analysis (NND), and K-Order NND (kNN).

Crown detection. An approach to spatial characterization of encinal stands was developed using semi-automated crown delineation and point pattern analysis. Individual crowns from oak woodlands with sparse vegetation can be discriminated easily on aerial images (Hudak and Wessman 1998). The spectral signature of an oak crown can be detected in relation to surface elements, where lower DNs represent tree crown and higher DNs surrounding the crown represent grass or soil.

Identification of individual crowns in a forest stand is key to generating, plotting, and analyzing point pattern data. Hand digitizing individual crowns in a scene of substantial geographic scale can be time consuming and costly, an issue that has prompted recent interest in developing automated techniques for tree crown detection from high resolution aerial imagery (Hudak and Wessman 1998, Falkowski *et al.* 2006, Strand *et al.* 2006). The semi-automated crown delineation approach used in this study utilizes a Maximum Likelihood Classifier (MLC) method to determine the spatial locations of crowns with minimal manual effort. Methods used for this approach included: 1) development of spectral signatures for maximum likelihood classification of raster data, 2) classification of raster data to yes/no (crown/no-crown) matrix, 3) assignment of *x,y* coordinates to central points of classified crowns, and 4) creation of additional *x,y* points for unclassified or incorrectly classified crowns (Figures 3, 4 and 5).

An MLC approach based on four spectral signatures was utilized to plot crowns from nine encinal polygons in the three study areas. Individual signature files were created for each study area to minimize error associated with slight variation in DNs observed between different DOQs. Each stand was classified, re-classed with the inclusion of missed crowns, and assigned *x,y* coordinates for individual crowns.

Analysis of Crown Pattern. Once geographic locations of all crowns were inventoried and plotted, point pattern statistics and indices were calculated. Each encinal patch was stratified with a 30 m grid for quadrat analysis. To avoid influencing statistics with edge effects, only quadrats located completely within the area designated by original patch polygon were used.

Total number of crowns was calculated for each patch and average grid density was measured for each 30 m cell. We computed Chi Squared Poisson tests of Complete Spatial Randomness (CSR), Nearest Neighbor Analysis (NND) and kNN to determine whether patches conform to or diverge from regular spatial patterns.

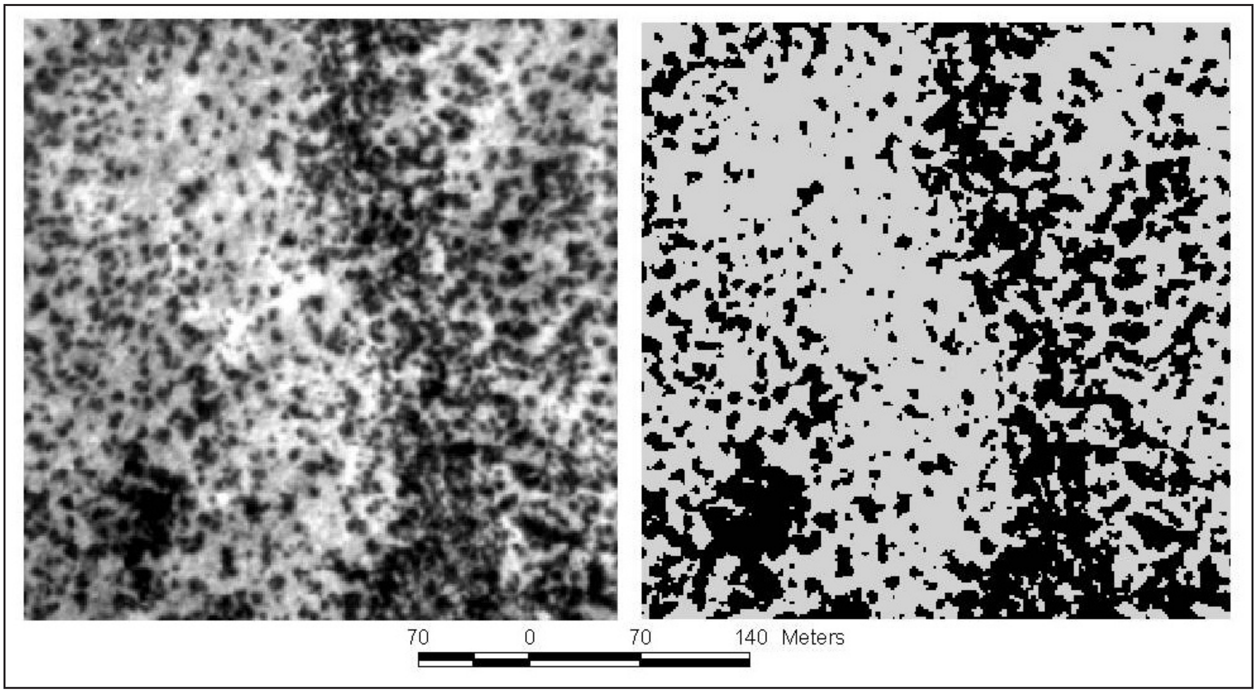

Figure 3. Original DOQ from the Huachuca Mountain study area transformed to raster matrix.

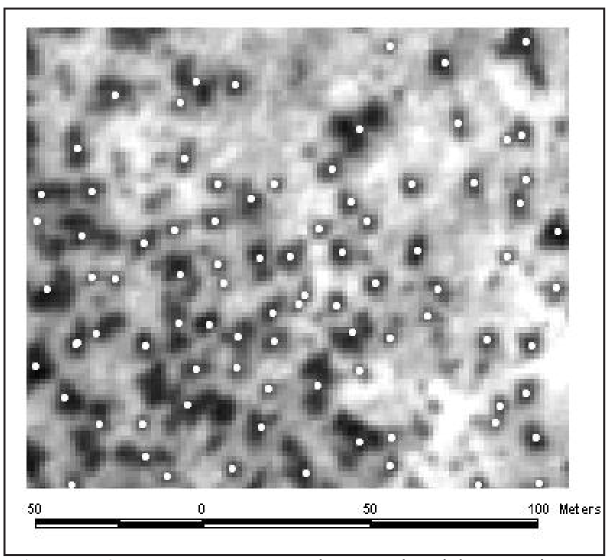

Figure 4. Tree crowns detected with Maximum Likelihood Classifier and GIS.

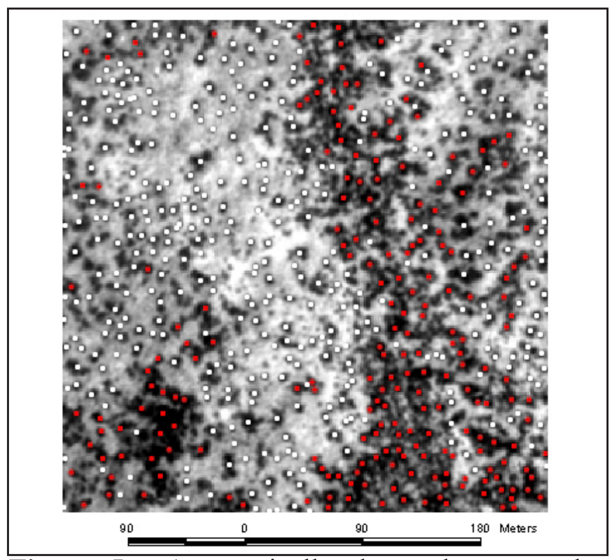

Figure 5. Automatically detected crown plus manually detected crowns. Red points are locations where MLC failed to separate crowns.

Chi Squared: Complete Spatial Randomness. A Chi Squared test for a Poisson distribution was calculated to compare number of tree crowns per cell to an expected distribution with the following formula:

$$X^2 = \sum \frac{(X_i - \overline{X})^2}{\overline{X}}$$

where X_i is the number of points in each quadrat and $\overline{X}$ is the number of points per quadrat. Standard error and Z score were tested as:

$$SE_x = \sqrt{\frac{2}{N-1}}$$

$$z = \frac{\text{observed ratio} - \text{expected ratio}}{SE_x}$$

The null hypothesis for this test of Complete Spatial Randomness states that the number per sampling unit follows a random Poisson distribution.

Nearest neighbor analysis. The null hypothesis of Nearest Neighbor Dispersion Analysis states that points are arranged randomly throughout the study area; a rejection of the null hypothesis assumes a non-random arrangement of points. To avoid negative edge effects in NND calculation, a toroidal edge correction was used in analysis, where points on opposite cell edges are considered near (Ripley 1979). Calculation of NN expected distance was completed with the following formula:

$$\bar{r}_e = 0.5 * \sqrt{\frac{A}{N}}$$

where $\bar{r}_e$ = average expected distance, A = area of study region, and N = number of points.

Nearest Neighbor K-Order statistics. Distance analysis was computed using K-Order statistics for each patch. Each patch was tested for nearest neighbor distance versus expected distance. A K value of 100 was selected for analysis, and expected NN was calculated with the above formula.

RESULTS

Tree Density

In general, the number of crowns recorded in HM patches greatly outnumbered those found in SLA patches of similar area, including cases where HM patches are smaller than paired SLA patches (Tables 3 and 4). The average number of crowns per 30 m cell for HM patches is at least twice that of SLA patches with similar elevation and aspect. When patches of each study area are combined, the mean number of crowns per cell was significantly (p = 0.0001) greater at the HM site (Table 4). These figures describe a greater density of oak and juniper trees in fire managed forests of the HM.

Complete Spatial Randomness

The null hypothesis for the CSR test states that number of crowns per grid unit follows a random Poisson distribution. Two out of three SLA patches fit a random or uniform distribution (Table 5). Two HM patches, HM1

Table 3. Site characteristics of HM and SLA encinal groupings, N and quadrat values.

Patch ID	Aspect	Elevation (m)	Average elev. (m)	Area (m^2)	Crowns (no.)	Cells (no.)	Cells (ave.)	Cells (var.)	Cells (SD)
HM1	SW	1990 - 2250	2120	56 181	768	88	8.73	22.81	4.78
HM2	S, SE	1830 - 2050	1940	289 029	3187	267	9.87	8.64	4.78
HM3	SE, S	1970 - 2280	2125	200 808	2004	173	8.78	8.15	2.86
HM4	SE	2000 - 2350	2175	109 773	1518	84	11.66	13.44	3.67
HM5	S, SW	1840 - 2040	1940	253 177	2741	223	9.04	21.66	4.65
HM6	S, SE	1816 - 2070	1943	153 288	1693	140	9.88	6.34	2.52
SLA1	SW, S	2000 - 2200	2100	89 549	464	48	3.83	2.31	1.52
SLA2	S, SW	1830 - 2040	1935	268 111	1481	223	4.36	3.86	1.96
SLA3	S, SE	1910 - 2200	2055	228 340	1089	197	4.03	3.18	1.78

and HM5, with high test values (23.697 and 86.749 respectively) showed a high degree of clustering under the CSR hypothesis (Table 5).

Table 4. Number of crowns and Nearest Neighbor values for both study sites.

	Huachuca Mountains	Sierra los Ajos
Crowns (no.)	1985	1011
Cells (no.)	163	156
Cells (ave.)	9.66	4.07
Cells (variance)	13.51	3.11
Cell (SD)	3.57	1.76
NM distance (m)	6	9
NM SD (m)	0.078	0.213
NM exp. distance (m)	6.4	12.0

Table 5. Results of Complete Spatial Randomness Hypothesis Test.

Patch ID	Lambda	Test value	P value
HM1	8.727	23.697	0.001
HM2	9.873	11.456	0.050
HM3	8.780	11.103	0.030
HM4	11.655	5.99	0.500
HM5	9.043	86.749	0.001
HM6	9.879	15.352	0.010
SLA1	3.833	3.752	0.300
SLA2	4.363	10.034	0.200
SLA3	4.025	13.648	0.030

Nearest Neighbor Analysis

For all plots, with the exception of HM4, the null hypothesis was rejected (Table 6). The null hypothesis states that the mean distance calculated for points in each patch is similar to an expected distance, and tree crowns in these patches follow a random Poisson distribution. In plots where the hypothesis was rejected, the mean NN distance of individual crowns is much smaller than expected, implying a clustered pattern for these sites. A random distribution of crowns occurs in HM4 where the mean is close to expected. The mean NN distance for combined SLA patches ($\bar{x}$ = 8.8 m) is significantly greater (p = 0.000 3) than HM ($\bar{x}$ = 5.9 m), correlating with the lower number of crowns found in the SLA (Figure 6).

Table 6. Results of Nearest Neighbor Dispersion Analysis.

Patch ID	Mean	SD	Expected Mean	Z score
HM1	5.70	0.10	5.23	4.81
HM2	6.29	0.07	7.47	-17.08
HM3	6.43	0.08	6.87	-5.52
HM4	5.49	0.07	5.36	1.89
HM5	5.23	0.07	7.16	-27.02
HM6	6.36	0.08	6.01	4.65
SLA1	9.18	0.29	11.92	-9.52
SLA2	8.31	0.18	13.48	-28.27
SLA3	8.91	0.17	10.57	-9.95

One drawback of the simple NN test is an inability to describe the spatial pattern of tree crowns in each patch. A K-Order Nearest Neighbor test was used to measure the 100th NN over distance, providing information on the spatial distribution of crowns for each patch. The kNN values describe greater distance in late orders between nearest neighbors for the SLA indicating a spatially dispersed crown pattern (Figure 7). Conversely, greater local clustering of trees seems to occur in HM patches (Figure 7).

DISCUSSION

Enabling detailed analysis of the spatial composition of each patch, the point analysis approach provides important ecological response information, deriving patch patterns arising from different fire management and land use histories. Establishing the number of trees per patch with the crown detection

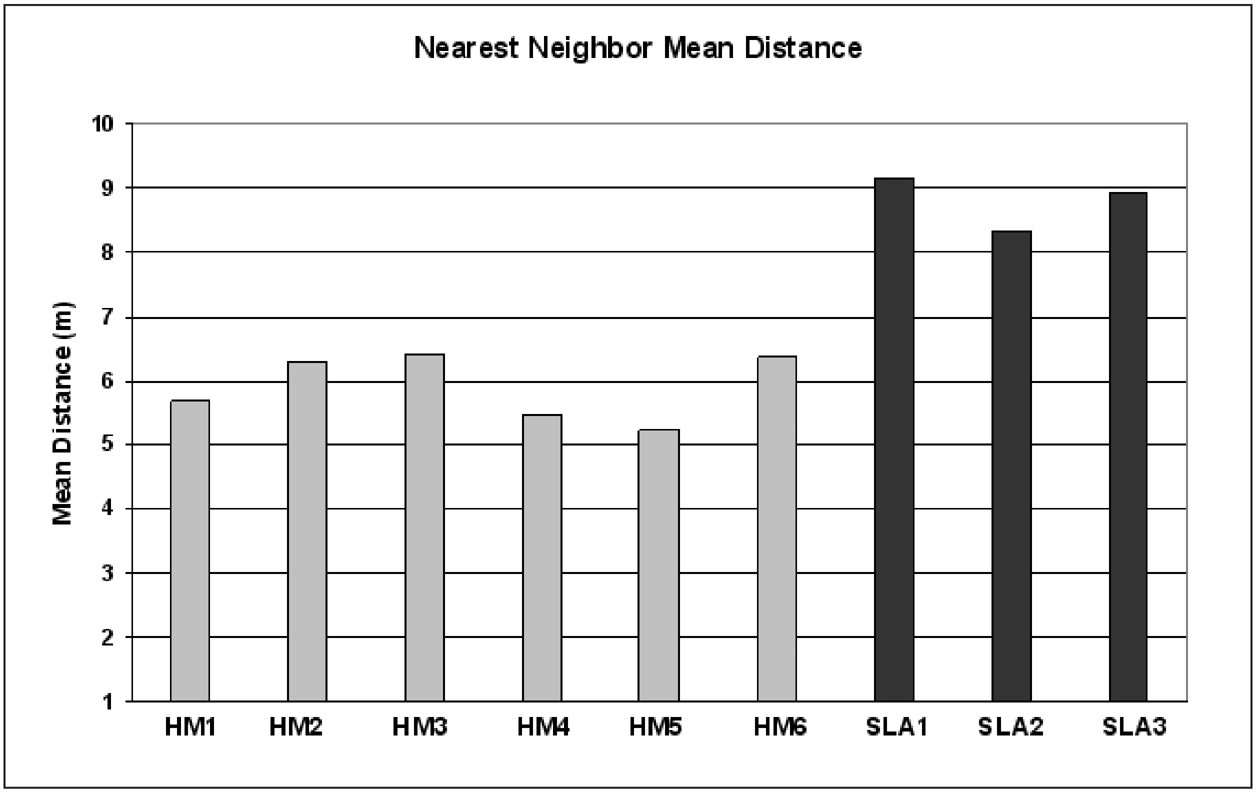

Figure 6. Nearest Neighbor mean distance by patch.

Figure 7. K-order Nearest Neighbor index describing spatial pattern of crowns over distance.

method permits both simple and complex comparisons of community populations in managed and unmanaged forests. Summaries of crown numbers and quadrat analysis reveal a relationship between fire exclusion and abundance of canopy fuels in the HM study sites. Tree density in HM patches far exceeds density in the SLA, an occurrence that can be considered a product of contrasting land use history.

By assessing distributions of points in quadrat cells over an entire patch, the CSR test provides analysis at a spatial scale greater than the K-order tests. In general, CSR tests suggest a level of randomness in the SLA over the entire patch. CSR tests show crowns within SLA patches may be randomly distributed over the entire area, which is consistent with oak savannah patterns under natural conditions. K-order tests indicate that crowns are clustered in smaller sub-areas, suggesting a level of local heterogeneity in SLA patches. CSR tests of the HM plots describe a non-random distribution over the entire area. Two HM plots have a high degree of clustering at the patch scale, and likewise, K-order tests point toward clustering distributions at a smaller scale. The overall pattern of HM crowns is better understood in the context of overall patch density where the NN clustering seen in HM stands indicate less heterogeneous and more overcrowded patches.

The NN and K-order analysis of spatial patterns delineate further differences: In each case, mean NN distance in the SLA exceeded those found in similar plots in the HM, while K-order analysis of HM plots describe significant clustering within small areas. The SLA plots, with fewer trees and greater mean distance, are clustered, yet K-order graphs explain that these patches have more local dispersion than HM patches.

Assuming that sites in the SLA experience similar seasonal precipitation patterns as the HM and were not recently harvested, the effects of livestock grazing and fire exclusion on the HM encinal ecosystem are considerable. Past research suggests that high oak density and canopy closure on the US side of the border is related to fire exclusion following years of grazing (Bahre and Minnich 2001). The savannah-like conditions in the SLA can be attributed to continued, low intensity grazing on ejido lands, multiple mid-20th century grassland fires, or a combination of both, that controlled oak and juniper populations.

Findings derived from point pattern analysis are consistent with current knowledge concerning effects of fire and human land use on Madrean ecosystems. Decades of fire exclusion in the HM contributed to greater stand density and homogeneity when compared with the SLA. The point data describe a situation where fire exclusion, land management, and land use have encouraged species propagation in lower elevations of the HM at densities not seen in unmanaged areas of the SLA. Spatial analysis of HM patches describe a level of density, clustering, and spatial homogeneity likely to contribute to intense fire conditions. Spatial analyses of unmanaged areas in the SLA portray more sparsely populated and spatially heterogeneous patches, likely maintained by centuries of semi-frequent fire. These findings confirm a longstanding view among fire ecologists that a century of fire exclusion in US forests has altered the pattern of species over the landscape.

A recent fire in the HM (Oversite Fire 2002) near the study site confirms the fact that encinal and pine-oak forests contain enough continuous fuels to carry an intense fire through oak woodlands into higher elevation mixed conifer stands. Patterns described in encinal forests of the SLA illustrate thinning effects of continued fire regimes on stand pattern. Although frequent fires are no longer common in the SLA, a moderately large surface fire (3500 ha) was reported in 1997 in upper elevation stands in the SLA, a testament to healthy conditions of SLA forests (Kaib 1998). Success with fuels treatment in the sky islands was demonstrated recently during the Bullock and Aspen Fires (2002-2003) in the Santa Catalina Mountains. A 69 ha area of pine forest treated through thinning and chipping was spared from crown fire during both fires (Bill Hart, Coronado National Forest, personal communication). When considering future restoration and treatment projects in forests of southern Arizona, managers in the US may benefit from acknowledging heterogeneous spatial patterns found in forests of the SLA.

Several uncontrolled factors may have limited or influenced the conclusions and findings in this paper. We hypothesized that land use and fire were the two main controlling factors of fuel distribution in encinal and pine-oak ecosystems. It should be noted that several other factors play important roles in biomass production and distribution. Topo-edaphic properties, preferential herbivory, soil moisture differences between sites, and micro climates all have major impacts on local site productivity and could have potentially contributed to differences observed in this study. Such factors could not be individually addressed when conducting a study at the landscape scale due to the considerable amounts of field research required.

The research and findings reported in this paper are based on a small number of patch-sized samples. The decision to work at the patch scale has benefits and drawbacks. Benefits of the patch scale include natural boundaries and the reduction of arbitrary sampling methods, but analysis of large patches can reduce the detection of fine-scale patterns occurring within a patch and reduce the total number of samples in the study.

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