Growth and Yield of Southwest Pinyon-Juniper Woodlands: Modeling Growth and Drought Effects

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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. Most public and scientific attention has been given to the extent of drought-related mortality and causal factors. At the same time, there has been relatively little attention given to non-lethal drought effects. As part of standard data collection protocol, the Interior West Forest Inventory and Analysis program measures radial increment on a portion of tally tree species. Between 1981 and 2005, data were collected on 14,929 plots with pinyon or juniper species present. These data included 10-year increment measurements on 23,080 pinyon and juniper trees. These data were used to characterize the "typical" growth patterns of pinyon and juniper species, and to analyze the effects of drought on radial increment. In addition, these measured increments were compared to those projected by the Forest Vegetation Simulator (FVS). Most species showed a reduction in diameter increment when data from pre-drought years were compared to post-drought years. FVS produced diameter increments that were within the range found in the data, but height growth may be over-predicted in some cases.*

Keywords: *diameter increment, height growth, Forest Inventory and Analysis (FIA), mortality, Forest Vegetation Simulator*

Introduction

Recent mortality in pinyon-juniper woodlands has been caused by a complex of drought, insects, and disease. The dramatic appearance of dying pinyons across the landscape brought much public and scientific attention to the episode, and there have been many attempts to assess the extent and severity of the mortality (Breshears and others 2005, Shaw and others 2005, Shaw 2006a, 2006b). However, there has been little attention given to the non-lethal effects of the drought. Tree rings are well-known as indicators of precipitation in dendrochronological and dendroecological studies (e.g., Baisan and Swetnam 1990, Swetnam and Betancourt 1990). Most of these studies look at long-term trends, commonly for the purpose of climatic reconstructions. Ogle and others (2000) found that variations in growth increment preceded mortality in pinyons that eventually succumbed to drought.

In this paper, increment data are used to make a preliminary assessment of growth patterns in pinyon and juniper species of the Southwest. Growth is evaluated from three perspectives: 1) typical radial growth patterns, 2) yield expectations from typical stands (i.e., growth-growing stock relationships), and 3) factors, including drought, that affect growth patterns. In addition, the diameter growth modeling approach used by the Forest Vegetation Simulator is examined.

In: Gottfried, Gerald J.; Shaw, John D.; Ford, Paulette L., compilers. 2008. Ecology, management, and restoration of piñon-juniper and ponderosa pine ecosystems: combined proceedings of the 2005 St. George, Utah and 2006 Albuquerque, New Mexico workshops. Proceedings RMRS-P-51. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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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 6000 acres. IW-FIA is responsible for lands in Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming. These states contain over 85% of the pinyon-juniper forest in the Western United States.

FIA field staff documented and measured 14,929 plots that included pinyon or juniper species between 1981 and 2005. Radial increment was measured on 23,080 pinyon and juniper trees (table 1). Increment from the 10 years prior to plot visit was measured from a core and recorded to the nearest 1/20 inch. This value was transformed to the 10-year diameter increment as a percentage of starting diameter (i.e., diameter 10 years prior to measurement). Diameter and increment are measured at the root collar for all pinyon and juniper species, except for western juniper, which is measured at breast height.

Several other variables were measured or calculated at the plot level, including elevation and basal area. Data were aggregated for the purpose of comparing pre-drought and post-drought conditions. Based on analyses of mortality on FIA plots (Shaw and others 2005, Shaw 2006b), data from 1981-2002 are considered to be pre-drought and data from 2003-2005 are post-drought.

A flexible nonlinear function (equation [1]) was fitted to the transformed increment data in order to explore growth sensitivity to different factors. For the purpose of evaluating the effect of different factors (e.g., stand basal area), the factors were grouped into classes and the model was fitted to each class separately.

$$diapctgrow - a(b - \exp(-c \cdot dia10ago)) \qquad [1]$$

where *diapctgrow* is diameter increment expressed as a percentage of starting period diameter,

*dia*10*ago* is stem diameter at beginning of increment period,
and *a*, *b*, and *c* are parameters to be estimated.

Using the modeled increment curve and a generalized height growth curve, 10-year periodic growth and yield were simulated for a hypothetical "average" stand of common pinyon. In the hypothetical stand, all trees are of identical diameter and height. The stand was initiated using a starting diameter of 3.8 inches and

Table 1—Number of records including increment data for pinyon and juniper species in the IW-FIA database.

Species	Common name (FIA code)	Number of increments
Juniperus coahuilensis (Martinez) Gaussen	redberry juniper (59)	116
Juniperus deppeana Steud.	alligator juniper (63)	1436
Juniperus monosperma (Engelm.) Sarg.	oneseed juniper (69)	2291
Juniperus occidentalis Hook.	western juniper (64)	143
Juniperus osteosperma (Torr.) Little	Utah juniper (65)	6498
Juniperus scopulorum Sarg.	Rocky Mountain juniper (66)	1908
Pinus discolor Bailey & Hawksworth	border pinyon (134)	198
Pinus edulis Engelm.	common pinyon (106)	8761
Pinus monophylla Torr. & Frem.	singleleaf pinyon (133)	1569
Pinus monophylla var. *fallax* (Little) Silba	Arizona pinyon pine (143)	160

a height of 11.3 ft. For each 10-year period in the simulation, diameter increment was predicted as a function of starting period diameter, and height was calculated as a function of diameter. Yield was calculated for each period based on stem densities of 50, 100, 150, 200, 250, 300, and 400 trees per acre.

In addition to data-based projections, the Forest Vegetation Simulator (FVS) (Johnson 1997) was used to project a number of pinyon-juniper stands using FIA data collected in New Mexico. These simulations were not a formal test of FVS performance, but rather a comparative check of FVS output in terms of diameter and height growth.

Results

General Growth Patterns

Growth varied somewhat among species, but followed general patterns; results are shown for representative species. Detailed statistical evaluations are not included because the analyses presented here are exploratory in nature and only presented for illustration of general relationships.

All species showed similar growth patterns: high variability in early growth followed by a decrease that follows a negative exponential pattern (figure 1). In general, starting diameter alone predicted less than 50% of the variation in diameter increment, using equation [1] or related equations. While these equations were sufficiently flexible to capture the basic relationship and produce unbiased fits, the regression models could not account for the high variability of increment in small trees.

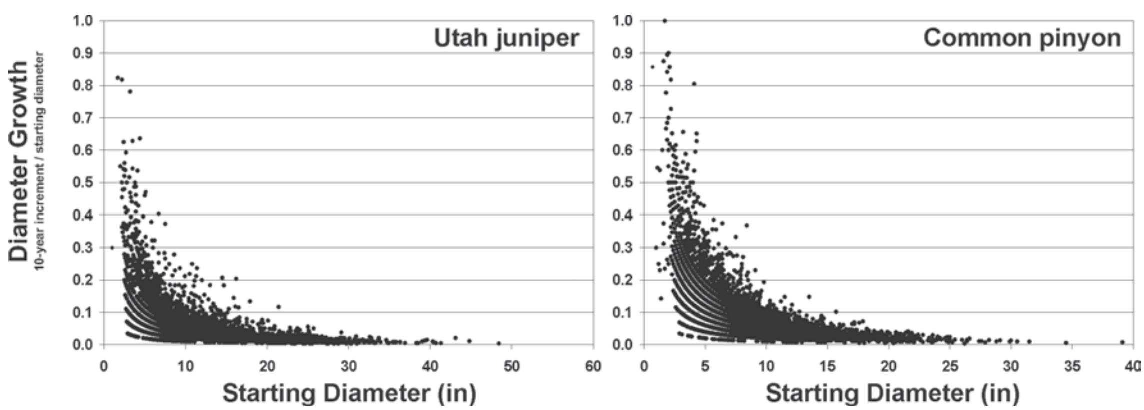

Figure 1— Ten-year radial increment data for Utah juniper (n = 6498) and common pinyon (n = 8761). Radial increments have been transformed to diameter growth as a fraction of starting diameter (i.e., diameter at the start of the 10-year growth period).

Growth and yield of the hypothetical average pinyon stand was consistent with expectations (table 2). Periodic annual increment at most combinations of age and density was generally lower than commonly considered as productive forest land (a minimum of about 10 ft^3/ac/yr). Yields higher than 10 ft^3/ac/yr could be achieved in highly-stocked conditions, but there was an apparent stocking-limited ceiling on yield at approximately 14 ft^3/ac/yr. This situation arises because combinations of size and density needed to achieve higher yield are at the limits of possible relative density—i.e., stand density index greater than about 350. As a result, limits of age and stocking appear to keep mean annual increment below 10 ft^3/ac/yr (figure 2). However, it should be noted that this simulation represents an "average" condition, and that yield could be substantially higher on better sites.

Table 2—Mean annual increment (cubic ft per acre per year) for a hypothetical pinyon stand for stand densities of 50 to 400 trees per acre. Diameter growth is based on average modeled 10-year radial increment of common pinyon. Light shading indicates combinations of age and density that achieve yield considered to be in the commercial range. Dark shading indicates yields that are not likely to be achievable because of limitations on relative density.

Age	DRC	Height	TPA50	TPA100	TPA150	TPA200	TPA250	TPA300	TPA400
40	3.8	11.3							
50	5.0	12.9	1.5	2.9	4.4	5.8	7.3	8.7	11.6
60	5.7	13.9	1.2	2.4	3.6	4.8	6.1	7.3	9.7
70	6.4	14.6	1.3	2.6	3.8	5.1	6.4	7.7	10.2
80	7.0	15.3	1.4	2.7	4.1	5.5	6.9	8.2	11.0
90	7.6	15.9	1.5	3.0	4.5	5.9	7.4	8.9	11.9
100	8.1	16.5	1.6	3.2	4.8	6.4	8.0	9.7	12.9
110	8.7	17.1	1.7	3.5	5.2	7.0	8.7	10.4	13.9
120	9.2	17.6	1.9	3.8	5.6	7.5	9.4	11.3	15.0
130	9.7	18.1	2.0	4.0	6.1	8.1	10.1	12.1	16.2
140	10.2	18.6	2.2	4.3	6.5	8.7	10.9	13.0	17.4
150	10.8	19.1	2.3	4.7	7.0	9.3	11.7	14.0	18.7
160	11.3	19.5	2.5	5.0	7.5	10.0	12.5	15.0	20.0
170	11.8	20.0	2.7	5.3	8.0	10.7	13.4	16.0	21.4
180	12.3	20.4	2.9	5.7	8.6	11.4	14.3	17.1	22.8
190	12.8	20.8	3.0	6.1	9.1	12.2	15.2	18.3	24.3
200	13.3	21.2	3.2	6.5	9.7	13.0	16.2	19.4	25.9
210	13.9	21.7	3.4	6.9	10.3	13.8	17.2	20.7	27.6
220	14.4	22.1	3.7	7.3	11.0	14.6	18.3	22.0	29.3
230	14.9	22.5	3.9	7.8	11.7	15.5	19.4	23.3	31.1
240	15.4	22.9	4.1	8.2	12.4	16.5	20.6	24.7	32.9
250	16.0	23.3	4.4	8.7	13.1	17.4	21.8	26.2	34.9

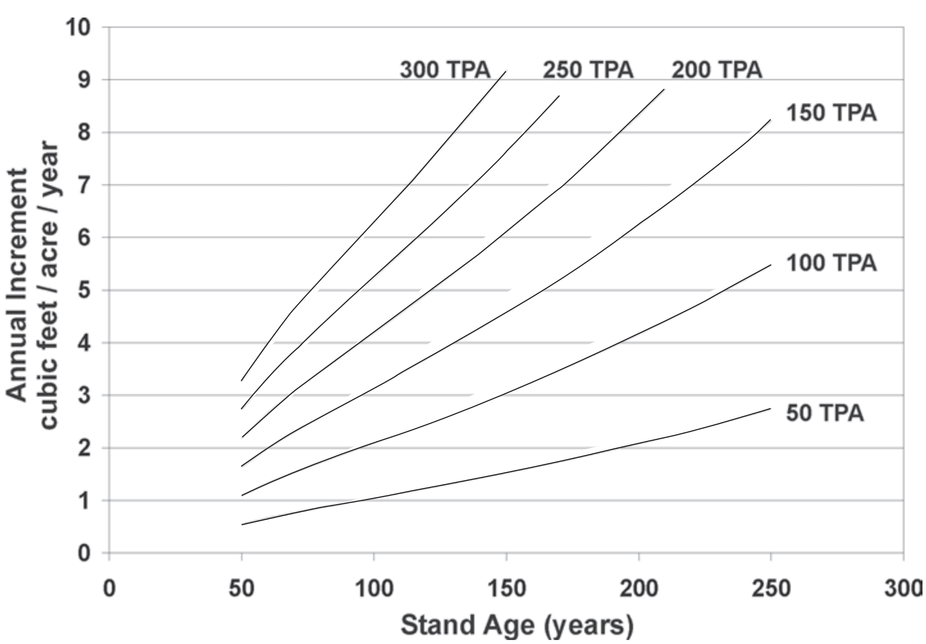

Figure 2—Mean annual increment in cubic feet per acre per year for hypothetical stands of common pinyon at stem densities of 50 to 300 trees per acre. Diameter growth is modeled from 10-year increment data (see figure 1).

Effects of Stand and Site Factors

In most cases, diameter growth responded to stand and site factors as expected. However, there were some exceptions. To evaluate the effect of elevation, plots were grouped into four 2000-ft elevation classes and fitted growth curves to each class separately. Utah juniper showed a clear negative relationship between elevation and diameter increment (figure 3a). The results for common pinyon were mixed, with the 2000-ft class having the smallest increment; diameter growth was higher in the other 3 elevation classes, but there was no clear pattern among those (figure 3b). To evaluate the effect of stand density, classes of 50, 100, 150, and 250 trees per acre were used. As expected, there was a negative relationship between growth and stand density (figure 3c,d). The effect of stand density on diameter growth was clearest when starting diameter was less than 18 inches. In larger trees, there appeared to be little to no effect of density on diameter increment.

Effects of Drought

In general, drought had a negative effect on increment, although the magnitude and range of diameters over which it appeared strongest varied by species. Increment reductions were relatively small for most species, and in the case of common pinyon, larger trees had slightly better growth during drought years (figure 4). This situation may be attributable to the number of large pinyons that succumbed to drought. Average growth of residual trees may have been effectively increased by removal of mortality trees, which tend to have smaller increments

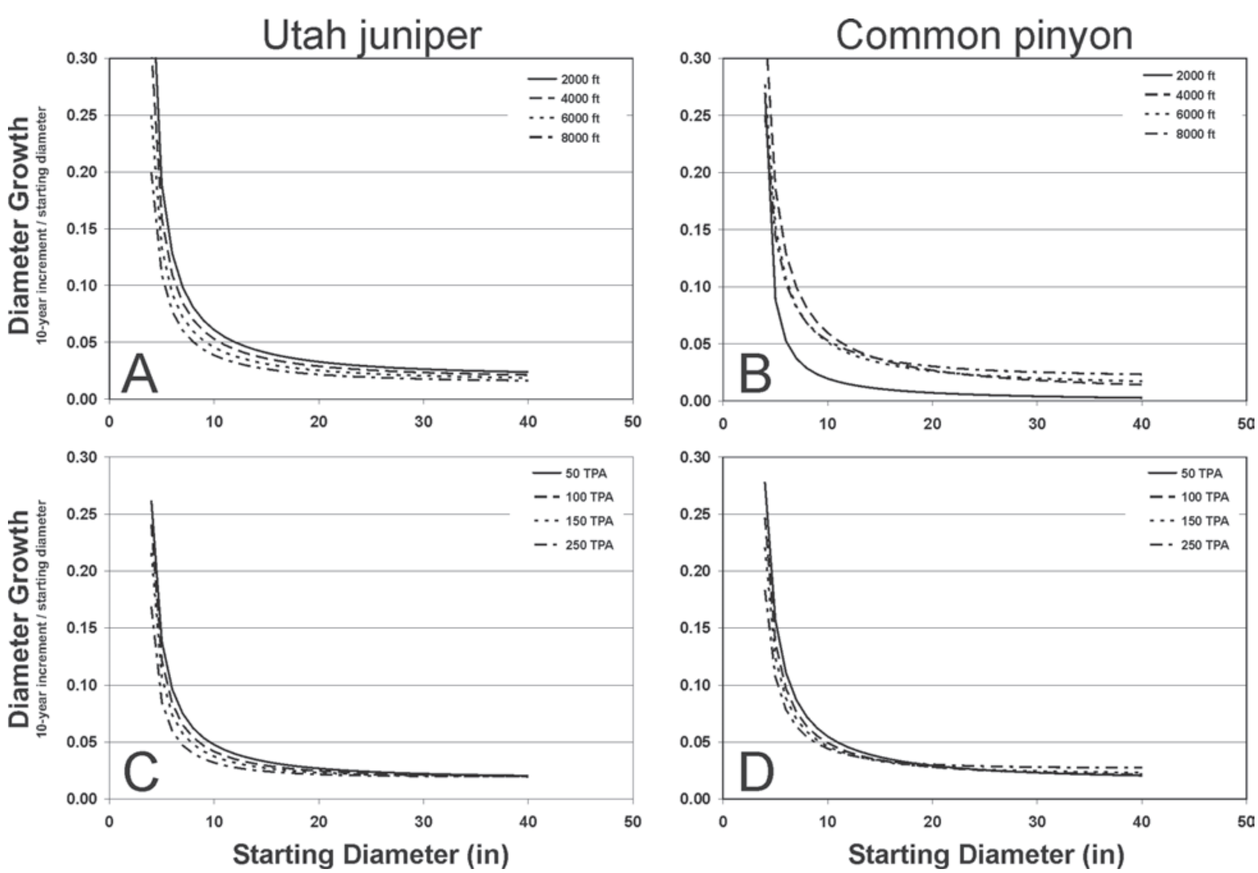

Figure 3—Variation in diameter growth of Utah juniper and common pinyon as a response to elevation (A and B) and stand density (C and D).

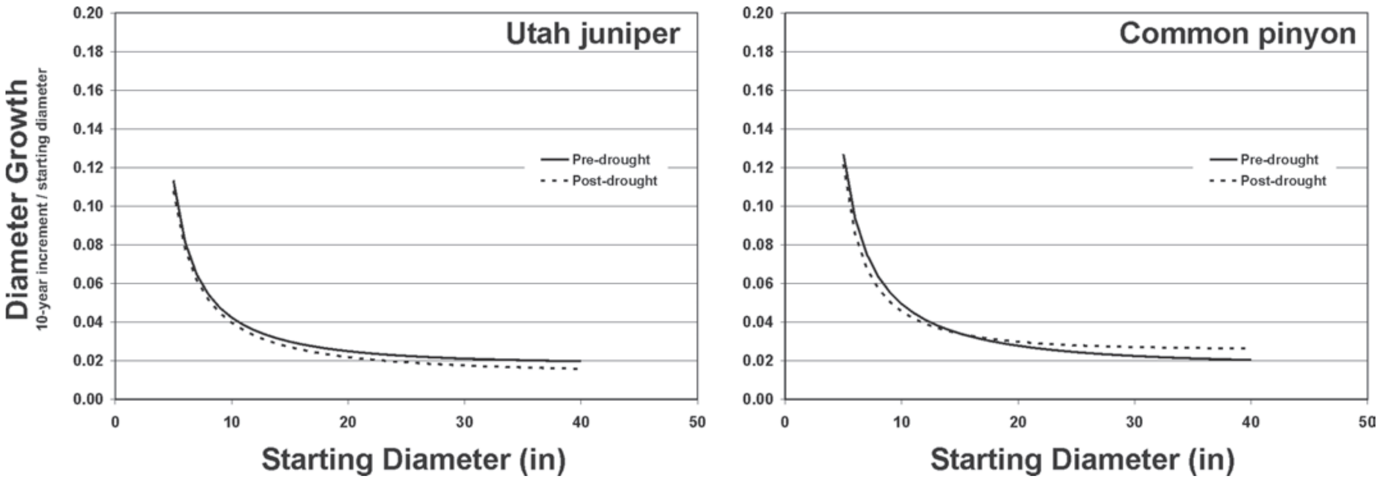

Figure 4—Variation in diameter growth of Utah juniper and common pinyon as a response to drought. Pre-drought data include all increment observations recorded 1981-2002 and post-drought data include increment measurements record 2003-2005.

during drought than similar-sized trees that ultimately survive the drought (Ogle and others 2000). However, for some species there were substantial reductions in increment. At 12 inches diameter, alligator juniper showed a 9 percent reduction and singleleaf pinyon showed a 17 percent reduction.

Forest Vegetation Simulator Projections

In our simulations, FVS appeared to project diameter growth without bias, but only captured a fraction of the natural range of variability found in young trees. However, the limited range of projected growth could be a function of the geographic limits of the source data. Height growth was somewhat over-projected, resulting in slightly higher yield projections.

Discussion

Growth patterns of pinyon-juniper woodlands have been studied in the past (Howell 1941, Reveal 1944, Daniel and others 1966, Chojnacky 1987, Little 1987, Smith and Schuler 1987), but not to the extent of commercially important species. Interest in pinyon-juniper woodlands has been cyclic, with high points of interest based on changing management needs (Van Hooser and Casey 1987). Currently interest is at a high point due, at least in part, to the recent drought and associated mortality of pinyon across the landscape. Some interest in pinyon-juniper woodland may also be attributable to the increased attention given to climate change, carbon sequestration, and wildfire. The recent increase in interest has been shown by an increase in ecological studies, but little in the way of basic productivity research.

Although pinyon-juniper woodlands are only marginally important from a wood productivity standpoint, basic growth information is an important element of ecological studies. Knowledge of growth and yield is essential to understanding how long it will take woodlands to recover from drought- or fire-related mortality, and how carbon balances might change over time. It is also important to understand the effects of climate on growth. The data show relatively predictable growth patterns in pinyon-juniper woodland, but to accurately project growth it will be necessary to account for the variation observed in smaller trees. Much of this variation can be accounted for by various stand and site factors, which will be investigated further in ongoing studies. Additional variation, found in all size classes, is apparently a result of climatic factors—most likely precipitation, temperature, or both. The recent drought had a demonstrable impact on growth and mortality, and only the latter has been taken into account in any detail. Better prediction of future stand growth should be possible by taking climatic factors into account.

The Forest Vegetation Simulator (Johnson 1997) predicts growth reasonably well according to practitioners who have used it to project pinyon-juniper stands. The limited testing done here generally supports their claims, although some improvements can be made. The current FVS diameter growth model has a linear, 13-parameter form and accounts for several stand and site factors, in addition to diameter-based variables. Although this model works reasonably well, there may be limitations based on model form (Shaw and others 2006).

The results presented here suggest that a modeling approach in which the basic, nonlinear size-increment model can be built upon using stand and site factors. Using sensitivity analysis, Vacchiano and others (in press) have shown differential contributions of variables in the current diameter growth model used in the Southern Variant of FVS. Further exploration of the relative importance of stand and site variables may lead to development of a new model form in which variables are added by importance rank. Such an approach may produce a parsimonious model that captures the maximum amount of variability that is practical.

Finally, existing variants of FVS do not account for climate, although development of climate-based variants is under investigation (Crookston 2007). Although the emphasis of this work is on long-term climate change, analysis of recent increment data indicate that incorporation of a climate component would benefit even short-term growth simulations.

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