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MAPPING "OLD" VS. "YOUNG" PIÑON–JUNIPER STANDS WITH A PREDICTIVE TOPO-CLIMATIC MODEL

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Abstract. Piñon pine and juniper woodlands in the southwestern United States 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 that predate 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 stands 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 predating 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, postsettlement origin. We present 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" vs. "young" piñon–juniper stands. Presettlement 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 United States 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 presettlement origins (although widely thickened and infilled historically), and old-growth structure is not uncommon in appropriate upland settings.

Key words: juniper; pinyon (piñon); predictive modeling; restoration; topo-climatic modeling; woodland.

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 (Fig. 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 ~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, and 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 predate 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

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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- vs. 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," presettlement piñon–juniper types, as distinguished from "younger" stands (i.e., post-1850 origin), and demonstrate a predictive approach for modeling and mapping of pre- vs. postsettlement-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 semiarid 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 multilayered 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 shrubland 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 vs. 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 photogaphs suggest piñon–juniper has become more abundant at many locations since Euro-American settlement, ca. 1850 (e.g., Miller and Wigand 1994, Tausch 1999*a*, 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 prehistoric); (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; or (7) 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 1999*b*, 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 vs. infilling may differ in some basic ways, both processes are thought to have been enhanced historically by intensive land use 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," presettlement vs. "younger," postsettlement piñon–juniper in a monsoonal, north-central New Mexico study area. Our approach implicitly tests the idea that "older," presettlement age piñon–juniper woodlands occupy an ecological space distinct from "younger," postsettlement stands. We sample across "old" vs. "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 piñon–juniper types in the southwestern United States, 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 (Figs. 1 and 2). The intensive plot data were used to inform development of a diagnostic key (Box 1) distinguishing "older," presettlement woodlands (>150 years) from "younger," postsettlement 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 (Fig. 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; Fig. 1). The study area was centered on Bandelier, a well-researched landscape 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- vs. postsettlement 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 data set was 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 downslope 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 ~30 cm above the 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

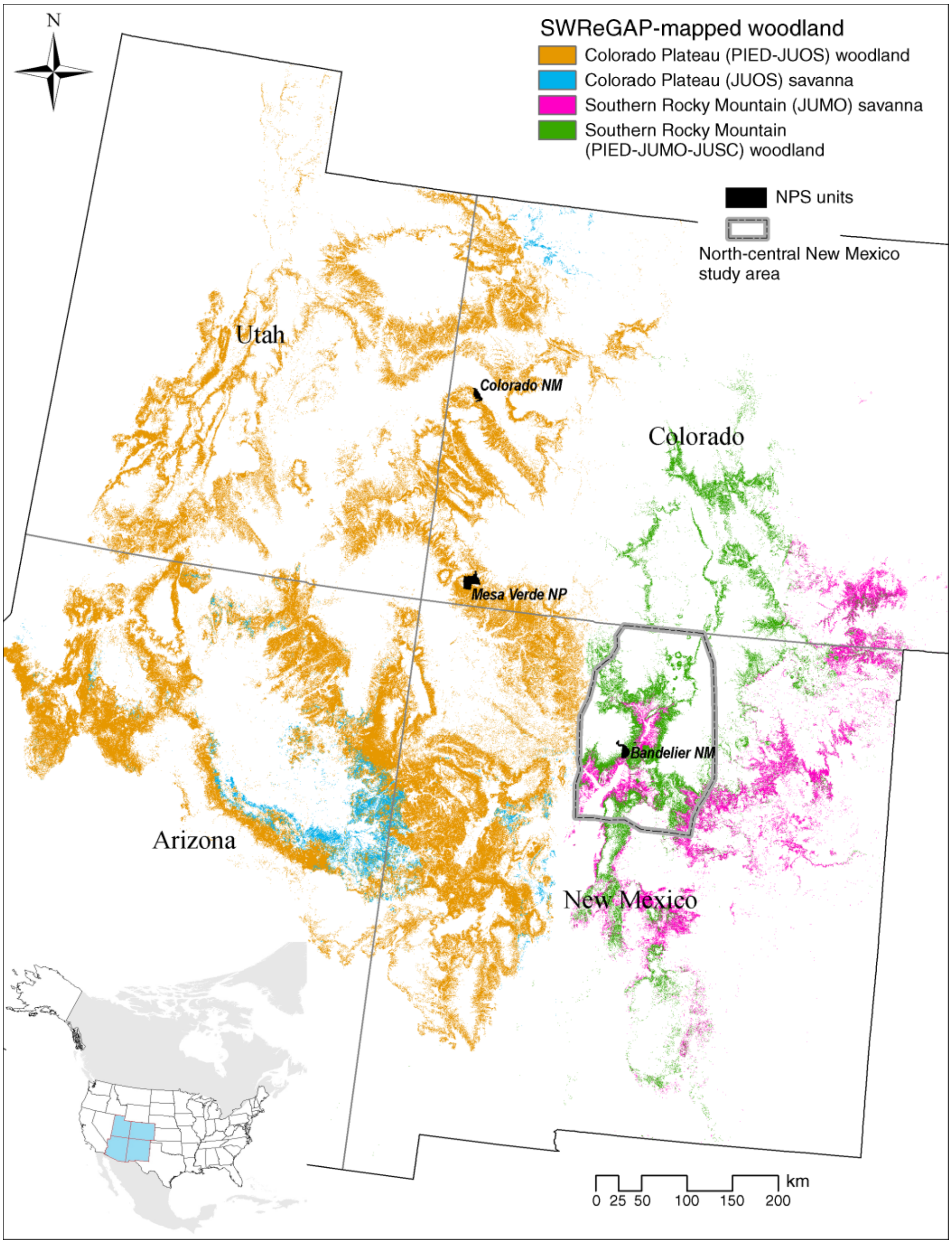

FIG. 1. Generalized distribution of Colorado Plateau and southern Rocky Mountain piñon–juniper savanna and woodland types within the Four Corners states: piñon–juniper covers are ~14.5 million ha or ~13% of the total land area (modified from data provided by the Southwest Regional Gap Analysis Project [SWReGAP]). Three National Park Service (NPS) units (Bandelier National Monument [NM], Mesa Verde National Park [NP], 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. Abbreviations are: PIED, *Pinus edulis*; JUOS, *Juniperus osteosperma*; JUMO, *Juniperus monosperma*; JUSC, *Juniperus scopulorum*.

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 the plot center using a 5.6-cm auger; a representative soil sample was obtained at a depth of 0–10 cm. Cores (and associated diameters) were obtained

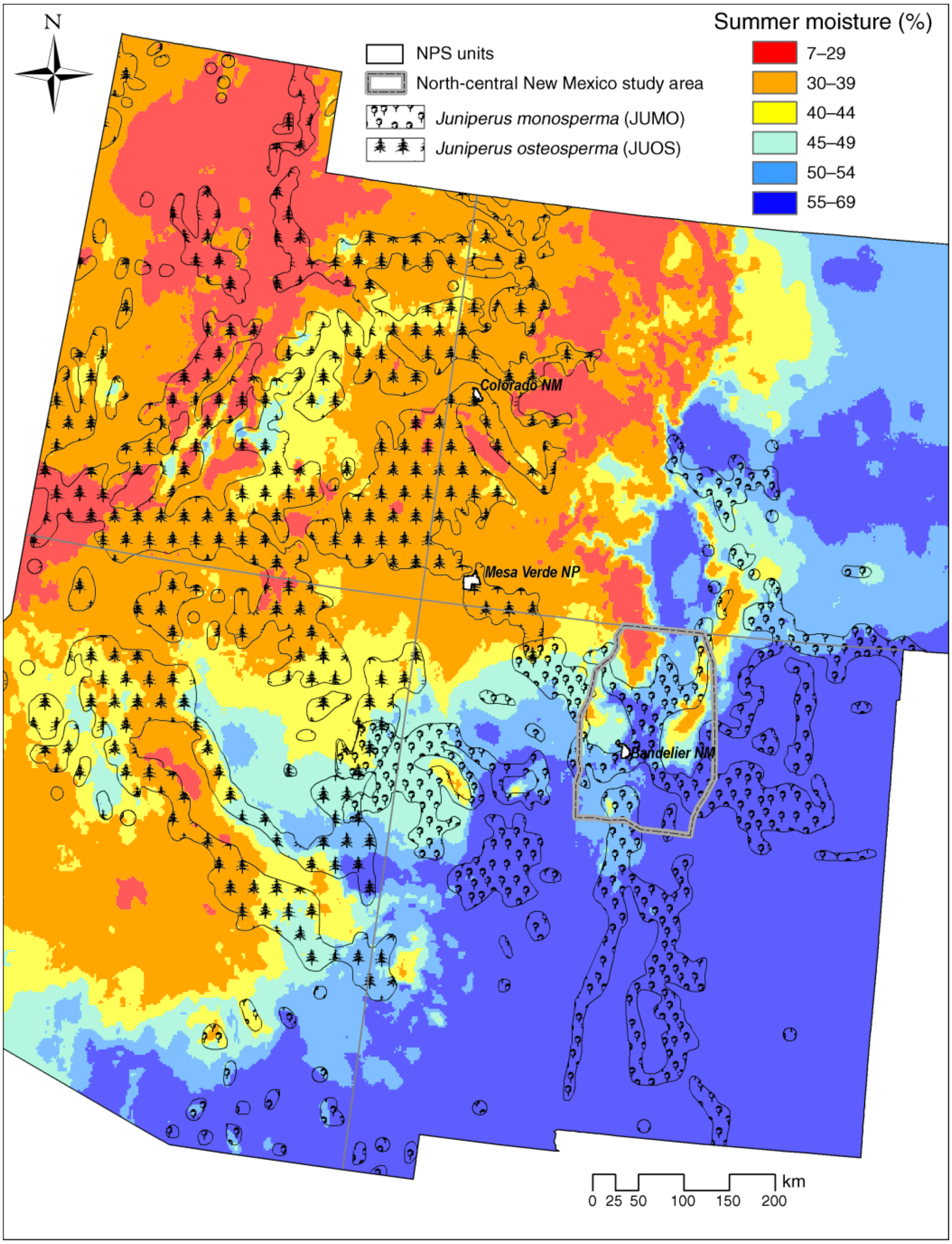

FIG. 2. Index of growing-season moisture (MONSOON), calculated as the June–September percentage of mean annual precipitation (MAP) across the Four Corners states. We highlight the casual association of one-seed (JUMO) and Utah (JUOS) juniper ranges (Little 1971) with MONSOON. Extensive sampling (and 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). Abbreviations are: PIED, *Pinus edulis*; JUMO, *Juniperus monosperma*; JUOS, *Juniperus osteosperma*. See Fig. 1 for further explanations of site abbreviations.

(at 30 cm above base) from the largest five 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 (P. M. Brown, *personal communication*).

Box 1. Diagnostic criteria and artificial key for delineation of southwestern U.S. piñon–juniper, savanna, and woodland communities (*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 (piñon-dominated)	Group I
2b) Mature juniper (live or dead) well represented (piñon–juniper codominant)	Group II
3a) Mature juniper (live or dead) well represented (juniper dominated)	Group III
3b) Mature juniper few or absent (successional piñon and/or juniper)	Group IV

Individual Group Keys

Group I: Piñon-Dominated Woodland or Savanna

Canopy closure usually $\geq$25% (20–80+%); juniper, if present, mostly younger.

A. *Old-growth trees present: Old-growth piñon-dominated woodland or savanna.*—Individual old trees ($\geq$5 trees/ha on average), live or dead, average diameter (of largest three trees) for piñon near base $\geq$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, 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.

B. *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 $\geq$20% (15–60+%); mature piñon and juniper present.

A. *Old-growth trees of both species present: Old-growth piñon–juniper woodland.*—Individual old trees ($\geq$3 old trees/ha on average, piñon and/or juniper), live or dead, average diameter (of largest three trees) near base for piñon $\geq$30 cm† and/or juniper $\geq$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, 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).

B. *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 $\leq$15% (5–30+%); piñon, if present, mostly younger.

A. *Old-growth trees present: Old-growth juniper savanna.*—Individual old trees ($\geq$1 old tree/ha on average), live or dead, average diameter (of largest three trees) for juniper near base $\geq$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, 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).

B. *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/Juniper Woodland or Savanna

Canopy closure $\geq$5%‡ (5–80+%); average diameter (of largest three living trees) near base for piñon $\leq$30 cm† and/or juniper $\leq$25 cm.†

A. *Evidence of prior woodland community apparent: Recovering woodland.*—Sites with evidence of long-term woodland occupation, but subjected to prior disturbance, e.g., fire, drought, harvest, and/or insect-/disease-induced mortality and

Box 1. Continued.

lacking extant old growth. Evidence of disturbance to former old-growth woodland is 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, or down wood (average diameter of three largest down-wood remnants of piñon ≥30 cm† and/or juniper ≥25 cm);† large-diameter down wood (piñon or juniper) is often bleached, polished, or decomposed, with well-developed lichen growth.

B. *Lacking above evidence of prior woodland community: Expanding woodland.*—Sites without evidence of a prior woodland community and apparently expanding into non-woodland vegetation, usually onto deeper soils or productive settings capable of supporting robust understory growth, as indicated by presence of suppressed or remnant understory components typical of adjacent grassland, shrubland, and/or pine savanna communities. These expanding woodland sites may include scattered living or dead, standing or fallen ponderosa pine and other non-woodland conifer tree species, but are lacking large-diameter (piñon and/or juniper) snags, stumps, or down wood.

† Diameter thresholds for *Pinus edulis* and *Juniperus monosperma* in upland settings with moderate soil depth (i.e., 15–35 cm deep) in north-central New Mexico; (add 2–5 cm for mesic, depositional soil sites [i.e., >35 cm deep] and subtract 2–5 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 (~30 cm or core height), and for multibranched trees (e.g., one-seed juniper), measure diameter of largest stem just above junction.

‡ Minimum tree canopy cover ≥5% to be considered here as a piñon–juniper type.

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- vs. postsettlement 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 15 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- vs. postsettlement age stands sometimes can be difficult. In addition, nine of the 15 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 that 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 land use or historical disturbance. Assignment of piñon–juniper type, pre- vs. postsettlement stand age, landform, and depositional setting initially were made onsite. Field

TABLE 1. Number of samples across landform (LANDFORM) strata and depositional environment (FLOW) by stand age (pre- vs. postsettlement stand age) for the full ($n = 210$), training ($n = 146$, 69.5% of the full data set), and test ($n = 64$, 30.5% of the full data set) data sets within a north-central New Mexico, USA, study area.

			No. samples					
			LANDFORM (number)				FLOW	
Stand age	Sample size	Percentage	Valley (1)	Mesa (2)	Terrace (3)	Slope (4)	0 (Losing)	1 (Gaining)
Full								
Young	64	30.5	7	23	30	4	30	34
Old	146	69.5	2	67	25	52	137	9
Subtotals			9	90	55	56	167	43
Training								
Young	45	30.8	6	17	19	3	22	23
Old	101	69.2	1	45	18	37	94	7
Subtotals			7	62	37	40	116	30
Test								
Young	19	29.7	1	6	11	1	8	11
Old	45	70.3	1	22	7	15	43	2
Subtotals			2	28	18	16	51	13

Note: See *Methods: Development of GIS data sets for modeling* for additional explanation of LANDFORM and FLOW parameters.

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 data sets for modeling

A variety of geospatial data sets, 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 (Corvallis, Oregon, USA), a vendor of 2-km-resolution climate products developed by the Parameter-elevation Regressions on Independent Slopes Model (PRISM) group at Oregon State University, Corvallis, Oregon, USA, and seamless 30-m-resolution digital elevation model (DEM) coverage was purchased from the U.S. Geological Survey Center for Earth Resources Observation and Science (USGS-EROS, Sioux Falls, South Dakota, USA). Vegetation and landform coverages (30-m resolution) were obtained from SWReGAP (Comer et al. 2003, 2004, Lowry et al. 2005). Different spatial references and resolutions necessitated some standardization to create compatible data sets for analysis (Latimer et al. 2006); all data were projected to Albers Equal Area Conic, NAD83.

Surface analysis of 30-m DEMs was used to create slope (in degrees), hill shade, and flow accumulation data sets 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 evapotranspiration (PET). Seasonal indices of PET (winter and summer) were calculated as the product of $\log_n$(hill shade) 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 10), 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 1). 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 1).

Predictive modeling and map realization

Statistical modeling was performed in SAS version 9.1 (SAS Institute, Cary, North Carolina, USA) 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 devel-

TABLE 2. Leave-one-out (LOO), cross-validated probability (XP) classification results ("old" = event) for the full data set model.

Model	Sample size (n)	Observed		Correct		Incorrect		Percentages				
		Old	Young	Old	Young	Old	Young	Total	Sensitivity (old)	Specificity (young)	False positive	False negative
Full	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	146	101	45	92	38	7	9	89.0	91.1	84.4	7.1	19.1
Test	64	45	19	42	16	3	3	90.6	93.3	84.2	6.7	15.8

Notes: Results are itemized by class level for variable LANDFORM. Four explanatory parameters were used (effective winter precipitation [EWP], depositional environment [FLOW], landform [LANDFORM], digital elevation model [DEM]) with a probability prediction threshold (probability cutoff) of 0.45 for the full model. 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 ($n = 64$) data sets, with a 0.60 probability cutoff. The test data were scored using the model fit independently with the training data set. 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 data set (see Table 1).

oped by combining precipitation and temperature with DEM-derived surfaces (e.g., hill shade) 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 were imported to SAS for model development. A potential set of some 20 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 data set. Table 1 presents a frequency distribution (percentages) 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 ($n = 64$) data sets.

Modeling runs were conducted using both the full data set ($n = 210$) and a split training/test data set ($n = 146/n = 64$) partitioned using a simple rule. Alternative models developed using the full and training data sets 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., 0.40–0.60) of probability cutoffs (Table 2). Comparable models with fewer and/or more easily interpretable predictors were given preference. For the split data set modeling effort, the test data set was scored using the model independently fit with the training data. The LOO XP, receiver operating characteristic (ROC), and area-under-curve (AUC) values (LOO XP ROC AUC) also were calculated for full, training, and test models. The 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 types. 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 (Box 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 (Box 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 ($P < 0.0001$, $n = 398$; see Appendix). The P values are provided in lieu of r^2 values, which cannot be used to evaluate zero-intercept models (Eisenhauer 2003). Diameter thresholds are intended to provide a pre- vs. postsettlement (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 (15–35 cm). Our diameter–age estimates are comparable to those in published reports of piñon and juniper growth rates in New Mexico (Barger and Ffolliott 1972). The key provides minimum densities of old trees below which detection of individuals >150 years could be considered

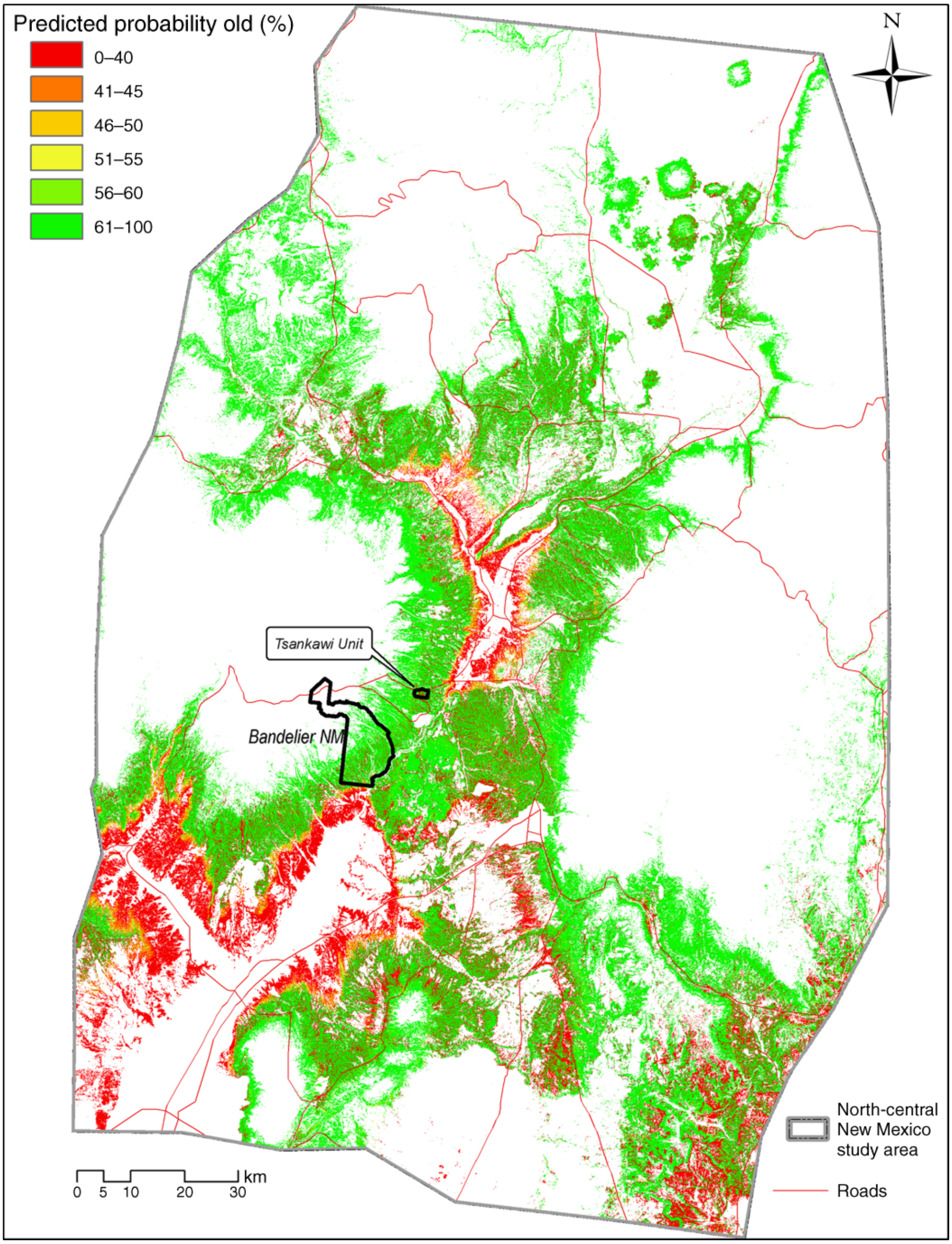

FIG. 3. Predictive map of "old" vs. "young" (percentage probability "old") piñon–juniper stands within the 2.9 million-ha north-central New Mexico study area. Fig. 4 is a close-up of Tsankawi Unit (see inset), a disjunct part of Bandelier National Monument (NM).

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- vs. postsettlement stands in the north-central New Mexico study area was assessed using data from 15 (0.1-ha) intensively sampled plots within Bandelier National Monument. Using the key 13 of 15 of stands were correctly assigned to a pre- vs. postsettlement 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

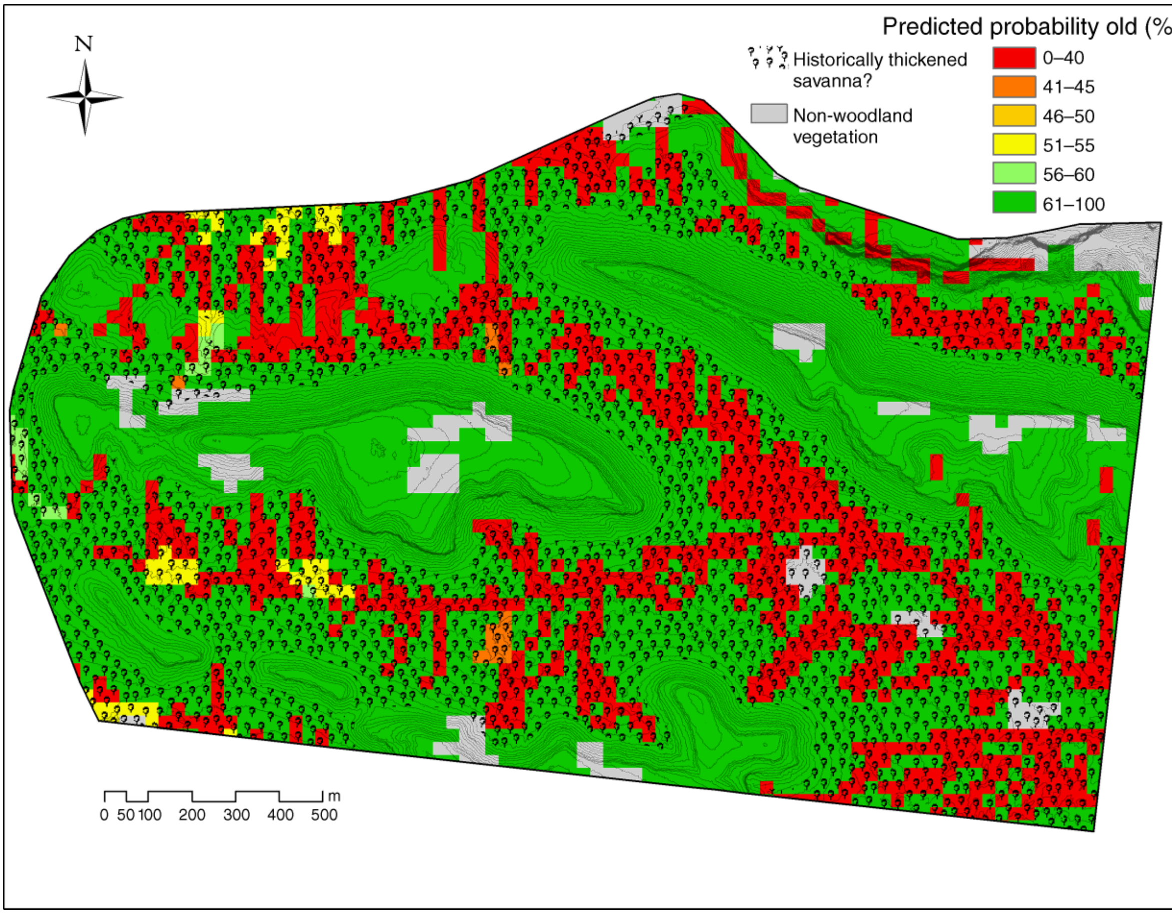

FIG. 4. Predictive map of "old" vs. "young" (percent probability "old") piñon–juniper stands within the (336-ha) Tsankawi Unit, Bandelier National Monument, New Mexico. Green with scattered tree overlay, delineated using high-resolution soil coverage, highlights inferred areas of historically thickened savanna structure in marginal depositional settings and indicates where mechanical thinning of the younger tree component might be considered an appropriate restoration treatment. The map resolution of predicted pre- vs. postsettlement woodland cover is 30 m, but an appropriate scale (e.g., minimum map unit) for field application in this location would be ~1 ha.

"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 presettlement stands (136 of 146) and 81.3% of postsettlement stands (52 of 64) were correctly classified (Tables 1 and 2). 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 ($n = 64$) data set (0.60 probability cutoff) using the same four predictors; the total correct for the training data set 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 data set correctly classified 90.6% of all observations: 93.3% of presettlement stands (42 of 45) and 84.2% of postsettlement stands (16 of 19). The 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 (Fig. 3) and the Tsankawi subunit of Bandelier National Monument (Fig. 4). 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 one-third (29%) of this extant piñon–juniper cover is postsettlement in origin. We noted during fieldwork, 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 postsettlement woodland in the north-central New Mexico area. The majority of these "younger," postsettlement 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 postsettlement expansion of piñon–juniper into non-woodland (e.g., grass and shrub) vegetation types.

Discussion

A diagnostic key (Box 1), using a combination of semi-quantitative and qualitative features, was developed to facilitate rapid field distinction of piñon–juniper type and pre- vs. postsettlement stand age. We used the key only to assign sampled stands to "old" vs. "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 presettlement 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 50–55% of the annual total) might be expected to range between 150 and 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 <150 years old (Fig. 2). Within local areas, growth rates were observed to be greater on depositional vs. 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- vs. postsettlement woodlands within a 2.9-million ha study area comprising a north-central New Mexico extent. Sampled stands were classified as "old" vs. "young" using the diagnostic key and each sample point was associated with potential topo-climatic predictors in a GIS. The resulting data set 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 vs. locations that would have formerly supported non-woodland (e.g., grass and shrub) vegetation types (Fig. 4). 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 (Figs. 1 and 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; Fig. 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 (Fig. 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," postsettlement stands in locations roughly corresponding to the distributional limits of one-seed juniper (Little 1971) and a shift to summer monsoonal moisture patterns (Fig. 2). These "younger" stands, usually dominated by one-seed juniper, 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 microsites 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 postsettlement 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," postsettlement 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," presettlement-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 Great Basin region influenced by winter/spring moisture, western juniper (*Juniperus occidentalis*) also has expanded dramatically since 1860 into sagebrush steppe communities (Miller et al. 2008).

In summary, we developed a diagnostic key to distinguish between "older," presettlement and "younger," postsettlement piñon–juniper woodlands in the southwestern United States. We assigned a pre- vs. postsettlement 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 data set was used for predictive modeling and mapping of pre- vs. postsettlement ("old" vs. "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- vs. "younger," postsettlement 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" presettlement woodlands in locations with bimodal or winter moisture patterns (Romme et al. 2003).

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APPENDIX

Stand-level data for 15 intensive plots sampled within Bandelier National Monument, New Mexico, USA (*Ecological Archives* A018-055-A1).