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

Ecological History and Natural Range of Variability

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Abstract—*Juniper savanna and piñon-juniper 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 United States 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, that occur over various spatial and temporal scales.*

Introduction

Juniper savanna and piñon-juniper (P-J) woodlands in the American Southwest have often been viewed by researchers and land managers alike as an ecological unit that 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.

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Distribution

Juniper savanna and piñon-juniper 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*), oneseed (*J. monosperma*), Rocky Mountain (*J. scopulorum*), alligator (*J. deppeana*), and western juniper, (*J. occidentalis*), and two of piñon, Colorado (*Pinus edulis*), and singleleaf (*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-BRD, with taxonomy and nomenclature following Flora North America (Flora of North America Editorial Committee, eds., 1993+).

Colorado piñon has a distribution centered on the Four Corners state area of UT, CO, NM and AZ, while the closely related singleleaf piñon is found to the west in NV, northwest AZ, southeast CA and southwest 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 oneseed 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 British Columbia, Canada, while alligator juniper, also more mesic than Utah or oneseed 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 and others 2005). Within the Four Corners state area, oneseed and alligator junipers predominate in locations under the seasonal influence of the Arizona summer monsoon, defined by Mitchell's climate zone VI (Mitchell 1976), with alligator juniper more common in southern New Mexico and east-central Arizona, while oneseed juniper dominates woodlands in the rest of New Mexico. 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 singleleaf 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 redberry 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 eastern Californa and northern Nevada, but with a range extending northwest to Oregon, Washington and Idaho, and Pinchot's juniper (*J. pinchotii*), ashe juniper (*J. ashei*) and eastern red-cedar, (*J. virginiana*) to the east in Texas and Oklahoma.

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 oneseed, oneseed with alligator, redberry with Pinchot's, and Rocky Mountain with eastern red-cedar (*J. scopulorum* is sometimes classified as a variety of *J. virginiana*); the sprouting ability of redberry and Pinchot's junipers, and small, oneseeded 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 that 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 Corners state area plus NV) of the American Southwest, and following community classifications prepared by NatureServe (Comer and others 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 that 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 that 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 that 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. It appears more opportunistic than inevitable, largely dependent on local site conditions, and not obviously essential to maintenance of 'normal' system structure and function. 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 0-30 cm 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 that 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 and others 2005) and oneseed 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 that 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 and others (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 that 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 oneseed 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 that 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 that 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 1,000 years (Jackson and others 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 that attempt to balance stated societal needs and desires.

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Customized displays of piñon and juniper distributions and climate data can be created and viewed within a GIS environment. USGS digitized shapefiles of individual tree species based on Little (1971) can be downloaded at (http://esp.cr.usgs.gov/data/atlas/little/) and PRISM climate data (4km and 800m resolution) from (http://www.ocs.orst.edu/prism/).

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