Using a Terrestrial Ecosystem Survey to Estimate the Historical Density of Ponderosa Pine Trees

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Abstract: *Maps of historical tree densities for project areas and landscapes may be useful for a variety of management purposes such as determining site capabilities and planning forest thinning treatments. We used the U.S. Forest Service Region 3 terrestrial ecosystem survey in a novel way to determine if the ecosystem classification is a useful a guide for estimating historical (1880) ponderosa pine (*Pinus ponderosa*) tree densities on a northern Arizona landscape. Based on sampling 53 sites spanning 9 ecosystem types, we grouped the types into low and high density categories. Tree density was less than 24/ acre on 91 percent (21 of 23) of sites in cinder, dry limestone, and clay basalt ecosystems. In contrast, 70 percent (21 of 30) of sites that contained densities exceeding 24 trees/acre were in basalt, mixed igneous, and moist limestone ecosystems.*

Introduction

The study of historical forest structure has revealed the dramatic changes that have occurred in ponderosa pine (*Pinus ponderosa*) forests since the late 1800s following fire exclusion and irruptions of tree density (Covington and Moore 1994). In northern Arizona, for instance, Fulé and others (1997) used forest reconstruction methods to determine that ponderosa pine density rose more than 11-fold from 26 trees/acre in 1883 (the year of the last surface fire prior to fire exclusion) to 291 trees/acre in 1995. The persistence of dead wood (stumps, fallen logs, and snags) in the semi-arid climate of ponderosa pine forests, combined with fire exclusion preventing the wood from burning, facilitates reconstructing where historical trees were located (fig. 1). To complete the reconstruction of historical density, currently living old trees also are recorded (Harrod and others 1999). The accuracy of this reconstruction method has been assessed by re-measuring 15 stem-mapped plots established by the U.S. Forest Service's Southwestern Region (Region 3) from 1909 to 1913 (Moore and others 2004). This assessment confirmed that dead wood that was mapped in 1909 was still present in 1999. The reconstructed density was within 9 percent of the densities recorded in the early 1900s.

As a result of the known deviance of present forest conditions from historical conditions, there is interest in decreasing the probability of severe wildfires by thinning ponderosa

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Figure 1. Examples of stumps (foreground, and to the left of the large tree), indicative of historical tree locations, and a live tree of pre-settlement origin (left-center). Photo by S.R. Abella in 2009, Forest Road 3E, Coconino National Forest, northern Arizona (UTM: 440,918 m E, 3,885,850 m N, North American Datum 1983).

pine forests. The goal of thinning is not necessarily to replicate historical conditions (prior to late 1800s Euro-American settlement), but rather to reduce tree densities to levels that support surface fires instead of crown fires (Covington 2003). As a result, knowledge of the historical forest structure can help with the planning of thinning projects by providing estimates of tree densities that were sustainable through at least several generations of trees (Allen and others 2002).

A map of historical tree density for project areas and landscapes could be valuable for several management purposes (Harrod and others 1999). First, it would help managers understand spatial variation in tree structure and factors (such as soils) that may have been associated with the variation, thereby helping managers understand long-term site capability for supporting trees. Second, historical tree densities could be compared to present forest inventories to identify areas of the landscape that have experienced the greatest or least change in tree density, thus helping prioritize areas for management (Bell and others 2009). Third, the historical densities, in combination with other management considerations, can provide rough density targets for forest thinning projects when considering past reference conditions in management planning.

The terrestrial ecosystem survey (TES) in the Southwestern Region maps ecosystems across landscapes based on climate, geology, soils, and late-successional vegetation (U.S. Forest Service 1986). This system is similar to other ecological land classification and mapping initiatives such as the terrestrial ecological unit inventory (also a Forest Service program), USDA Natural Resources Conservation Service ecological site types, and ecosystem classifications developed in individual research projects (Abella and Covington 2006). The major concept underpinning these systems is that climate, geology, soils, and vegetation are interrelated and form repeating combinations across the landscape that can be classified and mapped (Robbie 1992). We used the TES in a novel way to determine if it could help estimate historical ponderosa pine tree densities across the landscape. We hypothesized that dry ecosystems, where pine establishment may be limited, contained lower densities than moist ecosystems. We anticipated that the TES would capture this variation.
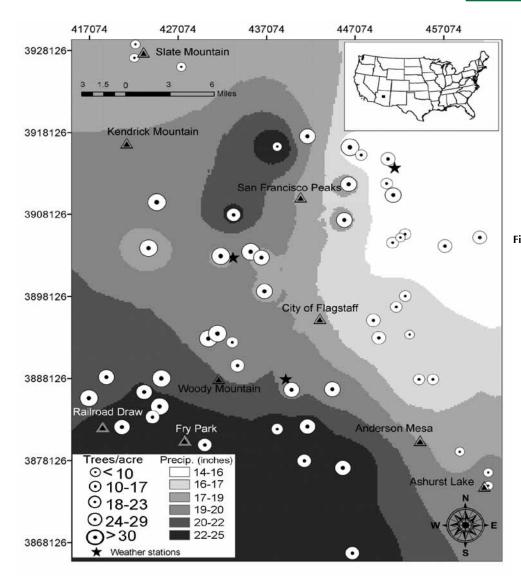
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Figure 2. Location of 53 sample sites on a northern Arizona landscape. Sizes of points for sites are scaled to reflect ponderosa pine tree density reconstructed for 1880 forests. Shading depicts gradients in annual precipitation estimated from sample site values using the PRISM model (Daly and others 2008). Coordinates are UTM, North American Datum 1983.

Methods

Study Area

We conducted this study within a 250,000-acre area in northern Arizona on the northern half of the Coconino National Forest and on the Northern Arizona University Centennial Forest surrounding the city of Flagstaff (fig. 2). Study sites ranged in elevation from 6300 to 8410 ft and were located in ponderosa pine forests. Half of the annual precipitation occurs in winter as snow and much of the rest occurs in July through September as monsoonal storms. Slope gradients are typically less than 10 percent, but cinder cones,

ravines, and undulating hills of greater slope gradient are present. These forests historically experienced frequent surface fires, with fire intervals of two to five years based on five fire-history studies (Van Horne and Fulé 2006). Understories were and are dominated by grasses and sedges such as blue grama (*Bouteloua gracilis*), White Mountain sedge (*Carex geophila*), squirreltail (*Elymus elymoides*), Arizona fescue (*Festuca arizonica*), and mountain muhly (*Muhlenbergia montana*) (Pearson 1942).

The study area is covered by the Coconino National Forest TES (http://alic.arid.arizona.edu/tes/tes.html) that maps ecosystem types at a 1:24,000 scale with a minimum mapping unit of 40 acres (Miller and others 1995). Ecosystem

Table 1. Characteristics of terrestrial ecosystem survey types sampled in ponderosa pine forests of northern Arizona. Ecosystem types are arranged in order of increasing tree density classes according to table 2.

Ecosystem type[a]	Mean ± SD[b]	Median (CI)[c]	Precipitation[d]	Description[e]
Clay basalt (523)	2 ± 3 d	1 (0 to 4)	22	Basalt, clay loam soils with large cracks and clay subsoils
Red cinder (513)	23 ± 25 bc[f]	15 (10 to 16)	19	Dry, red volcanic cinders, sandy loam
Dry limestone (500)	16 ± 7 c	16 (12 to 21)	20	Climatically dry, sandy loam limestone
Black cinder (558)	22 ± 5 bc	19 (18 to 26)	18	Dry, nitrogen-poor, sand-gravel, black volcanic cinders
Benmorite (570)	34 ± 19 ab	27 (19 to 48)	23	Benmoritic, loam, sometimes rocky, clay subsoils
Mixed igneous (551)	23 ± 9 abc	25 (15 to 29)	24	Mixed igenous, loam soils around the San Francisco Peaks
Rocky basalt (585)	29 ± 8 abc	28 (25 to 35)	27	Rocky basalt, loam surface soils with clay loam subsoils
Moist limestone (536)	28 ± 4 abc	27 (25 to 31)	25	Moist, sandy loam limestone, productive understories
Moist basalt (582)	40 ± 19 a	46 (27 to 53)	25	Basalt, silt loam, widespread type, productive understories

[a] Numbers in parentheses are the ecosystem unit identification number in the ecosystem survey manual (Miller and others 1995).

[b] Historical tree density (stems/acre) reconstructed for the year 1880. Values are mean ± standard deviation. Means without shared letters differ at $P<0.05$.

[c] Median historical tree density (stems/acre) with lower and upper bounds of 95 percent confidence intervals for medians in parentheses.

[d] Average precipitation in inches/year estimated from sample site values using the PRISM model (Daly and others 2008).

[e] Soil parent material and 0- to 6-inch soil texture, unless specified as corresponding to 6- to 20-inch subsoils. Data from Miller and others (1995) and Abella and Covington (2006).

[f] The red cinder ecosystem had a site with an unusually high density of 74 trees/acre, which was 16 trees/acre greater than any of the other 52 sites and 4.4-fold greater than the next highest density (17 trees/acre) within this ecosystem. If the site with 74 trees/acre is excluded, the mean tree density of the red cinder ecosystem falls to 13 ± 4 trees/acre and the pattern of significant differences among ecosystems is (by ecosystem unit number): 523d, 513c, 500c, 558bc, 570ab, 551bc, 585ab, 536ab, and 582a.

types were primarily classified and delineated based on soil parent material, landform, climate, and secondarily by dominant overstory trees and understory species (Robbie 1992). The TES identified ecosystem types by a numerical code. In this paper, we name the ecosystems based on soil parent material and moisture status and provide the corresponding numerical codes in table 1.

Site Selection and Sampling

With a digital map of the TES for the study area (Miller and others 1995), we randomly selected a Universal Transverse Mercator (UTM) coordinate for a sample location within each of five to seven mapping units of nine ecosystem types. This resulted in 53 independent sites replicated across the landscape (fig. 2). The slight variation in the number of sites among ecosystems resulted from rejecting mapping units for sampling if a post-settlement fire or other disturbance destroyed evidence of historical trees. The nine ecosystem types encompass a range of soil parent materials, including basalt, benmorite, limestone, and volcanic cinders (Miller and others 1995). Four soil orders are represented in the ecosystems, including the predominant subgroups of Typic and Udic Argiborolls, Typic and Mollic Eutroboralfs, Typic Ustorthents, and Vitrandic Ustochrepts. Soils ranged from sandy, dry, nitrogen-poor volcanic cinders in the black cinder ecosystem to silt loam and nitrogen-rich in the moist basalt ecosystem. Soil, climate, and other characteristics of all nine ecosystems are summarized in table 1.

We established a 328-ft × 328-ft, 2.5-acre plot at the randomly selected UTM coordinate at each site. Using the methods of Fulé and others (1997), we counted the number of evidences of pre-settlement trees based on the presence of dead wood and living, old trees. We selected the year 1880 as the forest reconstruction year because the start of fire exclusion associated with Euro-American settlement has been dated between 1876 and 1883 in the study area (Van Horne and Fulé 2006). We identified pre-settlement-origin live trees based on the observation that ponderosa pine develops orange, platy bark by about 100 years of age (White 1985). To ensure the accuracy of this observation, we cored trees of uncertain status (typically 10 percent of the total live trees) and counted rings in the field to classify these trees as pre- or post-settlement. We did not attempt to reconstruct stem diameters that evidence would have had in 1880. Reconstruction of stem diameters is more complicated than that of density, requiring information on year of death and decomposition models for the dead wood and cross-dated tree cores, and bark thickness for currently live trees (Fulé and others 1997). Tree size and basal area data could be useful to obtain in future research for understanding potential variation in tree growth rates and biomass among ecosystems.

Analysis

We compared the mean tree density among TES types with a one-way analysis of variance followed by Fisher's protected least significant difference for multiple comparisons (SAS Institute 1999). Data were analyzed on a transformed scale (square root) to improve equality of variance and normality. Medians, with confidence intervals at the 95 percent level determined through bootstrapping (1000 samples),

were also calculated. We further grouped densities into five categories ranging from low to high (<10, 10 to 17, 18 to 23, 24 to 29, and ≥30 trees/acre) and assessed the number of sites of each ecosystem type that fell into the categories. These density categories were based on natural breaks in the data and contained approximately equal numbers of total sites. These categories were also anticipated to have ecological significance by representing a gradient from extremely low to high densities.

To help formulate hypotheses about possible causes of variation in density within and among ecosystems, we used data on understory vegetation and soil collected in 2003 during previous research at the study sites (Abella and Covington 2006). We examined Pearson correlation coefficients for associations between tree density and understory grass cover; percent sand, silt, and clay; volumetric nitrogen and organic carbon content of the 0- to 6-inch soil layer; and average annual precipitation estimated for each site using the PRISM model (Daly and others 2008). For grass cover, we are not implying that understory vegetation is necessarily the same in contemporary forests as in historical forests, but rather that variation in current understories across the landscape corresponds to variation in the productivity of ecosystems reported in the TES (Miller and others 1995; Abella and Covington 2006). We further subjected the environmental variables (soil and climate only) to a principal components analysis (cross-products matrix derived from correlation coefficients) using the software PC-ORD (McCune and Mefford 1999) to evaluate whether tree density was correlated with multivariate combinations of variables as synthesized by principal components. Using Pearson coefficients, we related tree density to plot scores of the first principal component (no additional component accounted for ≥18 percent of the variance).

Results

The density of historical trees differed significantly among ecosystem types ($F_{8,44}$ statistic = 8.14; $P<0.0001$). Means varied 20-fold, ranging from 2 trees/acre in a clay basalt to 40 trees/acre in a moist basalt ecosystem (table 1). Medians similarly ranged from 1 to 46 trees/acre across ecosystems. Patterns also emerged when partitioning density into classes, with the clay basalt, red cinder, and dry limestone ecosystems containing the most sites in the low and low-medium density classes (table 2). The black cinder ecosystem had the most medium density sites. Mixed igneous, basalt, benmorite, and moist limestone ecosystems possessed the most medium-high and high density sites. Four of the six sample sites of the moist basalt ecosystem were in the highest density class (≥30 trees/acre)—the largest proportion of any ecosystem.

Variation in density among ecosystems became even more pronounced when simply dividing ecosystems into low (<24 trees/acre) and high (≥24 trees/acre) density categories (table 3). This classification accurately portrayed 42 of the 53 (79 percent) sample sites by ecosystem type.

In examining continuous variation, density was not strongly correlated with any single variable or principal component. Correlations (r) of density with understory and environmental variables were as follows: -0.25 (grass cover), -0.17 (sand), 0.35 (silt), -0.14 (clay), -0.23 (nitrogen), 0.07 (organic carbon), and 0.24 (average annual precipitation). In principal components analysis, the first principal component accounted for 60 percent of the variation in the environmental variables. This component had a positive loading (0.92) for sand and negative loadings (-0.68 to -0.84) for the other variables. However, density was not strongly correlated ($r = 0.05$) with this component.

Table 2. Distribution of density classes of ponderosa pine trees reconstructed for historical, 1880 forests on 53 sites of 9 terrestrial ecosystem survey types in northern Arizona. Ecosystems are arranged in general order of low to high tree density.

Ecosystem type	Trees/acre					
	<10	10 to 17	18 to 23	24 to 29	≥30	Total
	Number of sites					
Clay basalt	6					6
Red cinder	1	4			1	6
Dry limestone	1	3	2			6
Black cinder		1	3	1		5
Benmorite		1	1	1	2	5
Mixed igneous	1		1	3	1	6
Rocky basalt			2	4	1	7
Moist limestone			1	4	1	6
Moist basalt		1	1		4	6
Total	9	10	11	13	10	53

Table 3. Grouping of terrestrial ecosystem survey types into low and high density classes of ponderosa pine trees reconstructed for historical, 1880 forests on 53 sites in northern Arizona.

Ecosystem types	Trees/acre		
	<24	≥24	Total
	Number of sites		
Clay basalt, red cinder, dry limestone, black cinder	21	2	23
Benmorite, mixed igneous, rocky basalt, moist limestone, moist basalt	9	21	30
Total	30	23	53

Discussion

Variation in overall historical density of ponderosa pine trees across the landscape was well-captured by the TES framework. The TES was especially useful for identifying where low and high density sites occurred (table 3). Since the TES already is in map form, managers could use the TES to anticipate density ranges for mapping units in project areas. These expected densities should be checked by site-specific field surveys, since 21 percent of sites were exceptions that did not fit the typical low or high density classification of ecosystem types.

Our hypothesis that dry ecosystems contained the lowest tree densities was only partially supported by the data. The four ecosystems that received the least precipitation did have the lowest densities (table 1). However, within this group, the black cinder ecosystem had 18 percent less precipitation, but possessed 11-fold greater mean density, than the clay basalt ecosystem. These findings were consistent with the relatively weak correlation (0.24) of density with precipitation. Density was likely influenced across the landscape by multivariate interactions with moisture and other factors such as soil clay content affecting frost-heaving (Haasis 1923), species-specific competition with perennial grasses and sedges (Pearson 1942), fire regimes shaping availability of safe sites for seedling establishment and survival (White 1985), and possibly rock cover providing protection for seedlings in some ecosystems. The TES may have captured variation in these factors, explaining why specific ecosystem types within the TES were more closely related to density than was moisture alone.

Variability within the broad dry and moist ecosystem type groupings and within specific ecosystem types could be related to several factors. For example, the TES mapping units contain variability in soils and vegetation, which is inherent in any ecological mapping effort that breaks continuous variation into discrete mapping units (Miller and others 1995). Competition with understory vegetation could have influenced tree densities within ecosystems (Pearson 1942). The two sites, for instance, in the moist basalt ecosystem that contained the lowest densities (table 2) exhibited 25 percent more plant species/10.8 ft^2 in the understory at the sites in 2003 (Abella and Covington 2006). Whether or not understory vegetation has changed since historical times, we can say that contemporary sites with especially species-rich and productive understories did not support the highest historical tree densities. While no quantitative data are available on variation of historical understory vegetation across the landscape, future research that examines effects of soil influences mediated through understory vegetation on tree densities in contemporary forests could help assess understory effects on trees within the TES framework. Fire regimes were not part of TES development, and while it is unclear how variable fire regimes were across the landscape given that five investigations in the study area have reported a tight range of two- to five-year fire return intervals (Van Horne and Fulé 2006), the possibility that fire regimes influenced tree densities within ecosystem types cannot be dismissed. Other factors that were not part of the TES could have influenced density, such as wildlife, insects/disease, local disturbances, or patterns of pine seed dispersal.

In the following sections, we describe density patterns within each ecosystem type.

Clay Basalt

None of the six sample sites of this ecosystem had greater than 8 ponderosa pine trees/acre and four of six sites contained less than 1 tree/acre, making this the least dense among the nine ecosystem types examined. Study sites were situated on Anderson Mesa and southwest of Slate Mountain, at an average elevation (7167 ft) identical to the average of all 53 sites, and with medium modeled precipitation (table 1). Based on the high average 0- to 6-inch soil clay concentration (31 percent), we suspect that clayey soils limited density in this ecosystem. Large cracks in the soil, sometimes a foot wide and several feet deep, suggest that soil expansion/contraction (frost-heaving or drought-related) could have reduced seedling survival (Haasis 1923). Ponding of water on the clay surface in spring also may have influenced survival. The few ponderosa pine trees occurring on sample sites were often associated with rocky outcrops. A study by Gascho Landis and Bailey (2005) on Anderson Mesa in this ecosystem indicated that densities of Utah juniper (*Juniperus osteosperma*) and two-needle pinyon pine (*Pinus edulis*) were much greater than ponderosa pine. These data suggest that this ecosystem historically was a juniper-pinyon woodland with only scattered ponderosa pine.

Red Cinder

Density of five of the six sites was in the range of 7 to 17 trees/acre, among the lowest of all ecosystems. Low precipitation combined with gravelly, sandy textured soils low in moisture probably limited seedling establishment. However, the sixth site of this ecosystem contained 74 trees/acre, 4.4 times greater than the next densest site of this ecosystem and 16 trees/acre greater than the second densest site (58 trees/acre) of all 53 sample sites. This unusually dense site in this ecosystem is perplexing because the site's soil textural class (sandy loam) is the same as the average for this ecosystem, and there were no readily apparent soil or topographic differences with sites that possessed lower densities. There was a high incidence of

fire-scarred trees at this site (Abella 2008), although this could simply have been related to the high density of trees available for recording fires.

Dry Limestone

Density was 14 to 24 trees/acre at five of the six sites, placing this type in the low half among ecosystems. Tree establishment was likely limited by dry climates and sandy soils low in available water. The site with an unusually low density (6 trees/acre) for this ecosystem had sandy loam-loamy sand surface soils like the other sites. Precipitation and topography also were comparable. However, similar to the clay basalt ecosystem, more juniper (*Juniperus* spp.) trees were present at this site, possibly indicating a marginal site for ponderosa pine or greater interspecific competition.

Black Cinder

This ecosystem contained the least understory vegetation of all sampled ecosystems, with soil patches of 0.025 acres commonly having no plants at all. Therefore, competition with understory plants likely minimally affected pine establishment in this ecosystem. The same dry, surficial layer of gravelly cinders limiting understory vegetation would be expected to reduce tree establishment (Hanks and others 1983). Apparently, however, pine had the ability to root through the cinders to finer textured bands below (Abella and Covington 2006) because density was medium in this ecosystem. The site with the highest density of trees in this ecosystem (30 trees/acre, 8 trees/acre greater than the next highest site) had a slight increase in silt in the surface layer making it a loamy sand (rather than a sand). We hypothesize that tree density increases when the thickness of the surficial layer of cinders declines or as the silt content increases.

Benmorite

This ecosystem could benefit from additional sampling as three sites contained densities of 16 to 27 trees/acre, while the remaining two sites had particularly high densities of 52 and 57 trees/acre. All sites exhibited loam textures for the 0- to 6-inch layer and 23 to 24 inches of precipitation/year. The two sites with elevated densities contained 1.7 times more total nitrogen on average than the three low density sites.

Mixed Igneous

Density was between 24 and 29 trees/acre at four of the six sites, but it was comparatively low at 6 and 20 trees/acre at the other two sites. These two sites were northwest and north of the San Francisco Peaks and had the highest precipitation,

soil total nitrogen, and cover of understory grasses and sedges within this ecosystem. Arizona fescue, the dominant grass, is considered the strongest competitor with pine among perennial grasses (Pearson 1942). We hypothesize that understory competition especially limited pine establishment on these sites that otherwise had climates and soils favorable for supporting high pine densities.

Rocky Basalt

Six of the seven sites had a tight range of 21 to 29 trees/acre, while the seventh site contained 46 trees/acre. This site had loam surface textures typical of the other sites within this ecosystem, only 54 percent of the average soil nitrogen, slope gradients less than 8 percent like the other sites, and within an inch of the ecosystem's average precipitation. Further work is needed to resolve why these types of rare exceptions occurred to the typical densities in this ecosystem.

Moist Limestone

This ecosystem exhibited the most consistent density among the TES types, ranging from 22 to 34 trees/acre with four of six sites differing by fewer than 3 trees/acre. Although soils are derived from limestone, pH from a 0- to 20-inch depth averaged 6.1 to 6.4, similar to the basalt and benmorite ecosystems (Abella and Covington 2006). Precipitation also was similar. Soil texture from 0 to 6 inches was sandier (sandy loam) in this ecosystem than in the basalt-benmorite types (loam-silt loam). This sandier texture may have constrained the ability of this ecosystem to support the particularly high densities that some sites of the basalt-benmorite ecosystems did. On the other hand, this ecosystem did not have the low density sites that the basalt-benmorite ecosystems contained.

Moist Basalt

This ecosystem had four (39 to 58 trees/acre) of the seven densest sites among the 53 sample sites. The other two sites in this ecosystem, however, contained only 16 and 18 trees/acre. Surface textures on these sites were loams rather than silt loams as in the other sites of this ecosystem. Still, silt + clay content differed little (62 percent on the low density versus 69 percent on the high density sites). Precipitation actually averaged 3 inches greater on the low density than on the high density sites, and all plots had similar topography (slope gradients <5 percent). These sites illustrate that chance or factors (for example, fire regimes) other than those that we measured may be important in explaining exceptions to typical density patterns.

Collectively, patterns of tree density among the individual ecosystems suggest that the TES effectively corresponded with

generalized variation in tree density classes across the landscape. Managers should be aware, however, that exceptions to the typical density patterns within an ecosystem did occur. Reasons for these exceptions are poorly understood and could be related to variation within the TES (such as soil inclusions that are not typical of the rest of the mapping units), factors like fire regimes that are not part of the TES, or continuous variation in factors (for example, rock cover) or combinations of factors constraining tree densities. Further research on the potential relationships of these factors with historical density could be useful to advance our understanding of the use of the TES for estimating tree density.

Management Implications

- The TES is useful for understanding variation in the historical density of ponderosa pine trees across the landscape. The TES correctly categorized 79 percent of 53 sample sites as low (<24 trees/acre) or high (≥24 trees/acre) density.

- The TES is available as a map (Miller and others 1995); therefore, managers can identify ranges of anticipated historical densities for TES mapping units within project areas.

- Having these density estimates facilitates an understanding of the tree densities that different ecosystems supported in the past. These densities may be useful for assessing site capability, evaluating the degree to which forest structure has changed, and preparing tree thinning prescriptions.

- Future research could refine anticipated densities among the TES types through further sampling and could seek to understand exceptions within ecosystems to their typical densities.

Acknowledgments

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