CHARACTERIZE SOUTHWESTERN U.S. PIÑON-JUNIPER WOODLANDS

FINAL REPORT

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Chapter 2:

Jacobs, B.F. In press. Southwestern U.S. Juniper and Piñon-Juniper Savanna and Woodland Communities: Ecological History and Natural Range of Variability. In: G. Gottfried, J. Shaw, and P.L. Ford (eds.). Ecology, Management, and Restoration of Pinyon-Juniper and Ponderosa Pine Ecosystems: Combined Proceedings of the 2005 St. George, Utah and 2006 Albuquerque, New Mexico Workshops. RMRS-###, Fort Collins, CO.

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Chapter 4:

Jacobs, B.F. and W.H. Romme. In preparation. Regional scale modeling of southwestern U.S. piñon-juniper woodlands: predictive mapping of "old" versus "young" stands in the Four-Corner states, USA.

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The early naturalists who so elegantly captured the nature of scale with simple prose of spider webs and stars seem far beyond the understanding of modern ecologists who garble the literature with a tangled language that even advocates have trouble digesting. The truth of scale is that it is endemic to the universe and if there is an exception it is finding a pattern or process which occurs only in one place and time and without effect on anything else. Scale does matter, and we get different results and make different interpretations depending on the scale of measurement and analysis, but this reality is all around us and even within us. The important thing is to be cognizant about the relevant scales for a particular inquiry, be explicit about the choices of scale and its effect on findings, and realize that in the end there is no optimal scale and all scales matter. *B.F. Jacobs*

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PART I

Environmental controls of "old" or persistent woodland:

A study proposal

Abstract

Piñon-juniper woodlands are widely distributed on millions of acres across the southwestern U.S. Recent, historical changes in woodland occurrence and stand density have been variously interpreted as continued adjustment to Holocene climate, recovery from harvest (historic and pre-historic), succession after fire, drought, insect, and/ or disease induced mortality events, or response to grazing practices, altered fire regimes, elevated temperatures and CO_2 levels. The broad ecological amplitude of southwestern piñon-juniper woodland tree species is demonstrated by the wide range of sites on which these trees can grow. Conversely, these species are extremely sensitive to fire disturbance and easily killed; drought, insect, and disease mortality can also have large effects on woodland stand dynamics, structure, and local distribution patterns. We suggest that while ecological amplitude and regional climate set broad limits on potential woodland species distribution, environmental factors and associated disturbance regimes formerly constrained the local extent and expression of woodland species occurrence on the landscape. If competitive interactions with understory, and disturbances like periodic surface fire, formerly restricted woodlands to a more limited range of sites (i.e., through competition with grasses and shrubs or fire avoidance) we could expect to detect meaningful relationships between "old" or persistent woodland stands (i.e., pre-dating Euro-American settlement) and suites of environmental site parameters. Delineating "old" or persistent stands, on the basis of semi-quantitative and qualitative characters using a diagnostic key, and relating the occurrence of these aged stands to environmental site conditions through spatial modeling efforts, would potentially provide a means for predictively mapping "older" (i.e., pre-settlement) stands, and thereby delineate "younger" (i.e., post-settlement) woodlands to facilitate appropriate and targeted management actions.

Introduction

Piñon and juniper dominated woodlands occupy millions of acres throughout the western United States (West, 1999), and are thought to have expanded several fold since 1850 (Miller and Wigand, 1994; Swetnam et. al., 1999; Tausch, 1999a ; Miller and Tausch, 2001;). Research and management efforts have primarily addressed the recent, post- Euro American settlement expansion of woodlands onto degraded rangelands and into forests understories, absent fire disturbance. Often ignored, or poorly recognized however, are the "old" or persistent stands (in various stages of successional development), which in some areas account for only a few percent of the total acreage (Waicher et. al, 2001), but in other locations may be much more common than previously thought (Eisenhart, 2004.). These pre-settlement status piñon and juniper woodlands, typically exceeding 150 years in age, are often thought to be restricted to low productivity sites where shallow soils and natural topographic barriers may combine to provide fire-safe conditions (Miller and Tausch, 2001). Old growth woodlands often create structurally complex and biologically diverse habitat supporting many unique organisms; individual trees can live several hundred to more than a thousand years, with juniper snags and logs often persisting for several hundred years (Floyd et. al., 2003). Yet, because these "old" or persistent growth communities are poorly understood, undervalued, and not easily distinguished from stands of more recent origin, they are increasingly at risk of being "restored" or burned over. Unrecognized, these old growth woodlands can be inadvertently harmed by management actions (i.e., restoration, rangeland improvement, and fuel mitigation efforts) designed for post- Euro American settlement woodlands (Eisenhart, 2004); conversely, crown fire is much more likely to occur in old growth stands contiguous with post-Euro American settlement woodlands

occupying more productive sites (Waicher et. al., 2001; Romme et. al. 2003).

Much of the confusion about the nature of woodlands can be attributed to overly simplistic classification methods utilizing current tree overstory as the primary determinate of community type, regardless of age-structure, understory composition, or site history. Thus often lumped together with woodland, are former pine savanna, grass- and shrub- land communities only recently (i.e., <150 years) characterized by a significant piñon and/or juniper overstory component (Tausch, 1999a). Key to discerning "old" or persistent woodland types from former pine savanna, grass- and shrublands, may be the soils and corresponding understory communities, inherent site productivity, topographic setting, and fire history (Tausch, 1999a). Shallow soils and broken topography are often thought to support "old" or persistent woodland where fire disturbance is infrequent owing to low site productivity and discontinuous fine fuels (Miller and Tausch, 2001). Conversely, deeper, more productive soils, and unbroken topography are thought to favor fire dependent pine savanna, grass- and shrub- land communities where fine fuel continuity allows more regular fire disturbance and culling of fire sensitive woodland species (Brackley, 1987). Romme et. al. (2003) presented general criteria for discerning three putative types of woodland in western North America in order to stimulate critical review of woodland system dynamics and classification.

Southwestern piñon-juniper woodlands are dynamic systems, some very "old", although in various stages of development or recovery, and many others of apparently recent origin. Individuals and stands can often persist hundreds and thousands of years respectively, yet be consumed by crown fire in a single afternoon and require 50 to 100 years or more to re-establish

dominance. In other settings, where piñon and/or juniper have recently colonized more productive sites, the woodland type is best characterized as invasive. Paleo-vegetation reconstructions, based largely on pollen and macro-fossil evidence (Betancourt, 1987), document changing patterns of woodland distribution (i.e., northward and to higher elevations) and composition in response to prevailing regional climate (Neilson, 1987) and episodic weather events which facilitate pulsed establishment and mortality (Miller and Wigand, 1994; Swetnam et. al., 1999; Tausch, 1999a). Long-term records document a tidal advance and retreat of woodlands, coming and going repeatedly as climatic conditions fluctuate; the current dynamics of southwestern woodlands could be viewed as merely the latest response of this system to prevailing climate (Betancourt, 1987; Neilson, 1987; Swetnam et. al., 1999). Current stand distributions (figures 2,3,4), local occurrences, and structures are best interpreted as the cumulative result of episodic establishment and mortality in relation to prevailing climatic conditions, figure 1 (Mitchell, 1976; Betancourt, 1987; Eisenhart, 2004); although the ecophysiological traits expressed by species and populations are assumed to be unchanged over longer periods of time (Neilson, 1987). Across much of the southwest a relative expansion of woodlands was likely ongoing prior to European settlement (Miller and Wigand, 1994; Swetnam et. al, 1999; Tausch, 1999a); intensive historic land-use activities (e.g., grazing), beginning in the mid-late 1800's, are thought to have altered natural dynamics (e.g., loss of fire regime) in grass and shrub dominated systems and opened up additional sites for woodland colonization essentially unavailable during previous prehistoric expansions (Brackley, 1987). With sustained grazing pressure and in the absence of fire disturbance, these tree species have wide ecological amplitudes and can aggressively colonize adjacent communities (Brackley, 1987; Tausch, 1999a; Miller and Tausch, 2001). Southwestern woodlands thus include "old" or persistent stands of

considerable age, structural and biological diversity, as well as stands of more recent origin which have often displaced or suppressed the community formerly occupying the site.

Colorado piñon is typically shorter lived, and less drought/ insect and disease tolerant than either juniper species, but is more productive with faster growth rates during wet periods and in more mesic (e.g., higher elevation) settings (Chambers et. al., 1999; Nowak et. al, 1999; Martens et. al., 2001). One-seed and Utah juniper in constrast, are longer lived and relatively resistant to drought, insect, and disease, but less productive than piñon during wet periods or in more mesic settings. One-seed juniper, with extensive shallow roots which harvest water from canopy interspaces, may compete more directly with herbaceous cover for available moisture than either Utah juniper or piñon; reported foliar uptake of moisture by one-seed juniper (Breshears et. al., 2008) may also enhance this species apparent resistance to drought. Alternatively, some woodland trees may be able to reallocate harvested surface water to deep root storage where transpirational losses would be reduced (West, personal communication.).

Current distributional patterns of the three species appear to be constrained in part by the relative positions of summer and winter potential air mass temperature boundaries (Neilson, 1987) which Mitchell (1976) uses to define broad western climatic regions. For example, *J. monosperma* appears to be more dependent on a summer dominated moisture pattern (i.e., climate region VI, south and east of the summer monsoonal boundary) and less cold tolerant than *J. osteosperma*, which occurs mostly in areas north and west of the summer monsoonal boundary (i.e., climate region V). *Pinus edulis* and *J. osteosperma* are both distributed south of the winter polar front, but J. osteosperma is reported to occur elevationally above, as well as below, piñon (Neilson,

1987). Presumed differences in root system architecture between the two junipers, and relative dependence on deep versus shallow sources of water, may be reflected by their distributional patterns (and differential establishment and mortality) relative to seasonality of moisture. Establishment patterns for woodland species are often episodic and associated with favorable climatic patterns (e.g., for establishment) and suitable microsites (e.g., shrub nurse plants) assuming seed availability; piñon masts infrequently at intervals of several years and seed are heavily predated and short lived in the soil seed bank, while juniper which produces a more consistent seed crop with longer viability (Chambers et. al., 1999). Mature individuals of either tree species can serve as nurse plants for seedlings of one or both species, forming distinct multi-aged patches. Persistence patterns for woodland species may be related, in part, to site conditions which promote deep infiltration and enhance subsoil water availability. While shallow soil sites may not provide sufficient water storage to support well developed herbaceous cover, fractured substrates underlying these soils may provide deep water storage accessible only by woody plants. Piñon can attain dominance at higher, more mesic sites or during prolonged wet periods (except for localized fungal disease outbreaks), but juniper is usually favored at lower and drier sites and through drought periods which make piñon susceptible to insect mortality. Establishment of woodland onto deep soil sites during relatively moist periods, and in absence of fire disturbance, may proceed to closed canopy woodland (and eventual suppression of the understory community) given adequate subsoil water availability; however, sustained drought which limits deep soil water recharge at earlier stages of woodland establishment, and competitive interactions with herbaceous understory for growing season moisture, may result in widespread tree mortality.

Prolonged and severe drought episodes, insect and disease outbreaks, and fire, are the primary disturbances limiting maximum age. Both piñon and juniper are extremely susceptible to fire and heat damage, and are usually killed outright, as opposed to merely scarred, by even moderate fire behavior. Given this fire intolerance and the several hundred years required for trees to attain site dominance, it seems unlikely woodland would normally persist on sites where extant understory vegetation could potentially support fire return intervals of less than 50 to 100 years (in absence of grazing or fire suppression). Long-term avoidance of lethal fire effects can be afforded by fire-safe settings (i.e., on sites which generally support only sparse or patchy surface fuels and/ or in topographic settings limiting fire spread from adjacent areas); protection from ground fire may also afforded to individuals or woodland patches by compact litter mats and competitive suppression of adjacent understory cover. Sites with shallow, rocky soils are often considered unproductive because insufficient and/ or irregular water availability (within rooting depths of herbaceous plants) can only support sparse surface fuels, but the underlying, fractured rock substrate may provide a source of deep water accessible to deep rooted woody plants. Similarly, deep, but coarse and well drained, soils may be unproductive for understory cover (where water drains or perches below effective understory rooting depths), but may support good tree growth if water is perched and available within effective tree rooting depths). Soils or substrates which effectively inhibit deep water filtration and storage, through soil texture, presence of argillic horizons or impermeable layers at shallow depths, may favor herbaceous cover and show increased resistance to woody plant establishment even under sustained grazing pressure (McAuliffe, 2003). Alternatively, Walker et. al., (1981) describe overgrazed savanna systems where dispersed infiltration into grass dominated sites becomes progressively more focused, as decreasing herbaceous cover allows rain drop splash to seal surface soil pores and enhance

runoff from intercanopy spaces; this runoff is then captured by canopy patches whose litter mounds and root profiles may facilitate rapid infiltration to depth. Canopy interception may also focus water inputs around the dripline of trees and thus potentially enhance deep infiltration of even relatively small precipitation events.

Seasonality of moisture (and temperature) regime patterns across an apparent southeast to northwest moisture seasonality gradient (mediated by climatic zone boundaries and locally amplified by elevational and orographic effects) also influences site potential. Sites within Mitchells' (1976) climate zone V are often dominated by cool season moisture patterns (i.e., with extended late summer to spring elevated plateau moisture patterns which may favor deeper rooted, perennial or woody species, whose dominance could promote longer fire return intervals), while other locations have somewhat uniform annual distributions; with either pattern there is often a relative trough in the late May-June time period. Sites within Mitchells' (1976) climate zone VI, by contrast, are often strongly dominated by a warm season dominated moisture pattern (i.e., with a distinct summer peak and a depressed plateau moisture pattern the rest of the year) which may favor shallow rooted herbaceous cover and higher fire return intervals; at locations near the summer monsoon boundary, precipitation patterns may include elements of both the cool season moisture and summer peak patterns with the most notable feature being a narrow trough in late May to June. In zone V locations, increasing moisture patterns after the late-May-June trough is best interpreted as a return to normal cooler season moisture levels. Thus, while sites within Mitchells' (1976) climate zones V and VI may both experience low moisture conditions during the late May to June period when temperatures are rising (creating relative moisture deficits at most locations), areas within zone V may be buffered by recent cool

season moisture inputs, while in zone VI, the same period may culminate an extended low moisture pattern beginning the previous fall. In addition, most of the summer peak moisture in Mitchells' (1976) climate zone VI arrives in the form of convective thunderstorms with significant levels of lightning strikes (and potential for ignitions), while cool season moisture patterns have both lower levels of summer lightning (and perhaps lower potentials for ignition of fuels with residual winter moisture).

Finally, we might expect interactions between topographic position (and effects on soil properties such as texture and infiltration depth) and the dominant precipitation pattern to influence woody plant distribution. For example, in areas dominated by a winter precipitation pattern, infiltration to depth may be sufficient across a range of topographic positions to promote woody plant dominance across a variety of landscape settings; conversely, as summer dominated precipitation patterns become increasingly important, associated losses due to evapo-transpiration would increase, and topographic effects (i.e., which mediate deeper infiltration and retention of deep soil moisture) would become increasingly more influential in determining where woody plants could occur. These same interactions, and effects on soil moisture, would promote occurrence of grass dominated communities (and increased surface fire potential) across a broader range of landscape positions in areas with summer dominated precipitation patterns.

The relative absence of fire evidence in many extant woodlands of apparently recent origin suggests they have developed since the last fire disturbance in a formerly non-woodland community, as mediated by the effects of historic grazing. Conversely, recovery of woodland post-crown fire or post-drought would usually provide some evidence of the previous stand. The

general scarcity of fire scarred piñon or juniper in many "older" or persistent growth woodlands suggests ground fire is uncommon in these systems, particularly in light of the often sparse herbaceous fuels and compact needle litter; when scars can be found they are often associated with crown fire patch margins or interfaces with high fire frequency (i.e., grassland or Ponderosa) communities. Where fire evidence (i.e., charred wood, stumps and snags) is present, it usually suggests an infrequent, high severity, crown fire of variable pattern and patch size as the predominant regime (Baker and Shimmeman, 2004; Romme et. al., 2003). With reduced herbaceous competition and in absence of fire disturbed, being direct and indirect effects of historic grazing pressure, piñon and juniper can successfully colonize a wide range of sites as illustrated by establishment patterns during the last century (Tausch, 1999a; Miller and Tausch, 2001).

Study Overview and Objectives

The regional scope of the study was defined by the ranges of Colorado piñon pine (*Pinus edulis*), and several associated species of non-sprouting juniper (One-seed, *Juniperus monosperma*; Utah, *J. osteosperma*, and Rocky Mountain, *J. scopulorum*) representing Southern Rocky Mountain and Colorado Plateau savanna and woodland types as recently mapped by the Southwest Regional Gap Analysis Project (SWReGAP; Lowry et. al., 2005) within the Four Corners states (i.e., Arizona, Colorado, New Mexico, and Utah) of the southwestern U.S. To gain regional perspective and inform development of a diagnostic key, we intensively sampled within three National Park Service units representing along an apparent southeast to northwest moisture seasonality gradient. Colorado National Monument, Mesa Verde National Park, and Bandelier National Monument were selected to provide a geographically dispersed sample of relatively

undisturbed examples of southwestern US woodland along the seasonal moisture gradient. The intensive plot data were used to inform identification of qualitative and semi-quantitative criteria and development of a diagnostic key for distinguishing "old" or persistent piñon-juniper individuals and stands from "younger" woodlands of more recent origin.

Subsequently we extensively sampled across the Four Corners states to provide adequate data for regional scale predictive modeling efforts. Extensive sampling was initially focused within the north-central New Mexico area and then expanded across the entire regional area. Field samples were assigned a pre- versus post-settlement status using the diagnostic key and individual points associated with environmental metrics within a GIS. The compiled dataset was exported to statistic software for model development using both global, parametric and local, non-parametric procedures. Predictive modeling and mapping was first conducted within the north-central New Mexico area using a simple logistic model to predict a binary ("old" versus "young") response. We then validated a more sophisticated piece-wise linear regression approach in the north-central New Mexico area before using this approach to model the larger regional dataset.

The specific objectives of this study were to: 1) identify meaningful and consistent qualitative and semi-quantitative criteria for recognition and delineation of "old" or persistent (>150 years age) piñon and juniper individuals and stands from "younger" woodlands of more recent, post-settlement origin and develop a diagnostic key; 2) assess the relative importance of (and availability of spatial coverage for) potential environmental (i.e., topographic, climatic, edaphic) factors relevant to woodland distribution and stand-age; and 3) predictively model and map the distribution of "old" versus "young" stands across the range of *Pinus edulis* and associated

junipers (*Juniperus monosperma*, *J. osteosperma*, *J. scopulorum*) within the Four Corners states (i.e., Arizona, Colorado, New Mexico, and Utah) of the southwestern U.S.

An initial task was to identify and validate qualitative and semi-quantitative criteria for recognition of "old" or persistent woodlands, distinguishing these from more recent woodlands which have only established in the last one-hundred and fifty years (i.e., or since initiation of historic landuse activities) and use these in development of a diagnostic key. We report on this effort in Chapter 3 including presentation of a diagnostic key for delineating "older" pre-settlement woodlands from "younger" stands of post-settlement origin.

For our purposes, development of the diagnostic key was primarily in support of regional scale modeling efforts. However, the key also provides managers with consistent criteria for determining the status of individual woodland stands and whether they warrant active management. Whatever the goals and objectives, stands of recent, post-settlement origin (i.e., without "old" or persistent growth components) will be more likely to retain understory elements that can respond favorably to overstory treatments. Stand densities in many woodlands are often dominated by younger age-classes; this can be variously interpreted as either a response to historic landuse, or normal demographic and success ional dynamics reflective of episodic patterns of establishment and mortality. More intensive evaluations (i.e., outside the scope of the present proposal) of individual woodlands with "old" or persistent growth components would be required to assess whether these stands have also been affected by post-Euro American settlement activity (e.g., increased tree densities), or if they simply represent examples of woodland structure typical of pre- Euro American settlement.

The second task was to relate the occurrence of "old" or persistent (i.e., pre-dating the effects of Euro American settlement) woodland stands to one or more environmental site factors (e.g., climate, landform, elevation, slope, aspect, soils, geology) for which regional spatial data was available. Our initial work on this task was at the scale of a north-central New Mexico study area and is reported in Chapter 3 and we expanded this effort to encompass the regional extent of the Four Corners states in Chapter 4. A large component of this task involved the development and evaluation of secondary metrics with potential ecological relevance, for example indices of effective moisture derived from seasonal measures of precipitation and potential evaporation, or creating categorical variables from continuous parameters to highlight threshold effects in measures such as depositional environment.

Fire, drought, insect, and disease disturbances, and competitive interactions with grass and shrub understories (as mediated by one or more environmental site factors) are thought to have formerly limited potential woodland occurrence within the distributional bounds imposed by regional climate. These same processes control stand dynamics, including episodic establishment and mortality, and thus influence stand structure, as well as persistence of woodland on a particular site. While drought, insect, and disease disturbance processes continue to operate, as evidenced by recent widespread piñon mortality, surface fire disturbance and / or competitive interactions with grass and shrub understories (in areas formerly dominated by grass- and shrub-land systems) were likely interrupted by historic grazing practices. The latter direct and indirect effects of historic grazing are thought to been important drivers of recent woodland expansion into adjacent non-woodland communities (and thickening of formerly more open stands) within

the context of favorable regional climate patterns for tree establishment. General vegetation patterns developed during the historic period should reflect a combination of climatic and historic influences, while patterns established earlier may be attributed primarily to climatic effects (with assumption that pre-historic landuse effects were more localized). If "old" or persistent growth woodland, and the range of environmental site factors which support this old growth, can be adequately circumscribed, then delineation of "younger" woodlands of more recent origin (i.e., post-Euro American settlement) which occupy a range of site conditions previously unavailable for woodland colonization, may also be possible. We present an overview of southwestern U.S. woodland ecological history and natural range of variation in Chapter 2 (Jacobs, in press) along with maps showing the distribution of component piñon and juniper species.

The final task was to predictively model and map pre- versus post-settlement aged woodland stands within the Four Corners state study area. First we needed to create a dataset for predictive modeling by associating the GPS location of each sampled stand (assigned an "old' versus "young" status using the diagnostic key) with the spatial coverage of potential explanatory variables developed within a GIS. The compiled dataset was exported to statistical software and used for model development (using both global, parametric and local, non-parametric procedures). Selected model parameters were implemented within a GIS (using SWReGAP woodland coverage as an analysis mask) and used to realize map products showing probability of "old" versus "young" woodland. Predictive modeling and mapping efforts were initially conducted within a north-central New Mexico study area (Chapter 3, Jacobs et al, in press) and then expanded to the larger Four Corners states regional extent (Chapter 4).

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PART II

Southwestern U.S. Juniper and Piñon-Juniper Savanna and Woodland Communities:

Ecological History and Natural Range of Variability

Abstract

Juniper and piñon-juniper savanna and woodland communities collectively represent a widespread and diverse vegetation type that occupies foothill and mesa landforms at middle elevations in semi-arid portions of the American Southwest. Ecological understanding and proper management of these juniper and piñon types requires local knowledge of component species, site history and potential, set within a regional floristic and climatic context. The wide distribution and broad ecological amplitude of this vegetation type across a six-state area of the southwestern U.S. is best appreciated as the sum of the individual ranges of the component piñon and juniper species, and their environmental tolerances. Key environmental controls of juniper and piñon occurrence, stand age-structure, and composition, include the interaction of climate, topography, soils, and disturbance processes, in combination with biotic interactions, and over various spatial and temporal scales.

Introduction

Juniper and piñon-juniper (P&J) savanna and woodland in the American Southwest has often been viewed by researchers and land managers alike as an ecological unit which can be understood and managed as a single, if variable, entity. The consequences of this approach include confusing and contradictory research findings, ongoing controversy, inappropriate management, and potentially undesirable outcomes. In reality, the P&J type is a simplistic grouping of many different species distributed across diverse climatic and topographic settings, each species with a unique history and range of environmental tolerances. While ecological amplitude of the component species and regional climate set broad limits on potential woodland distributional limits, smaller scale competitive and disturbance factors may ultimately constrain

the extent and expression of species occurrence on local landscapes. Recent, historical changes in woodland occurrence and stand density have been variously interpreted as continued adjustment to Holocene climate, recovery from harvest (historic and pre-historic), succession after fire, drought, insect, and/ or disease induced mortality events, or response to grazing practices, altered fire regimes, elevated temperatures and CO_2 levels. The following sections provide an overview of the distribution, ecology, environmental controls, disturbance regimes, and historical land use impacts relevant to an understanding of extant southwestern U.S. woodlands.

Distribution

Juniper and piñon-juniper savanna and woodlands collectively constitute one of the most widespread vegetation types in the American Southwest. These plant communities typically occupy foothill, mesa, and mountain slope positions, at middle elevations within a semi-arid climatic zone and between desert grass- and shrub-lands and upland coniferous forests. Within the American Southwest, defined here by New Mexico (NM), Arizona (AZ), Utah (UT), Colorado (CO), Nevada (NV), and eastern California (e. CA), there are five common species of juniper, Utah (*Juniperus osteosperma*), one-seed (*J. monosperma*), Rocky Mountain (*J. scopulorum*), alligator-bark (*J. deppeana*), and western juniper, (*J. occidentalis*), and two of piñon, Colorado (*Pinus edulis*), and single-leaf (*P. monophylla*), which alone and in various assemblages, account for the majority of extant P&J types. An overview of component piñon and juniper species and their respective distributions was obtained by referencing distribution maps originally prepared by Little (1971), subsequently digitized by the USGS, with taxonomy and nomenclature following Flora North America (Flora of North America Editorial Committee, eds., 1993+). See Supplemental Digital Appendices: Part II Supplemental Figures.

Colorado piñon has a distribution centered on the four-corner state area of UT, CO, NM and AZ, while the closely related single-leaf piñon is found to the west in NV, se. CA and sw. UT. Piñon typically dominates the upper, or more mesic, end of the woodland zone (although Utah and Rocky Mountain junipers may exhibit greater cold tolerance), while Utah and one-seed junipers gain importance at the lower, or more xeric end. Of the common junipers, Rocky Mountain is the most mesic species with a range extending north to BC, Canada, while Alligator-bark juniper, also more mesic than Utah or one-seed junipers, gains importance in warmer areas to the south with a range extending into Mexico. Western juniper is both drought and cold tolerant, and its range, unlike the other four junipers considered, is not associated with any of the piñon species (Miller et. al., 2005). Within the four-corner state area, one-seed and alligator-bark junipers pre-dominate in locations under the seasonal influence of the Arizona summer monsoon, defined by Mitchell's climate zone VI (Mitchell, 1976), with alligator-bark juniper more common in s. NM and east-central AZ, while one-seed juniper dominates woodlands in the rest of NM. Utah juniper conversely, is more common in winter moisture areas, defined by Mitchell's climate zone V, (Mitchell, 1976) north and west of the monsoon boundary, and is the most widespread juniper in the American Southwest, forming associations with both Colorado and Single-leaf piñon. The ranges of Colorado piñon and Rocky Mountain juniper span the monsoon boundary (although piñon distribution is bounded to the north by the position of the winter polar front, defined by the northern boundary of Mitchell's climate zone V), perhaps in part because moisture patterns tend to lose strong seasonality with increasing elevation.

Looking around the six-state area, and noting piñon and juniper species whose ranges bound the American Southwest, we find California piñon (*Pinus quadrifolia*), Mexican piñon (*P. cembroides*) and rose-berry juniper (*Juniperus coahuilensis*, sensu ~*J. erythrocarpa*, Little, 1971) just entering our area, but with ranges mostly to the south in Mexico, western juniper, (*J. occidentalis*) occurring in e. CA and n NV, but with a range extending northwest to OR (WA) and ID, and red-berry juniper (*J. pinchotii*), Ashe juniper (*J. ashei*) and eastern red-cedar, (*J. virginiana*) to the east in TX and OK.

While each of these P&J species are distinctive enough to be afforded specific taxonomic status, and even retain integrity as a distinct taxon in the paleo-record, modern distributions are relatively recent and extant populations representing recognized taxa likely represent or express only a portion of the underlying genetic diversity present; further, many or most of the piñon and juniper species have some level of gene flow between related species, which presents additional opportunities from both ecological and evolutionary perspectives. For example, western juniper reportedly hybridizes with Utah juniper, Utah with one-seed, one-seed with Alligator, red-berry with rose-berry, and Rocky Mountain with eastern red-cedar (*J. scopulorum* is sometimes classified as a variety of *J. virginiana*); the sprouting ability of red-berry and rose-berry junipers, and small, single-seeded cone features, may suggest relationships between these taxa and *J. deppeana* and *J. monosperma*. *Pinus edulis* can reportedly hybridize with *P. monophylla* (~*P. edulis var. fallax*) and *P. cembroides* (~*P. remota*), while *P. quadrifolia* was formerly recognized as a variety of *P. cembroides*.

From an evolutionary perspective, closely related piñon taxa which maintain capacity for genetic exchange, and whose shifting ranges both maintain intermittent contact while promoting expression of discrete entities, might be more productively viewed as components of larger meta-populations. Long-lived perennials like piñon and juniper, which have potential maximum lifespans exceeding 500 years, are buffered against shorter-term fluctuations in climate, requiring only occasional favorable windows for successful establishment. In contrast, climatic requirements for persistence of mature P&J individuals are often minimal. Long-lived, wind pollinated, out-crossing, perennials could be expected to maintain high levels of genetic diversity in a population, while also being a conservative force mitigating rapid shifts in allele frequency.

Ecology

Southwestern P&J types viewed collectively span an impressive range of environmental settings and present challenges to traditional ways of categorizing vegetation assemblages and interpreting ecological processes. Piñon dominated stands with multi-layered and nearly closed canopies, can occur at the moist, upper elevation end of the woodland zone, while at the interface with desert grasslands, it is common to observe open stands of juniper interspersed with grasses, forbs, and shrubs. In between these extremes, and depending on a variety of local site conditions and histories, and within the context of regional biogeography, one can delineate a great variety of juniper and piñon-juniper types in association with various shrub, grass, and forb understories. Recent vegetation mapping efforts as part of the Southwest Regional Gap Analysis Project, SWReGAP (Lowry and others, 2005) with a five-state area (four-corner state area plus NV) of the American Southwest, and following community classifications prepared by NatureServe (Comer et. al., 2004), circumscribe four major P&J categories, primarily as groupings of the

major piñon and/or juniper species: Great Basin (*P. monophylla* and *J. osteosperma*), Colorado Plateau (*P. edulis* and *J. osteosperma*) , Southern Rocky Mountain (*P. edulis* and *J. monosperma*), and Madrean (*P. edulis*, *P. cembroides*, *J. deppeana*, *J. monosperma*, *J. coahuilensis*, and *J. pinchotii*). These four major groupings are further sub-divided on basis of structure and composition (that is, piñon-juniper woodland versus juniper savanna) with additional community assemblages noted as having a juniper and/ or piñon component. Finer grained community and habitat typing in juniper and piñon-juniper types have typically subdivided major tree overstory groupings by dominant shrub-grass-forb understory. Understory composition can be an important indicator of site history and site potential, particularly when the tree overstory is of relatively recent origin; Tausch (1999) suggests understory composition can be key to understanding the potential of particular P&J sites, providing insight on available soil and water resources, and presumably this information would be critical to management at local scales.

Climate, modified by local topographic and soil factors, provides fundamental control over potential species distributions; while disturbance regimes and stochastic events help to shape actual occurrence patterns. A range of potential vegetation types is possible for most locations, and extant vegetation may or may not represent a balanced or optimal state from natural or human perspectives. Extant plant communities should be viewed as the cumulative outcome of multiple interacting factors, and over shorter temporal and smaller spatial scales there appear to be repeating patterns and a sense of dynamic stasis; however, paleo-vegetation reconstructions reinforce the idea that species assemblages are neither prescribed nor static at longer or larger scales (Betancourt and others, 1993). Still, ecological concepts such as succession and

restoration are still meaningful and useful within the limited spatial and temporal scales that land managers (and researchers) typically operate. More problematic is how to integrate rare, episodic, and/ or extreme events into our ecological understanding and short term, local management of vegetation systems, especially when these low frequency events have large and long term consequences on community structure, composition and function.

Disturbance

Interpreting the relative importance of disturbance processes and episodic events, like fire, wet and dry climate patterns, and insect or disease outbreaks, in controlling spatial pattern and structure of vegetation is challenging, especially when the current vegetation on a site is, in part, an outcome of earlier disturbances or events which occurred within the context of a different vegetation assemblage. For example, fire disturbance is possible or likely given suitable fuel structures, which are produced by particular vegetation assemblages, and which in turn depend on favorable suites of climate, topographic, and soil factors; fire events and patterns may be strongly associated with particular vegetation assemblages to the extent we can recognize recurring burn patterns (intensity and frequency) and/ or infer meaningful relationships between vegetation composition, structure, and life history. Southwest Ponderosa Pine, tall grass prairie, or northern Rocky Mountain Lodgepole Pine communities can be somewhat easily assigned to fire regime categories, and there are often meaningful synergies which exist between these vegetation types, life history attributes of dominant species, and recurring fire disturbance.

In contrast, Baker and Shinneman (2004) review a number of fire history studies and note that evidence to substantiate spreading surface fire behavior in woodlands is generally lacking; fire

scars on living trees are usually infrequent, and often found at what could be interpreted as ecotonal boundaries (such as rocky outcrops, or an interface with Ponderosa Pine savanna) or woodland burn patch edges. Thus, although fire histories have been reconstructed for selected P&J sites where abundant fire evidence is available, this fire evidence may be reflective of historic upper and lower ecotonal boundaries where woodlands abutted high fire frequency forest and grassland systems, or locations where fine scale woodland mosaics (superimposed on topo-edaphic patterns) formerly intermingled with fire prone, non-woodland types, than of the general P&J type in a larger sense. The historic role of surface fire disturbance in maintaining stand structure and composition in pre-settlement P&J types then, is problematic; for example, most of the piñon and juniper species are fire sensitive and easily killed by even moderate fire intensity and the species as a group generally lack life history attributes which can be easily associated with recurrent fire disturbance (although several juniper species can resprout after burning, and one can infer possible mechanisms, such as dense litter mats or suppressed herbaceous, for mitigating fire mortality and scarring).

Observations by the author at numerous field locations in the four corners state area, in connection with an effort to model occurrence of pre-settlement woodlands relative to topo-climatic factors, suggest fire disturbance in pre-settlement Colorado Plateau and South Rocky Mountain P&J types was at best uneven, perhaps more opportunistic than inevitable, largely dependent on local site conditions, and not obviously essential to maintenance of 'normal' system structure and function; rather historic evidence of fire, when present, often suggests a patchy crown fire behavior, with charred stumps, logs, and snags, as might be expected with the

discontinuous fuel structure (surface and crown) associated with this vegetation type (Muldavin and others, 2003).

Water

Water is a major limiting resource in semi-arid systems, and it is reasonable to infer that extant P&J types are largely responsive to and shaped by (spatial and temporal) variability in available soil moisture. For example, it is widely reported that there is an inverse relationship between increasing density of overstory in P&J types and decreasing understory cover (interpreted as a response to limited soil water); conversely, it has also been demonstrated that mechanical thinning, fire treatment, and drought-insect induced mortality of overstory, will often yield increases in understory cover. Available soil moisture then is an important, perhaps central, environmental control in P&J systems, affecting where they can occur, which species can be present, influencing stand structure by mediating episodic establishment and mortality, and potential for fire or drought-insect disturbance. Eisenhart (2004) proposes density dependent regulation of stand density in *P. edulis – J. osteosperma* types (that is, self-thinning) and periodic drought-insect mortality as viable mechanisms for maintenance of stand structure in P&J types, particularly in the absence of any fire evidence. Savanna structure in low end juniper dominated types could also be interpreted as a density dependent response to limited soil moisture, particularly on shallow substrates where trees are primarily accessing deeper water stored in fractured bedrock. Site productivity and potential in semi-arid settings is largely a function of (spatial and temporal availability of) soil moisture (McAuliffe, 2003) which is controlled by the interactions of climate, topography, and soil.

Different growth forms and species employ a variety of strategies for extracting available soil moisture. A site may be productive for deep rooted trees, if available water is mostly at depth, either due to a deep, well drained soil or a shallow soil with fractured bedrock; conversely, a site may be productive for shallow rooted, herbaceous species, if available water is primarily in upper 0-30cm due to fine textured soils, high clay or organic content, or presence of shallow argillic (that is, water perching) horizons. Some, or most, sites can support a mixture of both shallow and deeper rooted species, and many species (including piñon and juniper) have dimorphic root morphologies and flexible strategies which allow them to opportunistically (and temporally) harvest water from both shallow and deep sources, as well as from wide horizontal extents encompassing adjacent intercanopy locations (McAuliffe, 2003). Thus, even with a uniform climate context, extant vegetation and site potential can be strongly influenced by local topographic setting and soil properties.

For example, at Bandelier National Monument, NM, pumice soils can strongly influence local vegetation patterns and associated disturbance processes though enhanced water capture and storage. Julius (1999) documented differences in piñon-juniper age-class and density, as well as in composition and cover of associated understory, across three soil types within a 100 acre study area at Bandelier. Woodlands on pumice soils, with an argillic horizon, had both the lowest tree densities and youngest age-class, relative to pumice and non-pumice soils, without an argillic horizon; non-pumice, non-argillic soils had the highest densities and oldest age-class, while pumice, non-argillic soils were intermediate for both density and age-class. In addition, pumice argillic soils supported the highest understory cover, with a composition dominated by grasses, (such as *Schizachyrium scoparium*), while non-argillic, pumice soils had forb dominated

understories, and non-pumice, non-argillic soils were characterized by only sparse understory cover (Julius, 1999).

Germination and successful establishment are critical life stages for all plants, but in semi-arid climates, proper timing is especially important. Successful establishment of piñon and juniper individuals is enhanced by sufficient moisture during the time period between germination and establishment of a secondary root system, below the average depth of the herbaceous rooting zone; Johnsen (1960, 1962) reported that seedlings of *J. monosperma* were very vulnerable while in direct competition for water with shallow and fibrous rooted herbaceous species, and could only successfully establish during years when soil water was effectively not a limiting resource. As noted by Neilson (2003), the effective window for successful tree establishment may have been enhanced by the reduction of herbaceous competition through sustained grazing.

Grazing

Considerable attention has been focused on the presumed effects of historic grazing, both in altering the structure and composition of pre-settlement P&J types (that is, infill and thickening), as well as in promoting tree encroachment into formerly non-woodland (including forest, shrub- and grass- land) communities. Effects of long-term, sustained grazing in semi-arid systems, particularly during drought episodes, can include reduced herbaceous cover, vigor, and (above and below ground) biomass, increased runoff and sediment transport, and initiation and facilitation of desertification processes (that is, re-allocation of limited nutrient and water resources to shrub and tree 'islands'). Alternatively, simultaneous reduction of understory competition and associated interruption of surface fire regimes, during favorable climatic

intervals, would appear to be plausible effects of historic grazing in facilitating P&J encroachment into non-woodland areas. Both of these mechanisms, acting in concert, are likely important factors mediating recent 'invasion' of western rangelands (cool and warm season respectively), by western juniper in OR (Miller et. al., 2005) and one-seed juniper in AZ and NM (Johnsen, 1960, 1962). However, within extant, pre-settlement, savanna and woodland communities (where evidence to support a role for recurrent surface fire in maintaining stand structure is absent), it may be reasonable to conclude that historic grazing effects alone would have been sufficient to alter the competitive environment and facilitate establishment of tree seedlings, by reducing herbaceous competition for water, focusing runoff and enhancing deeper infiltration through reduction of effective ground cover. Recent attention has also been given to the idea of CO_2 facilitated enhancement of tree growth through increased water use efficiency, but this proposed effect may be largely offset by increased evaporative demand and thermal stress from warmer temperatures associated with increased levels of CO_2.

It has also been noted that grazing effects can be extremely variable across different soil types within the same climatic zone, suggesting some sites and soils are more tolerant of grazing, while conversely, other sites and soils are more susceptible to desertification (that is, shrub and tree encroachment). McAuliffe (2003) notes grazed soil types, with shallow argillic horizons, are much more resistant to woody plant encroachment than sites which promote deeper infiltration. As Nielson (2003) suggests, recent and widespread encroachment of woody plants into many western rangelands (and thickening of savanna types) is probably best interpreted as a synergistic interaction of climate and grazing, on susceptible soil sites, and where woody plant populations are proximate.

In some areas of the American Southwest, particularly on portions of the Colorado Plateau characterized by winter moisture patterns, the paradigm of a pervasive and ongoing, grazing induced, western woodland invasion is overstated, or at best mis-applied. For example, Floyd et al (2003) report extant stand densities at Mesa Verde National Park, CO are generally within the range of historical variability, while Eisenhart (2004) suggests that reports of 'thickened' woodlands in west-central CO woodlands may actually be normal stages in stand development prior to onset of density dependent thinning as trees mature.

Summary

Recent field reconnaissance in southwestern U.S. woodlands, suggests there is an abundance of pre-settlement status woodland on the Colorado Plateau, where precipitation patterns are either winter dominated or lack strong seasonality. These observations are consistent with the results of detailed stand reconstructions by Floyd-Hanna and others (2003) and Eisenhart (2004) in woodlands of Colorado. Conversely, occurrence of post-settlement status woodland becomes increasingly frequent in rangeland areas of northern New Mexico and east-central Arizona, where they occupy lower gradient basin and valley landform settings, adjacent slopes and rolling hills, in locations characterized by wet summer and comparatively dry winter-spring precipitation patterns. The transition zone, those areas where occurrence of post-settlement woodland becomes increasingly frequent, also roughly corresponds to the distributional limits of one-seed juniper (although both piñon and Rocky Mountain juniper are also commonly present in post-settlement stands). Pre-settlement woodland in the monsoon climate area becomes increasingly restricted to a narrower range of settings, including steeper gradient landforms, with

shallow rocky substrate, and/ or isolated or broken topographic settings, presumably reflecting locations which promote deeper water infiltration and/ or limit fire effects.

Interpreting regional patterns of pre- versus post- settlement woodland occurrence in relation to climatic, topographic, and edaphic variables, can be complicated by associated changes in both woodland species assemblages and geomorphic settings. However, seasonality of moisture appears to be an important determinant of woodland patterns in both areas, but perhaps for different reasons. In winter moisture dominated areas, woodland can successfully occupy a wider range of landform settings, since moisture is available both at greater depth and during the early spring season, promoting woody growth, limiting herbaceous competition, production of fine fuels, and potential for surface fire. Conversely, in summer moisture dominated areas, shallow moisture enhances herbaceous competition, fine fuel production, and the potential for surface fire, effectively restricting woody vegetation to coarser textured soil settings where moisture can infiltrate to depth (on steep slopes, and fractured rocky substrates) or locations where grass production is otherwise limited (reducing potential for surface fire); even discontinuous topographic settings with adequate soils could still be expected to have relatively high potentials for surface fire (in absence of grazing), given the increased incidence of lightning ignition associated with a summer monsoonal precipitation pattern.

Whatever the mechanisms (such as, favorable climatic patterns, grazing effects on herbaceous competition and fire disturbance) responsible for the initial establishment of woodland species onto a new site, persistence of the tree component can be enhanced by positive feedback on local environmental conditions; for example, suppression of herbaceous vegetation by maturing piñon

and juniper overstory, and associated reductions in intercanopy cover, changes in soil texture and runoff which promote deeper infiltration, and reduced potential for surface fire, tend to reinforce conditions favorable to woody plant establishment and persistence. We can think of these woodland influences on local site conditions in terms of moisture and fire shadow effects, which in the absence of a disturbance, allow woodland to establish into, persist on, and eventually dominate a wide range of settings.

From a landscape perspective, infilling and thickening of patchy, pre-settlement woodland mosaic patterns by post-settlement woodland, was likely facilitated by regional, synchronous and/ or synergistic, effects of climate and grazing. Some reports of woodland thickening may also be a function of the relative spatial and temporal perspective in sampling or observation. As woodland patches expand and merge, ground fuels become limiting while canopy fuel structure becomes more continuous across larger areas; under this scenario, the probability of fire spread from a point ignition can be expected to change, along with the potential frequency, nature, and extent of fire events. Discerning patterns of recent woodland expansion from longer term migrational dynamics, may be possible by comparing the range of environmental settings associated with pre- versus post- settlement stands. For example, while relatively few new northerly locations appear to have been successfully colonized in response to migrational dynamics of piñon pine during the last 1000 years (Jackson et al, 2005), the extent of woodland occurrence across its range has apparently increased several fold since 1850 (West, 1999).

Management of the P&J type then, need not be strictly bound by idealistic notions of pre-settlement ecological status and dynamics, which we struggle to reconstruct in any case, but

rather informed by ecological knowledge of site potential and vegetation dynamics, in support of the application of sustainable and appropriate management practices which attempt to balance stated societal needs and desires.

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PART III

Mapping "old" versus "young" piñon-juniper stands with a predictive topo-climatic model in north-central New Mexico, USA

Abstract

Southwestern U.S. piñon pine and juniper woodlands are often represented as an expanding and even invasive vegetation type, a legacy of historic grazing and culpable in the degradation of western rangelands. A long standing emphasis on forage production, in combination with recent hazard fuel concerns, has prompted a new era of woodland management with stated restoration objectives. Yet, the extent and dynamics of piñon-juniper communities pre-dating intensive Euro-American settlement activities are poorly known or understood, while the intrinsic ecological, aesthetic, and economic values of old-growth woodlands are often overlooked. Historical changes in piñon-juniper include two related, but poorly differentiated, processes: recent tree expansion into grass or shrub dominated (i.e., non-woodland) vegetation and thickening or infilling of savanna or mosaic woodlands pre-dating settlement. Our work addresses the expansion pattern, modeling the occurrence of "older" savanna and woodland stands extant prior to 1850, in contrast to "younger" piñon-juniper growth of more recent, post-settlement origin. We present qualitative criteria in the form of a diagnostic key for distinguishing "older", pre-Euro-American settlement piñon-juniper from "younger" (post-1850) stands, and report results of predictive modeling and mapping efforts within a north-central New Mexico study area. Selected models suggest a primary role for soil moisture in the current distribution of "old" versus "young" piñon-juniper stands. Pre-settlement era woodlands are shown to occupy a discrete ecological space, defined by the interaction of effective (seasonal) moisture with landform setting and fine-scale (soil-water) depositional patterns. "Older" stands are generally found at higher elevations or on skeletal soils in upland settings, while "younger" stands (often dominated by one-seed juniper, *Juniperus monosperma*) are most common at lower elevations or in productive, depositional settings. Modeling at broad regional scales can enhance

our general understanding of piñon-juniper ecology, while predictive mapping of local areas has potential to provide products useful for land management. Areas of the southwestern U.S. with strong monsoonal (summer moisture) patterns appear to have been the most susceptible to historical woodland expansion, but even here the great majority of extant piñon-juniper has pre-settlement origins (although widely thickened and infilled historically) and old-growth structure is not uncommon in appropriate upland settings.

Introduction

Piñon-juniper savanna and woodland communities collectively constitute one of the most widespread vegetation types within the Four Corners states of Arizona, Colorado, New Mexico, and Utah in the American Southwest (Figure 1). Within this four-state region piñon-juniper types represented by Colorado piñon (*Pinus edulis*) and one of the three commonly associated non-sprouting juniper species (one-seed, *Juniperus monosperma*, Utah, *J. osteosperma,* and Rocky Mountain, *J. scopulorum*) cover ca. 14.5 million ha (Lowry et. al., 2005). Recent attention has focused on presumed historical changes in piñon-juniper distribution and dynamics, particularly tree invasion of former grass and shrub communities, and associated effects on habitat, forage, soil, water resources (Everett, 1987; Miller and Wigand, 1994; Monsen and Stevens, 1999; Miller and Tausch, 2001). There is widespread interest in restoring degraded western rangelands, often through removal of the tree or shrub components, but managers proposing large-scale woodland restoration often face serious challenges, in part because field distinction between piñon-juniper stands of relatively recent origin and those with older trees that pre-date intensive Euro-American settlement activities (ca. 1850) can be problematic (Romme et. al., 2003). Selected qualitative features of individual trees and stands can be reliably associated with general

categories of stand age or development, such as old-growth (Kaufmann et. al., 1992; Miller et. al., 1999; Waichler et. al., 2001; Floyd et. al., 2003) or successional status (Miller et. al., 2005), allowing these features to be used as a proxy to infer a pre- versus post-Euro-American settlement stand age. Using this general approach, we present criteria in the form of a diagnostic key for consistent field recognition of "older", pre-settlement piñon-juniper types, as distinguished from "younger" stands (i.e., post-1850 origin) and demonstrate a predictive approach for modeling and mapping of pre- versus post-settlement aged woodlands (*P. edulis* and *J. monosperma / J. scopulorum*) in a north-central New Mexico study area.

Southwestern piñon-juniper types span an impressive range of environmental settings, occurring on foothill, mesa, and mountain slope positions at middle elevations within a semi-arid climatic zone, between lower elevation desert grass and shrub communities and higher elevation ponderosa pine and mixed coniferous forests (Pieper and Lymbery, 1987; West, 1999). However, despite the apparently broad ecological amplitude and wide distribution of piñon-juniper types across diverse climatic and topographic settings, each component species has a unique life history and range of environmental tolerances (Neilson, 1987; Ronco, 1987; Chambers et. al., 1999). Colorado piñon and Rocky Mountain juniper are often dominant within the more mesic, or upper elevation (and northerly) portions of the woodland zone (Pieper and Lymbery, 1987; Martens et. al., 2001) sometimes forming multi-layered stands with nearly closed canopies. At lower elevations or more xeric interfaces of woodlands with grass and shrub dominated communities, it is common to observe open savanna-like stands of one-seed or Utah junipers (and even piñon in some locations) with grass, forb, and / or shrub understories (Pieper and Lymbery, 1987; West, 1999). Utah juniper however, being both cold and drought tolerant also

occurs at both higher elevations and latitudes than piñon (Neilson, 1987). The elevation limits (upper and lower) of woodland distribution are likely reinforced by disturbance regimes (e.g., fire) and competitive interactions associated with ponderosa pine and grass- or shrub-land systems (Neilson, 1987; Gottfried et. al., 1995). Between these extremes a great variety of juniper and piñon-juniper types can be recognized as associations with various understories (Ronco, 1987; Gottfried et. al., 1995), depending on local site conditions and histories, and within the regional biogeography of individual species distributions (West and Van Pelt, 1987). While discrete piñon-juniper types can be delineated, savanna and woodland structures may alternatively be viewed as points along a continuum from open, non-woodland to closed canopy forest, with observed structure and individual species composition strongly influenced by the temporal and spatial scale of measurement, underlying topo-edaphic controls, species pool, and site history (Neilson, 1987; Martens et. al., 2001).

Drought, insects, disease, and fire are commonly recognized natural disturbances in piñon-juniper types, but interpreting the relative importance of these in controlling the spatial pattern of vegetation can be challenging (Baker and Shinneman, 2004). Competitive interactions, both between and among growth forms, are also thought to have been important mechanisms historically in maintaining grass-tree ecotones and internal stand structure (Johnsen, 1960, 1962; Eisenhart, 2004). The role of infrequent or extreme events can be especially difficult to integrate into local and typically short-term land management contexts. Establishment and mortality of woodland may result from pulsed disturbance or climatic events (Betancourt et. al., 1993; Chambers et. al., 1999; Swetnam et. al., 1999; Breshears et. al., 2005; Shinneman, 2006), while long-term persistence on newly colonized sites can be enhanced by positive feedbacks (i.e.,

desertification) of established vegetation on soil moisture and nutrient patterns (Walker et. al., 1981; West and Van Pelt, 1987; Schlesinger and Pilmanis, 1998; Breshears and Barnes, 1999) or through suppression of understory vegetation and associated potential for surface fire (Brackley, 1987; Miller and Tausch, 2001). Observed patterns in the occurrence and composition of woodlands are related to both local topo-edaphic conditions (Chambers et. al., 1999) as well as the regional climatic context. For example, coarse, shallow soils may lack sufficient soil moisture to support well-developed herbaceous cover, yet the fractured substrates underlying these sites can allow rapid infiltration and provide abundant deep water accessible primarily to woody plants (McAuliffe, 2003). At regional scales, seasonality of precipitation (i.e., summer versus winter dominance) can strongly influence water availability at depth and thus potential vegetation, given the large intra-annual differences in evaporative demand (Mitchell, 1976; Neilson, 1987).

Reconstructed stand age structures, paleoecological evidence, and visual comparisons of current conditions with historic photos suggest piñon-juniper has become more abundant at many locations since Euro-American settlement, ca. 1850 (e.g., Miller and Wigand, 1994; Tausch, 1999a; Miller and Tausch, 2001; Fuchs, 2002). Observed or reconstructed changes in southwestern piñon-juniper since settlement have been variously interpreted as (1) ongoing migrational adjustment to Holocene climate (2) natural demographic response (i.e., pulsed establishment) to fluctuating weather patterns (3) stages in normal stand development (4) recovery from harvest (historic or pre-historic) (5) succession after fire, drought, insect or disease induced mortality events (6) response to grazing practices including altered competitive interactions, soil properties, hydrologic patterns, and fire regimes (7) or accelerated growth as a

result of elevated temperatures and CO_2 levels associated with recent anthropogenic climate changes (Betancourt, 1987; Neilson, 1987; Betancourt et. al., 1993; Tausch, 1999b; Miller and Tausch, 2001; Baker and Shinneman, 2004; Eisenhart 2004; Floyd et. al., 2004; Shinneman, 2006). The relative importance of these mechanisms and processes likely differs from place to place, with both synchronous and synergistic interactions across multiple spatial and temporal scales (Neilson, 1987, 2003; Wagner and Fortin, 2005).

Historical changes in piñon-juniper include two distinct, but often poorly differentiated, processes: tree expansion into non-woodland areas (e.g., shrublands and grasslands) and thickening or infilling of piñon-juniper savanna and mosaic woodland communities extant prior to intensive Euro-American settlement (ca.1850). While expansion and infilling both involve new tree establishment, they often occur in different, albeit sometimes adjacent, edaphic and landform settings. The scale of observation or sampling approach, therefore, can determine whether results from different studies are comparable, particularly in regard to how fine-scale topographic patterns and associated vegetation mosaics are interpreted (Johnsen, 1960; Pieper and Lymbery, 1987; Wilcox and Breshears, 1994; Weisberg et. al., 2007). Although the underlying mechanisms driving expansion versus infilling may differ in some basic ways, both processes are thought to have been enhanced historically by intensive landuse and relaxation of competitive and disturbance constraints (Chambers et. al., 1999).

Predictive vegetation modeling has recently gained attention both as a practical tool for land managers and for its potential to inform ecological research through an integrated method of inquiry. A variety of statistical and geospatial methods have been used successfully to predict

and map discrete vegetation patterns from spatially explicit environmental variables (Franklin, 1995; Jensen et. al., 2001; Wagner and Fortin, 2005) with a recent emphasis on modeling species bio-climatic envelopes to infer potential for climate induced range shifts (Araujo and Guisan, 2006; Latimer et. al., 2006). Here we apply these predictive modeling methods to model and map "older", pre-settlement versus "younger", post-settlement piñon-juniper in a monsoonal, north-central New Mexico study area. Our approach implicitly tests the idea that "older", pre-settlement age piñon-juniper woodlands occupy an ecological space distinct from "younger", post-settlement stands. We sample across "old" versus "young" stands, associate these sites with relevant topo-climatic metrics, and develop predictive relationships between woodland stand-age and environmental variables.

Methods

Overview

We used an intensive, plot-based sampling approach to characterize southwestern U.S. piñon-juniper types, represented by Colorado piñon pine and several associated species of non-sprouting juniper (one-seed, Utah, and Rocky Mountain) in three National Park Service units (Bandelier National Monument, Mesa Verde National Park, and Colorado National Monument) representing a southeast to northwest, moisture seasonality gradient across the Four Corners states (Figures 1, 2). The intensive plot data were used to inform development of a diagnostic key (Table 1) distinguishing "older", pre-settlement woodlands (>150 years) from "younger", post-settlement stands of more recent origin. Intensive plot data were also used for exploratory analysis to provide insight into regional-scale woodland patterns. Subsequently, we identified a focal study area in north-central New Mexico representing the southeastern (monsoonal) end of

the regional moisture gradient initially sampled, where summer seasonal precipitation averages half or more of the annual total (Figure 2) and woodlands are mapped as southern Rocky Mountain types (*P. edulis* and *J. monosperma / J. scopulorum*) by the Southwest Regional Gap Analysis Project (SWReGAP); Lowry et. al., 2005, (Figure 1). The study area was centered on Bandelier, a well researched landscape and protected from wood harvest and livestock grazing since 1932. Within the focal study area we conducted extensive sampling to provide data for predictive modeling of piñon-juniper stand age. Each point was assigned a pre- versus post-settlement stand age (i.e., "young" or "old") using the diagnostic key. Subsequently, all sample points were associated with potentially relevant topo-climatic metrics and the compiled dataset used for modeling. Models were fit using stepwise logistic regression and evaluated using several standard measures of accuracy. Selected models for the north-central New Mexico study area were mapped within a geographic information system (GIS).

Intensive Field Sampling and Development of Diagnostic Key

Intensively sampled plots were circular, 50 m in diameter (0.2 ha) and with a single 25 m radial transect. Plots were established within homogeneous settings in which piñon-juniper was the dominant overstory and exceeded 5% canopy cover. Plot centers were anchored to the upslope drip-line of the oldest piñon and / or juniper individuals apparent within a local search area. A radial transect was established down slope from the plot center and aligned with site aspect. Within a designated quarter-plot section, a complete tree census (including dead individuals) was conducted: diameters were taken approximately 30 cm above ground surface (i.e., at core height); for multi-stemmed individuals (e.g., one-seed juniper) we measured the basal diameter of the largest primary stem. Qualitative features (e.g., crown shape, amount of dead wood in

living canopy, lichen growth on dead wood or axe-cut limbs, trunk cavities, large exposed roots, burned wood) were noted for each sampled tree. At the full plot (i.e., stand) level we also noted additional qualitative features, including presence of stumps, down-wood, or snags, and other evidence of historic cutting or fire disturbance. At 5-m intervals along the radial line transect we recorded overstory canopy cover by species, and understory vegetation and ground cover by form, within a 0.5-m quadrat; soil depths (<50 cm) were also sampled at each 5-m interval. Intersections of large down-wood (>6 cm) were tabulated along the entire transect. Maximum soil depth was obtained at plot center using a (2 ¼-inch) auger; a representative soil sample was obtained at a depth of 0 to 10 cm. Cores (and associated diameters) were obtained (at 30 cm above base) from the largest 5 to 10 piñon trees within the full plot. Cores were mounted, sanded, ring-counted, and subsequently cross-dated to validate ring-count estimates. Although juniper may represent the oldest trees in some stands (Shinneman, 2006), they are problematic to core and many species (e.g., one-seed and Utah junipers) cannot be dated precisely (Peter M. Brown, pers. comm.).

Quantitative stand age estimates were calculated as the average (ring-count) age of the three largest piñon (and three largest juniper when these data were available). In constructing the diagnostic key we selected qualitative characters that were easily recognizable and consistently present in trees and stands with quantitative age estimates of 150 years or more. Diameter thresholds (for distinguishing stands of pre- versus post-settlement age) were developed as an additional component of the diagnostic key, using regressions of ring-count on diameter from *Pinus edulis* and *Juniperus monosperma*. Sample data for regression analysis were obtained from nine woodland plots (stratified across three topo-edaphic settings representing shallow to deep

soils) established as part of an earlier study within Bandelier National Monument (Julius, 1999) and supplemented with six intensive plots sampled as part of the current project. Piñon tree diameters were measured near core height (i.e., 30 cm) and juniper stem diameters were measured near their base. Since diameter was being associated with ring-count at sample height, no standard adjustment (in ring-count for sample height above ground) was deemed necessary for developing regressions. We used a no-intercept linear regression model for predicting ring-count from diameter since both parameters can be expected to equal zero at time zero (Eisenhauer, 2003).

Reliability of the diagnostic key for use in north-central New Mexico was assessed using data from the fifteen plots sampled within Bandelier National Monument (Appendix). The plots at Bandelier provided a suitable test of the qualitative diagnostic criteria approach because the park supports a mosaic of "older" and "younger" stands that span the settlement threshold period (ca. 1850), and visual distinction between pre- versus post-settlement age stands sometimes can be difficult. In addition, nine of the fifteen plots at Bandelier had ring-count data available for one-seed juniper from an earlier study (Julius, 1999), and this allowed for a more robust estimate of quantitative stand age. For each plot, we compared the stand age assigned using the qualitative diagnostic criteria, with a quantitative stand age based on the average ring-counts of the three largest trees.

Extensive Field Sampling for Predictive Modeling

Extensive field sampling was focused initially within Bandelier and subsequently extended onto the surrounding Carson and Santa Fe National Forests, as well as along accessible public right-

of-ways, to acquire a more wide-ranging sample of woodlands from the north-central New Mexico study area. Using existing trails and roads as transects, we selected routes which sampled across the range of topographic and elevation settings where woodland occurred. Sampling was stratified across four general landforms: (1) valleys, including swales and drainage bottoms, (2) mesas and ridges, (3) upland terraces, and (4) steeper slopes and cliffs. These landform categories were readily discernible in the field, provided an ecologically relevant approach for dispersion of points across local landscapes, and were available as spatial coverage within a GIS (Lowry et. al., 2005). Along each transect, we sampled successive landform strata as they were encountered; this approach distributed sampling effort across the different strata in proportion to their availability.

For each sample point we established a 50-m circular plot within which we collected the following information: geographic coordinates and elevation; apparent landform and (soil-water) depositional context; diameter near base of trunk or largest stem of the three largest individuals per species (including snags, stumps, and logs), qualitative old-growth characteristics of sampled trees; and qualitative features of the stand including successional status or signs of obvious landuse or historical disturbance. Assignment of piñon-juniper type, pre- versus post-settlement stand age, landform, and depositional setting initially were made onsite. Field assignments were subsequently reviewed to ensure consistent application of diagnostic key criteria and correspondence of sampled field points with GIS landform coverage.

Development of GIS Datasets for Modeling

A variety of geospatial datasets, including elevation, climate (temperature and precipitation), vegetation cover, landform, geology, and soils, were acquired to provide baseline GIS data for the Four Corners states. Geospatial climate variables were procured from Climate Source Inc., a vendor of 2-km resolution climate products developed by the Parameter-elevation Regressions on Independent Slopes Model (PRISM) group at Oregon State University, and seamless 30-m resolution digital elevation model (DEM) coverage was purchased from USGS-EROS. Vegetation and landform coverages (30-m resolution) were obtained from SWReGAP (Comer et. al., 2003; Comer et. al., 2004; Lowry et. al., 2005). Different spatial references and resolutions necessitated some standardization to create compatible datasets for analysis (Latimer et. al., 2006); all data were projected to Albers Equal Area Conic, NAD83.

Surface analysis of 30-m DEM's was used to create slope (in degrees), hillshade, and flow accumulation datasets using standard utilities in ArcGIS 9.1 (ESRI, 2005). Precipitation and temperature values were available as 30-year (1961-1990) monthly means from PRISM at 2-km resolution; these data were then used to calculate annual and seasonal means. Mean annual precipitation (MAP) was calculated by averaging the 30-year monthly means. Seasonal (summer and winter) precipitation represents growing or dormant season moisture (mean monthly values) summed for the June-September and October-May periods respectively. A seasonal moisture index (MONSOON) represents growing season (June-September) precipitation as a percentage of MAP. Metrics of effective (summer and winter) moisture (ESP and EWP) were developed by adjusting seasonal precipitation with seasonal estimates of potential evapo-transpiration (PET). Seasonal indices of PET (winter and summer) were calculated as the product of $\log_n$(hillshade) for summer or winter solstice solar parameters (1300 hours) and mean maximum or minimum

monthly temperatures respectively (method adapted from Penman, 1948). Landform coverage originally developed by SWReGAP (Lowry et. al., 2005) was generalized to four categories (from ten) delineated using slope and flow accumulation thresholds. This yielded a class variable (LANDFORM) with four levels: 1 = alluvial slope positions, swales, and valley bottoms, 2 = upland mesas and ridges, 3 = upland terraces, 4 = steeper slope positions, shoulders, and cliffs (Table 2). Relative runoff accumulation and soil depositional patterns were compiled using LANDFORM specific, flow accumulation thresholds, to generate a class variable (FLOW) with two levels: 0 = *losing* soil-water settings; 1 = *gaining* soil-water settings (Table 2).

Predictive Modeling and Map Realization

Statistical modeling was performed in SAS 9.1 (SAS, 2005) using a binary logistic procedure (where "old" = event and "young" = nonevent) and stepwise model selection with default thresholds (P-values) for entry ($P < 0.2$) and retention ($P < 0.1$) of individual explanatory variables. Topographic and climate data, including secondarily derived metrics, were used as potential explanatory variables of stand age. Secondary metrics were developed (as detailed above) by combining precipitation and temperature with DEM derived surfaces (e.g., hillshade) to create variables with potential ecological relevance (e.g., ESP, EWP, PET). Topo-climatic data associated with each sample point were extracted using the spatial analyst sample utility in ArcGIS 9.1 (ESRI, 2005) and the data imported to SAS for model development. A potential set of some twenty topo-climatic predictors, including both discrete and continuous data versions of some variables, were provided to the logistic program for initial selection. Prior probabilities were not specified and defaulted to the observed ratio of "old:young" in each dataset. Table 2 presents a frequency distribution (%) of samples across the two class variables used in modeling:

LANDFORM (four levels) and FLOW (two levels), for the full (n = 210) and split training (n = 146) / test (n = 64) datasets.

Modeling runs were conducted using both the full dataset (n = 210) and a split training / test dataset (n = 146 / n = 64) partitioned using a simple rule. Alternative models developed using the full and training datasets were evaluated using several standard measures of accuracy, including leave-one-out (LOO), cross-validated probability (XP), classification table outputs (i.e., total correct, sensitivity, specificity, false positive / negative) across a limited range (i.e., 0.40 to 0.60) of probability cutoffs (Table 3). Comparable models with fewer and / or more easily interpretable predictors were given preference. For the split dataset modeling effort, the test dataset was scored using the model independently fit with the training data. LOO XP, receiver operating characteristic (ROC), area under curve (AUC) values (LOO XP ROC AUC) also were calculated for full, training, and test models. ROC AUC values represent a plot of LOO XP sensitivity * specificity measures across all probability levels, providing a single integrated measure of model predictive accuracy.

Spatial analysis of logistic model outputs in ArcGIS (throughout the north-central New Mexico study area) involved calculation of predicted probabilities using SWReGAP woodland coverage as an analysis mask to represent occurrence of southern Rocky Mountain piñon-juniper. Intercept and partial slope regression parameters were used to calculate individual cell probabilities of class membership (i.e., "young" or "old") using the raster calculator utility. Cell probabilities were then grouped into two or more response classes (e.g., "young" < 0.5 or "old" ≥ 0.5) and color coded for map visualization.

Results

Diagnostic Key

A diagnostic key (Table 1) was developed to facilitate rapid field assignment of piñon-juniper type, and is used here to distinguish "older", pre-Euro-American settlement woodlands (>150 years) from "younger" stands of more recent (post-1850) origin. Tree diameter thresholds presented in the key (Table 1) are based on diameter to age (ring-count) regressions, using a zero-intercept model and developed with samples from Bandelier National Monument: Colorado piñon age = 5.49 * diameter ($P < 0.0001$, $n = 204$) and one-seed juniper age = 6.65 * diameter ($P < 0.0001$, $n = 398$); Appendix. P-values are provided in lieu of r-square values which cannot be used to evaluate zero-intercept models (Eisenhauer, 2003). Diameter thresholds are intended to provide a pre- versus post-settlement (ca. 1850) approximation of stand age for Colorado piñon (30 cm) and one-seed juniper (25 cm) in upland settings of north-central New Mexico with moderate soil depths (15 to 35 cm). Our diameter-age estimates are comparable to those in published reports of piñon and juniper growth rates in New Mexico (Howell, 1940). The key provides minimum densities of old trees below which detection of individuals >150 years could be considered incidental to the site under consideration. Although the key delineates woodland and savanna types, our experience in the field tells us that these stand structures can intergrade or occur in mosaic patterns reflecting variable site histories along complex environmental gradients.

Reliability of the diagnostic key for delineating pre- versus post-settlement stands in the north-central New Mexico study area was assessed using data from fifteen (0.1 ha) intensively sampled plots within Bandelier National Monument. Using the key, 13 of 15 of stands were correctly

assigned to a pre- versus post-settlement age, based on stand age computed from average ring-counts of the three largest sampled piñon (and juniper in nine plots) trees in each stand (Appendix). The key performed well when used to delineate "older" (>175 years) from "younger" (<125 years) stands. Stands of median age (i.e., 150 years ± 25 years) were sometimes problematic given the nature of criteria used, particularly when assessing "young" stands (with large diameter trees) in productive settings or "old" stands (with small diameter trees) on poor sites. Plot *BAND12* was misclassified as "young", but ring-counts of the three largest piñon averaged 150 years, suggesting a marginally "old" stand with slower-growing piñon. Plot *BAND15* was misclassified as being "old", although the ring-count data suggested a marginally "young" stand with several large (>30-cm stems), fast-growing junipers averaging <135 ring years.

Predictive Modeling and Mapping

The full model correctly classified 89.5% of observations (0.45 probability cutoff) using four predictors: effective winter moisture (EWP, $P < 0.0001$), flow accumulation (FLOW, $P < 0.0001$), landform (LANDFORM, $P < 0.0015$) and elevation (DEM, $P < 0.0014$); 93.2% of pre-settlement stands (136 of 146) and 81.3% of post-settlement stands (52 of 64) were correctly classified (Tables 2, 3). The leave-one-out, cross-validated probability, receiver operator characteristic, area under curve (LOO XP ROC AUC) value for the full model was $c = 0.932$. Comparable classification results were obtained for the split, training ($n = 146$) / test ($n = 64$) dataset (0.60 probability cutoff) using the same four predictors; total correct for the training dataset was 89.0%, with an LOO XP ROC AUC value of $c = 0.938$. The test data scored using the model fit independently with the training dataset correctly classified 90.6% of all

observations: 93.3% of pre-settlement stands (42 of 45) and 84.2% of post-settlement stands (16 of 19). LOO XP ROC AUC value for the scored test data was $c = 0.913$.

Map realizations of the full model were generated in ArcGIS at various spatial extents, including the north-central New Mexico study area (Figure 3a) and the Tsankawi subunit of Bandelier National Monument (Figure 3b). Within the north-central New Mexico study area, SWReGAP coverage indicates that *P. edulis* / *J. monosperma* types occupy 28% (820,955 ha) of land area. Our model results suggest that less than a third (29%) of this extant piñon-juniper cover is post-settlement in origin. We noted during field work, however, that SWReGAP coverage often classified sites with scattered "young" piñon-juniper stands (<50 years) as non-woodland types, so using this coverage as an analysis mask for map realization likely underestimates total acreage of post-settlement woodland in the north-central New Mexico area. The majority of these "younger", post-settlement stands occur either below critical EWP thresholds in lower elevation valley and terrace landform settings or in strongly depositional areas within an upland landform context. An equally important result is the corollary finding that >70% of extant piñon-juniper was savanna or woodland prior to 1850. Although widely thickened or infilled, these "older" stands should not be misinterpreted as part of the post-settlement expansion of piñon-juniper into non-woodland (e.g., grass and shrub) vegetation types.

Discussion

A diagnostic key (Table 1), using a combination of semi-quantitative and qualitative features, was developed to facilitate rapid field distinction of piñon-juniper type and pre- versus post-settlement stand age. We used the key only to assign sampled stands to "old" versus "young"

categories in preparation for logistic modeling within our north-central New Mexico study area, although the key provides for finer classification of piñon-juniper types. Notably the key does not distinguish historically thickened or infilled savanna and mosaic woodland structures, where tree cover was sparse or patchy prior to 1850, from woodlands where tree density and cover has been relatively high or continuous since before settlement. For our purposes, both of these structures would be classified as pre-settlement if they contained old or persistent piñon-juniper features.

Use of the diagnostic key outside of the north-central New Mexico area, or within selected landform and climatic settings, may require local calibration of the semi-quantitative (e.g., diameter thresholds) criteria. Piñon cores collected from intensively sampled plots across the Four Corners states (data not presented) indicate that differences in seasonal moisture patterns and landform setting may strongly influence relative growth rates. For example, growth rates of one-seed juniper at Bandelier are nearly twice those reported for Wupatki National Monument, Arizona (Hassler, 2006), where MAP is about half of that reported for Bandelier and summer moisture averages only 45-50% of MAP. Across areas having comparable ranges of MAP, a 30-cm diameter piñon in the Bandelier area (where summer precipitation averages 50 to 55% of the annual total) might be expected to range between 150-180 years old, whereas in winter moisture dominated portions of the Colorado Plateau (MONSOON < 0.5) a similar piñon would generally exceed 200 years, and in strongly monsoonal portions of southern New Mexico (MONSOON > 0.55) the same diameter trees would often be less than 150 years old (Figure 2). Within local areas, growth rates were observed to be greater on depositional versus immediately adjacent non-depositional settings (Appendix), whereas nearby upland settings with exposed bedrock and little

capacity for subsurface water storage often supported surprisingly old, but relatively small diameter, trees.

We predictively modeled and mapped the occurrence of pre- versus post-settlement woodlands within a 2.9-million ha study area comprising a north-central New Mexico extent. Sampled stands were classified as "old" versus "young" using the diagnostic key and each sample point was associated with potential topo-climatic predictors in a GIS. The resulting dataset was used for logistic modeling, and the selected models were implemented within a GIS to realize predictive map products. This approach allowed us to evaluate the relative importance of individual explanatory variables, and generate map outputs for use by land managers. The topo-climatic metrics selected (i.e., FLOW, LANDFORM, EWP, DEM) were both spatially explicit and ecologically relevant. Our model and map realizations highlight environmental settings inherently favorable to the growth and long-term persistence of piñon-juniper savanna and woodland versus locations that would have formerly supported non-woodland (e.g., grass and shrub) vegetation types (Figure 3b). Nonetheless, woodland vegetation is dynamic and positive feedbacks can effectively mitigate environmental or disturbance constraints on potential distribution. Once established, woodland can persist even in strongly depositional settings if tree cover effectively usurps resources, suppresses understory cover and potential for surface fire, or alters hydrologic and soil properties (West and Van Pelt, 1987; Schlesinger and Pilmanis, 1998; Breshears and Barnes, 1999).

Within the north-central New Mexico study area, woodland expansion appears largely attributable to establishment of one-seed juniper into historically degraded grasslands in

depositional valley and terrace settings under monsoonal influence. Although many valley locations in north-central New Mexico experienced domestic grazing pressures as early as the 1600s, the influence of intensive Euro-American settlement beginning ca.1850 was likely the overriding historic influence on age-structure of extant woodland vegetation. Across the Four Corners states our intensive plot work suggests that seasonal patterns of moisture and occurrence of different juniper species (Figures 1, 2) may influence the relative susceptibility of southwestern U.S. landscapes to historic woodland expansion. For example, one-seed juniper (Little, 1971) is associated with a summer monsoonal influence (Mitchell, 1976; Neilson, 1987, 2003; Figure 2) and this species has life history attributes that relate successful seedling establishment to adequate growing season moisture (Johnsen 1960, 1962; Chambers et. al., 1999). In contrast, Utah juniper (Little, 1971) occurs primarily in weakly bimodal and winter moisture dominated areas to the northwest (Figure 2). Rocky Mountain juniper gains importance northward and eventually replaces one-seed juniper as the common associate of piñon in portions of south-central Colorado where early spring moisture becomes an important component of the annual total (Woodin and Lindsey, 1954). Among closely related piñon species there is also an apparent relationship between needle number and seasonality of moisture. The range of Colorado piñon with two-needles encompasses areas influenced by both summer and winter moisture. Its one-needle relative, *Pinus monophylla,* located to the west is exclusively under the influence of winter moisture, and its three-needle relative, *Pinus cembroides,* found to the south is under the influence of strong summer monsoon moisture patterns (Neilson, 1987).

Along a northwest-to-southeast moisture seasonality gradient (within woodlands of the Four Corners states) we observed a dramatic increase in the frequency of "younger", post-settlement

stands in locations roughly corresponding to the distributional limits of one-seed juniper (Little, 1971) and a shift to summer monsoonal moisture patterns (Figure 2). These "younger", usually one-seed juniper dominated, stands are typically found in low gradient valley and terrace landform settings (including gentle slopes and rolling hills). Chambers et al (1999) suggest that tree establishment into grasslands may be facilitated by adequate growing season moisture, which can mitigate the need for favorable micro-sites otherwise provided by woody nurse plants in winter moisture areas. Although arid grasslands are susceptible to desertification processes (Walker et. al., 1981; Schlesinger and Pilmanis, 1998), McAuliffe (2003) found that sites with shallow argillic horizons (which inhibit infiltration and deep water storage) can apparently resist woody plant establishment even under sustained grazing pressure. Colorado piñon, along with Rocky Mountain and Utah juniper, while present in many post-settlement stands, are more commonly observed as components of expansive woodlands colonizing higher elevation, depositional settings occupied by grass and sage types (Weisberg et. al., 2007), as well as infilling ponderosa pine understories on adjacent toeslopes.

On the Colorado Plateau (northwest of north-central New Mexico), where seasonal moisture patterns are weakly bimodal or winter-dominated, the occurrence of "young", post-settlement woodlands becomes correspondingly less frequent. In this bio-climatic zone, landform and (soil-water) depositional patterns increasingly delineate woodland from non-woodland areas across relatively sharp ecotonal boundaries. Notably, woodland expansion into grassland vegetation appears much less extensive outside the range of one-seed juniper (for example in the areas where Utah juniper is dominant). However, environmental constraints of woodland distribution and age structure can also be variously reinforced, amplified, or muted by associated disturbance

processes (e.g., fire) and competitive interactions (Neilson, 1987). Our intensively sampled plot data from the Colorado Plateau (not presented here) suggest that this area supports an abundance of "older", pre-settlement aged woodlands, and these observations are consistent with recent findings by Eisenhart (2004), Floyd et. al., (2004; 2008), Hassler (2006), and Shinneman (2006). Although we found a relationship between summer monsoonal patterns, one-seed juniper distribution, and susceptibility of landscapes in the Four Corners states to historic woodland expansion, further west in the winter-spring moisture influenced Great Basin region, western juniper (*Juniperus occidentalis*) also has expanded dramatically since 1860 into sagebrush steppe communities (Miller et. al., 2007).

In summary, we developed a diagnostic key to distinguish between "older", pre-settlement and "younger" post-settlement piñon-juniper woodlands in the southwestern U.S. We assigned a pre- versus post-settlement age (ca. 1850) to sampled stands using this key. Topo-climatic metrics associated with sampled points were extracted and compiled within a GIS, and the resulting dataset was used for predictive modeling and mapping of pre- versus post-settlement ("old" versus "young") stands of piñon-juniper within a north-central New Mexico study area. Our modeling results suggest that "older" stands occupy an ecological space largely distinct from the settings where "younger" woodlands are commonly found, allowing us to use the associated environmental parameters to predict these occurrence patterns. Map realization of selected models highlights that landscape patterns of "older" pre- versus "younger" post-settlement woodland are likely structured by gradients of effective moisture and (soil-water) depositional environment (Pieper and Lymbery, 1987; Wilcox and Breshears, 1994). Our field observations reinforce the idea that woodlands growing under winter-dominated or weakly bimodal moisture

regimes have a fundamentally different character than those strongly influenced by summer monsoonal patterns. These findings contribute to a basic understanding of piñon-juniper ecosystems and can help inform appropriate management. Historic woodland expansion in north-central New Mexico is largely attributable to establishment of one-seed juniper into degraded rangeland settings under a summer monsoonal influence, and ecological restoration of grasslands and savanna structures in these locations appears generally warranted. In contrast, proposals for restoration of woodland sites on the Colorado Plateau should be reviewed more cautiously given our findings and reported prevalence of "older" pre-settlement woodlands in locations with bimodal or winter moisture patterns (Romme et. al., 2003).

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Table 1. Diagnostic criteria and artificial key for delineation of southwestern U.S. piñon-juniper, savanna and woodland types* (*Pinus edulis*, *Juniperus osteosperma*, *J. monosperma*, and *J. scopulorum),* in the Four Corners states (Arizona, Colorado, New Mexico, and Utah)

KEY TO GROUPS

1a. Mature piñon (live or dead) well represented …**2**

1b. Mature piñon few or absent …**3**

2a. Mature juniper few or absent …**Group I**

(Piñon Dominated)

2b. Mature juniper (live or dead) well represented …**Group II**

(Piñon-Juniper Co-Dominant)

3a. Mature juniper (live or dead) well represented …**Group III**

(Juniper-Dominated)

3b. Mature juniper few or absent …**Group IV**

(Successional Piñon and / or Juniper types)

INDIVIDUAL GROUP KEYS

Group I: Piñon Dominated, Woodland or Savanna

Canopy closure usually ≥25% (20 to 80+%); juniper, if present, mostly younger

4a. Old-growth trees present… **Old-growth Piñon Dominated, Woodland or Savanna**

Individual old trees (≥5 trees / ha on average), live or dead, average diameter (of largest 3 trees) for piñon near base ≥30 cm**; AND with two or more of following old-growth characteristics: truncate crown formed by terminals with short, often gnarled, internodes; attached dead wood in canopy, often polished and with well developed lichen growth; basal trunks with exposed polished wood or well developed cavities; individual old tree(s) form the center of an established patch of mature and / or suppressed trees; large girth roots with exposed polished wood, and widely trailing on shallow substrates; stands with large diameter down-wood (comparable in girth to standing old trees), polished, bleached, and with well developed lichen growth; signs of historic woodcutting evidenced by large girth, axe-cut, limbs and trunks, with cuts covered by lichen growth; historic fire evidence, when present, suggestive of patchy crown fire (fire sculpted snags, burned out stumps, and down-wood from which the charcoal may have worn off) and / or surface fire with occasional scarring at grass and forest ecotones

4b. Old-growth trees absent… Group IV

Old trees generally absent, peripheral (in different topographic settings along margins of site under consideration) or present only as large diameter, remnant (sometimes burnt) snags, stumps, or down-wood (evidence of past disturbance)

Group II: Piñon and Juniper Woodland

Canopy closure usually ≥20% (15 to 60+%); mature piñon and juniper present

5a. Old-growth trees of both species present… **Old-growth Piñon-Juniper Woodland**

Individual old trees (≥3 old trees / ha on average, piñon and / or juniper), live or dead, average diameter (of largest 3 trees) near base for piñon ≥30 cm** and / or juniper ≥25 cm** ; AND with two or more of following old-growth characteristics: truncate crown formed by terminals with short, often gnarled, internodes; attached dead wood in canopy, often polished and with well developed lichen growth; basal trunks with exposed polished wood or well developed cavities; individual old tree(s) form the center of an established patch of mature and / or suppressed trees; large girth roots with exposed polished wood, and widely trailing on shallow substrates; stands with large diameter down-wood (comparable in girth to standing old trees), polished, bleached, and with well developed lichen growth; signs of historic woodcutting evidenced by large girth, axe-cut, limbs and trunks, with cuts covered by lichen growth; historic fire evidence, when present, suggestive of patchy crown fire (fire sculpted snags, burned out stumps, and down-wood from which the charcoal may have worn off)

5b. Old-growth trees absent… Group IV

Old trees generally absent, peripheral (in different topographic settings along margins of site under consideration) or present only as large diameter, remnant (sometimes burnt) snags, stumps, or down-wood (evidence of past disturbance)

Group III: Juniper Savanna

Canopy closure usually ≤15% (5 to 30+%); piñon, if present, mostly younger

6a. Old-growth trees present… **Old-growth Juniper Savanna**

Individual old trees (≥1 old tree / ha on average), live or dead, average diameter (of largest 3 trees) for juniper near base ≥25 cm**; AND with two or more of following old-growth characteristics: truncate crown formed by terminals with short, often gnarled, internodes; attached dead wood in canopy, often polished and with well developed lichen growth; basal trunks with exposed polished wood or well developed cavities; individual old tree(s) form the center of an established patch of mature and / or suppressed trees; large girth roots with exposed polished wood, and widely trailing on shallow substrates; stands with large diameter down-wood (comparable in girth to standing old trees), polished, bleached, and with well developed lichen growth; signs of historic woodcutting evidenced by large girth, axe-cut, limbs and trunks, with cuts covered by lichen growth; historic fire evidence, when present, suggestive of surface fire (occasional scarring) with torching of individual trees (fire sculpted snags, burned out stumps, and down-wood from which the charcoal may have worn off)

6b. Old-growth trees absent… Group IV

Old trees generally absent, peripheral (in different topographic settings along margins of site under consideration) or present only as large diameter, remnant (sometimes burnt) snags, stumps, or down-wood (evidence of past disturbance)

Group IV: Successional Piñon and / or Juniper Woodland or Savanna

Canopy closure ≥5%* (5 to 80+%); average diameter (of largest 3 living trees) near base for piñon ≤30 cm** and / or juniper ≤25 cm**

7a. Evidence of historic disturbance to former old-growth woodland based on remnant (e.g., fire, drought, insect, or disease killed, cut, chained, burned, or mechanically harvested) large girth, (piñon and / or juniper) snags, stumps, trunks, down-wood (average diameter of 3 largest down-wood remnants of piñon ≥30 cm** and / or juniper ≥25 cm**); large diameter down-wood (piñon or juniper) often bleached, polished, or decomposed, and with well developed lichen growth…

… **Recovering Woodland Types** (historically disturbed and lacking extant old-growth) Sites with evidence of long-term woodland occupation, but subjected to historic disturbance, e.g., fire, drought, harvest, and / or insect / disease induced mortality

7b. Lacking above evidence of former old-growth woodland elements (may include dead -standing or fallen- ponderosa pine or other non-woodland tree species); stands lacking large diameter (piñon and / or juniper) snags, stumps, or down-wood…

... **Expanding Woodland Types** (expanding into non-woodland vegetation types)

Sites without evidence of a prior woodland community, on deeper soil sites, or settings capable of supporting robust understory growth, often with suppressed or remnant components of non-woodland, grass, shrub, and pine savanna types

* minimum tree canopy cover ≥5% to be considered as a piñon-juniper type

** diameter thresholds for *Pinus edulis* and *Juniperus monosperma* in upland settings with moderate soil depth (i.e., 15 to 35-cm deep) in north-central New Mexico; (add 2 to 5 cm for mesic, depositional soil sites (i.e., >35 cm deep) and subtract 2 to 5 cm for dry sites with shallow, skeletal soils (i.e., <15 cm deep) with exposed bedrock). For single stem trunks, measure diameter just above base (ca. 30 cm or core height), and for multi-branched trees (e.g., one-seed juniper), measure diameter of largest stem just above junction.

Table 2. Number of samples across landform (LANDFORM*)* strata and depositional environment (FLOW), and by stand age (pre- versus post-settlement stand age) for full (n = 210), training (n = 146), and test (n = 64) datasets within a north-central New Mexico study area. Relative percent of "young" versus "old" samples in each dataset, and of total samples in the split training and test datasets are noted. See *Development of GIS Datasets for Modeling* in Methods section for additional explanation of LANDFORM and FLOW parameters.

Dataset *sample size* (%)	**Stand age**	**LANDFORM (#)**				**FLOW**	
		Valley (1)	**Mesa (2)**	**Terrace (3)**	**Slope (4)**	**0 (Losing)**	**1 (Gaining)**
Full		Number of samples				Number of samples	
64 (30.5)	**Young**	7	23	30	4	30	34
146 (69.5)	**Old**	2	67	25	52	137	9
n = 210	Sub-totals	9	90	55	56	167	43
Training							
45 (30.8)	**Young**	6	17	19	3	22	23
101 (69.2)	**Old**	1	45	18	37	94	7
n = 146 (69.5)	Sub-totals	7	62	37	40	116	30
Test							
19 (29.7)	**Young**	1	6	11	1	8	11
45 (70.3)	**Old**	1	22	7	15	43	2
n = 64 (30.5)	Sub-totals	2	28	18	16	51	13

Table 3. Leave-one-out (LOO), cross-validated probability (XP), classification results ("old" = event) for the full dataset model, n = 210, (with results itemized by class level for variable LANDFORM) using four explanatory parameters (EWP, FLOW, LANDFORM, DEM) and a probability prediction threshold (prob. cutoff) of 0.45. We report a LOO XP receiver operator characteristic (ROC), area under curve (AUC) value (LOO XP ROC AUC) for the full model of c = 0.932. Comparable results were obtained for the split, training (n = 146) and test (n = 64) dataset, with a 0.60 prob. cutoff. The test data were scored using the model fit independently with the training dataset. We report LOO XP ROC AUC values for the training data of c = 0.938, and scored test data of c = 0.913. Prior probabilities for the full and training models reflect the sampled ratios of "old" to "young" in each dataset (see Table 2).

Model		Observed		Correct		Incorrect		Percentages				
(prob. cutoff) *ROC c = value*	Sample size (*n*)	**Old**	**Young**	**Old**	**Young**	**Old**	**Young**	**Total**	**Sensitivity (Old)**	**Specificity (Young)**	**False positive**	**False negative**
Full (0.45) ***c = 0.932***	**210**	**146**	**64**	**136**	**52**	**12**	**10**	**89.5**	**93.2**	**81.3**	**8.1**	**16.1**
LANDFORM1 (Valley)	9	2	7	1	6	1	1	77.8	50.0	85.7	50.0	14.3
LANDFORM2 (Mesa)	90	67	23	62	18	5	5	88.9	92.5	78.3	7.5	21.7
LANDFORM3 (Terrace)	55	25	30	21	27	3	4	87.3	84.0	90.0	12.5	12.9
LANDFORM4 (Slope)	56	52	4	52	1	3	0	94.6	100.0	25.0	5.5	0.0
Training (0.60) *c* = 0.938	146	101	45	92	38	7	9	89.0	91.1	84.4	7.1	19.1
Test (0.60) ***c = 0.913***	**64**	**45**	**19**	**42**	**16**	**3**	**3**	**90.6**	**93.3**	**84.2**	**6.7**	**15.8**

Figure Captions

Figure 1. Generalized distribution of Colorado Plateau and southern Rocky Mountain piñon-juniper savanna and woodland types within the Four Corners states: piñon-juniper covers ca. 14.5 million ha or ~13% of the total land area (modified from data provided by SWReGAP). Three National Park Service units (Bandelier National Monument, Mesa Verde National Park, and Colorado National Monument) were sampled intensively to inform selection of qualitative criteria and development of the diagnostic key, and to provide data for exploratory modeling. Extensive sampling and modeling efforts were conducted within the north-central New Mexico study area where SWReGAP-mapped piñon-juniper represents southern Rocky Mountain (PIED-JUMO-JUSC) savanna and woodland types. *Pinus edulis* = PIED; *Juniperus monosperma* = JUMO; *Juniperus scopulorum* = JUSC; *Juniperus osteosperma* = JUOS.

Figure 2. Index of growing season moisture (MONSOON) is calculated as the June-September percent of mean annual precipitation (MAP) across the Four Corners states. We highlight the casual association of one-seed (JUMO) and Utah (JUOS) juniper ranges (Little, 1971) with MONSOON. Extensive sampling (and predictive modeling and mapping efforts) were conducted within (and for) the north-central New Mexico study area where one-seed juniper woodlands (as delineated by Little, 1971) occur primarily within areas receiving half or more of MAP during the (June-September) growing season (MONSOON $\geq$ 50%); the range of Colorado piñon (not shown) within the north-central New Mexico study area coincides with the mapped distribution for one-seed juniper (Little, 1971). *Pinus edulis* = PIED; *Juniperus monosperma* = JUMO; *Juniperus osteosperma* = JUOS.

Figure 3a. Predictive map of "old" versus "young" (percent probability "old") piñon-juniper stands within the 2.9 million-ha north-central New Mexico study area. Figure 3b is a close-up of Tsankawi Unit (see inset), Bandelier National Monument.

Figure 3b. Predictive map of "old" versus "young" (percent probability "old") piñon-juniper stands within the (336 ha) Tsankawi Unit, Bandelier National Monument, New Mexico. Green with scattered tree overlay -delineated using high resolution soil coverage- highlights inferred areas of historically thickened savanna structure in marginal depositional settings, and indicates where mechanical thinning of the younger tree component might be considered an appropriate restoration treatment. Light gray denotes areas mapped as non-woodland vegetation. Map resolution of predicted pre- versus post-settlement woodland cover is 30 m, but an appropriate scale (e.g., minimum map unit) for field application in this location would be ~1 ha.

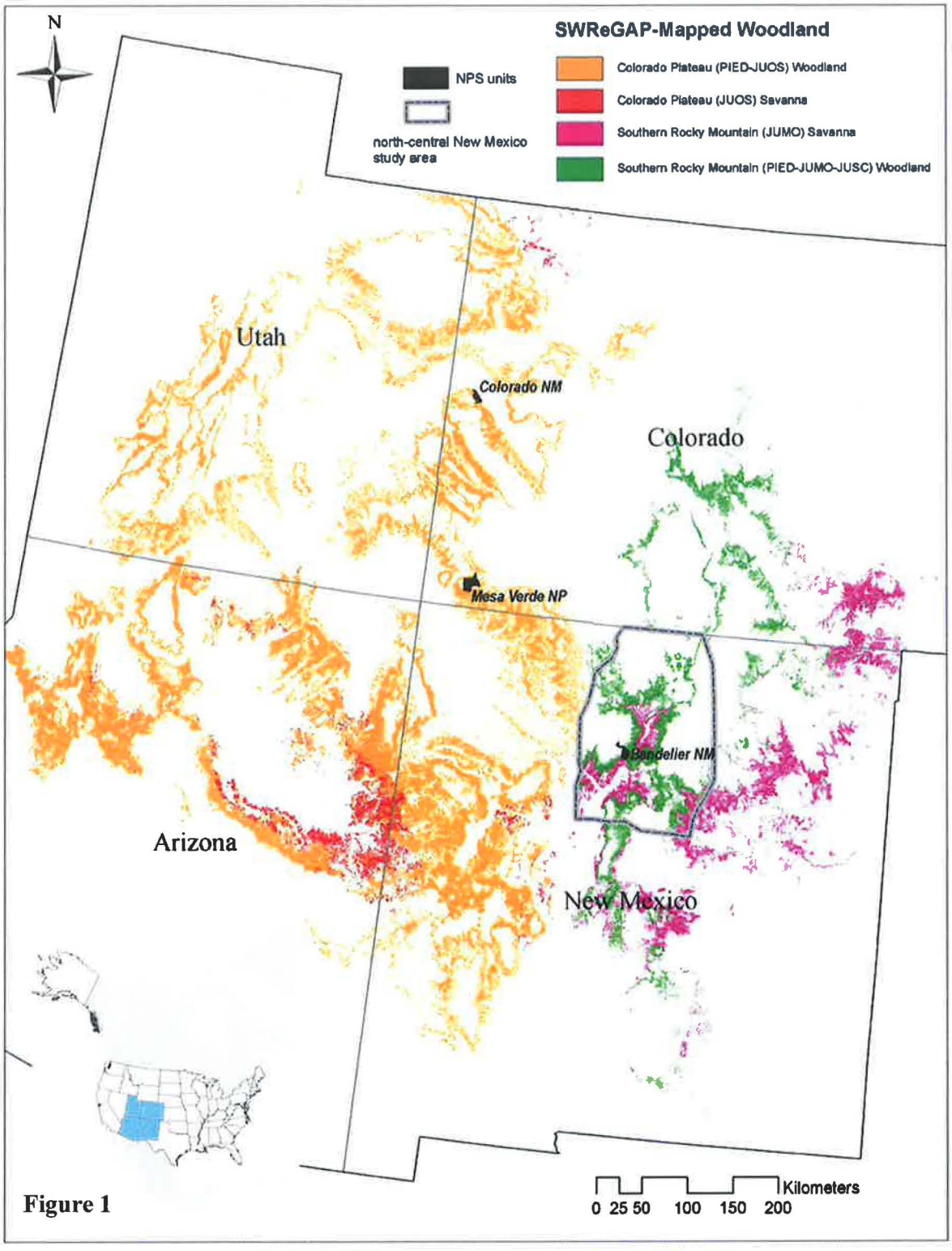

N
SWReGAP-Mapped Woodland
NPS units
north-central New Mexico study area
Colorado Plateau (PIED-JUOS) Woodland
Colorado Plateau (JUOS) Savanna
Southern Rocky Mountain (JUMO) Savanna
Southern Rocky Mountain (PIED-JUMO-JUSC) Woodland
Utah
Colorado NM
Colorado
Mesa Verde NP
Bandelier NM
Arizona
New Mexico
Kilometers
0 25 50 100 150 200

Figure 1

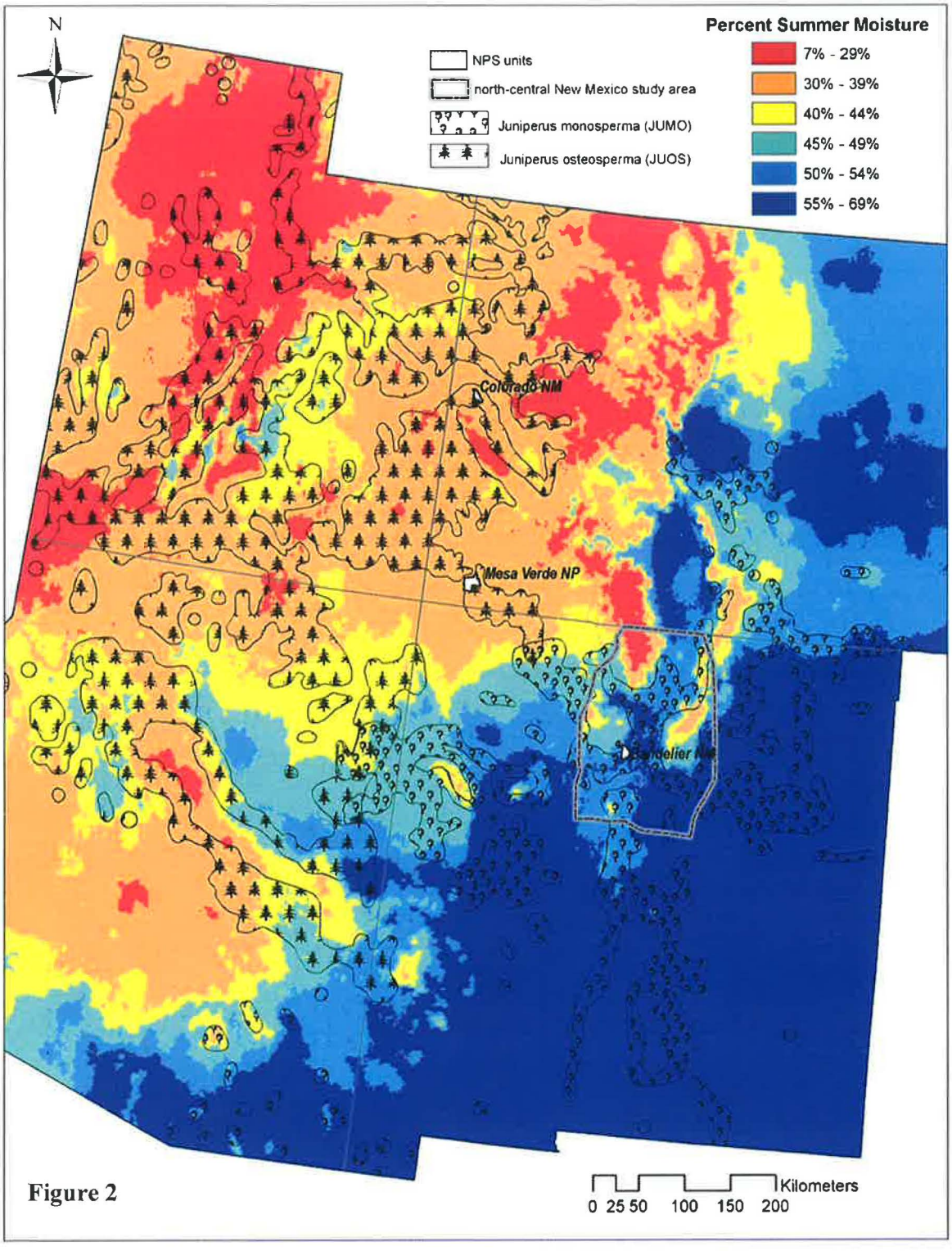

N
Percent Summer Moisture
NPS units
north-central New Mexico study area
Juniperus monosperma (JUMO)
Juniperus osteosperma (JUOS)
7% - 29%
30% - 39%
40% - 44%
45% - 49%
50% - 54%
55% - 69%
Colorado NM
Mesa Verde NP
Kilometers
0 25 50 100 150 200

Figure 2

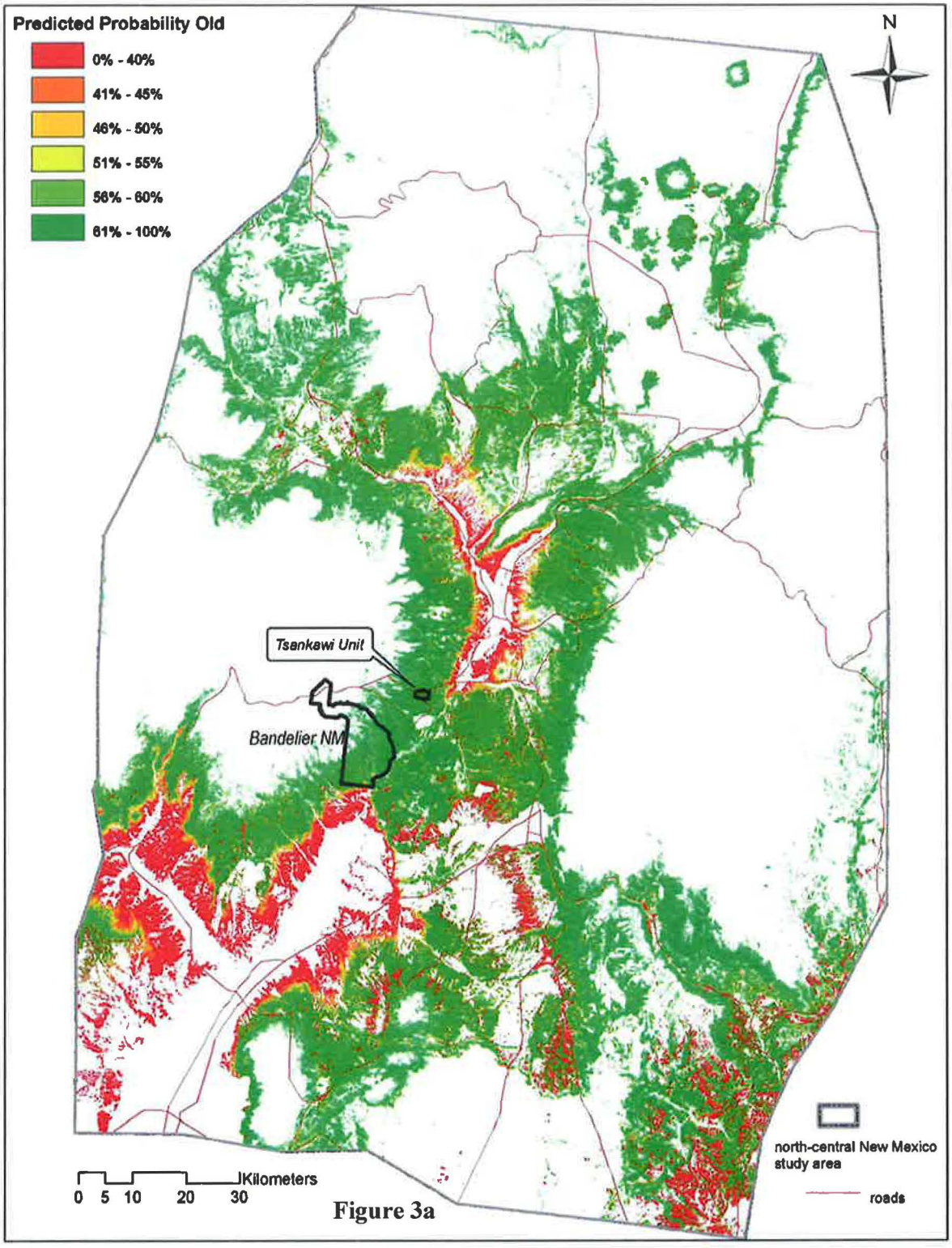

Predicted Probability Old
0% - 40%
41% - 45%
46% - 50%
51% - 55%
56% - 60%
61% - 100%
N
Tsankawi Unit
Bandelier NM
north-central New Mexico study area
roads
0 5 10 20 30
Kilometers

Figure 3a

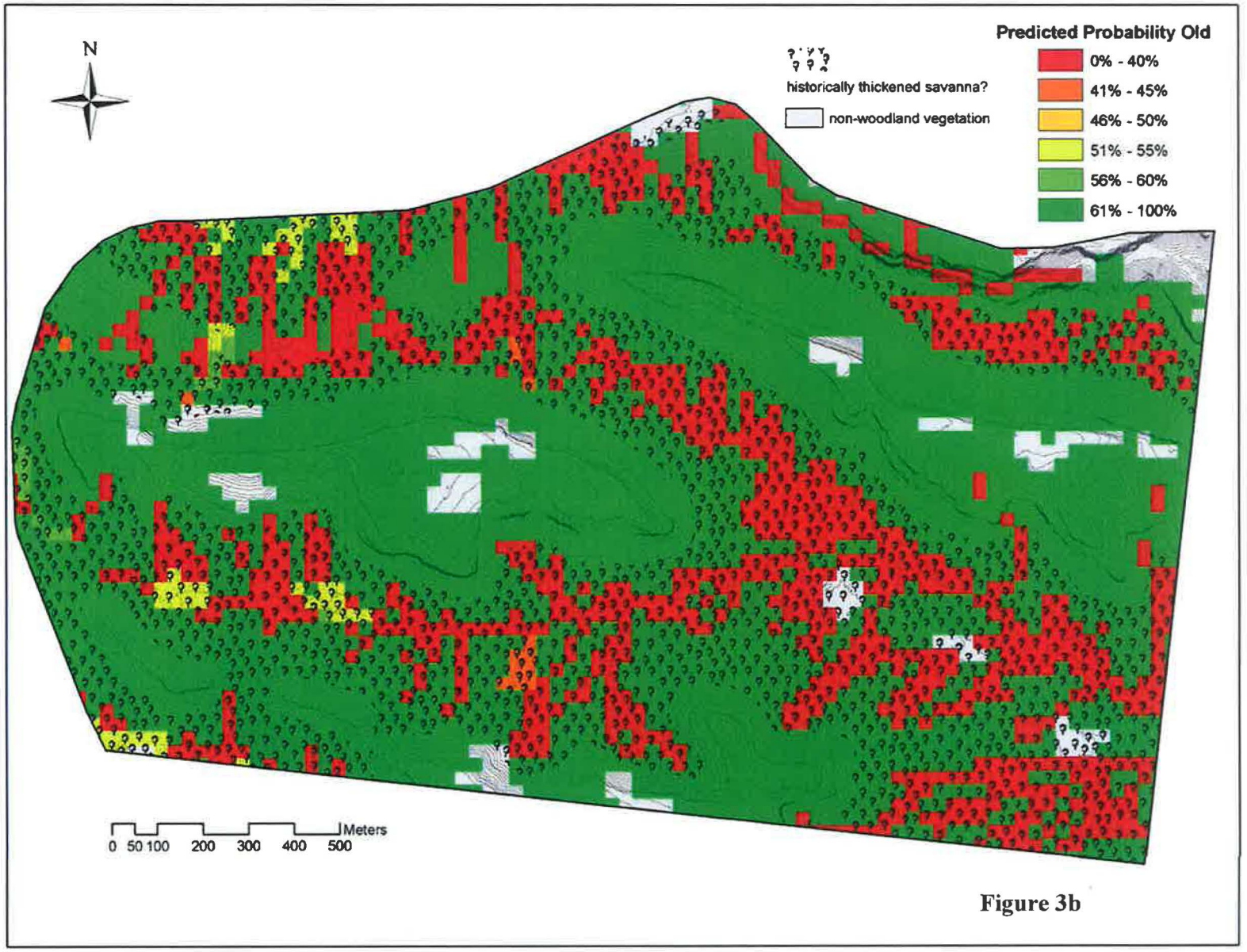

N
Predicted Probability Old
historically thickened savanna?
non-woodland vegetation
0% - 40%
41% - 45%
46% - 50%
51% - 55%
56% - 60%
61% - 100%
0 50 100 200 300 400 500
Meters

Figure 3b

Appendices

Appendix. A table presenting stand level data for fifteen intensive plots sampled within Bandelier National Monument, New Mexico, USA. This table represents an excel spreadsheet with embedded formula which assign a woodland type and pre- vs. post-settlement stand age by applying the diagnostic key criteria to stand level data; a functional copy of the original excel spreadsheet can be found in the Supplemental Digital Appendices: (Appendix.xls).

Intensive Plot Data, Bandelier National Monument, New Mexico, USA

SITE	p1	ring_p1	p2	ring_p2	p3	ring_p3	pinyon-3	R_Age-P	Ring_P-3	OGC-P	j1	ring_j1	j2	ring_j2	j3	ring_j3	juniper-3	R_Age-J	Ring_J-3	OGC_J	SITE	HARVEST	FIRE	DEBRIS	STATUS-P	STATUS-J	STATUS	PERSIST	KEY	TYPE
Conservative pre-settlement thresholds:							*30.0*	*165.8*									*25.0*	*167.3*							POST	POST	POST	POST	7b	Expanding Woodland Types
BAND1	39.5	210.0	28.5	210.0	28.0	174.0	32.0	176.8	198.0	y	46.0		26.5		23.0		31.8	212.7		y	**BAND1**	N	N	Y	PRE	PRE	PRE	PRE	5a	Old Growth Piñon-Juniper Woodland
BAND2	27.5	162.0	27.5	154.0	28.0	168.0	27.7	153.0	161.3	n	30.0		27.0		23.5		26.8	179.5		y	**BAND2**	N	N	Y	POST	PRE	PRE	PRE	6a	Old Growth Juniper Woodland Savanna
BAND3	39.0	185.0	40.0	180.0	42.5	210.0	40.5	223.5	191.7	y	45.0		22.5		20.5		29.3	196.1		y	**BAND3**	Y	Y	N	PRE	PRE	PRE	PRE	5a	Old Growth Piñon-Juniper Woodland
BAND4	38.5	173.0	37.5	196.0	34.0	160.0	36.7	202.5	176.3	y	54.0		28.5		28.0		36.8	246.0		y	**BAND4**	Y	N	Y	PRE	PRE	PRE	PRE	5a	Old Growth Piñon-Juniper Woodland
BAND5	35.5	220.0	32.0	210.0	32.0	220.0	33.2	183.2	216.7	y	30.0		22.0		19.0		23.7	158.4		y	**BAND5**	N	N	N	PRE	PRE	PRE	PRE	5a	Old Growth Piñon-Juniper Woodland
BAND6	38.0	150.0	30.0	180.0	36.0	160.0	34.7	191.5	163.3	y	38.0		35.0		32.0		35.0	233.8		y	**BAND6**	N	Y	N	PRE	PRE	PRE	PRE	5a	Old Growth Piñon-Juniper Woodland
BAND7	27.5	154.0	28.0	168.0	44.5	153.0	33.3	184.2	158.3	y	29.5	201.0	35.0	169.0	38.5	241.0	34.3	229.3	203.7	y	**BAND7**	N	N	Y	PRE	PRE	PRE	PRE	5a	Old Growth Piñon-Juniper Woodland
BAND8	35.0	200.0	33.0	174.0	30.5	157.0	32.8	181.4	177.0	y	29.0	240.0	29.0	173.0	32.0	242.0	30.0	200.5	218.3	y	**BAND8**	Y	Y	N	PRE	PRE	PRE	PRE	5a	Old Growth Piñon-Juniper Woodland
BAND9	37.0	207.0	32.0	202.0	32.0	200.0	33.7	186.0	203.0	y	27.0	145.0	25.0	184.0	23.0	153.0	25.0	167.3	160.7	n	**BAND9**	N	N	Y	PRE	POST	PRE	PRE	4a	Old Growth Piñon Dominated Woodland
BAND10	28.0	185.0	22.0	113.0	18.0	68.0	22.7	125.5	122.0	n	31.0	223.0	29.0	125.0	25.0		28.3	189.4	174.0	y	**BAND10**	N	N	N	POST	PRE	PRE	PRE	6a	Old Growth Juniper Woodland Savanna
BAND11	35.0	164.0	31.5	135.0	29.0	142.0	31.8	175.9	147.0	y	33.0	167.0	27.5	213.0	25.0	124.0	28.5	190.5	168.0	y	**BAND11**	N	N	N	PRE	PRE	PRE	PRE	5a	Old Growth Piñon-Juniper Woodland
BAND12	**30.0**	**164.0**	**27.0**	**111.0**	**26.0**	**175.0**	**27.7**	**153.0**	**150.0**	**n**	**29.0**	**157.0**	**27.0**	**156.0**	**25.0**	**104.0**	**27.0**	**180.6**	**139.0**	**n**	**BAND12**	**N**	**N**	**N**	**POST**	**POST**	**POST**	**POST**	**7b**	**Expanding Woodland Types**
BAND13	25.0	41.0	12.0	42.0	9.0	52.0	15.3	85.3	45.0	n	25.0	86.0	25.0	90.0	24.0	89.0	24.7	165.1	88.3	n	**BAND13**	N	N	N	POST	POST	POST	POST	7b	Expanding Woodland Types
BAND14	23.0	77.0	20.5	77.0	16.5	76.0	20.7	114.6	76.7	n	23.0	91.0	23.0	93.0	24.5	125.0	23.5	157.3	103.0	n	**BAND14**	N	N	N	POST	POST	POST	POST	7b	Expanding Woodland Types
BAND15	**35.0**	**107.0**	**19.0**	**83.0**	**24.0**	**78.0**	**26.0**	**143.9**	**89.3**	**n**	**39.0**	**161.0**	**38.0**	**108.0**	**33.0**	**133.0**	**36.7**	**244.9**	**134.0**	**y**	**BAND15**	**N**	**N**	**N**	**POST**	**PRE**	**PRE**	**PRE**	**6a**	**Old Growth Juniper Woodland Savanna**

DATA HEADER NOTES

p1, p2, p3= 3 largest sampled pinon
ring_p1, 2, 3=regression age of p1, p2, p3
pinon-3=average diameter largest three sampled pinon
Ring_P-3=actual average ring count of three largest diameter pinon
R_Age-P=regression age pinon-3

j1, j2, j3= 3 largest sampled juniper stems
ring_j1, 2, 3=regression age of j1, p2, p3
juniper-3=average diameter largest three sampled juniper stems
Ring_J-3=actual average ring count of three largest diameter juniper stems
R_Age-J=regression age juniper-3

OGC-J=old growth characteristics juniper
OGC-P=old growth characteristics pinyon

Fire=historic fire evidence
Debris=large woody debris
Harvest=historic cutting evidence

Diameter-Age Regressions

Colorado Piñon Age = 5.49 * Diameter (n=264) p<.0001
One-seed juniper Age = 6.65 * Diameter (n=398) p<.0001

Note: r-squared values cannot be used to evaluate performance of no-intercept models

Classification Header Notes

Status-P=pre- vs. post-settlement status based on ring age-P and OGC-P
Status-J=pre- vs. post-settlement status based on ring age-J and OGC-J
Status=pre- vs. post-settlement stand status based on older of Status-P or Status-J components
Persist=updates stand status on basis of fire or historic harvest disturbance evidence
Key=number/letter of assigned PJ type in diagnostic key
Type=PJ type name in diagnostic key

Classification Results

13 of 15 plots were corrected classifed
(BAND12 was misclassified as POST 'young')
(BAND15 was misclassifed as PRE 'old')

Note: see text for additional discussion of classification results

PART IV

Regional scale modeling of southwestern U.S. piñon-juniper woodlands: predictive mapping of "old" versus "young" stands in the Four-Corner states

Abstract

Predictive modeling and mapping of "old" versus "young" piñon-juniper stand-age was conducted in southwestern U.S woodlands characterized by *Pinus edulis* and three associated junipers (*Juniperus osteosperma*, *J. monosperma*, *J. scopulorum*) within the Four Corners states (i.e., Arizona, Colorado, New Mexico, and Utah). Extensive samples collected across the four state region provided inputs for spatial modeling with each field point assigned an "old" versus "young" stand-age using a diagnostic field key previously developed (Chapter 3). Sample points were associated with a suite of relevant topographic, edaphic, and climatic variables within a GIS, and the compiled regional dataset used for model development with a piece-wise linear regression program. Selected models were implemented within a GIS and probabilities of "old" (versus "young") stands calculated for extant, Southern Rocky Mountain (SRM) and Colorado Plateau (CP), woodland communities recently mapped by the Southwest Regional Gap Analysis Project (SWReGAP). Map products depict color coded probabilities of stand-age and provide a visual means for assessing the relative magnitude and extent of woodland expansion patterns across the Four Corners states. Our regional scale models, developed using piece-wise linear regression procedures and a regional dataset, are generally consistent with previous models (Chapter 3), using logistic regression and a local dataset, when compared within the same north-central New Mexico extent. The regional models continue to suggest a strong association of "young", post-settlement expansion stands with productive, depositional settings, but also highlight the association of expanding woodlands with seasonal moisture (i.e. monsoonal) patterns. Modeling at more heterogeneous regional scales, with a greater variety of woodland types, and topographic, edaphic, and climatic settings, required the use of non-parametric procedures and more complicated models in order to obtain acceptable levels of predictive

accuracy. In well sampled areas, map realizations can be used to visually evaluate model assumptions at landscape scales, including choice and weighting of individual predictors, adequacy of the training sample, and whether standard measures of predictive model accuracy are consistently reliable indicators of real world performance.

Introduction

Southwestern US piñon-juniper woodlands are poorly understood ecological systems and present significant challenges to both researchers and managers (Gottfried et. al., 1995; Tausch, 1999). Colorado piñon pine (*Pinus edulis*) and several associated species of non-sprouting juniper (One-seed, *Juniperus monosperma*; Utah, *J. osteosperma*, and Rocky Mountain, *J. scopulorum*) are broadly distributed across the Four Corners states (i.e., Arizona, Colorado, New Mexico, and Utah) of the American southwest. The distributions of these woodland tree species were mapped by Little (1971) and community level coverage was recently developed by the Southwest Regional Gap Analysis Project (SWReGAP; Comer et. al., 2003, 2004; Lowry et. al., 2005). Differing interpretations of post-Euro American settlement dynamics in these woodlands, particularly in the aftermath of widespread and indiscriminate type conversion of woodlands for forage production, has sometimes limited even appropriate management efforts designed to improve watershed, wildlife, and range conditions on productive sites, and mitigate impending wildfire hazards. Conversely, old growth woodlands now embedded within "younger" post-settlement stands are increasingly vulnerable to both crown fire and indiscriminate restoration (Romme et. al., 2003).

Increasing application of geospatial analysis, including predictive modeling techniques, to address ecological questions has been facilitated by enhancement of PC based (statistical and GIS) software, and availability of high resolution spatial datasets, allowing even field oriented biologists with little prior modeling experience to utilize these powerful tools (Franklin, 1995). However the complex interactions of (biotic and physical) process and structure, at different spatial and temporal scales, may not be amenable to standard linear models (Wagner and Fortin, 2005). We use a piece-wise linear modeling approach Multivariate Adaptive Regression Splines (MARS) developed by Friedman (1991) to predictively model relationships between environmental factors and distribution of "old" (i.e., pre-settlement) woodlands versus "younger" stands of more recent (i.e., post-settlement origin) in a study area defined by the range of *Pinus edulis* and associated juniper species within the Four Corners states of the southwestern U.S. Predictive models were developed using a regional database where sampled stands are assigned a pre- versus post-settlement age using a diagnostic key previously developed (Chapter 3) and associated with a suite of environmental parameters within a GIS. Map realizations of selected models present the predicted probability of "old" woodland using the SWReGAP woodland coverage as an analysis mask.

Several authors note that a sound ecological understanding of the system being modeled is as critical to credible model outputs as the particular statistical approach employed (Austin et. al., 2000; Wagner and Fortin, 2005). The logistic method used for model development within the north-central New Mexico extent (Chapter 3) was easily implemented, parameters were interpretable ecologically, and predictive accuracy was high even with relatively small training datasets. However, logistic procedures and global models are likely to have less utility at larger

regional extents where there is greater range and variability in environmental controls and changes in the dominant woodland species. One approach would be to model a series of smaller extents for which woodland type and/ or dominant environmental parameters remain within some defined boundaries. For example, model extents could be constrained by the range of Southern Rocky Mountain (SRM) versus Colorado Plateau (CP) woodlands (as mapped by SWReGAP, or limited to areas having summer (versus winter) moisture patterns. However, there are only a limited number of discrete extents which could be defined in this way, and while these may increase accuracy (by reducing variability) they can also limit the scope and applications of the resulting models. In addition, there will likely always be additional confounding (known and measured, or unknown and/ or unmeasured) factors present within these smaller extents. In addition, interactions between explanatory variables may exhibit threshold or non-linear relationships and these effects may occur at any spatial scale. Given our experience with logistic modeling within the north-central New Mexico extent, and the apparent relationship of seasonal precipitation patterns to the ranges of one-seed and Utah juniper, we anticipated that global parametric modeling approaches would be insufficient to accurately predict the complexity of regional scale patterns. After a review of easily implemented non-parametric modeling options, we elected to employ a piece-wise linear regression approach (i.e., MARS) that could accommodate local or asymmetric relationships among and between predictor and response variables (Muñoz, and Felicísimo, 2004). In particular, Leatherwick et al (2005) report that since MARS allows interactions between variables to be fit locally within specified sub-ranges of the variables, this method can effectively capture complex, non-linear patterns while preserving model interpretability.

Methods

We follow the general methods presented earlier in Chapter 3 and only highlight notable additions or changes to those procedures. In particular, given the large geographic extent of our study area, extensive sampling was more dispersed and sampling was predominantly conducted along public right-of-ways across a great variety of public and private, state, federal, and tribal ownerships. In addition, at locations with multiple landforms, we created two or more virtual points by assigning apparent stand-age and topographic setting to projected points (i.e. visually evaluated and assigned geographic coordinates) where we were confident of our interpretation of woodland stand-age and could readily identify the associated landform. We calibrated our diagnostic key (Table 1 in Chapter 3) for use in different climatic zones, primarily by adjusting estimates for pre- versus post-settlement aged tree diameter thresholds on the basis of sampled core data from piñon; some qualitative criteria such as lichen growth on dead wood were not reliable old growth indicators in strongly monsoonal areas. Additional potential environmental predictors were identified, developed and / or evaluated, while others previously used were modified or dropped. We also added variables for which we had only coarse scale coverage not suitable for modeling within smaller extents. Perhaps the most important change in regional scale modeling is the use of a non-parametric modeling technique which allowed for inclusion of more local and non-linear effects. The outputs from the non-parametric model were subsequently refit using a logistic procedure and implemented within a GIS to realize map products as before.

To support modeling efforts we developed a regional dataset (Digital Archive) with 1129 observations representing individual woodland stands (represented by *Pinus edulis* and three associated junipers (*Juniperus osteosperma, J. monosperma, J. scopulorum*) and mapped by

SWReGAP as Southern Rocky Mountain (SRM) and Colorado Plateau (CP) savanna and woodland types) from across the Four Corners States (Fig xxx) and assigned an "old" or "young" stand-age using the diagnostic key criteria. The distribution of "old" vs. "young" stands relative to potentially important environmental factors such as landform, depositional setting, and soil-geologic substrate are provided in Tables 1a,b. Intensive plot samples from three National Park Service units and extensive samples collected previously for modeling within the north-central New Mexico extent are included in the regional dataset.

The compiled regional dataset samples a geographic extent encompassing the range of *Pinus edulis* within the Four Corners states (Figure 1). Fieldwork was conducted over the course of four field seasons from 2004 to 2007, but the majority of extensive samples for regional modeling were collected during the final two field seasons (2006-2007). Fieldwork during the initial two seasons (2004-2005) emphasized collection of intensive samples from woodlands within three southwestern U.S. national park units (Colorado National Monument, Mesa Verde National Park, and Bandelier National Monument) along a presumed seasonal moisture gradient. These intensive data were used to facilitate development of a diagnostic key for assignment of pre- versus post-settlement stand-ages to extensive regional sample points collected subsequently. Our use of the diagnostic key and qualitative criteria was tailored to different climatic regions primarily through collection and dating of piñon tree cores from selected extensive sample locations (Digital Archive). While our core data were too limited to support development of diameter to age regressions for any specific locale, they were adequate to inform calibration of our diagnostic key at a sub-regional scale. For example, cores from the strongly monsoonal Lincoln County, NM area suggested extremely rapid rates of tree growth, while trees

sampled in winter moisture dominated areas of northwestern CO, central AZ, and southeastern UT often displayed relatively slow growth. The effects of depositional environment on apparent tree age were most pronounced in areas with median monsoonal patterns such as north-central NM. In bimodal and winter moisture areas depositional environments increasingly supported non-woodland (shrub and grass dominated) vegetation across abrupt ecotonal boundaries at lower elevations; however depositional settings in winter moisture areas can also support old growth woodland in some higher elevation, mesic settings. Chapter 3 provides additional discussion of this topic.

General procedures for development of the explanatory variable spatial coverage are detailed in Chapter 3 and we discuss only notable differences in methods used for modeling at the regional extent. For regional scale modeling we developed a potential set of 25 explanatory variables for which we were able to procure or develop suitable spatial datasets. We used higher resolution PRISM climate data (400m grid resolution) which recently became available for modeling the regional extent, as compared with the 2-km grid resolution PRISM climate data originally used for the north-central New Mexico study area (Chapter 3). In addition, a geologic-soils substrate coverage (SWSUBS) compiled from NRCS data by SWReGAP which was too coarse for use with the north-central New Mexico extent was found to be a useful explanatory variable at larger regional scales. We continued to use HILLSHADE as a proxy for solar radiation in our current modeling efforts, although the most recent version of ArcGIS 9.2 (ESRI, 2005) now includes a utility for calculating insolation. However, we found development of an insolation dataset for our regional extent to be too computationally and time intensive, although it would be potentially useful to evaluate the statistical relationship of HILLSHADE to solar radiation. We added

metrics of aspect, (ASPECT), curvature (CURVATURE) and plan profile (PRO_FILE) to our potential suite of predictors, including a categorical version of profile (PROFILE) where 1 = concave profiles with values <0, and 0 = convex profiles with values ≥0. ASPECT was a categorical metric (with 9 classes) condensed from a continuous (0 to 360 degree) aspect coverage. We also developed and evaluated various metrics of surface roughness or topographic breaks (calculated as the standard deviation and / or maximum range of elevation, slope, and/ or aspect values within the surrounding eight cell neighborhood) to be used a proxy for fine fuel continuity and fire propagation potential and therefore delineate fire safe sites. However, these surface roughness metrics were dropped during the evaluation stage and prior to final modeling efforts. To facilitate computational development of spatial coverage (and subsequent spatial analysis) within A GIS, the Four Corners state (regional) extent was functionally broken down into ten sub-extents as defined by the base DEM 30-m resolution digital elevation data (each sub-extent spans two degrees of latitude and six degrees longitude). For calculation of HILLSHADE we used the center point of each DEM area to estimate solar parameters, and the summer or winter solstice (@ 1300 hours) to represent $\text{HILLSHADE}_{(\text{maximum})}$ and $\text{HILLSHADE}_{(\text{minimum})}$, respectively.

Inherent positional error associated with GIS coverage and GPS locations required some post-processing of sample points. Prior to modeling, we verified that landform (FORM) and depositional environment (FLOW) coverage associated with each sample's GPS location corresponded to what had been observed in the field. Some points were simply moved into the appropriate landform and/ or flow settings when it was immediately adjacent to the GPS location; in other instances we also added points to represent the broader range of observed

settings documented by our photos and field notes and where we were highly confident of both the appropriate setting and corresponding stand-age. Stand-age assignments made in the field were subsequently reviewed for consistent application of diagnostic criteria on basis of field data, associated notes, and photos. Values from each of the 25 data layers were extracted with the sample utility in ArcGIS 9.1 (ESRI, 2005) using the coordinates of 1129 sample points and subsequently exported to a excel spreadsheet.

A standard logistic program (SAS, 2005) was initially used to model the regional dataset using the same basic approach as detailed in Chapter 3 and a comparable set of potential predictor variables. Logistic modeling and development of a global parametric model provided useful benchmarks for both predictive model accuracy and relative importance of explanatory variables at regional extents. Subsequently we employed a local, non-parametric approach to develop a regional model using a piece-wise linear regression procedure (i.e, MARS). We use the version of MARS developed and licensed by Salford Systems, San Diego, CA. When modeling a binomial response, MARS outputs need to be refit using a generalized linear model in order to constrain the range of values to those appropriate for a binomial response (Friedman, 1991); we refit outputs from MARS using the SAS 9.1 (SAS, 2005) logistic procedure to impose a 0 to 1 probability range.

In order to gain confidence and expertise with the piece-wise linear approach and MARS software, we initially developed MARS models within the north-central New Mexico extent using the dataset developed for logistic modeling (Chapter 3). Our earlier logistic modeling efforts provided a sound foundation for understanding how MARS handled the same data and

whether MARS outputs were equivalent or superior at detecting and predicting relevant landscape patterns with the available data. An untransformed MARS model is nearly equivalent to a linear model since each predictor can have only a single (global) slope. Allowing transformation of variables effectively enables MARS to partition individual variables into two or more segments or base functions (encompassing a discrete range of values for that variable), and assign each a different (local) slope. With the addition of interactions between and among variables (and variable segments or base functions) MARS can essentially model local effects between discrete ranges of one or more variables. This is a very powerful and intuitive approach to modeling ecological systems where non-linear and threshold interactions between important environment factors are likely the norm and we could expect a flexible non-parametric model to be somewhat better at capturing these underlying complexities. Leatherwick et al (2005; 2006) provide an excellent overview of the piece-wise linear modeling approach including a tangible regional scale application of MARS using an R-code version of the software. The creation of base functions by MARS extends the development of potential explanatory metrics by partitioning out local effects and interactions while a subsequent pruning phase allows the final model to retain only the most important base function predictors.

Within MARS one can set various modeling parameters including: pool of available predictors (and whether continuous or categorical in nature), allowance for transformation of variables, permitting interactions between variables (and setting maximum levels), specification of allowable numbers of base functions, minimum number of observations between knots, speed and accuracy of modeling, and degrees of freedom charged per base function. In our modeling efforts we started with default program settings and those most comparable to a general linear

model, then successively altered one or model parameters to assess its effect on the model building process. We initially built simple models directly comparable to logistic models using the smaller dataset from the north-central New Mexico extent and then progressed to more complex models by first allowing transformations and then successively higher orders of interaction. Allowing higher levels of interaction required increasingly higher numbers of base functions, although final model selection involves a pruning process (best model option) or the modeler can also manually select a lower performance model from a full range of model outputs (all model option). We generally used the all model option and selected models which combined the lowest number of base functions with the highest performance; this selection was facilitated by a line graph plotting number of base functions by model performance which highlighted the relative cost-benefit relationship.

Within SAS, MARS base functions are calculated from the raw predictor variables using the code output from the MARS modeling run and the logistic procedure implements the MARS model. In addition to having the individual probabilities adjusted for a binary response, the SAS logistic procedure also allows for the easy computation of leave one out cross validated (LOOCV) individual probabilities, and cross validated area under the curve (AUC) receiver operator characteristics (ROC) values for robust evaluation of model performance as described in Chapter 3.

We refit our MARS model outputs using the logistic procedure in SAS 9.1 (SAS, 2005) which provided options for generating a range of model diagnostics including classification tables, and supports calculation of LOOCV individual probabilities and AUC ROC values for robust model

evaluation. Given our prior experience showing comparable model performance based on LOOCV probabilities and LOO AUC ROC values for the full versus a split training / test dataset, we elected to use the entire regional dataset (minus one point at a time) using the LOOCV approach to conduct and evaluate our regional modeling efforts. Logistic model parameter outputs (intercept and partial slopes for each basis function) were then used to implement the MARS model within ArcGIS 9.1 (ESRI, 2005) using the raster calculator utility. When implementing a MARS model in a GIS, a new raster corresponding to each basis function needs to be calculated; since some basis functions may represent second or third order interactions of explanatory variables and there is no requirement that all of interacting variables be retained as primary effects in the final model, the number of new rasters which need to be generated can exceed the number of basis functions. Degrees of freedom (df) reported for MARS models refit using the logistic procedure are equivalent to the number of base functions included in the final model; the number of explanatory variables used (not including classes of categorical variables) is typically the same or fewer. Models with higher order interactions generally have a number of component base functions (i.e., which contributed to the development of the retained base functions) excluded from the final model. Computationally, implementation of complex MARS models within a GIS can be very intensive using a standard windows based computer platform, especially with large numbers of predictors and across broad spatial extents. Given our somewhat limited computational resources, we limited implementation and map realization to MARS models with 16 or fewer base functions, although the basic procedure would be the same for implementing models of any complexity. Implementation of the final model including development of map products was accomplished at the sub-extent (i.e., individual DEM areas) scale with the final map products for the entire region subsequently stitched together. The

display of regional scale map products within a GIS (using nearest neighbor re-sampling) with component outputs compiled from the individual DEM sub-extents can result in a systematic shift of ca. 15-30m which is enough to bump individual points sitting close to edges, across mapped probability boundaries. A comparable issue addressed earlier is the inherent error in both the GPS locations (of sampled points) and or mismatch with associated environmental coverage in a GIS, both which can create problems for the correct classification of individual points. While these effects do not impact the mapped probability patterns, they make it appear that the mapped probability for selected points differs from the actual values calculated during modeling. Another potential source of predictive model error is the mismatch between the scale of field observations (i.e., of stand-age relative to local topo-edaphic patterns) and the resolution of available coverage for environmental variables within a GIS. For example, using coarse resolution DEM coverage, a fine scale rocky mosaic interspersed with depositional settings (which could in turn support a mosaic of "old" and "young") would not incorporate fine scale topographic influences or predict a mosaic of "old" and "young". However, higher resolution coverage is not always better since the most appropriate scales for modeling can vary by predictor or for interactions among different predictors.

Results

A series of MARS models of increasing accuracy and complexity were generated using the dataset (n = 210) previously prepared for logistic modeling (Chapter 3) within the north-central New Mexico extent in (Table 2). A baseline MARS model was developed for direct comparison to the full logistic model by initially restricting model development to the same four predictor variables (FLOW, FORM, EWP, DEM) used previously and not allowing explanatory variables

to be transformed (i.e., maintaining a global model) or interact. This baseline, untransformed MARS model (BASE MARS) provided comparable results to the full logistic model, using all 4 explanatory variables and with a LOO AUC ROC value of $c = 0.938$ ($df = 4$); at a probability cutoff of 0.50 the model correctly assigned 90.0% of samples with a sensitivity of 93.8% and a specificity of 81.3%. The full logistic model (Full) had a LOO AUC ROC value of $c = 0.932$ ($df = 6$) and correctly assigned 89.5% of samples at a 0.45 probability cutoff with a sensitivity of 93.2% and a specificity of 81.3%. A low-range MARS model (MARS LR) was developed by limiting potential explanatory variables to the same four used by the full logistic model, but now allowing both transformations and interactions. The MARS LR model showed a slightly improved performance over the BASE MARS model with a LOO AUC ROC value of $c = 0.948$ ($df = 3$); at a probability cutoff of 0.44 the model correctly assigned 90.5% of samples with a sensitivity of 92.5% and a specificity of 85.9%. Additional MARS modeling was conducted using a dataset with 12 potential predictors, the core set of explanatory variables previously used for logistic modeling of the north-central New Mexico extent (Chapter 3). A mid-range MARS model (MARS MR) using 9 explanatory variables provided a LOO AUC ROC value of $c = 0.976$ ($df = 8$); at a probability cutoff of 0.62 the model correctly assigned 93.8% of samples with a sensitivity of 93.8% and specificity of 93.8%. A high-range MARS model (MARS HR) generated to explore the upper limits of measured predictive success using the available explanatory variables, although likely at the expense of being over fit. The MARS HR model used 10 explanatory variables and provided a LOO AUC ROC values of $c = 0.984$ ($df = 12$); at a probability cutoff of 0.50 the model correctly assigned 96.2% of samples with a sensitivity of 97.9% and a specificity of 92.2%.

A range of alternative regional models was developed using the entire regional dataset (n = 1129) and beginning with a baseline (global parametric) logistic model and followed by a series of piece-wise linear (local, non-parametric) models with increasing accuracy, but typically at the expense of additional variables and complexity (Table 3a). The baseline logistic model (BASE LOGISTIC) used 13 explanatory variables and provided a LOO AUC ROC value of c = 0.876 (df = 24); at a probability cutoff of 0.64 the model correctly assigned 80.8% of samples with a sensitivity of 81.0% and specificity of 80.3%. Similar to the logistic model developed for the north-central New Mexico area, the regional model selected metrics of landform (FORM), depositional environment (FLOW and PROFILE), elevation (DEM), seasonal precipitation (MONSOON, MAPS, MAPW), and seasonal temperature / sun exposure (TMEANS, TMEANW, HILLSHADE) as important explanatory variables for predicting "old" versus "young" stands, but also included soil-geologic substrate (a coarse resolution predictor which was not suitable for use within the smaller north-central New Mexico extent). A logistic (global) model was developed to provide a baseline for subsequent development of MARS (local) models using the piece-wise linear regression procedure; the logistic model used 13 explanatory variables and provided a LOO AUC ROC of c = 0.876 (df = 24); at a probability cutoff of 0.64 the model correctly assigned 80.8% of samples with a sensitivity of 81.0% and a specificity of 80.3%.

A low-end MARS model (MARS 001) using 5 explanatory variables provided a LOO AUC ROC value of c = 0.870 (df = 5); at a probability cutoff of 0.66 the model correctly assigned 80.2% of samples with a sensitivity of 79.9% and specificity of 80.8%. An enhanced low-end MARS model (MARS 002) using 8 explanatory variables provided a LOO AUC ROC value of c

= 0.886 (df = 8); at a probability cutoff of 0.58 the model correctly assigned 84.2% of samples with a sensitivity of 86.4% and specificity of 80.3%. A slightly more complex MARS model (MARS 003) using 8 explanatory variables and one additional base function provided a LOO AUC ROC value of c = 0.894 (df = 9); at a probability cutoff of 0.64 the model correctly assigned 84.2% of samples with a sensitivity of 86.4% and specificity of 80.3%. A mid-range MARS model (MARS 004) using 11 explanatory variables provided a LOO AUC ROC value of c = 0.903 (df = 12); at a probability cutoff of 0.58 the model correctly assigned 85.7% of samples with a sensitivity of 88.6% and specificity of 80.3%. An alternative mid-range MARS model (MARS REGION) selected for subsequent map realization used 12 explanatory variables provided a LOO AUC ROC value of c = 0.900 (df = 13); at a probability cutoff of 0.60 the model correctly assigned 84.9% of samples with a sensitivity of 86.7% and specificity of 81.6%. A high-end MARS model (MARS 005) using 13 explanatory variables provided a LOO AUC ROC value of c = 0.919 (df = 16); at a probability cutoff of 0.60 the model correctly assigned 85.9% of samples with a sensitivity of 88.1% and specificity of 82.1%. A max-end MARS model (MARS 006) generated primarily to illustrate the practical upper limits of measured predictive success using the available explanatory variables for this extent used 17 explanatory variables and provided a LOO AUC ROC of c = 0.932 (df = 29); at a probability cutoff of 0.60 the model correctly assigned 86.7% of samples with a sensitivity of 88.2% and specificity of 84.0%.

Additional indicators of model performance were provided by comparison of P-values for individual model parameters (i.e., base functions) in the SAS logistic output (i.e., maximum likelihood estimates). Individual parameters for the selected regional model (df = 13) and lower df models had P-values within the range of $P < 0.0001$ while individual parameters of all higher

end regional models (df = 14 and up) began to exceed that range and indicated inclusion of less significant terms in final models. Although more complex models often have higher measures of accuracy, implementation of these models in a GIS may sometimes produce uneven results when mapped across regional landscapes, and this is one of the rationales for giving preference to models with fewer and only highly significant terms. In addition, where models had generally comparable performance, we preferred those which were more either easily interpreted or that included the range of explanatory variables thought to be most influential (and ecologically relevant) based on prior logistic modeling efforts.

After a review of alternative regional models, including relative complexity and performance, and consistency of map realizations with previous logistic model outputs for the north-central New Mexico extent, we selected one of the mid-range models (MARS REGION) for implementation within a GIS to produce map products for the Four Corner states (Figure 2). In addition to standard measures of model performance and visual map inspection, we found an evaluation of how individual sample points were scored by alternative models to be a tangible approach for interpreting model outcomes at more local scales and for known areas. We also looked at the regional distribution of misclassified points to assess whether the mid-range model performed evenly across geographic locations and woodland types. Misclassified points were uniformly distributed across the entire region, although the false positive ("young" misclassified as "old") rate was slightly higher (and specificity lower) for CP woodland areas (Table 3b). MARS REGION model map realizations for the north-central New Mexico (Figure 3a) and Bandelier National Monument, Tsankawi Unit (Figure 3b) extents are provided for higher resolution of detail. Comparison of the MARS REGION map output with several alternative

MARS models for the same extents (BASE MARS and MARS 002) are presented in Figures 3b,c and 4b,c (see Supplemental Digital Appendices), respectively, as well as to the full logistic model (FULL) developed in Chapter 3. We also present MARS REGION model map realizations for selected NPS units within the Four Corners states to provide examples of how a single regional model is implemented across a variety of topographic-edaphic-climatic settings (Figures 5a-h, Supplemental Digital Appendices).

While woodland type (CP versus SRM) was a potential predictor, it was only included in a few of the more complicated MARS models. Our point by point evaluation of the selected mid-range model (MARS REGION) suggested we might be able to improve predictive performance by splitting the regional dataset using woodland type and modeling each area separately. As noted earlier, this approach can improve accuracy but at the expense of limiting a models scope and applicability. This effort yielded a slightly improved model (MARS SRM) for the SRM woodland area dataset ($n = 552$). The MARS SRM model used 11 explanatory variables and provided a LOO AUC ROC value of $c = 0.931$ ($df = 14$); at a probability cutoff of 0.65 the model correctly assigned 87.1% of samples with a sensitivity of 87.1% and specificity of 87.6%. In contrast, the regional model (MARS REGION) continued to provide the best predictive outcomes for the CP woodland area dataset ($n = 577$); a specificity of 81.6% suggests misclassification of "young" stands in CP woodland areas was a weak spot for the regional model. Results of SRM versus CP woodland area modeling, with SRM woodland area outcomes shown for both the MARS REGION-SRM and MARS SRM models, and estimated performance for a hybrid model (MARS HYBRID) that combines MARS SRM model outcomes with regional model results for CP area (MARS REGION-CP) in comparison to MARS REGION are

presented in Table3b. Map implementation of the MARS SRM model for the north-central New Mexico and Tsankawi Unit extents are presented in Figures 3d and 4d, respectively.

Discussion

Explanatory Predictors

A core group of explanatory predictors was selected by all of the alternative models, with simple, low-range models composed primarily of the core predictors, and more complex, mid-range models distinguished by the addition of one or more predictors to the core group. There was also a core group of base functions that was largely analogous to the core predictor group; the base functions being discrete ranges of the core variables and, where applicable, interactions between. The methods section provides a more complete description of how explanatory variables used in regional modeling were developed. The core group of predictors and in general order of importance included: (1) FLOW (a categorical metric representing soil-water accumulation with two levels: 0 = non-depositional or losing, and 1 = depositional or gaining; (2) EPW (an index of effective winter precipitation); (3) FORM (a categorical metric representing general landforms with six classes: 1 = valley, 2 = swale, 3 = mesa, 4 = terrace, 5 = slope, and 6 = cliff; and (4) EPS (an index of effective summer precipitation). Predictors selected to enhance the core group included: (5) DEM (30-m digital elevation model); (6) SWSUBS (a categorical metric representing general soil-geology types with 10 classes, not including water and unknown; (7) $\text{HILLSHADE}_{(x \text{ and } m)}$ (a surface metric calculated from DEM to represent relative insolation for $\text{summer}_{(x)}$ and $\text{winter}_{(m)}$ seasons); (8) $\text{TMEAN}_{(x \text{ and } m)}$ (mean monthly temperatures for the June to $\text{September}_{(x)}$ and October to $\text{May}_{(m)}$ time periods; (9) $\text{SLOPE}_{(30m \text{ and } 180m)}$ (a surface metric

calculated from DEM representing slope perpendicular to contour in degrees was calculated at two scales using 30m and 180m DEM's); and (10) MAP (mean annual precipitation), MAPS (mean summer precipitation), MAPW (mean winter precipitation). Two additional metrics: (10) ASPECT (a categorical version of aspect in degrees calculated from DEM with 9 classes); and (11) MONSOON (a relative index of growing season moisture) were only included in the more complicated regional models (as well as by a model developed for the SRM woodland extent) because they were likely collinear with other effects like HILLSHADE, MAPS, and MAPW. Jensen et al. (2001) suggest environmental variables considered for inclusion in a predictive vegetation model should be tested at various spatial scales, with the resolution of the mapped response ideally several times coarser than the variables used to predict it. The relative importance of individual explanatory variables, and the respective resolution of these data, can influence the minimum scale at which predicted responses can be meaningfully interpreted. Thus, minimum map units of predicted vegetation response may need to be determined post-modeling, in combination with the resolution or scale of important predictors.

Concepts of Scale

Scale is a useful concept in ecology and generally references discrete units of time or space at which processes, patterns, or interactions are thought to occur. However, scale is fundamentally continuous and discrete units are more a matter of convention or practicality. Even so, within the continuum there are real discontinuities which matter at least from an ecological standpoint. For example time can be associated with discrete weather or landuse patterns and space with abrupt topographic breaks. However, what constitutes large versus small scale, discrete versus continuous phenomenon, and what criteria or boundaries should used to make these distinctions

lacks any general consensus. Most would consider climate to be a large scale phenomenon, but the individual raindrops and lighting strikes associated with a weather pattern would likely be considered small or local scale effects. In a real sense there are many things which are simultaneously occurring or having effects across both large and small scales, with interactions and feedbacks across these multiple scales. Effects of historic grazing occurred at local scales, but historic grazing happened regionally within discrete time periods and promoted by a national land settlement program. Measurements of runoff and sediment transport are notoriously scale dependent, but the important scales to the runoff or sedimentation processes may be related to intrinsic properties of water and specific soils, substrates and landforms. A lighting ignition could be a small scale local outcome of regional weather patterns; likewise the potential for fire spread from a point ignition may be linked to regional climate and associated vegetation patterns, but impacted by local weather conditions as well as regional land management practices being implemented differentially at local scales.

Related to scale is the concept of an edge, threshold, or temporally discrete effect where patterns or processes change abruptly across a discrete spatial or temporal boundary. Remote sensing can potentially provide high quality datasets at multiple spatial and temporal scales for a range of parameters. However, we are often limited by what data are easily available at particular spatial scales and for specific timeframes within our study areas and for parameters of interest. Realistically we are also often limited by cost and computing power when developing high resolution models for large spatial extents. Curvature might be an important predictor of available soil moisture or relative soil depth when calculated at an appropriate neighborhood size. Likewise drainage cuts or canyon rims might be important topographic breaks relative to surface fire spread, but modeling these features may require sub-meter resolution elevation data

or proxies derived from these surface data (e.g., standard deviations of elevation, slope, and aspect within small neighborhoods) for delineating relevant boundaries in a GIS. Curvature parameters and the delineation of fine scale topographic features will be influenced by the resolution of the surface data they are developed from, and will yield variable model results depending on whether the process or pattern of interest is appropriately matched to the scale of the data. Coarse resolution spatial data may blur important boundaries, with a canyon rim edge hidden within a steep slope that is averaged across the adjacent mesa and cliff. A deep drainage cut may become a gentle swale when averaged across the adjacent valley cells. Distinguishing the thickening or infill of existing woodlands from an expansion into non-woodland types requires careful attention to scale concepts as well as clear definition of terms and assumptions. We suggest infill and thickening occur on similar topo-edaphic settings proximal to existing woodland, while expansion is distal to "older" stands and into a fundamentally different topo-edaphic context.

Predictive models are limited both by the available data and its resolution, as well as the appropriate matching of data resolution to the process or pattern of interest. Initial evaluation of available datasets and resolutions for representation and predictive modeling of ecosystem patterns and processes is best accomplished within small spatial extents within the larger area of interest. This approach also allows for construction and evaluation of potential proxies to represent poorly delineated features (i.e., canyon rims) or unmeasured parameters (soil moisture and soil depth) which might be important for predictive modeling, for example where these parameters influence soil-water accumulation or constrain propagation of a disturbance process.

Map Implementation

Implementation of selected MARS models in a GIS and generation of map products provided for visual inspection of model predictions at landscape scales. In addition to measures of model performance, it is instructive to evaluate map realizations to assess how the model predictions are implemented at landscape scales both in known or well sampled areas and in less known or poorly sampled settings. We initially evaluated our alternative regional model map outputs for the well sampled and previously modeled north-central New Mexico extent, and compared predicted patterns to those generated using the smaller north-central New Mexico dataset (using both logistic and MARS models). This provided us with a well known landscape context within which we could critique and interpret alternative regional scale map predictions, ultimately selecting a few to implement across the entire regional extent. Each model attempts to provide a best fit of the training points to a predictive relationship given the various constraints imposed during model development, and each can be expected have varying levels of success as measured by model performance and inferred from visual map assessments. However, quantitative model performance is not always a reliable indicator of how well map predictions will track actual landscape patterns, and we attribute this discrepancy to a combination of factors. Over fitting or increasing local model performance at the expense of global relationships can reduce the accuracy of map outputs when models are extrapolated beyond the range of conditions used to train the model (amplifying poorly characterized effects through the modeling and mapping process) or where the training dataset does not adequately represent the spatial extent and variability of modeled landscape settings. While even the best models can only represent a partial truth, even relatively simple and low performance models may provide useful insights. Our low end models highlight the selection of core explanatory variables by all models, which

are enhanced by additional variables and interactions in the increasingly complex and more accurate higher end models. However our mid to low-end models appear to provide the most realistic landscape scale patterns, to the degree that they correspond with our knowledge of woodland age structures within selected map areas.

While field validation of map products is beyond the scope of this study, response class groupings for visualization of map products follow probability cutoffs values which maximize model performance and allow for a cursory assessment of map predictions at various scales. As MARS models become more complex in an attempt to fit a model to the data, they can degrade or swamp signals from the more basic environment controls important in the distribution of "old" versus "young" woodland. At some point then the models are over-fit and the idiosyncratic signals generated by fitting rare outliers or poorly sampled settings generate a model which has higher predictive performance, but produces map products which appear to deviate in notable ways from observed patterns. For example a mid- to high-range ($df = 16$) regional MARS model appears to erroneously over predict "young" woodland on north facing aspects with the north-central New Mexico area, an effect which is contrary to observed patterns (usually north aspects will support "older" woodland relative to south aspects) and given the complexity of the model, it is hard to interpret the source of this mapping artifact. In another instance, the model developed for the SRM woodland area ($df = 14$) combines aspect with selected substrates, and predicts an increased probability of "young" woodland on east facing aspects with the likelihood increasing below $slopes_{(180)}$ of 3.5 degrees; whether this is a real effect or artifact of the model would require field validation of predicted points. Preliminary efforts to split the regional dataset into training and test components as an alternative modeling approach to address some of these

issues did not produce materially better results, and to the degree that model inputs are a limiting factor in constructing a fully adequate model, supported our decision to employ the entire dataset in model development. Given this experience we have tended to be conservative in our selection of the best or optimal model, preferring the lower end models with fewer and more basic explanatory variables despite lower measures of accuracy, and to place a greater reliance on visual inspection of map outputs in evaluating actual model performance. Given that the MARS outputs generated for the north-central New Mexico extent (using the smaller dataset originally created for logistic modeling of that extent) was comparable or better than the logistic model, our experience at the regional scale may be largely a sampling problem that could be remedied by enhanced sample numbers or targeted at under sampled environmental settings. However, we were able to improve results somewhat by modeling separately within the SRM woodland extent, while retaining the regional model outputs for CP woodland areas; this hybrid model provides a somewhat improved version of the final map product.

As noted in Chapter 3, the SWReGAP coverage generally mapped lower density, and often "younger" (<50 years) woodland, as non-woodland types. For example, in one portion of Wupaki National Monument shown (by SWReGAP) to have only a light scattering of woodland, we observed an expansive distribution of "younger" one-seed juniper, with scattered "older" stands, although this difference in part reflects our use of a lower threshold (i.e., 5% canopy cover) for delineating woodland from grass or shrub dominated types. SWReGAP also incorrectly mapped some lower elevation ponderosa pine or mixed conifer as woodland, and vice versa, while we observed some non-tree (i.e., grass and shrub) vegetation classified as woodland. Therefore, in some locations our estimated acreage of "younger", post-settlement aged woodland

(using SWReGAP coverage as an analysis mask) may be under represented and conversely the acreage of "older" woodland may be sometimes be over represented. Alternatively, in some locations (i.e., Colorado National Monument and Mesa Verde National Park in Colorado) the predictive maps show young woodland along secondary drainages in upland settings; in our experience these settings are mostly narrow non-woodland (shrub dominated) drainages or swales embedded in older growth woodlands and thus in this instance the analysis mask is highlighting settings with a potential (although often unrealized) to support young woodland. One option available for National Park Service units is to use the vegetation maps being developed for these units as a higher resolution analysis mask. In spite of these limitations, we found the SWReGAP vegetation coverage, along with the ancillary landform and soil-geologic substrate layers developed the same group, to be extremely valuable geospatial datasets and essential tools for conducting regional scale research within the southwestern U.S.

System Dynamics, Fire Disturbance, Succession, and Management Implications

Woodland vegetation is dynamic and positive feedbacks can sometimes mitigate environmental or disturbance constraints. For example, once established woodland vegetation can persist even in strongly depositional settings, if trees effectively suppress understory cover and potential for surface fire or alter hydrologic and soil properties (Schlesinger and Pilmanis, 1998; West and Van Pelt, 1987). Establishment of woodland onto deep soil sites during relatively moist periods, and in the absence of subsequent drought or fire related mortality, may proceed to closed canopy woodland with suppression of understory vegetation. Alternatively, prolonged droughts which limit deep water recharge during early stages of woodland establishment, or where woodlands have colonized settings with argillic horizons that inhibit infiltration and development of deep

root systems, may intensify competitive interactions with established shrub and herbaceous cover (and result in tree mortality). Enhanced growing season moisture may also affect the qualitative appearance (of individual trees and stands), effectively shortening average lifespan, while enhancing decomposition rates and growth of lichens; cumulatively this can present a misleading picture of advanced age in some strongly monsoonal areas. Our regional core samples suggest rapid growth rates during early years in monsoonal climates (perhaps corresponding to favorable establishment windows) versus more uniform growth rates throughout the life of a tree in winter moisture areas. However, suppressed individuals growing under mature nurse trees can be expected to exhibit slow growth rates until released, even under monsoonal influence.

We tend to think of ecological systems, and perhaps most natural or physical systems, in terms of cycles and repeated patterns; the tendency is so strong that we often measure our understanding by the degree to which we can classify the observed patterns and characterize the internal workings. Patterns and cycles, observed at various temporal and spatial scales of observation, are commonly interpreted to be under the control of some process or mechanism. Further, we often expect the processes and mechanisms involved to be the most expedient and efficient, or lacking that, the best solution available within system constraints. In our efforts to understand ecological systems, we often impose a logic and rationale on the system, by identifying key patterns (i.e., plant communities) and processes which both fit into our framework and appear to explain how the system works. However, piñon-juniper woodland systems have not been very amenable to standard classification approaches, and attempts to characterize woodland system dynamics appear to challenge many traditional ecological concepts.

Within their distributional ranges, the local occurrence of piñon and juniper species is commonly interpreted to be a function of favorable edaphic and topographic settings, which provide both sufficient moisture (for establishment and long-term persistence), and protection from surface fire or competitive effects (mediated by understory components). Relaxation of these local controls on occurrence (e.g., fire disturbance and understory competition) through historic grazing practices during the last 150 years is thought to have facilitated expansion of piñon-juniper woodland elements into former grass and shrub dominated communities (Miller and Tausch, 2001). Many piñon-juniper woodlands have also become denser, but the proximal causes (e.g., interruption of surface fire and/ or reduction of understory competitive effects by domestic grazing pressure) typically offered for changes in stand structure are generally unsubstantiated. Moreover, convincing evidence for surface fire disturbance in many piñon-juniper woodlands is often lacking or anecdotal (Baker and Shinneman, 2004). However, surface fire was an important disturbance process in many adjacent grass, shrub, and pine savanna communities, and in this role effectively reinforced woodland boundaries. While some shrub communities likely had longer fire return intervals, these still would have been too short, and the associated fires too severe, for persistence of woodland (Baker, personal communication).

Fire evidence in southwestern woodlands is generally in the form of burned juniper (and occasionally piñon) stumps, logs, and snags (Gottfried et. al., 1995; Baker and Shinneman, 2004; Floyd et. al., 2004, 2008). Piñon pine, Utah, one-seed, and Rocky Mountain juniper are extremely sensitive to fire effects, seldom scarring, and often killed by even moderate fire behavior. There are a number of possible factors (i.e., from thin bark, or susceptibility to disease after injury, flammability of the foliage, and inability to recover from loss of canopy) that might

account for the sensitivity of these species to fire, but the net result of fire disturbance in most instances appears to be high mortality of all age and size classes within burned areas. Individuals that survive fire events may often have simply avoided lethal fire effects (by some combination of chance, discontinuous or insufficient fuels). Juniper remains (charred or not) can persist on many sites for hundreds of years, while piñon usually degrades much more rapidly (Kearns et. al., 2005). Fire scars, recorded by piñon and/ or juniper trees which survived a fire event are infrequent, and woodland trees recording multiple fire events are apparently rare (Baker and Shinneman, 2004). Even when present, scarred trees may sometimes be incidental to the predominant fire pattern, for example located at ecotones with high fire frequency systems like Ponderosa savanna, or reflective an extremely fine, grained and patchy crown fire type behavior (Floyd et. al., 2008). However, the physical record available to interpret past fire events in woodlands might be misleading; low intensity surface fire might not scar or kill larger individuals and thus would leave little or no evidence, while more intense fires which scar surviving trees, or create patches and opening with burnt snags and stumps, and initiate pulsed recruitment of recognizable post-fire cohorts, would appear to be the only mode of fire disturbance.

Successional patterns following crown fire in woodland systems, where herbaceous and / or shrub stages are progressively re-colonized by woodland tree species can vary greatly depending on the nature of the fire (size and intensity which affects survivorship and seed source), climatic patterns, and understory response. Re-establishment of woodland onto burned sites can range from several decades to several hundred years or more, with type conversion to non-woodland types in extreme cases (Floyd et. al., 2004). Given this general pattern of lethal fire effects,

climatic extremes (wet and dry) and associated beetle or disease induced mortality events, along with inter- and intra-specific competitive effects, thus may be more important than previously thought in controlling woodland stand structure (Eisenhart, 2004) through the combined effects of pulsed recruitment, self-thinning, and differential mortality.

Many pre-settlement aged woodland communities, lacking any apparent fire disturbance or for which the return intervals are so long that evidence of the last fire is not discernable, are then apparently structured by the cumulative effects of differential establishment and mortality patterns related to site conditions, time since last disturbance, drought, insect, disease and intra-/inter- competition. An absence of fire is relative to the time period a site has been occupied by woodland; for example, many expansive post-settlement aged woodlands are thought to have developed as a consequence of historic grazing practices, which simultaneously reduced herbaceous competition and surface fuels (across a range of grass, shrub, and pine savanna types), promoting tree establishment while minimizing potential for fire effects lethal to woody plants. There are also many examples of "older", pre-settlement aged woodlands, with little to no fire evidence, that apparently do not require periodic fire disturbance to maintain structural or compositional integrity. Fire disturbance then occurred in some pre-settlement woodland systems, affecting structural and compositional attributes of these communities by creating a matrix of fine scale patches or larger openings and associated successional patterns. In many other pre-settlement status woodlands however, the apparent absence of, or long time interval between, fire disturbance events appears to pose no particular ecological crisis.

Recent paleo-vegetation findings have highlighted the transient and even unique nature of modern plant assemblages relative to those recorded during prior interglacial periods (Betancourt, 1987). Our piñon-juniper woodlands are composed of individual species whose ranges of environmental tolerance overlap at the spatial and temporal scales relevant to our experience. These woodland communities and their associated disturbance regimes, successional patterns, and suites of linked biotic organisms are a tangible ecological entity that researchers can study, the public can appreciate, and agencies can manage. Our research highlights the underlying environmental controls which tend to promote occurrence and persistence of one or more woodland tree species in particular topo-edaphic-climatic settings, but climatic conditions and associated vegetation assemblages are, have been, and always will be a dynamic and (albeit slowly) moving target. The dilemma for land managers is setting appropriate desired future conditions or target communities given this context and the overlay of historic and recent landuse effects. We believe a flexible ecological framework is an essential perspective today given the problematic nature of reconstructing vegetation structure or system process at sufficient levels of resolution or determining whether these would in any event are still relevant for current or future management. Certainly a full understanding of a plant community can only benefit management, but we increasingly believe this information is most useful not for recreating past conditions, but for appreciating the alternative potentials of individual species and sites. A renewed emphasis should be placed on maintaining functionality of ecological systems (and services), with reduced attention to specific structural or compositional targets; moreover, ecological process including disturbance patterns should be viewed less as intrinsic or recurring properties of a particular site or plant community and more as emergent phenomenon with a dynamic nature. What this means for management of woodland communities is the application of a more flexible and dynamic

approach which fully embraces the ideas of site potential and potential natural vegetation, and does not impose preconceived or static structural or disturbance targets, but simply promotes appropriate outcomes.

In summary, we utilize predictive modeling and mapping techniques to improve understanding and enhance management of southwestern U.S. piñon-juniper systems. In particular, the development of predictive maps depicting the probability of "old" or persistent woodland occurrence versus those locations more likely to support "younger" post-settlement stands could benefit land management efforts to restore former grass and shrub communities historically displaced by expanding tree cover. Our regional scale models highlight environmental factors that were likely important controls of pre-settlement piñon-juniper woodland distribution and map products express these relationships as landscape patterns. Visual review of map implementations for known woodland areas however, suggested standard measures of model performance may not always bear a direct correspondence to how well mapped stand-age probabilities reproduce observed patterns. Additional sampling of problematic locations, combined with the identification or acquisition of additional (and higher resolution) environmental control coverage, will likely improve future model and map outputs. Regional models might also be improved by incorporating additional environmental factors of enhanced resolution, or factors currently unmeasured and otherwise unavailable in geospatial format. Even so, dynamic and diverse systems like piñon-juniper will defy modeling and mapping efforts beyond a certain level of accuracy and pushing predictive approaches beyond intrinsic limits would be self defeating. Regional map products should be used primarily to infer landscape patterns and environmental controls of woodland stand-age that can inform local perspectives

and interpretations rather than as an absolute predictor for any particular hectare. Our work highlights the potential of predictive modeling methods for researchers and land managers of piñon-juniper systems, but also suggests there are practical limits to this approach and its predictive products.

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Table 1a. Frequency of sampled "old" versus "young" piñon-juniper woodland stands by landform (LANDFORM) strata and depositional (FLOW) environment (losing versus gaining soil-water) within the Four Corners states.

Dataset / sample totals (%) *sample size*	**Stand Age**	**LANDFORM (#)**				**FLOW**	
		Valley (1)	**Mesa (2)**	**Terrace (3)**	**Slope (4)**	**0 (Losing)**	**1 (Gaining)**
Regional		Number of samples				Number of samples	
407 (36.0%)	**Young**	47	114	214	32	216	191
722 (64.0%)	**Old**	8	316	160	238	673	49
n=1129	Sub-Totals	55	430	374	270	889	240

Table 1b. Frequency of sampled "old" versus "young" piñon-juniper woodland stands by soil-geologic substrate.

Dataset / sample totals (%) *sample size*	**Stand Age**	**Soil-Geologic Substrate (Unit #)**									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Regional											
407 (36.0%)	**Young**	30	27	1	10	28	10	90	59	46	106
722 (64.0%)	**Old**	44	54	6	11	143	17	95	78	80	194
n=1129		74	81	7	21	171	27	185	137	126	300

Key to Soil-Geologic Units

1	Metamorphic or igneous units with dominantly mafic composition all ages
2	Carbonate dominated formations either limestone or dolomites of all ages
3	Unconsolidated Aeolian sand deposits both active and stabilized
4	Evaporite units either halite, gypsum, or other saline mineral dominated formations of all ages
5	Metamorphic or igneous units with a dominantly silicic composition all ages
6	Quaternary age older alluvium and surficial deposits
7	Quaternary age younger alluvium and surficial deposits
8	Shale dominated formations of all ages
9	Siltstone and/or mudstone dominated formations of all ages
10	Sandstone dominated formations of all ages

Table 2. Comparative performance of regional models developed for the north-central New Mexico extent; reported values are leave-one-out (LOO), cross-validated probability (XP), classification results ("old" = event) and LOO XP receiver operator characteristic (ROC), area under curve (AUC) values (*c*).

Model		**Observed**		**Correct**		**Incorrect**		**Percentages**				
(prob. cutoff) *ROC c=value (df=degrees freedom)*	Sample Size (*n*)	**Old**	**Young**	**Old**	**Young**	**Old**	**Young**	**Total**	**Sensitivity (Old)**	**Specificity (Young)**	**False Positive**	**False Negative**
FULL (0.45) *c=0.932 (df=6)*	210	146	64	136	52	12	10	89.5	93.2	81.3	8.1	16.1
BASE MARS (0.50) *c=0.938 (df=4)*	**210**	**146**	**64**	**137**	**52**	**12**	**9**	**90.0**	**93.8**	**81.3**	**8.1**	**14.8**
MARS LR (0.44) *c=0.948 (df=3)*	210	146	64	135	55	9	11	90.5	92.5	85.9	6.3	16.7
MARS MR (0.62) *c=0.976 (df=8)*	210	146	64	137	60	4	9	93.8	93.8	93.8	2.8	13.0
MARS HR (0.50) *c=0.984 (df=12)*	210	146	64	143	59	5	3	96.2	97.9	92.2	3.4	4.8

Table 3a. Comparative performance of regional models developed for the regional extent; reported values are leave-one-out (LOO), cross-validated probability (XP), classification results ("old" = event) and LOO XP receiver operator characteristic (ROC), area under curve (AUC) values (*c*).

Model		**Observed**		**Correct**		**Incorrect**		**Percentages**				
(prob. cutoff) *ROC c=value* *(df=degrees freedom)*	Sample Size (n)	**Old**	**Young**	**Old**	**Young**	**Old**	**Young**	**Total**	**Sensitivity (Old)**	**Specificity (Young)**	**False Positive**	**False Negative**
BASE LOGISTIC (0.64) *c=0.876 (df=24)*	1129	722	407	585	327	80	137	80.8	81.0	80.3	12.0	29.5
MARS 001 (0.66) *c=0.870 (df=5)*	1129	722	407	577	329	78	145	80.2	79.9	80.8	11.9	30.6
MARS 002 (0.58) *c=0.886 (df=8)*	1129	722	407	624	327	80	98	84.2	86.4	80.3	11.4	23.1
MARS 003 (0.64) *c=0.894 (df=9)*	1129	722	407	605	326	81	117	82.5	83.8	80.1	11.8	26.4
MARS 004 (0.58) *c=0.903 (df=12)*	1129	722	407	640	327	80	82	85.7	88.6	80.3	11.1	20.0
MARS REGION (0.60) ***c=0.900 (df=13)***	**1129**	**722**	**407**	**626**	**332**	**75**	**96**	**84.9**	**86.7**	**81.6**	**10.7**	**22.4**
MARS 005 (0.60) *c=0.919 (df=16)*	1129	722	407	636	334	73	86	85.9	88.1	82.1	10.3	20.5
MARS 006 (0.60) *c=0.932 (df=29)*	1129	722	407	637	342	65	85	86.7	88.2	84.0	9.3	19.9

Table 3b. Comparative performance of sub-regional models developed for Southern Rocky Mountain and Colorado Plateau woodland extents; reported values are leave-one-out (LOO), cross-validated probability (XP), classification results ("old" = event) and LOO XP receiver operator characteristic (ROC), area under curve (AUC) values (*c*).

Model		**Observed**		**Correct**		**Incorrect**		**Percentages**				
(prob. cutoff) *ROC c=value (df=degrees freedom)*	Sample Size (*n*)	**Old**	**Young**	**Old**	**Young**	**Old**	**Young**	**Total**	**Sensitivity (Old)**	**Specificity (Young)**	**False Positive**	**False Negative**
BASE LOGISTIC (0.64) *c=0.876 (df=24)*	1129	722	407	585	327	80	137	80.8	81.0	80.3	12.0	29.5
MARS REGION (0.60) *c=0.900 (df=13)*	**1129**	**722**	**407**	**626**	**332**	**75**	**96**	**84.9**	**86.7**	**81.6**	**10.7**	**22.4**
MARS REGION-SRM (0.60)	552	334	217	289	182	35	46	85.3	86.5	83.9	10.8	20.2
MARS SRM (0.65) c=0.931 (df=14)	**552**	**334**	**217**	**291**	**190**	**27**	**44**	**87.1**	**87.1**	**87.6**	**8.5**	**18.8**
MARS REGION-CP (0.65)	*577*	*387*	*190*	*334*	*155*	*35*	*53*	*84.7*	*86.3*	*81.6*	*9.5*	*25.5*
MARS HYBRID	**1129**	**722**	**407**	**625**	**345**	**62**	**97**	**85.9**	**86.6**	**84.8**	**9.0**	**21.9**

Figures

Figure 1. Regional sample locations in relation to a generalized distribution of Colorado Plateau and southern Rocky Mountain piñon-juniper savanna and woodland communities recently mapped by SWReGAP within the Four Corners states.

Figure 2. Predictive map of "old" versus "young" (percent probability "old") piñon-juniper stands using the MARS REGION model for the Four Corners states.

Figure 3a. Predictive map of "old" versus "young" (percent probability "old") piñon-juniper stands using the MARS REGION model for the 2.9 million-ha north-central New Mexico study area. Figure 3b is a close-up of Tsankawi Unit (see inset), Bandelier National Monument.

Figure 3b. Predictive map of "old" versus "young" (percent probability "old") piñon-juniper stands using the MARS REGION model for the (336 ha) Tsankawi Unit, Bandelier National Monument, New Mexico.

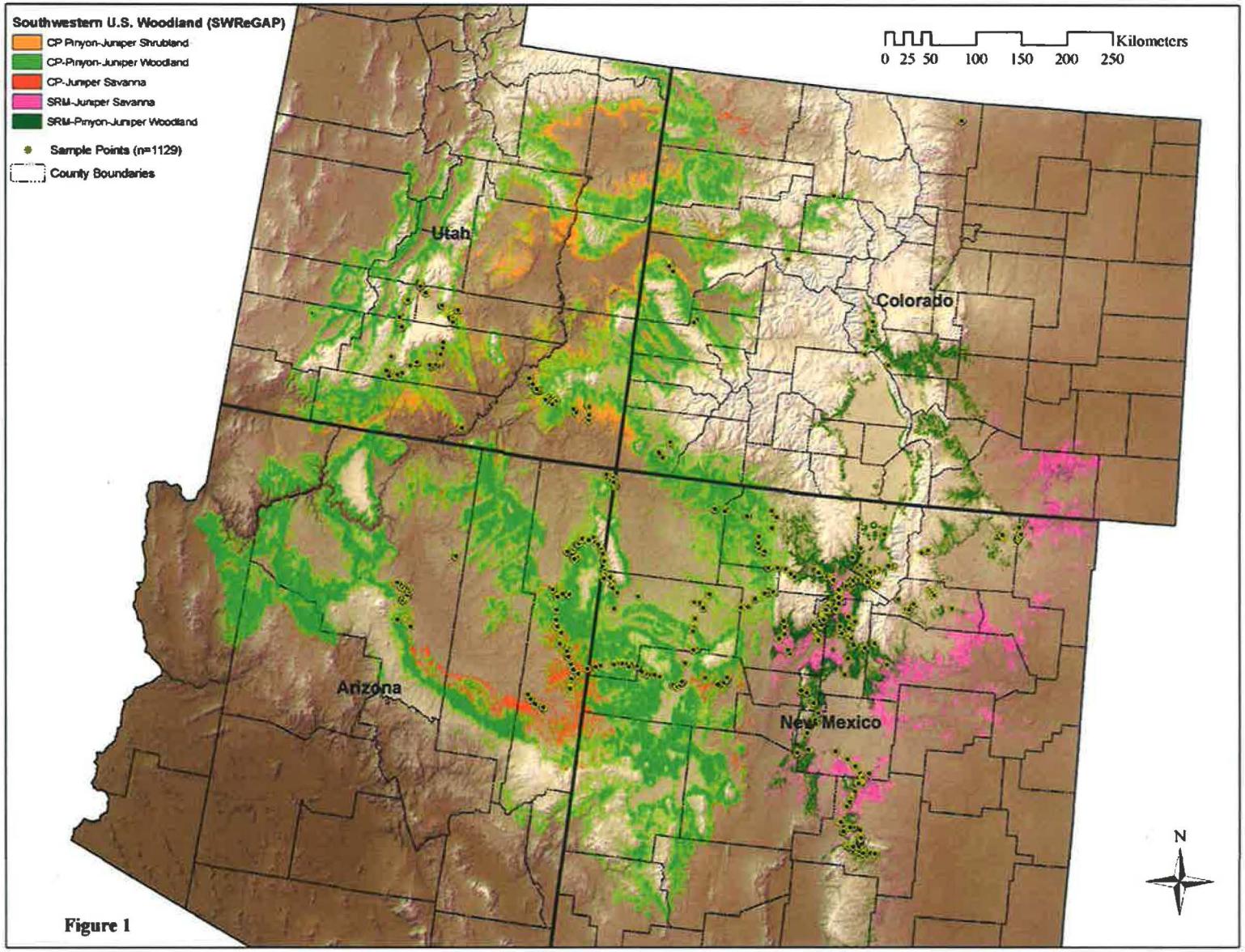

Southwestern U.S. Woodland (SWReGAP)
CP Pinyon-Juniper Shrubland
CP-Pinyon-Juniper Woodland
CP-Juniper Savanna
SRM-Juniper Savanna
SRM-Pinyon-Juniper Woodland
Sample Points (n=1129)
County Boundaries
Kilometers
0 25 50 100 150 200 250
Utah
Colorado
Arizona
New Mexico
N

Figure 1

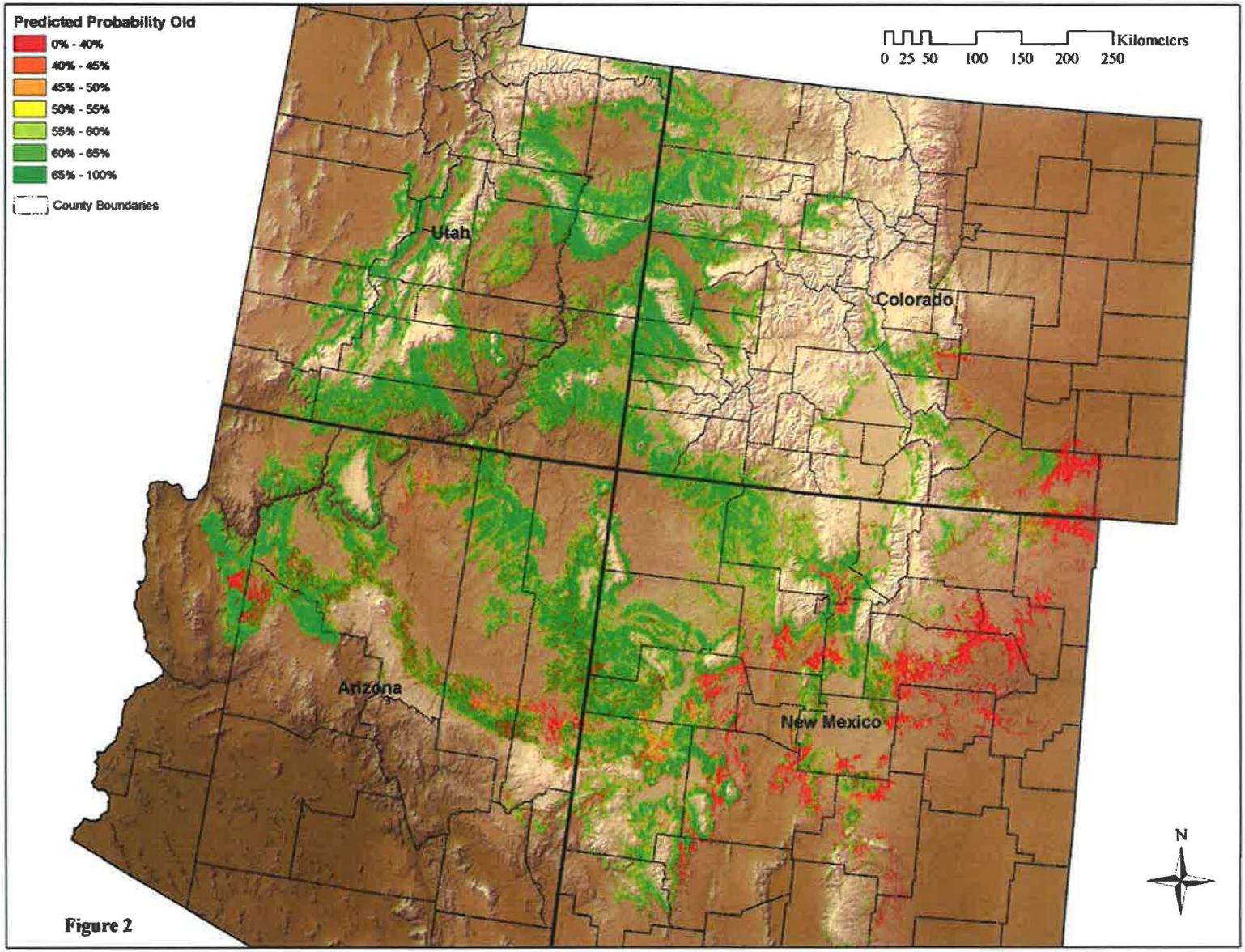

Predicted Probability Old
0% - 40%
40% - 45%
45% - 50%
50% - 55%
55% - 60%
60% - 65%
65% - 100%
County Boundaries
Kilometers
0 25 50 100 150 200 250
Utah
Colorado
Arizona
New Mexico
N

Figure 2

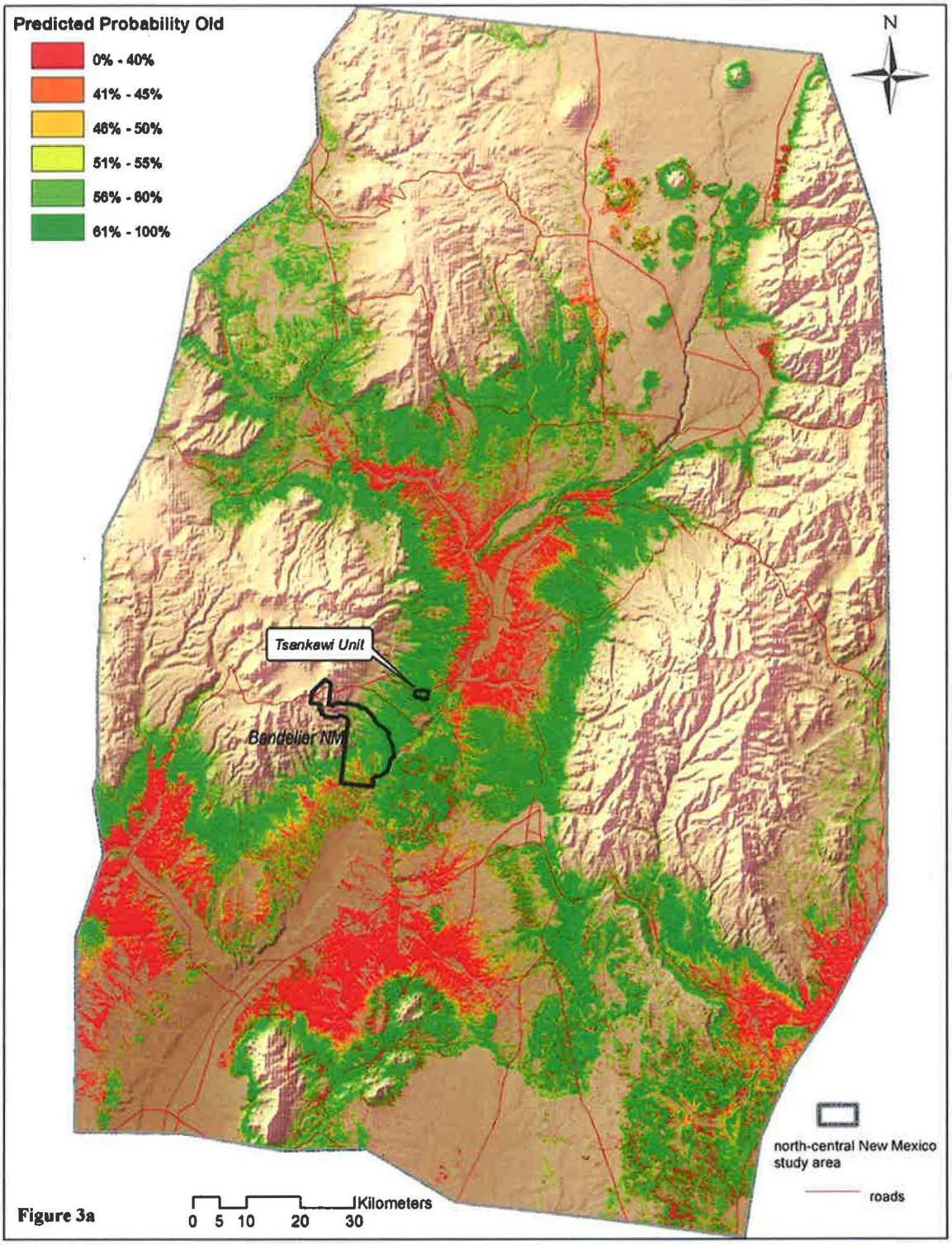

Predicted Probability Old
0% - 40%
41% - 45%
46% - 50%
51% - 55%
56% - 60%
61% - 100%
N
Tsankawi Unit
Bandelier NM
north-central New Mexico study area
roads
Kilometers
0 5 10 20 30

Figure 3a

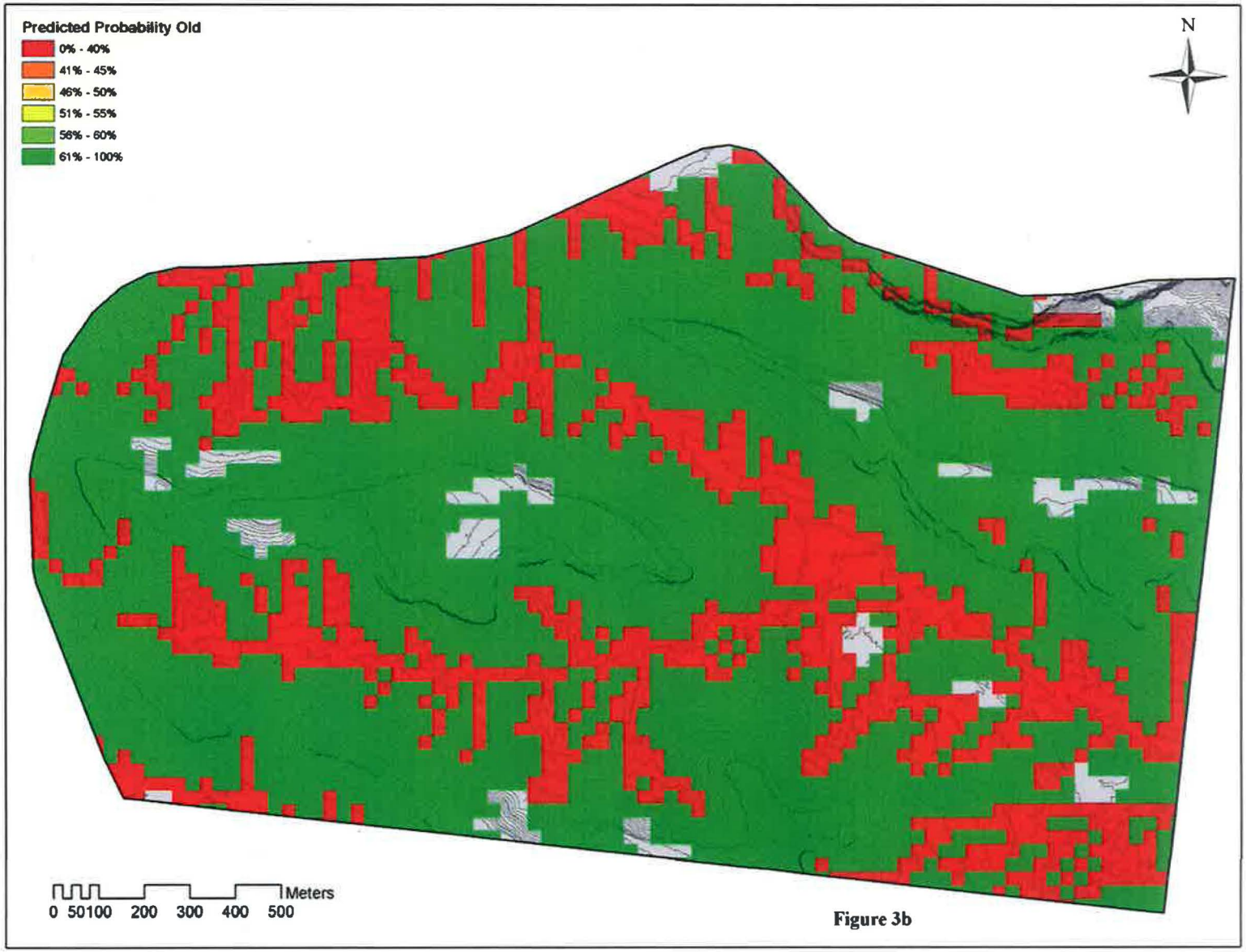

Predicted Probability Old
0% - 40%
41% - 45%
46% - 50%
51% - 55%
56% - 60%
61% - 100%
N
0 50100 200 300 400 500
Meters

Figure 3b

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