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Estimating Diameter Growth for Pinyon and Juniper Trees in Arizona and New Mexico

David C. Chojnacky

Abstract—Diameter growth measurement is difficult for pinyon and juniper trees because they are slow-growing, multiple-stemmed, and poorly suited to measurement methods used for other temperate tree species. This paper describes a model designed to estimate diameter growth for individual pinyon and juniper trees from a small subsample of growth measurements. Data for model construction include 10-year radial growth sampled from 1,536 trees on 176 plots spread throughout Arizona and New Mexico. Species include *Pinus edulis*, *Juniperus monosperma*, *J. deppeana*, *J. scopulorum*, and *J. osteosperma*. The model predicts past 10-year diameter growth from stand-level growth-index measurement, tree diameter, and number of basal stems in a tree.

Keywords: individual-tree model, *drc*, tree rings, inventory, log regression

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Estimating diameter growth is an important aspect of forest management and inventory. Coring trees and counting rings, a common method to estimate growth, is not easy to do in the field for pinyon-juniper species. Also, juniper trees often have multiple stems originating from a single root system, creating additional measurement complications (Chojnacky 1990). Measuring a few trees and extrapolating results to a larger population would be simpler. With this approach, an individual-tree model (Chojnacky, in preparation) was constructed to estimate diameter growth of all trees on a plot from growth measurement of a few trees:

$$\ln drc_g = \beta_0 + \beta_1 \ln drc + \beta_2 drc^2 + \beta_3 \ln g_{index} \quad (1)$$

where

drc_g = 10-year diameter growth at drc (cm)

$drc = \sqrt{\sum_{i=1}^{stems} d_i^2}$

d_i = stem diameter near the root collar, above groundline forks and major diameter swell (cm)

$stems$ = number of stems near the root collar with diameter (d_i) 3.8 cm or larger

$g_{index} = \left(Pqmd_g \sqrt{stems}\right)$ for pinyon, $\left(Jqmd_g \sqrt{stems}\right)$ for juniper

$Pqmd_g$ = 10-year qmd growth of the median qmd (median-sized tree) from a plot's pinyon distribution (cm)

$Jqmd_g$ = 10-year qmd growth of the median qmd (median-sized tree) from a plot's juniper distribution (cm)

$qmd = drc/\sqrt{stems}$

ln = natural logarithm with e as a base

β = equation parameter

This model was patterned after growth and yield models developed for temperate forests (Edminster and others 1991; Hann and Larsen 1991). It differs in using a stand-level growth index ($g_{(index)}$) instead of a site quality variable and in not using any variable to describe tree competition within plots. This strategy was necessary because site quality and stand competition in pinyon-juniper forests are not understood well enough to develop variables to measure these processes.

The purpose of this paper is presentation of an individual-tree model (eq. 1) that is applicable to Arizona and New Mexico. The equation 1 model form was developed from only New Mexico data (Chojnacky, in preparation). Now available Arizona data (Chojnacky 1988) are added and tested to estimate a single set of parameters for equation use in both States.

David C. Chojnacky is a Research Forester, with the Interior West Resource Inventory, Monitoring, and Evaluation Program, Intermountain Research Station, located at the Forestry Sciences Laboratory, Ogden, UT. Currently he is visiting assistant professor at Purdue University, West Lafayette, IN.

Data

Pinyon and juniper growth were available from 176 plots (fig. 1). Most plots were subsampled from inventories (Conner and others 1990; Van Hooser and others 1993) conducted in the 1980's by the U.S. Department of Agriculture, Forest Service, Interior West Resource Inventory, Monitoring, and Evaluation Program through its Forest Inventory and Analysis activity (commonly called FIA). In Arizona, 94 plots were systematically selected from FIA plots on private, State, Bureau of Land Management, Prescott National Forest, and Hopi Indian Reservation land ownerships (Chojnacky 1988). Arizona data were collected concurrent with the 1985 FIA inventory, which limited the sample to lands surveyed by FIA that year. Navajo, San Carlos, Fort Apache, Hualapai, and Havasupai Indian Reservations, and Kaibab, Coconino, Apache-Sitgreaves, and Coronado National Forests were not included in these surveys. In New Mexico, 82 plots were randomly selected in 1986 and 1987 from prior FIA and National Forest inventories (Chojnacky, in preparation).

All 176 growth plots were fixed-area and circular: 81 were 0.08 ha; 93 were 0.04 ha; and 2 were 0.02 ha in size. Tree measurements from these plots included species identification, diameter at groundline near the root collar (*drc*), total tree height, the number of stems (3.8 cm and larger) at *drc*, and 10-year radial growth cores. Trees were defined as having one or more stems originating from a single root system with at least one stem at a diameter of 7.6 cm. Increment cores were taken by diameter classes from trees randomly selected within each pinyon and juniper genus. This design subsampled about half the trees on each plot and it covered all tree sizes. Two or more 10-year radial increment cores were collected from each tree subsampled for growth. Increment cores were glued into holders in the field and were later sanded and measured under magnification.

Although researchers dispute how well ring counts assess growth rates, Despain (1989) has shown that ring counting can estimate 10-year diameter growth if some error can be tolerated. For Utah juniper in Arizona, Despain (1989) found that a 5 percent error should be expected for most trees, but errors exceeding

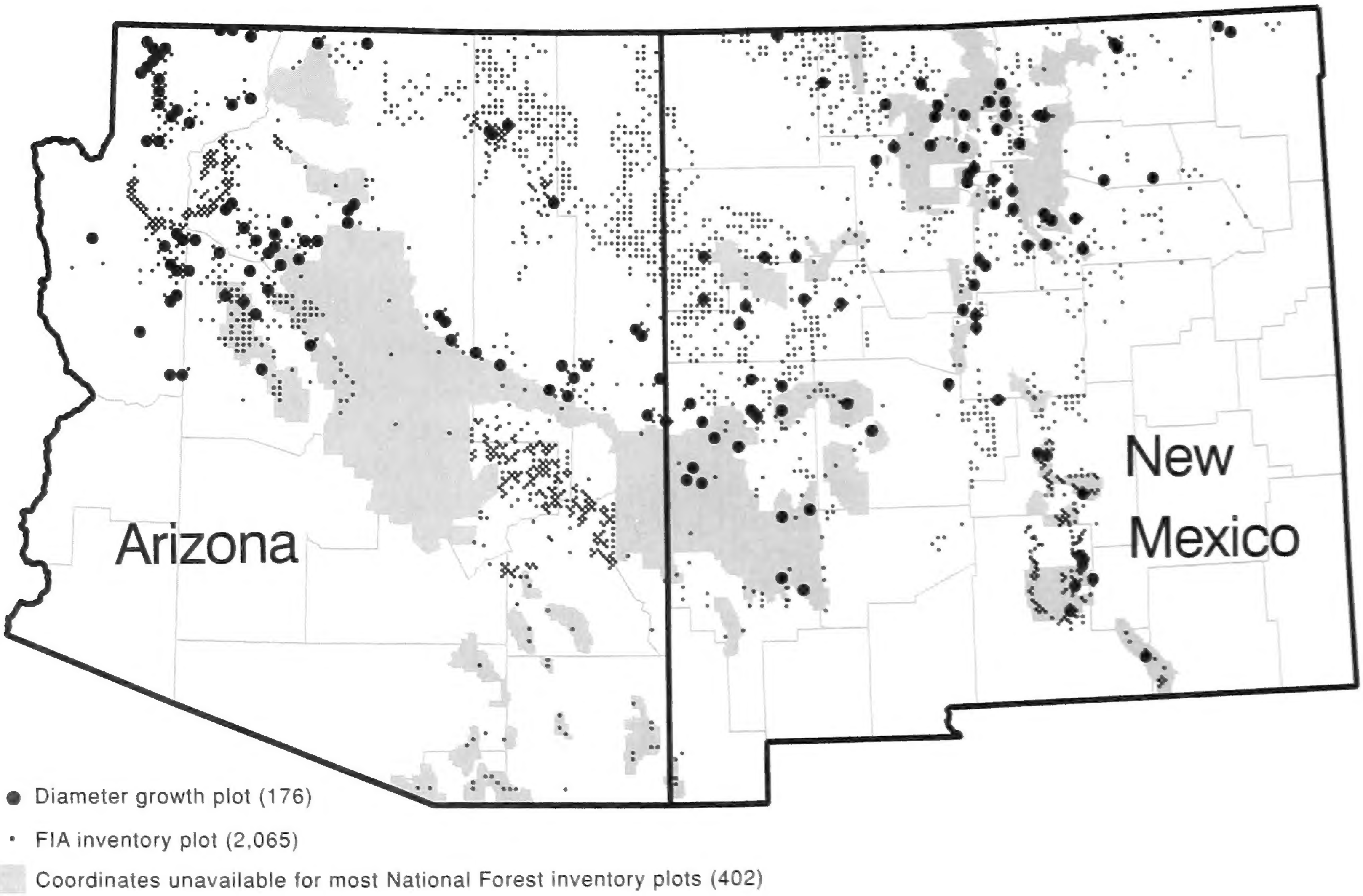

Figure 1—Diameter-growth data from 176 plots were used to estimate parameters for the growth model (eq. 1). Data represent a subsample of 2,467 plots from the Forest Inventory and Analysis (FIA) database for pinyon-juniper forest types. There are 402 plots in the FIA database supplied by the National Forests that have no geographic coordinates.

20 percent need only be expected for about 20 percent of the trees.

Tree-ring cores for Arizona data were collected by FIA crews, and measurements were done at Colorado State University. The New Mexico data were collected by a single study crew, and measurements were done at Utah State University. Ten-year growth was measured as the distance from the first visible ring (after the vascular cambium) to the eleventh ring. False rings were not identified; all rings were counted.

Growth data for Arizona and New Mexico (table 1) totaled 774 pinyon (*Pinus edulis* Engelm.), 375 oneseed juniper (*Juniperus monosperma* [Engelm.] Sarg.), 275 Utah juniper (*J. osteosperma* [Torr.] Little), 70 alligator juniper (*J. deppeana* Steud.), and 42 Rocky Mountain juniper (*J. scopulorum* Sarg.). Forty percent came from Arizona's 94 plots and 60 percent of the trees came from New Mexico's 82 plots.

Modeling

Computing Growth Index

The individual-tree growth model (eq. 1) was formulated differently than growth models for other temperate forest species. Because of difficulties finding suitable site quality and stand competition variables, an alternative "growth index" was used as a surrogate for site and stand description. A variant of Meeuwig and Cooper's (1981) work was utilized to devise an index representing diameter growth of the median-sized tree for each pinyon and juniper genus found on each plot. This method first computes the quadratic mean diameter (*qmd*) for each tree:

$$qmd = \frac{drc}{\sqrt{stems}} \qquad (2)$$

where

$stems$ = number of stems within a tree at drc with diameter (d_i) 3.8 cm or larger

$drc = \sqrt{\sum_{i=1}^{stems} d_i^2}$

d_i = stem diameter near the root collar, above groundline forks and above major diameter swell (cm)

Next, past 10-year diameter growth for pinyon ($Pqmd_g$) and juniper ($Jqmd_g$) is determined for each plot from trees corresponding to the median qmd for each genus:

$$Pqmd_g = \alpha_{0k} + \alpha_{1k}\, Pqmd_{50k} \qquad (3)$$

$$Jqmd_g = \beta_{0k} + \beta_{1k}\, Jqmd_{50k} \qquad (4)$$

where

α = parameters estimated within each plot (k) from all pinyon stem diameters (d_i) sampled for growth, average $R^2 = 0.32$ and average $n = 6.4$ stems per plot

$Pqmd_{50k}$ = the median qmd from the pinyon distribution of each plot (k)

β = parameters estimated within each plot (k) from all juniper stem diameters (d_i) sampled for growth, average $R^2 = 0.29$ and average $n = 6.2$ stems per plot

$Jqmd_{50k}$ = the median qmd from the juniper distribution of each plot (k)

These equations were constructed using a separate linear regression for each plot. About six stems per plot,

Table 1—Pinyon and juniper diameter (*drc*) growth data sampled from Arizona and New Mexico, 1985 to 1988.

State	Species	No. of trees	Median				90th percentile				Multiple-stem trees
			10-year growth	*drc*	Height	No. of stems	10-year growth	*drc*	Height	No. of stems	
			- - - - *cm* - - - -		*m*		- - - - *cm* - - - -		*m*		*Percent*
Arizona	Pinyon	157	1.8	16.5	4.0	1.0	3.6	32.8	7.0	1	3
	Alligator juniper	16	2.0	16.6	3.4	1.5	3.9	65.4	7.0	5	50
	Oneseed juniper	177	1.7	26.7	3.4	3.0	3.2	59.2	5.5	10	63
	Utah juniper	269	1.5	23.9	4.0	1.0	3.5	52.6	5.8	5	36
	Total juniper	462	1.6	24.8	3.7	1.0	3.3	55.2	5.5	7	47
New Mexico	Pinyon	617	1.3	16.8	5.2	1.0	2.2	29.7	7.9	1	7
	Alligator juniper	54	1.2	18.6	4.3	1.0	2.4	38.4	6.1	3	39
	Oneseed juniper	198	1.5	22.7	3.4	3.0	2.6	43.7	4.9	8	73
	Utah juniper	6	0.8	33.9	4.4	2.0	1.6	53.8	5.2	4	50
	Rocky Mountain juniper	42	1.3	18.9	4.3	1.0	2.5	33.3	6.1	2	26
	Total juniper	300	1.4	21.0	3.7	2.0	2.6	42.2	5.2	7	60
Total	Juniper	762	1.5	23.1	3.7	2.0	3.1	50.3	5.5	7	52
	Pinyon	774	1.4	16.8	4.9	1.0	2.6	30.2	7.9	1	6

spanning the range of pinyon and juniper stem diameters (d_i), were available for each regression. Regression slopes were both positive and negative; 58 percent of 118 pinyon and 58 percent of 152 juniper regression equations had positive slopes.

Even though R^2 values were low and regression relationships alternated between negative and positive slopes, I was not concerned because only the midrange of each regression equation was used to estimate a single value for each plot. If regression end points or extrapolations had been needed, linear regressions would not have been used. But from previous model construction experience (Chojnacky, in preparation) equations 3 and 4, which relied on the robust nature of medians, were found superior to indices based on mean, minimum, or maximum growth.

Estimating Parameters

Before estimating parameters, State and species differences within the growth data were examined statistically for possible data separation. A category for multiple- and single-stem trees was not included in the tests; instead, these two groups were initially made because of measuring differences.

An *F*-test (Graybill 1976, p. 247) showed little advantage for separating the Arizona and New Mexico data (table 2). Only single-stem pinyon trees tested significantly different between Arizona and New Mexico. And even for these data, the smaller Arizona sample (152 of 728) did not have enough replication from some tree sizes to warrant separate equations for each State.

An *F*-test was also used to compare possible species differentiation for combined Arizona and New Mexico data. An initial test showed a significant difference (Prob > F = 0.008) among species for multiple-stem trees. However, this result was highly influenced by a few trees greater than 70-cm *drc*. With recalculation, after excluding the 13 (out of 441) trees over 70-cm *drc*, no species differences were evident among multiple-stem trees (Prob > F = 0.136).

Therefore, all data (including trees over 70-cm *drc*) for both States and for all species were combined into multiple- and single-stem groups for parameter estimation (table 3). This strategy provided considerable data for both equations; yet the model still expressed some site and species differences through the growth index variable. Because a growth index was independently estimated for each plot, it automatically included some species and site effects.

Graphs of regression residuals supported grouping data by State and species, since no unreasonable patterns were observed (fig. 2). Although the residuals showed considerable variation, the lack of patterns gives confidence for unbiased model predictions for large sample sizes.

The growth index was the model's most important variable (fig. 3). Successive stepwise regressions showed that it accounted for more than 95 percent of variation explained by the model.

Summary

Parameters were estimated for an individual-tree diameter growth model from pinyon-juniper data

Table 2—*F*-tests comparing full[a] and reduced[b] growth models between Arizona and New Mexico data.

Tree form	Species	No. of trees Arizona	 New Mexico	*F*-value	Prob > *F*
Multiple-stem	Alligator juniper	8	21	0.99	0.4361
	Oneseed juniper	111	144	2.17	0.0732
	Utah juniper	97	3	0.88	0.4780
	Rocky Mountain juniper	0	11	0.00	1.0000
	Pinyon	5	41	0.44	0.7803
Single-stem	Alligator juniper	8	33	1.10	0.3738
	Oneseed juniper	66	54	0.73	0.5716
	Utah juniper	172	3	0.31	0.8682
	Rocky Mountain juniper	0	31	0.00	1.0000
	Pinyon	152	576	4.41	0.0016*

[a] Full model:

$$\ln drc_g = \alpha_0 + \alpha_1 \ln drc + \alpha_2\, drc^2 + \alpha_3 \ln g_{index} + \eta_0 + \eta_1 \ln drc + \eta_2\, drc^2 + \eta_3 \ln g_{index}.$$

where

α = parameter estimates for Arizona data, and 0 for New Mexico data.

η = parameter estimates for New Mexico data, and 0 for Arizona data.

[b] Reduced model:

$$\ln drc_g = \beta_0 + \beta_1 \ln drc + \beta_2\, drc^2 + \beta_3 \ln g_{index}.$$

where

β = parameter estimates for Arizona and New Mexico data combined.

*For the α-level set at 0.05, the full and reduced models are significantly different.

Table 3—Parameters for estimating pinyon and juniper diameter growth in Arizona and New Mexico.

Tree form	Parameter estimates[a] β_0	β_1	β_2	β_3	No. of trees	Regression statistics[b] R^2	C.V.	Bias[c]
							Percent	
Multiple-stem	0.777	0.1088	–0.0000913	0.8647	441	0.60	35	1.0684
Single-stem	0.661	0.1932	–0.0001594	0.9473	1,095	0.60	36	1.0705

[a] Diameter growth equation:

$$drc_g = \beta_0\, drc^{\beta_1}\, exp(\beta_2\, drc^2)\, (g_{index})^{\beta_3}$$

where

drc_g = past 10-year diameter growth at drc (cm)

$$drc = \sqrt{\sum_{i=1}^{stems} d_i^{\,2}}$$

d_i = stem diameter near the root collar, above groundline forks and major diameter swell (cm)

$stems$ = number of stems at drc with diameter (d_i) 3.8 cm or larger

g_{index} = $\left(Pqmdg\sqrt{stems}\right)$ for pinyon, $\left(Jqmd_g\sqrt{stems}\right)$ for juniper

$Pqmd_g$ = 10-year qmd growth of the median qmd (median-sized tree) from a plot's pinyon distribution (cm)

$Jqmd_g$ = 10-year qmd growth of the median qmd (median-sized tree) from a plot's juniper distribution (cm)

$qmd = drc/\sqrt{stems}$

[b] The coefficient of determination (R^2) and coefficient of variation (C.V.) were recomputed in original diameter-growth units.

[c] The β_0 parameter was corrected by this amount to compensate for log regression (Flewelling and Pienaar 1981).

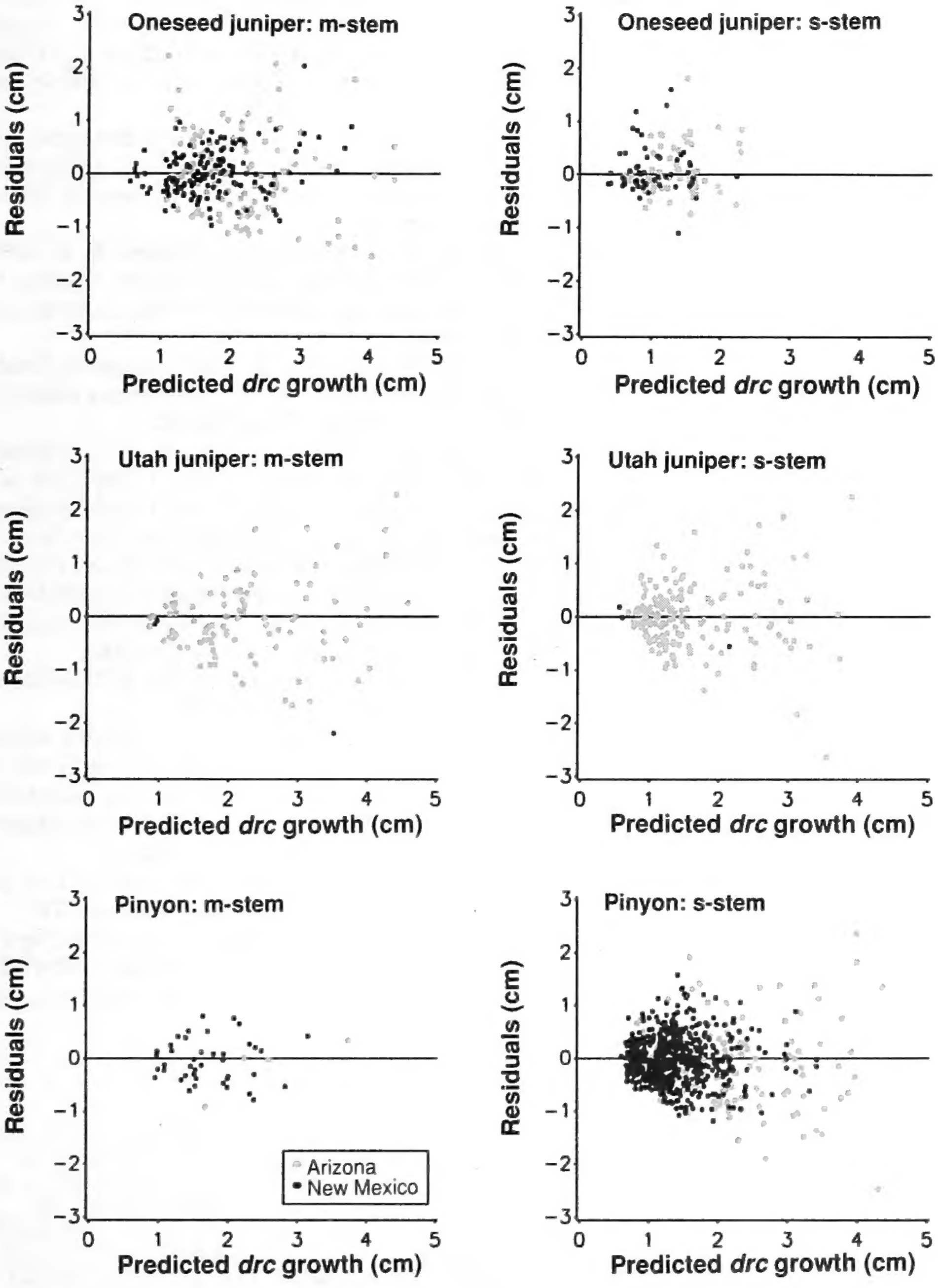

Figure 2—Regression residuals (observed minus predicted) for 10-year diameter-growth data fit to equation (1). Residuals are expressed in original units (not logs), and include the log bias correction (see table 3). Residual data are separated to show that no discernible patterns can be seen from fitting data combined by State and species. Seven *x,y* data points—(5.1, –1.9), (2.4, 3.1), (5.3, 0.1) for oneseed juniper; (5.3, –0.6), (5.8, –2.3), (3.4, –3.3) for Utah juniper; and (5.7, 1.0) for pinyon—are omitted from graphs because they are outside the axes ranges.

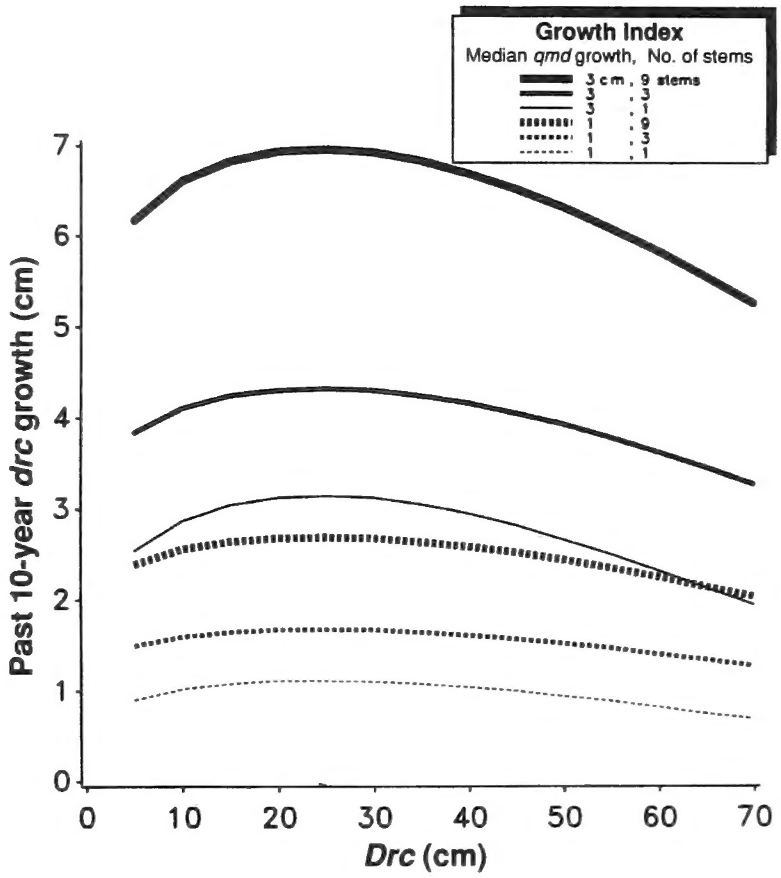

Figure 3—Past 10-year diameter (*drc*) growth (for either pinyon or juniper) predicted from drc and a growth index (g_{index}) by using equation (1). Components of the growth index—median-sized tree growth from the plot's quadratic mean diameter (*qmd*) distribution and number of stems—are illustrated for individual-tree predictions.

collected in Arizona and New Mexico (table 3). Measurements needed to use the model include *drc*, number of stems at *drc*, and growth index. The growth index requires estimation of pinyon and juniper growth indices, $Pqmd_g$ and $Jqmd_g$, for each plot or stand. In this study, growth indices were estimated from within-plot regressions by using past 10-year growth measurements from about six stem diameters (d_i) per plot for each pinyon and juniper genus.

In practice, a regression to estimate growth indices may not be desirable for each plot. It might be preferable to directly measure growth of the median-sized (*qmd*) pinyon and juniper on each plot. Or one might want to average the growth of the median-sized stem with additional stems close to the median. If a field method—other than a regression for each plot—is used to estimate the growth index, it should be compared to the regression approach because the model is calibrated to a regression estimate for median-sized tree growth. If radial cores are utilized to estimate 10-year diameter growth, I recommend at least three cores per stem (Chojnacky 1990).

Generally, a growth model is designed to predict growth without requiring any growth measurements, but since this model requires measuring median-sized pinyon and juniper growth, it is more like a traditional stand-table projection method (Husch and others 1982) where trees are assumed to grow at an average rate based upon initial measurements. However, until further research is done on pinyon-juniper growth processes, this model fills a present knowledge gap by allowing estimation of diameter growth from available inventory measurements and a "growth index."

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