

Forest Structure and Tree Recruitment Changes on a Permanent Historical Cinder Hills Plot Over a 130-Year Period

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Abstract—We examined forest structure, tree recruitment, and spatial pattern over a 130-year period on cinder soils in northern Arizona. Data were collected from a 3.24 ha permanent, stem-mapped plot established in 1909. This site is unique in that it represents ponderosa pine (*Pinus ponderosa* Laws. var. *scopulorum* Engelm.) growing on black cinder soils, which are of limited extent in the Southwest. Tree diameter, tree density and spatial data reconstructed from 1874 and actual measurements from 1909 and 2004 were compared, and the current stand age-structure of living trees was examined. Unlike most studies of stand dynamics in the Southwest, this site has experienced little change in structure or spatial pattern between 1874 and 2004. This difference is thought to reflect the unique environmental conditions associated with black cinder soils.

Introduction

In the past two decades, much attention has been given to understanding the dramatic structural and functional changes observed in the ponderosa pine forests of northern Arizona (Allen and others 2002, Covington and Moore 1994, Fulé and others 1997, Mast and others 1999, Moore and others 2004). While it is widely accepted that these changes have culminated in forest conditions consistent with catastrophic disturbances and widespread degradation of these ecosystems (Allen and others 2002), few studies have been able to quantify long-term (100+ years) temporal and spatial changes in forest structure (Moore and others 2004).

The objective of this study was to quantify changes in forest structure, tree recruitment, and associated spatial patterns between fire exclusion (~1874, Sánchez Meador and others 2008a) and contemporary conditions (2004). To do so, we analyzed forest structural data (tree size, tree density) and spatial pattern on a permanent plot at three points in time: onset of fire exclusion (1874), plot establishment (1909), and contemporary (2004). We also analyzed tree recruitment patterns as evidenced in spatial maps of regeneration from 1909 and 2004 and in the current stand age-structure. A particularly unusual aspect of this plot is that it occurs on a regionally unique parent material, cinder soils.

Methods

This study was conducted on a 3.24 ha (8 acre) site, denoted as COCS4A, located approximately 20 km north-east of Flagstaff, Arizona on the Coconino National Forest (35° 16.88'N, 111° 32.35'W). This plot is on the Fort Valley Experimental Forest unit east of Flagstaff, AZ (Unit 4) near Doney Park, and has also been referred to as the Cinder Hills or Cinder Plot, Greenlaw Plot, or Old Caves Crater plot. The plot was selectively harvested in 1909 (prior to plot establishment measurements) and in 1967.

The elevation of the study site is approximately 2,050 meters above sea level, mean annual total precipitation is approximately 430 mm, and mean annual average temperature is 7.6° C (Western Regional Climate Center 2006). The parent material and soils of the site are typical of the San Francisco Volcanic Field (Tanaka and others 1986) with a surface layer of volcanic ejecta (cinders) ranging in thickness from 2.5–60 cm. The Terrestrial Ecosystem Survey (TES) classifies the soil type of the site as ashy-skeletal, frigid Vintrandic Ustochrepts, which are extremely cindery sand loams (TES Map Unit 512, Miller and others 1995). The overstory vegetation is ponderosa pine with scattered pinyon pine (*Pinus edulis* Engelm.). The understory vegetation consists primarily of dispersed perennial bunchgrasses.

We used the original 1909 survey and forest inventory methods to reestablish the plots (see Moore and others 2004 for details). Methods used to map spatial locations of trees (x,y coordinates), collect age data, reconstruct plot conditions at fire exclusion, and conduct spatial analyses are outlined by Sánchez Meador and others (2008a, 2008b). In addition, ages were corrected for the time to reach 40 cm height by adding ten years (Cormier 1990). With the exception of analyses of recruitment, all analyses were conducted on live trees ≥ 9.14 cm diameter at breast height (1.37 m above ground level). We determined stand structural attributes (mean tree size, trees per ha, basal area, quadratic mean diameter, and seedlings per ha) at three points in time: onset of fire exclusion (1874), plot establishment (1909), and contemporary (2004).

Spatial analyses included a first-order point pattern analysis of nearest neighbor distances (Clark and Evans' R [Clark and Evans 1954]) to facilitate interpretation of changes in spatial pattern over time at the plot level and second-order point pattern analyses to examine changes at various spatial scales. Two second-order analyses were utilized: 1) Ripley's K(t) univariate analysis (Ripley 1976, 1977) to examine changes in spatial patterns with scale of observation for each stand structural scenario, and 2) Ripley's bivariate analysis (Ripley 1976, 1977) to quantify recruitment-establishment patterns of seedlings with respect to overstory trees.

Results

Stand structural and spatial conditions were similar in 1874 and 1909 to those observed in 2004 (Table 1). The 1909 group-selection harvest reduced the stand density (tree per hectare) by about a third and stand basal area by half, but had little effect on mean nearest neighbor distance. Contemporary age data revealed an uneven-aged structure with three main cohorts, centered in the mid-1800s, the early 1900s and in the mid-1900s. These pulses roughly correspond to periods of increased precipitation (Figure 1).

Live trees were clumped in all three scenarios (Figure 2). Ripley's univariate K analyses detected subtle differences among time periods in intensity and scale (Figure 3). In 1874 and 1909, trees were clumped at all scales, with maximum intensity at a distance of 10 m. In 2004, trees were clumped with maximum intensity at 6 m, but only out to 30 m, after which they were randomly arranged.

Seedling recruitment was spatially patterned at smaller scales in 1909 than 2004 (Figure 4). In 1909, seedlings were attracted to overstory trees up to six m away, whereas in 2004, seedlings were attracted to overstory trees up to 17 m away.

Discussion

The most important finding in this study is that unlike most other studies in southwestern ponderosa pine (Cooper 1960,

Covington and Moore 1994, Fulé and others 1997, Mast and others 1999, Moore and others 2004), forest structure on this black cinder site is largely unchanged from the onset of fire exclusion (1874) until 2004. Ponderosa pine stands on this study site have lower tree densities, yet higher tree growth and greater overall tree size compared with other stands on historical permanent plots in the Southwest (Moore and others 2004). Other studies have also noted greater average growth of trees on volcanic cinder soils in northern Arizona, and attribute it to a number of factors including: 1) minimal herbaceous competition, 2) deep subsoils that have moisture retaining layers, and/or 3) loose soils that facilitate development of extensive, branched tree root systems (Abella and Covington 2006, Colton 1932, Haasis 1921). In addition, we did not see the large population explosion of pine seedlings in 1919, as observed in many studies across northern Arizona (Savage and others 1996). Originally, we suspected that the harsh environment of the cinder soils may have prevented seedling establishment, but later we learned that a cone-weevil outbreak that occurred at this site in 1918 prevented the large seed and seedling crop seen in other areas around Flagstaff (Pearson 1923).

The spatial pattern has remained aggregated throughout the site's recorded history, and this is likely due to the patterns of pine recruitment. Recruitment is positively associated with the location of overstory trees. The existing tree canopy provides shade and increased soil moisture, which increases the chances of pine seedling survival (Stein and Kimberling 2003), especially on these more inhospitable surface soils (Abella and Covington 2006).

Summary

Ponderosa pine stands that occur on black cinders parent material account for a small proportion of the Coconino National Forest in northern Arizona (Miller and others 1995). Even though these stands do not occupy much area, they are unique. The uniqueness of this forest type was recognized in 1909 when G. A. Pearson established a FVEF East Unit (Unit 4) and several permanent plots to describe this forest type. We remeasured these permanent plots in 2004 and compared the forest structure (age, size, density) in 2004 to that in 1909 and to plots reconstructed to 1874. We found that the forest structure had not changed greatly from 1874 to 2004.

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Table 1. Stand-level structural and spatial attributes for live trees ≥ 9.14 cm dbh on COCS4A for presettlement (1874), plot establishment (1909), and contemporary scenarios (2004).

Attribute	1874	1909	2004
Structural			
Diameter at breast height (cm)			
Mean	40.8	34.4	42.9
Minimum	9.4	11.2	10.2
Maximum	96.4	96.5	92.2
Trees per ha	79.4	58.3	75.0
Basal area ($\text{m}^2 \text{ha}^{-1}$)	13.4	6.7	12.8
QMD (cm)	46.3	38.4	46.7
Seedlings per ha ^a	?? ^b	8.6	29.6
Spatial			
Nearest Neighbor Distance (m)			
Mean	4.4	4.2	4.5
Median	2.6	2.1	3.6
Minimum	0.6	0.1	0.2
Maximum	25.7	34.8	17.2
Clark & Evans R ^c	0.78	0.63	0.77

^a Seedlings are >0.3 m tall and <9.14 cm dbh.

^b 1874 seedlings per ha are not quantifiable with these data.

^c All values significant at the 95% confidence level.

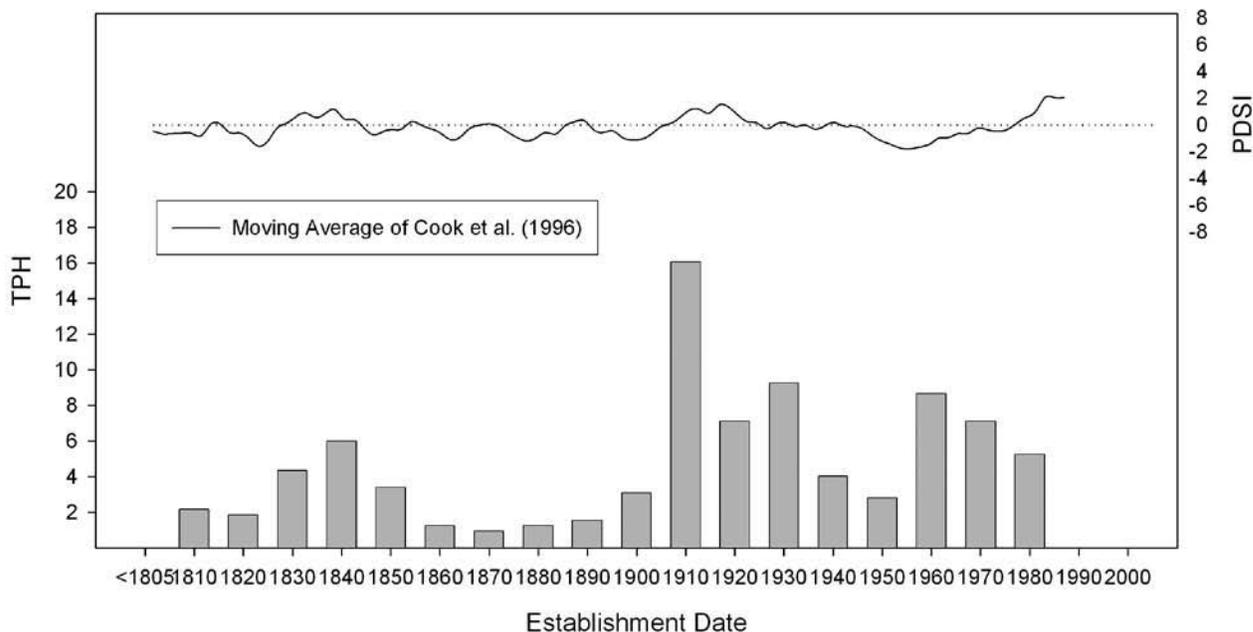


Figure 1. Age distribution by decade of COCS4A with overlay of Palmers Drought Severity Index showing the correlation between wet years and regeneration events.

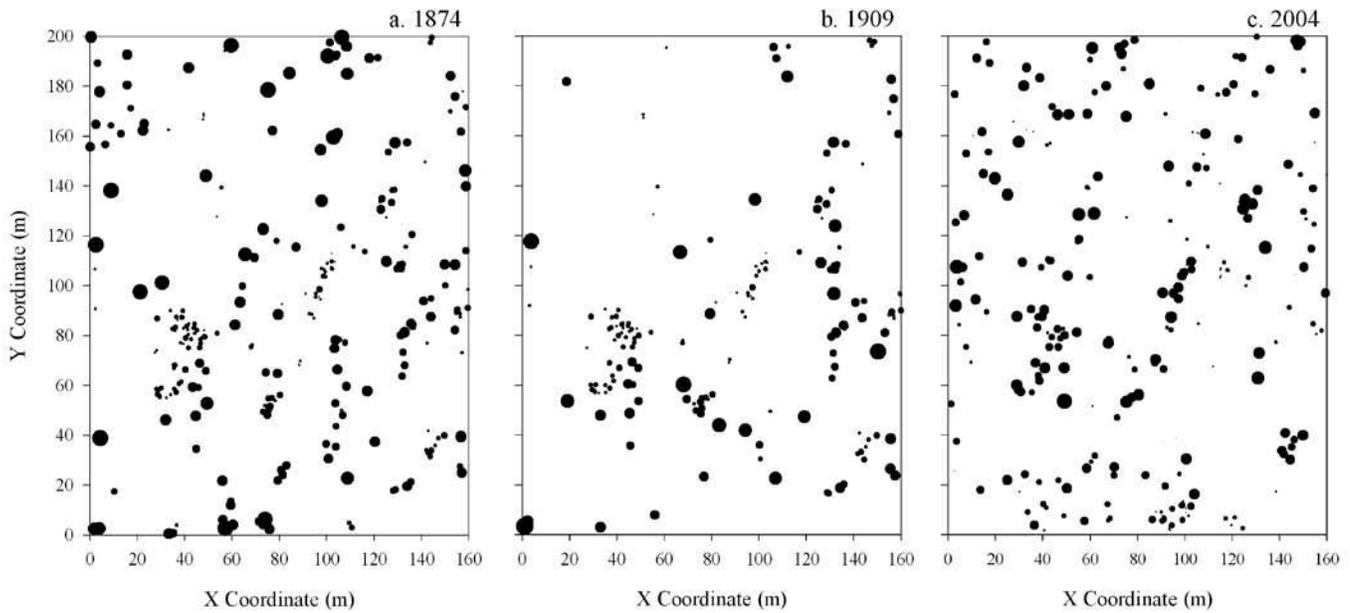


Figure 2. Stem maps of live trees ≥ 9.14 cm dbh for three time periods: (a) onset of fire exclusion (1874; $n = 257$), (b) plot establishment (1909; $n = 189$), and (c) contemporary (2004; $n = 243$). Point or circle size is proportional to stem diameter and on a different scale from tree coordinates for visual clarity.

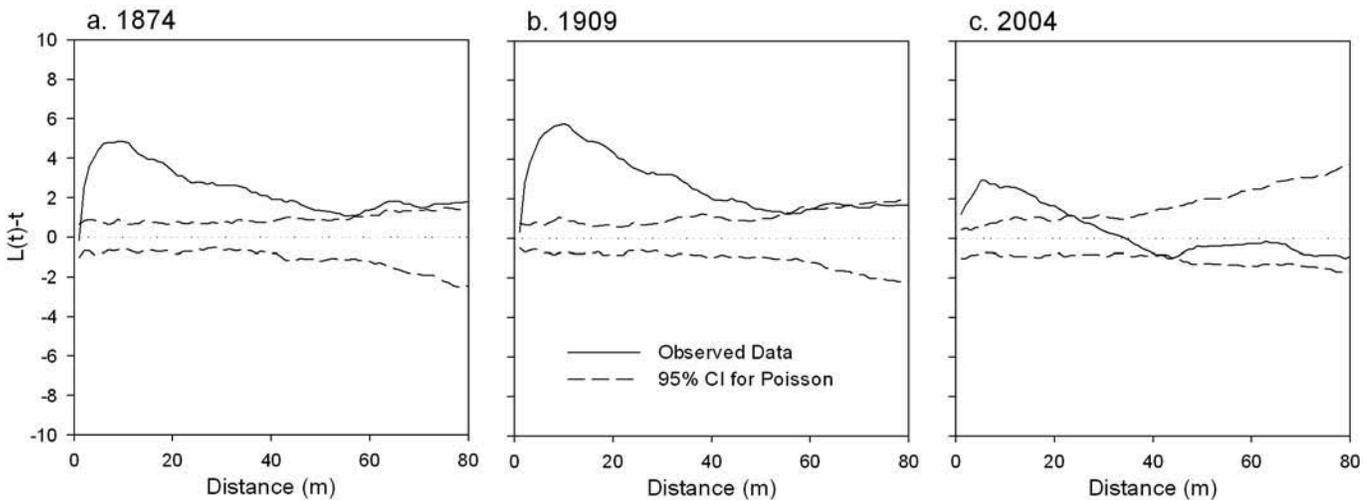


Figure 3. Ripley's $K(t)$ univariate statistic (transformed as $[L(t)-t]$) as a function of lag distance for three time periods: (a) onset of fire exclusion (1874; $n = 257$), (b) plot establishment (1909; $n = 189$), and (c) contemporary (2004; $n = 243$). The horizontal dashed line is the expectation if trees are randomly distributed. Calculated values that fall outside of the confidence interval are statistically significant; values > 0 indicate aggregation and values < 0 indicate uniform (regular) spatial distribution.

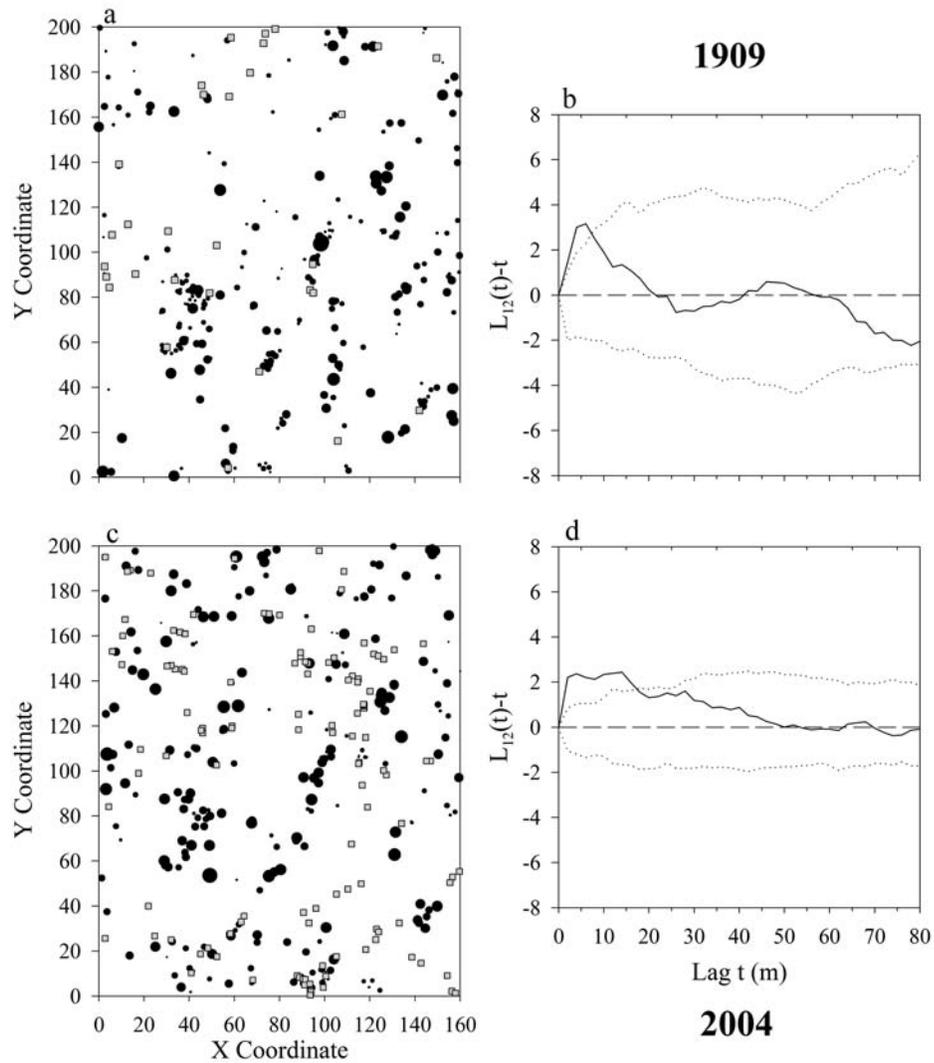


Figure 4. Stem maps showing overstory trees (black circles) and seedlings (grey squares) and the associated Ripley's $K_{12}(t)$ bivariate statistic (transformed as $[L_{12}(t)-t]$) as a function of lag distance) for 1909 plot establishment (a & b), and 2004 contemporary (c & d) conditions. The horizontal dashed line is the expectation if trees are randomly distributed, and the dotted lines are the 95% confidence limits. Calculated values that fall outside of the confidence interval are statistically significant; values >0 indicate attraction and values <0 indicate repulsion between the two populations.

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