Population-Wide Changes in Pinyon-Juniper Woodlands Caused by Drought in the American Southwest: Effects on Structure, Composition, and Distribution

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Abstract

A complex of drought, insects, and disease caused widespread mortality in the pinyon-juniper forest types of the American Southwest in recent years. Data from 14,929 plots spanning 25 years and representing over 25 million hectares were analyzed to characterize effects of drought-related mortality on the structure, composition, and distribution of pinyon and juniper species throughout their ranges. *Pinus edulis* experienced higher rates of mortality since 2003 than at any time between 1981 and 2002. Most *Juniperus* species experienced very low rates of mortality under normal conditions, and showed a small increase in mortality during the recent drought event. Trees affected by drought tend to be lower in elevation than the general population, and smaller trees appear to have experienced a higher proportion of mortality than larger trees. However, there is no evidence of elevational or geographic range contraction. This analysis quantifies landscape-level changes resulting from human, biological, and climatic influences.

Keywords: stand structure, mortality, species composition, species distribution, range contraction

1. Introduction

"Pinyon-juniper" is a catch-all term that includes mixtures of several pinyon and juniper species, as well as pure stands of any of the species used to define the type (Table 1). In the western U.S. the Forest Inventory and Analysis (FIA) program recognizes 4 forest types belonging to the pinyon-juniper group – Rocky Mountain juniper, western juniper, juniper woodland, and pinyon-juniper woodland – which are defined by composition of pinyon and juniper species. The first 2 types are defined by dominance of single species, but may include minority stocking of other species, whereas the other 2 types are defined by the dominance of 2 or more species in combination. Although defined as one type, juniper woodland actually includes species with non-overlapping ranges. Likewise, pinyon-juniper woodland is defined by the presence by at least 1 of 6 pinyon taxa, usually common pinyon or singleleaf pinyon, in association with one or more juniper species. In addition, most of the pinyons and junipers occur as minor components in many other forest types. The pinyon-juniper group comprises one of the widest ranging forest types in the U.S., covering over 22 million hectares.

Widespread tree mortality in pinyon-juniper forest types of the southwestern United States is associated with several years of drought. A complex of drought, insects, and disease is responsible for pinyon mortality rates approaching 100 percent in some areas, while other areas have experienced little or no mortality. Most mortality of pinyon species is the result of an

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explosion of the pinyon ips (*Ips confusus* LeConte) population between late 2002 and late 2003, which was facilitated by drought stress. The dramatic visual effect of drought-related mortality – dying trees with reddened foliage covering entire landscapes – brought much public and media attention to the event. Because of the locally intense nature of mortality, unbiased quantitative analyses of drought effects have generally been lacking. In some cases, mortality estimates were extrapolated from local sites to entire states. For example, one account reported that 90% of the pinyon trees in the state of Arizona had been killed (Society of American Foresters 2004). There has also been speculation of widespread range retractions and local extirpation.

There is considerable interest in placing the effects of the recent drought in the context of similar droughts that occurred in the early 1900s and mid-1950s (National Climatic Data Center 1994). Breshears et al. (2005) characterized the mortality event as response to “global-change-type drought”. The current study provides a broad view of recent drought effects on pinyon and juniper species by examining the distribution, composition, and structure of stands spanning nearly the entire range of pinyon and juniper types in the Interior West of the U.S.

2. Methods

Data used in this analysis come from the Interior West Forest Inventory and Analysis (IW-FIA) program of the U.S. Department of Agriculture Forest Service. The national FIA program conducts inventory on all forested lands of the U.S. using a nationally standardized plot design at an intensity of approximately 1 field plot per 2388 hectares. IW-FIA is responsible for lands in Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming. These states encompass over 85% of forest in the pinyon-juniper group in the western U.S.

Surveys conducted by IW-FIA prior to 2000 were generally statewide periodic inventories, but in some cases National Forests or tribal lands were inventoried as separate units. Under the periodic system, the entire plot grid in the area of interest was visited over a period of 1 to several years. As a result, the number of plots visited in any given year varied in number and geographic extent. In 2000, IW-FIA implemented a continuous annual inventory system. Under annual inventory, approximately 10% of plots from the full sample set are measured each year. Plots belonging to an annual panel are distributed across each state so as to be free of geographic bias. States have been gradually phased into the annual system (Utah, 2000; Arizona, 2001; Colorado, 2002; Idaho, 2003; Montana, 2003), increasing geographic coverage over the past 5 years. A pilot inventory of Nevada employed the annual plot system in 2004 and 2005.

Pinyon or juniper species were found on 14,929 plots, measured between 1981 and 2005, in the FIA database. Of the total number of plots, 10,807 were unique plot locations, with the remainder being repeat visits to plots in different inventory cycles. Of the 298,324 trees measured on all plots, 212,142 were pinyon or juniper species. Tree data included species, diameter (measured at root collar), mortality code, and agent code. Mortality code distinguishes 2 classes of dead trees: those judged by field observation to have died in the 5 years prior to plot measurement (mortality) and those that died more than 5 years earlier (standing dead). Estimation of time since mortality is relatively accurate when based on changes in snag condition – e.g., retention of needles and bark (Kearns et al. 2005). This distinction was devised to permit estimation of mortality rates from initial plot visits (i.e., plots lacking re-measurement data), but it has also proven to be extremely useful for tracking trends in drought-related mortality (Shaw et al. 2005, Shaw 2006). Agent code is used to attribute the primary cause of mortality. In this study, mortality due to fire has been excluded. Plot data included measurement year, latitude, longitude, and elevation.

From these data, the live, dead, and mortality components of each plot were computed, on a basal area (BA) per hectare basis, by species and species group. Dead and mortality components were computed differently in order to properly characterize recent (i.e., drought-related) compositional change (equations (1) and (2)):

$$\% \text{ mortality} = \text{mortality BA} / (\text{live BA} + \text{mortality BA}) \quad (1)$$

$$\% \text{ dead} = \text{dead BA} / (\text{live BA} + \text{mortality BA} + \text{dead BA}) \quad (2)$$

Because of variations in survey type and location over time, it was not practical to scale up to population-level estimates on an annual or multi-year basis. Rather, this study analyzes characteristics and trends found in the sample. Comparability among years is achieved by normalizing the data into proportions of live, dead, and mortality trees. For the purpose of comparing pre-drought and post-drought conditions, data from several years are aggregated. For general comparisons, data from 1981-2002 are considered to be pre-drought and data from 2003-2005 are post-drought. In cases where only annual inventory data are used, the pre-drought data include only the 2000-2002 measurement years.

3. Results and Discussion

Changes in stand composition, stand structure, and geographical distribution due to drought-related mortality varied by species. Because of space limitations, the analysis presented here is limited to the 6 most common species that are found in pinyon and juniper types: common pinyon, singleleaf pinyon, alligator juniper, oneseed juniper, Rocky Mountain juniper, and Utah juniper.

3.1 Temporal trends

All pinyon and juniper species showed similar mortality trends over time (Figure 1). Mortality rates were very low in most years. In the period since 2002, mortality has increased dramatically. The most affected species is common pinyon, with nearly 11% of tally trees recorded as recent mortality, followed by singleleaf pinyon with about 3% mortality. Consistent with field observations, juniper species appear to have lower mortality rates over time, and suffered less drought-related mortality since 2002. In many years there were no juniper mortality trees.

It is noteworthy that many of the species show a small increase in mortality in the late 1990s, which corresponds to the 1996 drought event reported by Mueller et al. (2005) to have caused some mortality in pinyon-juniper woodland. Most important, however, are the differential impacts of drought among the species. As a portion of all trees measured, the number of mortality trees differs by more than an order of magnitude between the highest (common pinyon, 10.7% by 2005) and lowest (oneseed juniper; 0.6% in 2004).

3.2 Geographic and elevational distribution

Mortality related to recent drought is more widespread than all mortality found in previous years (Figure 2). During pre- and post-drought time periods there were local “hot spots” and patchy mortality elsewhere. It also appears that most of the plots on which mortality occurred before 2003 were not affected in recent years. However, an estimate of the numbers of plots that were affected in one or both periods cannot yet be determined due to the relatively small number of plots that have been re-measured. The degree to which local landscapes were affected varies regionally. Plots on which >50% of the pinyon component died are mostly located in northern Arizona and southwestern Colorado. Plots on which 100% of the pinyon component has been eliminated are relatively rare and tend to be regionally clustered. The highest concentrations of such plots are in Arizona, above the Mogollon Rim from Flagstaff to the White Mountains, and on Black Mesa and vicinity. The southwest corner of Colorado also has a relatively large number of plots with 100% mortality of the pinyon component. Although post-drought data are not available for New Mexico, near-total pinyon mortality has been observed there in areas adjacent to the severely affected areas in Arizona and Colorado (pers. obs.).

Mortality appears to have occurred at somewhat lower mean elevation than the mean elevation of the general population, and more severely affected plots are at lower elevations than less affected plots. For example, mean elevation of all plots with common pinyon that were measured after the drought is 2403m, as compared with 2007m for plots with any amount of pinyon mortality, 1947m for plots with at least 50% mortality of the pinyon component, and 1899m for plots with 100% mortality of the pinyon component. Interestingly, the pattern is similar for plots measured prior to 2003 (i.e., pre-drought): plots with at least 50% mortality of the pinyon component averaged 1928m (vs. 1947m post-drought) and plots with 100% mortality averaged 1884m (vs. 1899m post-drought). The only exception was that the mean elevation of all plots with pinyon mortality (2106m) in pre-drought years was greater than the mean elevation (2053m) of all plots with pinyon measured in those years.

3.3 Stand composition

Because drought effects on juniper species have been minimal in comparison to pinyons, only plots including pinyon are described here. Pinyon species occurred on 9,419 plots over all years. The 5 pinyon species occurring on FIA plots were aggregated into 2 groups for the purpose of evaluating composition: the common pinyon group includes common pinyon, border pinyon, and Mexican pinyon, and the singleleaf pinyon group includes singleleaf pinyon and Arizona pinyon. Species from both groups occurred on 56 plots. In comparisons of the 2 pinyon groups, data from these plots are included in both groups.

In the pre-drought period, species in the common pinyon group accounted for an average of 36% of live plot basal area (per-hectare basis), with about 5.4% of plots being “pure” pinyon (97.5-100% pinyon BA). In the post-drought period, species in the common pinyon group averaged 37% of live basal area, with the portion of pure stands being 6.5%. In the pre-drought period, species in the singleleaf group averaged 53% of live basal area, with over 19% of plots being pure pinyon. After the drought, mean live basal area of the singleleaf group was close to the pre-drought figure (50%), but the portion of pure stands was reduced to 12%.

The distributions of composition percentages vary between groups as well. In the common pinyon group, pinyons occur as a minor component of the stand a large percentage of the time (Figure 3A). For example, pinyons make up less than 25% of the live basal area on over 40% of plots. In the singleleaf group, with the exception of pure stands, all compositional mixtures classes are about evenly represented in the sample (Figure 3B). In the singleleaf group, pinyons make up 25% or less of stand basal area only 21% of the time. In the post-drought period, the shape of the pinyon basal area distributions are similar to the pre-drought period, (Figures 3C and D), except that a relatively smaller number of singleleaf plots are pure, and singleleaf species appear to be a minor component in a larger portion stands (Figure 3D).

3.4 Stand structure

In pre-drought years, mortality appears to have occurred primarily in the larger diameter classes, with the mean diameter of mortality trees somewhat larger than the mean diameter of live trees. In post-drought years, the diameter distribution of mortality trees is similar to the diameter distribution of live trees. For example, in the pre-drought period, live trees >25 cm in diameter accounted for 21.6% of all trees measured, while 37.6% of mortality trees were >25 cm in diameter. In the post-drought period, live trees >25 cm in diameter accounted for 25.1% of all trees measured, whereas mortality trees >25 cm in diameter accounted for 20.2%.

The contribution of mortality trees to the standing dead component varies widely among species. Assuming that no additional mortality occurs, the recent drought will have increased the standing dead component of common pinyon by 3 to 4 times in smaller diameter classes, and nearly doubling the standing dead component in the largest classes. The quantity of standing dead singleleaf pinyon has nearly doubled. However, the change in standing dead trees appears negligible for the junipers. A notable aspect of the dead component is that, in the pre-drought period, it makes up a larger proportion of junipers than pinyons. This fact, coupled with the knowledge that junipers have a substantially lower background mortality rate than pinyons, implies that snag longevity of junipers may be considerably longer than that of pinyons.

4. Discussion

The recent drought has undoubtedly impacted the pinyon-juniper landscape, but the magnitude of effect varies by species. Differential mortality among species on the same site has been shown by Mueller et al. (2005), who found mortality of common pinyon to be 6.5 times higher than oneseed juniper mortality during 2 drought events in northern Arizona. Although a precise number has not yet been computed, common pinyon appears to have been reduced in basal area by 6 to 10% on a range-wide basis. Singleleaf pinyon has been affected to a lesser degree, and the impact to juniper species appears minimal, but detectable.

There does not appear to be evidence of wholesale range contractions in elevation or geographic extent, nor has there been substantial acreage on which type conversion has occurred due to elimination of one or more species. Allen and Breshears (1998) documented an up-slope forest-woodland ecotone shift resulting from differential mortality in ponderosa pine forests and pinyon-juniper woodlands in New Mexico. Observations suggest that similar shifts may have occurred at local scales during the recent drought. However, risk of mortality at the tree or stand scale may be more a function of edaphic factors, stand structural traits, and conditions conducive to rapid expansion of bark beetle populations, than elevation or proximity to a species' range limit.

Modern human influences have been at play in pinyon-juniper forests for at least 150 years, but their impacts are difficult to assess. For example, the effects of the 1950s drought were not well documented, but they are of high interest to ecologists who wish to understand the potential impacts of future climate change. However, the 1950s pinyon-juniper forests may offer limited opportunity for comparison because much of the acreage was in recovery from exploitation by railroad- and mining-related activity in the late 19th century. As a result, the 1950s drought acted on a younger forest than did the recent drought. There is also debate as to whether the current range of pinyon and juniper species has been influenced by grazing and fire suppression – i.e., in many cases we do not know if the forests are encroaching on land previously occupied by sagebrush and grasslands for a long period or if they are re-occupying ground periodically occupied by forest. This is an important distinction, because we would expect different responses to drought depending on the proximity of forest species to the edge of their ecological ranges.

Using FIA data, Shaw et al. (2005) documented recent drought-related mortality in the pinyon-juniper type and showed that annual FIA data could be used to monitor forest change over time. Their analysis was restricted to the pinyon component of plots classified as pinyon-juniper type. Plots occupied by junipers only and plots on which pinyons and junipers formed a minor component of another forest type were not analyzed. This study has taken the next step and examined pinyon and juniper species at nearly the entire extent of their range. Continued analysis should provide valuable insight into the past and future of these important forest types.

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Table 1: Species included in pinyon-juniper forest type definitions and number of records in the IW-FIA database.

Species	Common name	Number of trees	Number of unique plots
Juniperus californica Carr.	California juniper	84	11
Juniperus coahuilensis (Martinez) Gaussen	redberry juniper	327	73
Juniperus deppeana Steud.	alligator juniper	13,050	1,644
Juniperus monosperma (Engelm.) Sarg.	oneseed juniper	24,667	2,057
Juniperus occidentalis Hook.	western juniper	929	107
Juniperus osteosperma (Torr.) Little	Utah juniper	65,768	5,322
Juniperus scopulorum Sarg.	Rocky Mountain juniper	12,293	1,967
Pinus cembroides Zucc.	Mexican pinyon pine	231	20
Pinus discolor Bailey & Hawksworth	border pinyon	1,213	100
Pinus edulis Engelm.	common pinyon	68,966	4,971
Pinus monophylla Torr. & Frem.	singleleaf pinyon	23,696	1,767

Pinus monophylla var. *fallax* (Little) Silba	Arizona pinyon pine	918	134
Pinus quadrifolia Parl.	four-needled pinyon	0*	0*

* *P. quadrifolia* is included in the pinyon-juniper woodland type, but occurs only in California and Baja Mexico. As a result, there are no records in the IW-FIA database.

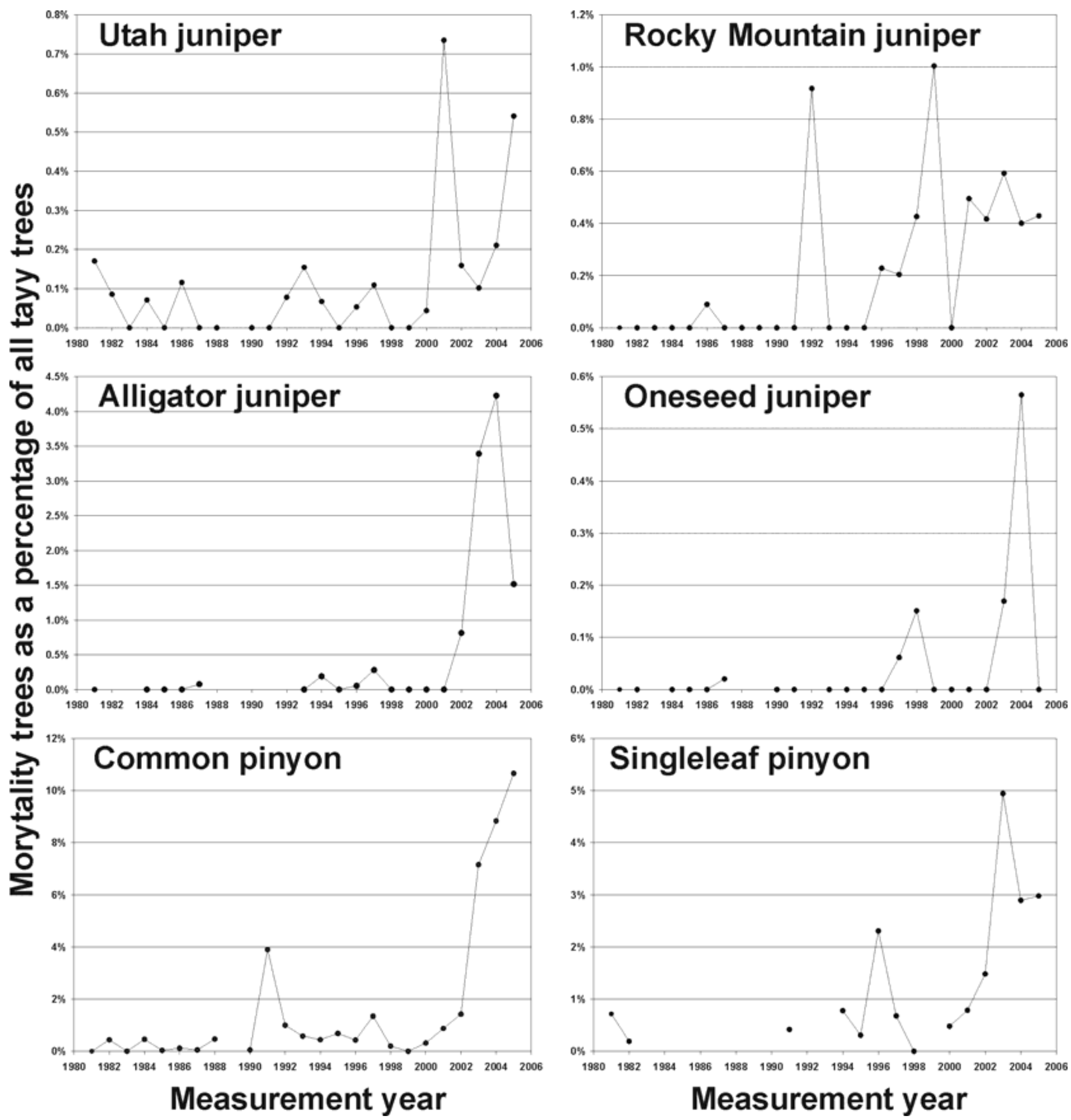

Figure 1: Mortality trees as a percentage of tally trees on all Forest Inventory and Analysis plots measured between 1981 and 2005. Mortality trees are those judged to have died during the 5 years prior to plot measurement. The number of observations for a particular species may vary year-to-year from 10s to 1000s, depending on geographic extent of inventory plots as that time. Note differing scales on y-axis.

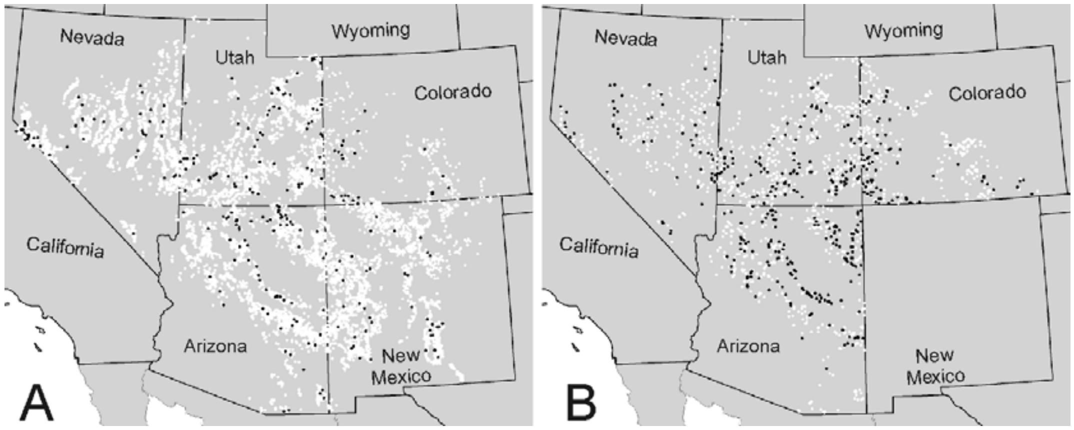

Figure 2: Forest Inventory and Analysis plots with pinyon species present measured 1981-2002 (A) and 2003-2005 (B). White points are plots on which no pinyon mortality trees were tallied, and black points are plots with at least 1 pinyon mortality tree.

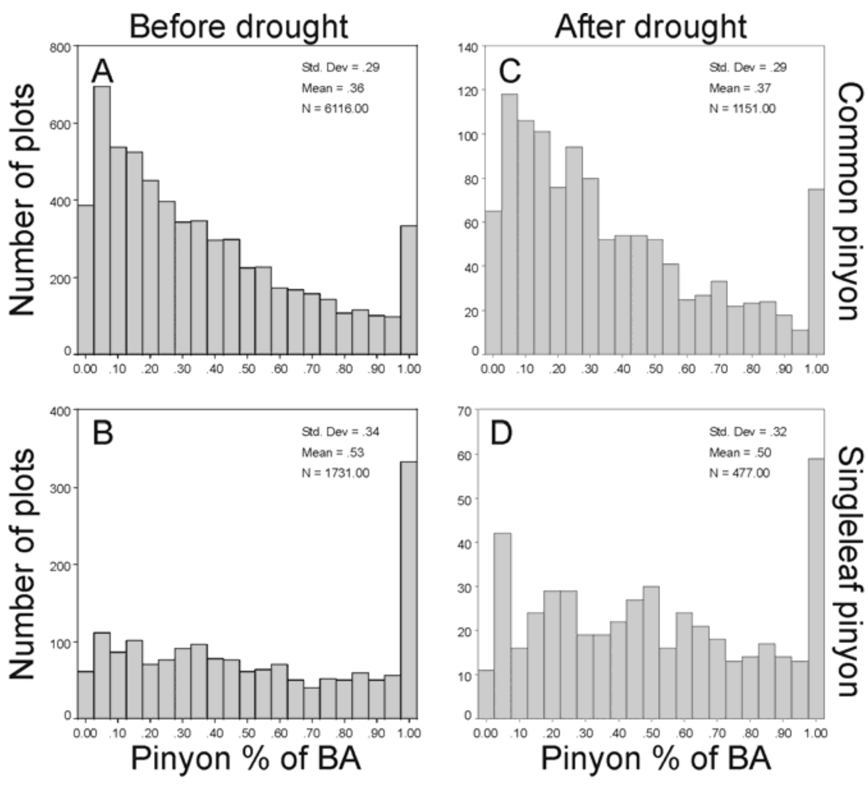

Figure 3: Pinyon species live basal area (BA) as a proportion of total plot live BA on a per hectare basis, before and after the recent drought-related mortality event. The common pinyon data include common pinyon, border pinyon, and Mexican pinyon, and the singleleaf data include singleleaf pinyon and Arizona pinyon. Note differing scales on y-axis.