DENDROCHRONOLOGICAL MODELING OF THE EFFECTS OF CLIMATIC
CHANGE ON TREE-RING WIDTH CHRONOLOGIES FROM THE CHACO
CANYON AREA, SOUTHWESTERN UNITED STATES

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ABSTRACT

Hypotheses about the causes of the growth and decline of the Chacoan regional interaction sys-
tem in the southwestern United States between A.D. 900 and 1200 are evaluated against tree-ring
evidence and the results of an empirical model (PRECON) that computes the statistical relations-
ships between climate and ring-width indices during the 20th century and applies the results to
hypothesized precipitation or temperature changes. The statistical responses of 23 indexed conifer
ring-width chronologies from New Mexico and Colorado to variations in monthly temperature and
precipitation were calculated. Simulated decreases in prior autumn-winter precipitation markedly
reduced ring widths, while decreased current summer precipitation was less effective, sometimes
reducing ring width or having little effect. Decreased prior winter temperature slightly reduced ring
width, while decreased growing season temperature usually increased or did not effect ring widths.
Evaluated in terms of these results, the Chaco Canyon area tree-ring record (1) indicates that favor-
able climatic conditions in the 10th, 11th, and early 12th centuries fostered the growth of the
Chacoan system, (2) shows that dry autumn-winter and summer conditions in the middle 1100s
contributed to the downfall of the system, (3) does not support the proposition that centuries-long
climatic fluctuations evident in southwestern Colorado affected Chaco Canyon, (4) does not sup-
port the idea of shifts from summer- to winter-dominant precipitation regimes, and (5) contributes
little to assessing the role of anthropogenic environmental change in the collapse of the Chacoan
system.

**INTRODUCTION**

Archaeologists and others have long been sensitive to the evident paradox implied by the occurrence of the most elaborate expression of the Anasazi (prehistoric Puebloan) cultural pattern in one of the least auspicious environments on the Colorado Plateau, Chaco Canyon in northwestern New Mexico (Figure 1). Located at an elevation of 1,875 m in the heart of the San Juan Basin, Chaco Canyon receives an average of only 200 mm of precipitation per year. The natural vegetation is correspondingly sparse, consisting primarily of xerophytic grasses and shrubs with isolated stands of pinyon (Pinus edulis) and juniper (Juniperus spp.) trees. Nonetheless, between A.D. 900 and 1200, Chaco Canyon was the center of a regional interaction system that extended far beyond the San Juan Basin. At its apogee, the Chacoan core included a dozen multistoried masonry pueblos of up to 800 rooms each, 300 smaller pueblos, great kivas, extravagant masonry styles, exotic material items, and a sophisticated agricultural system. Elaborate road and signalling networks radiated outward to connect the core to the peripheries of the system.

The apparent conundrum of an advanced organizational system developing in an especially inhospitable environment has focused attention on the past and present environment of the area. Early archaeologists, such as Judd and Hewett, encouraged pioneering paleoenvironmental research including the geomorphologic studies of Kirk Bryan (1954) and the dendrochronological work of A.E. Douglass (1929, 1935). Later archaeologists, particularly those associated with the University of New Mexico's Archaeological Field School and the National Park
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Service’s Chaco Project, encouraged research in geomorphology (Fisher 1934; Hall 1977, 1983; Love 1980), palynology (Hall 1977, 1983), packrat midden analysis (Betancourt et al. 1983; Betancourt and Van Devender 1981), and dendroclimatology (D’Arrigo and Jacoby 1991; Rose et al. 1982). The results of these studies were integrated into numerous attempts to assess the role of environmental conditions and changes in Chacoan prehistory (Dean 1992; Vivian 1990:391-492). Dendrochronological simulations of the effects of specified climatic changes on tree growth in the Four Corners area provides a basis for evaluating some of the hypotheses concerning environmental influences on the Chacoan regional system.

THE PROBLEM

Five general ideas have been proposed to characterize the impact of environmental variability on the development and decline of the Chacoan system. First, Douglass (1929, 1935) and others advanced the notion that wide tree-rings indicated wetter than average climate that
allowed, or perhaps even caused, the occupation of localities such as Chaco Canyon by large groups of people. Narrow rings were thought to indicate dry conditions that contributed to the decline of Anasazi population centers, including Chaco. Second, Douglass (1929, 1935), Hawley (1934), and others postulated that human activity (farming, tree cutting, large scale construction, etc.) destroyed the Chaco environment’s capacity to support large populations and complex social systems. Catastrophic erosion resulting from the deforestation of the surrounding area was seen as an important factor in the collapse of the system.

Third, alternating preponderances of arboreal and disturbed-ground pollen from archaeological and alluvial contexts led to the inference of alternating climatic regimes, one dominated by “low energy” winter frontal precipitation and one by “high energy” summer convectional rainfall (Schoenwetter 1967; Schoenwetter and Eddy 1964). The early development of the Chacoan core area occurred during a hypothesized summer dominant climatic regime in the 9th and 10th centuries. The presumed shift around A.D. 1000 to a winter dominant pattern has been advanced as a factor in the expansion of the regional system (Vivian 1970).

Fourth, based on reconstructed fluctuations in summer and winter precipitation and in the length of the summer growing season, Petersen (1988) reconstructed elevation and width shifts in the potential dry farming belt in southwestern Colorado. These shifts may represent regional-scale environmental processes that also affected the San Juan Basin. Petersen’s palynological work in the La Plata Mountains of southwestern Colorado led him to infer that the 1130-1180 period was characterized by low winter precipitation, unreliable summer rainfall, and elevated temperatures, conditions that would have severely impacted agricultural production throughout the Four Corners area and thereby contributed to the breakup of the Chacoan system in the late 12th century.

Fifth, Gillespie (1984), Judge (1989), Powers et al. (1983), and Sebastian (1992) used preliminary dendroclimatic reconstructions (Robinson and Rose 1979) to argue that prolonged summer drought between 1130 and 1180 contributed to the demise of the Chacoan system by reducing crop production throughout the San Juan Basin. The inability to produce enough food to support local populations or to fully engage the regional trade network resulted in the collapse of the interaction system and the demise of the complex society that depended on it.

Dendroclimatic modeling can be used to evaluate these ideas about the environmental dynamics of the Chacoan regional system. The effects of hypothesized climatic variation on tree growth in the San Juan Basin can be quantified, and characteristics of tree rings formed during the rise and decline of the Chacoan system can be examined for consistency with modeled tree-growth changes relevant to the five environmental hypotheses. In terms of the direct precipitation (wet vs. dry) constructs, modeling identifies the range of possible climatic effects on crop production indicated by observed variations in ring width. Modeling also has potential for isolating aberrant patterns in long tree-ring records that could be due to factors other than climate. If some of these nonclimatic effects could be identified as growth responses to human activities (such as tree cutting), the prehistoric deforestation hypotheses could be dendrochronologically evaluated.

Modeling and comparing the results to observed tree-ring characteristics also are relevant to testing the hypotheses based on pollen analyses. Separating summer climatic effects from winter or annual effects on tree growth would help determine whether the Chaco area tree-ring record reflects the hypothesized systematic, prolonged shifts in the seasonal patterning of precipitation or merely short-term fluctuations around a stable mean. Modeling also would help test Petersen’s ideas about long-term climatic changes and about reduced precipitation and elevated temperatures in the middle 12th century.
Finally, modeling is pertinent to evaluating the idea of a long summer drought between 1130 and 1180. Isolating summer input into tree growth would allow objective assessment of the reality of this summer drought, which is only weakly indicated by the available dendroclimatic reconstructions (Robinson and Rose 1979; Rose et al. 1982). Even the demonstration that local trees have too weak a summer climatic signal to discriminate summer precipitation would be a major contribution to the ongoing debate about the role of climatic variability in Chaco Canyon prehistory.

**THE APPROACH**

A computer model, developed by Fritts et al. (1991), simulates tree-ring structure from monthly and daily climatic data. The empirical part of this model, program PRECON (available from Dendrochronological Modeling), was used to calibrate the statistical relationships between tree-ring indices and monthly climatic data. The model allows one to choose: (1) the chronology and climatic data sets to be calibrated, (2) different candidate variables that may control growth variation, and (3) the interval to be calibrated. The user selects the types and sequence of analyses to examine "What if?" questions about ring growth and climate. In this study, different types of calibrations of 20th century climatic and tree-ring data are used to estimate the effects of particular climatic changes on ring-width growth. Assuming that prehistoric tree-growth responses were the same as those observed in the present (Fritts et al. 1965), the modeled relationships are applied to ring series from the time of the Chacoan system.

Both linear and curvilinear relationships were evaluated with this model. Analysis began with the evaluation of first order effects measured by simple correlation, multiple regression, and response function techniques (Fritts 1962, 1974, 1976; Fritts et al. 1971; Guiot 1993). Some curvilinear and interactive relationships were discovered (Fritts et al. 1965), but their effects were small compared to linear effects.

Once a calibration was obtained, a precipitation or temperature change was modeled to occur beginning in 1930 by incorporating the change into the instrumental record of precipitation or temperature and recalculating the growth using the calibrated coefficients. Differences between actual and modeled tree growth were used to evaluate which climatic factors could have produced the variations in ring widths in the Chaco Canyon tree-ring chronology during the A.D. 850-1200 period. This procedure establishes the relevance of the Chaco ring chronology to evaluating the hypotheses about environmental effects on the Chacoan system. Specifically, it allows us to address questions such as the following. Does ring-width variability in the 10th and 11th centuries reflect climatic conditions that would have favored the expansion of the regional system? Could dry winters or summers have produced the narrow rings in the mid-12th century? Could cold summers shorten the growing season, limit growth, and produce narrow rings? Can nonclimatic effects that might be related to human behavioral impact on tree growth be detected in the tree-ring record?

**ANALYSIS**

Twenty-three standardized ring-width chronologies were assembled for the Four Corners area (Figure 1) for ponderosa pine (*Pinus ponderosa*), pinyon (*P. edulis*), juniper (*Juniperus osteosperma*), and Douglas-fir (*Pseudotsuga menziesii*). They include eight sites from New Mexico — Chacra Mesa, Ditch Canyon, Fort Wingate, Ned Tank, Pueblito Canyon, Satan Pass, Burning Bridge Wash, and Washington Pass (Dean and Robinson 1978) — and fifteen
from Mesa Verde, Colorado (Fritts et al. 1965). All chronologies were calibrated with the modern record of monthly average temperature and total precipitation for fourteen months from July prior to the year of growth through August near the end of the growing season. Climatic data averaged for New Mexico, NOAA Climatic Divisions 1 or 2, from 1896-1983 were used in all calibrations (Magnetic tape TD-9640, NOAA Climatic Data Center, Asheville, NC). The climatic averages can be shown to be inhomogeneous because they were calculated differently before and after 1930, but they provide a continuous and relatively long set of regional data useful for evaluating the responses of trees growing on widely spaced sites surrounding Chaco Canyon. Sufficiently long and homogeneous single-station climatic data sets are not available for all the tree sites. Furthermore, the single-station data sets are highly variable in quality and often represent purely local conditions, especially in summer due to the spatial variability in summer precipitation. Before applying the divisional climatic data, we examined the responses of different tree species before and after 1931 and found no appreciable difference in the results concerning the hypotheses tested. Thus, to take advantage of the longest possible calibration interval, we used the entire 1896-1983 records for both tree-ring chronologies and climate. When the so-called higher quality data for 1931-1983 were used, the only appreciable differences were that fewer coefficients were significant because the degrees of freedom were reduced.

The model examined the correlations between growth and each monthly climatic variable, tested each for significance, and generated the most parsimonious set of regression coefficients, which were then used to simulate a climatic change. In addition, a response function analysis was run on the same data using a modification of the original response program written by Fritts et al. (1971), which was applied to different trees and sites by Fritts (1974). Because of variable intercorrelation, the error estimates of the original technique are underestimated (Cropper 1985; Draper et al. 1971; Rencher and Pun 1980). This problem was resolved with the help of Dr. Joël Guio, Laboratoire de Botanique Historique et Palynologie, Faculté de St Jérôme, Marseille, France, by using the bootstrap algorithms of Efron (1979, 1983; Fritts et al. 1990; Guio 1990, 1993) to obtain unbiased response error estimates. Reliability measurements of dependent estimates of yearly climatic data and growth are obtained by randomly drawing n observations from the original 1896-1983 data to obtain the calibration, where n is the number of years of overlap between the climatic and tree-ring data. In addition, independent estimates are obtained by drawing a second sample of n years from the pool of observations not selected in the first sampling for the dependent set. This procedure is repeated 30 times to obtain a population of response function coefficients, which are then averaged and their variances used to evaluate the coefficient significances (Guio 1993).

RESULTS

Figure 2 is a plot of the average monthly temperature and precipitation for New Mexico Climate Division 1. Average temperatures are in the low 50s (degrees F.) at the beginning of the possible growing season, but this also is a time of low precipitation. Precipitation from July through September amounts to 4.33 inches (110 mm), which is 40 percent of the annual total. The remaining 60 percent contributes to soil moisture recharge during the cooler late autumn, winter, and early spring seasons. In addition, the summer storms are highly variable and sometimes intense, often contributing to high runoff. Evapotranspiration is also higher in summer with rapid depletion of moisture from the upper soil levels.

Figure 3 shows an analysis of the effects of monthly temperature and precipitation on the
prewhitened (residual) ring-width indices of ponderosa pine from Ditch Canyon, New Mexico using Climate Division 1 data. The fractional variance reduced by the analyses ranged from .649 for the interactions to .710 for the response function analysis (Table 1). Correlation (Figure 3A), response function analysis (Figure 3B), and multiple regression analysis (Figure 3C) demonstrate the limiting effects of low precipitation on ring width and show that the linear relationships are predominantly direct ones. Temperature is primarily inversely related to growth especially in the warm season months concurrent with the growing season. The correlation coefficients for precipitation are positive and significant from November through July while those for temperature are inverse and significant for August and October of the previous calendar year and June and July of the growing season. The multiple regression analysis includes significant positive precipitation coefficients for August, October, and November of the previous calendar year and January, June, and July for the growth year. The inverse effect of prior July precipitation may be related to the collinearity between predictor variables of growth and the ARMA modeling, which may have over corrected for autocorrelation by not taking into account the nonrandom effects of prior summer climate on growth. Coefficients for temperature were significant and positive only in November and January, while those for July temperature were negative. This suggests that low temperatures in winter can limit subsequent ring-width growth, but the reverse occurs in summer when high rather than low temperatures limit growth.

Figure 2. Annual climatic regime from regionally averaged temperature and precipitation data, New Mexico Climate Division 1.
Figure 3. Analyses of ARMA modeled ponderosa pine ring-width indices at Ditch Canyon, New Mexico, and monthly precipitation and temperatures from New Mexico Climate Division 1 for the 14 months from July prior to the growth year through August of the growth year. A. Simple correlations between monthly climate variations and ring-width indices. B. Bootstrap response function coefficients for the relationships in A.
Figure 3 (continued) C. Stepwise multiple regression coefficients for the relationship in A. D. Calculated effect of a 4% decrease per year in prior September-February precipitation beginning in 1930 on the ring-width index using the stepwise multiple regression equation in C.
Figure 3 (continued) E. Same as D except for current June-August precipitation. F. Same as D except for a decrease in prior September-February temperature of 0.04°F per year.
Figure 3 (continued) G. Same as F except for a decrease in current June-August temperature of 0.04°F per year. H. A significant interaction between October-January precipitation and June-July precipitation, portrayed by solving for the effect of June-July precipitation on growth while holding October-January precipitation at five levels including 0, ±1, and ±2 standard deviations of that variable.
Table 1. The fractional variance reduced in the four chronologies by the multiple regression analysis, response function analysis, and multiple regression analysis of the interaction.

<table>
<thead>
<tr>
<th></th>
<th>Multiple Regression</th>
<th>Response Function</th>
<th>Climate</th>
<th>Prior Growth</th>
<th>Total</th>
<th>Interactions</th>
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<tr>
<td>Ditch Canyon</td>
<td></td>
<td></td>
<td>0.657</td>
<td>0.710</td>
<td>0.710</td>
<td>0.649</td>
</tr>
<tr>
<td>Ponderosa Pine</td>
<td>0.657</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.428</td>
<td>0.486</td>
<td>0.553</td>
<td>0.366</td>
</tr>
<tr>
<td>Ned Tank</td>
<td></td>
<td></td>
<td>0.428</td>
<td>0.486</td>
<td>0.553</td>
<td>0.366</td>
</tr>
<tr>
<td>Pinyon</td>
<td>0.428</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Park Point</td>
<td></td>
<td></td>
<td>0.627</td>
<td>0.541</td>
<td>0.672</td>
<td>0.496</td>
</tr>
<tr>
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<td></td>
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<tr>
<td>Satan Pass</td>
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<td></td>
<td>0.632</td>
<td>0.000</td>
<td>0.632</td>
<td>0.506</td>
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<tr>
<td>Douglas-fir</td>
<td>0.549</td>
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Only seven response function coefficients differed significantly from zero compared to thirteen for the correlation analysis and ten for the multiple regression analysis. The dominant positive effects of both prior winter and current July-August precipitation are evident. Only the coefficient for temperature in January was significant, which supports the inference of some direct effects of winter temperature on growth. Warm days can favor winter photosynthesis, increased food storage, and increased ring-width growth in the subsequent summer months (Fritts 1976). The response function analysis suggests that the inverse effects of temperature apparent in the correlation and regression analyses do not hold up when attempting to identify and analyze the collinearities between temperature and precipitation for the summer, although the coefficients for the dry period of May and June tend to be negative, and those for the wetter months of July and August are positive but small.

The coefficients from either the multiple regression or the response function can be applied to "What if" questions about the effects of climatic change on ring-width growth. We used the regression coefficients to generate the plots in Figure 3D-G because regression is a more conventional method and these coefficients can be easily tested for nonlinear effects. In these plots, the light solid line portrays the actual ring-width indices, the dashed line the regression estimates, and the dotted line the residuals from regression. The heavy solid line shows the solution of the multiple regression equation when the hypothesized climatic change amounts are incorporated into the climatic values used to generate the original regression estimates. The heavy line completely obscures the dashed line up to 1930, because no climatic change is simulated and no differences exist between the two estimates. After 1930, the heavy and dashed lines diverge indicating the degree to which a change in precipitation or temperature affects ring width. The dashed-dotted line shows the change in precipitation or temperature that was used in the simulation. In Figure 3D-G the change was applied to September-February precipitation, June-August precipitation, September-February temperature, and June-August temperature. Both declining winter and growing season precipitation contributed to lower growth. Declining temperature in winter contributed to slightly lower growth, but declining summer temperatures contributed to a slight growth enhancement, not a reduction in growth.
The program was used to check for nonlinear effects and interactions by generating squared and cross-product terms for all significant coefficients shown in Figure 3C. No curvilinear effects were noted, but there were three significant interactions. The largest interaction was between the two intervals of averaged precipitation (Figure 3H). When October-January precipitation was high, high June-July precipitation contributed to greater ring width; when October-January precipitation was low, high June-July precipitation had a small or an inverse effect on ring width. One interpretation of this relationship is that low winter precipitation results in low winter photosynthesis and soil moisture storage with early cessation of growth so that summer moisture comes too late to contribute to ring width. The second interaction involved precipitation in July of the year prior to growth and June-July precipitation during the period of growth. The effect of current June-July precipitation on growth was greater when prior July precipitation was low. Third, a significant interaction was found between the average temperature for November-January and precipitation in June-July. The warmer the winters the greater the effect of summer precipitation on ring width. The last two interactions can be interpreted as effects of climate on the prior season’s growth with consumption of stored carbohydrate and subsequent photosynthetic production and accumulation of food reserves that would favor potentially high rates of growth the following summer if June-July precipitation is adequate.

The simple correlations between New Mexico Division 2 precipitation and pinyon growth at Ned Tank, New Mexico, are positive throughout the entire year (Figure 4A). Significant simple correlations were noted for October and December-April. Except for February, temperature is inversely correlated with ring width, and values in November and April-July are significant. The regression simulations accounted for substantially less variance than the Ditch Canyon analysis (Table 1) indicating poorer modeling of these relationships. The fractional variance reduced ranged from 0.366 for the interactions to 0.553 for the response function. However, the results are similar to those for Ditch Canyon in that cool season precipitation is the primary limiting factor to growth, and the effects of growing season precipitation are small or unimportant. Cool winter temperatures are sometimes unfavorable to growth, and cool growing season temperatures appear to favor ring-width growth (Figure 4B-C). Since this chronology was not prewhitened, it was necessary to include prior growth for three years to assess autocorrelated relationships.

The response function supports earlier findings (Cleaveland 1986; Fritts 1974, 1976; Fritts et al. 1965) that total ring-width variations in pinyon primarily reflect winter precipitation. Only the coefficient for June temperature is significant, and temperature appears to be inversely associated with ring width, especially in spring and early summer, probably because it enhances evapotranspiration and water loss. Coefficients for temperature in the prior July, December through February, and August are positive. Prior growth for 1 and 3 lags is positively but not significantly associated with the current season’s ring width.

The greatest amount of growth reduction is simulated with a decline in prior autumn and winter precipitation (Figure 4D). When a decrease in summer precipitation was modeled (not shown in the figures), there was no simulated change in growth as no coefficient for summer precipitation was significant (Figure 4C). A simulated temperature decrease in spring and summer (not shown) caused a growth increase rather than a decrease, as in Figure 3G. Even when the coefficients of the response function were used in the simulation instead of the stepwise multiple regression coefficients (not shown), the effects of decreasing autumn and winter precipitation and summer temperature were practically the same. Examination of interactions for all variables significant in the stepwise multiple regression showed that every coefficient
Figure 4. Analyses of pinyon ring-width indices at two sites. A. Simple correlations between the Ned Tank, New Mexico, site and monthly precipitation and temperatures from New Mexico Climate Division 2 for July prior to the growth year through August of the growth year. B. Bootstrap response function estimates of the relationships in A.
Figure 4 (continued) C. Stepwise multiple regression analysis of the relationship in A.
D. Calculated effect of a 4% decrease per year in September-February precipitation beginning in 1930 on the ring-width index using the coefficients of the stepwise multiple regression equation in C.
Figure 4 (continued) E. Same as B except for the higher elevation site at Park Point, Mesa Verde, Colorado, and New Mexico Division 1 climatic data. F. Same as E except a stepwise multiple regression analysis.
Figure 4 (continued) G. Calculated effect of a 4% decrease per year in September-February precipitation beginning in 1930 on the ring-width index using the coefficients of the stepwise multiple regression equation in F. H. Same as G except for a decrease in June-August temperature of 0.04° F per year.
in Figure 4C interacted and revealed a slight direct but curvilinear May temperature effect. However, the interacting relationships reduced only 0.366 fractional variance (Table 1), which was 0.062 lower than the variance reduced by the linear regression and 0.187 lower than that reduced by the response function. Because of the low variance reduced by these interactions and inconsistencies with better defined relationships in other analyses, we concluded that these are simple chance relationships not worth illustration or further discussion.

It might be argued that these results could be quite different if we had chosen species closer to their high-elevation limits. Therefore, we examined species at widely different elevations. Figure 4E-H shows results for a stand of pinyons at Park Point on Mesa Verde, Colorado, which is 400 m higher than the Ned Tank data set. The more proximate New Mexico Division 1 climatic data set was used rather than the larger Colorado Division 2 set, which averages data over the entire western slope of Colorado. Figure 4E shows about the same response as Figure 4B. The coefficients of the stepwise multiple regression (Figure 4F) indicate a greater temperature response that is significant and inversely related to the temperatures of prior July and August and current July. Temperatures in prior November and in August of the growing season are significantly and directly related to growth. However, Figure 4G-H shows that declining September-February precipitation is associated with a decrease in ring-width index, while the net temperature effect for June-August still is associated with a ring-width increase even at this higher elevation site.

Figure 5 shows the results for New Mexico Division 1 and a residual Douglas-fir chronology from Satan Pass, New Mexico. As was the case for the responses of pinyon and ponderosa pine, precipitation is largely directly related to ring-width growth, and temperature is often inversely related to growth. One difference is the response to climatic conditions in June-August of the growing season when precipitation is inversely related to ring width with one coefficient significant in the response function analysis (Figure 5B). Growth measurements (Fritts et al. 1965) suggest that the Douglas-fir growing season is relatively short and independent of the climate during the growing period. Growth at the base of the stem may stop earlier than in the pines, so that the effect of summer climate on growth is delayed until the following growing season. Only coefficients for precipitation are significant in both the response function and the stepwise multiple regression (Figure 5B-C). Thus, a decrease in precipitation is associated with a marked decline in growth, but temperature change has little effect. Since no temperature coefficient was entered in the multiple regression analysis, we used the coefficients of the response function to simulate a climate change effect (Figure 5D-F) to allow for possible temperature effects. A decrease in annual precipitation produces a large ring-width index decrease (Figure 5D), but when June-August precipitation decreases, there is little or no simulated ring-width decrease (Figure 5E). A simulated decline in temperature had no effect on growth (Figure 5F).

Examination of possible interactions and curvilinear relationships using the significant multiple regression coefficients produced three significant interactions that accounted for 0.506 fractional percent variance (Table 1) but yielded no curvilinear effects. All three interactions were positive, and the two most important are shown in Figure 5G-H. When October precipitation is high, the effect of November precipitation is high (Figure 5G); when February precipitation is high, the effect of April precipitation is high (Figure 5H); when precipitation in the prior August is high, the effect of December precipitation is high.

None of the other chronologies tested produced results that contradicted the overall results shown in Figures 3-5, although there were small differences that were well within the statistical errors of the analysis. Except for the one interaction that was mentioned, no direct
Figure 5. Analyses of ARMA modeled Douglas-fir ring-width indices at Satan Pass, New Mexico, and monthly precipitation and temperatures from New Mexico Climate Division 1 for July prior to the growth year through August of the growth year. A. Simple correlations between monthly climate variations and ring-width indices. B. Bootstrap response function estimates of the relationships in A.
Figure 5 (continued) C. Stepwise multiple regression analysis of the relationship in A. D. Calculated effect of a 4% decrease per year in annual precipitation beginning in 1930 on the ring-width index using the coefficients of the response function in B.
Figure 5 (continued) E. Same as D except for June-August precipitation. F. Same as E except for a decrease in June-August temperature of 0.04° F per year.
Figure 5 (continued) G. The most important significant interaction between October precipitation and November precipitation, portrayed by solving for the effect of November precipitation on growth while holding October precipitation at five levels representing 0, ±1, and ±2 standard deviations of that variable. H. The second most important significant interaction between February precipitation and April precipitation, portrayed by solving for the effect of April precipitation on growth while holding February precipitation at five levels representing 0, ±1, and ±2 standard deviations of that variable.
effects of temperature were noted and there is no evidence that low temperatures occurred during the growing season, unless they had been accompanied and overridden by extremely low summer precipitation amounts.

**DISCUSSION AND CONCLUSIONS**

Simulations using the available tree-ring chronologies from the Chaco Canyon area show that ring-width growth is controlled primarily by annual or prior autumn-winter precipitation. While ring widths are primarily a response to autumn and winter moisture, the analysis of the two species of pines indicates that summer precipitation also might directly impact ring width. Occasionally, simulated prior winter temperatures affected ring-width indices. Few other temperature relationships were significant, especially when using the bootstrap response function approach, which attempts to consider collinear effects between the monthly precipitation and temperature data used as predictors of ring width. The one exception was associated with a low reduced variance and was not confirmed in other analyses. These results support the contention (Fritts 1976) that evergreen trees growing on low-elevation and arid sites appear to respond primarily to cool season moisture, probably through its positive effects on soil moisture recharge and net photosynthesis, which can occur throughout the dormant period and is highly efficient during sunny but cool winter days when daytime temperatures are above freezing and there is sufficient soil moisture.

Given the tree growth-climate relationships revealed by modeling, the Chaco Canyon tree-ring chronology can be used to assess the various ideas about environmental effects on the origin, development, and demise of the Chacoan regional system and its core in Chaco Canyon.

This study contributes little to evaluating the possibility that human activities damaged the local environment sufficiently to adversely affect food production. Because our model cannot simulate ring-width indices for the A.D. 850-1200 period, due to the lack of climatic predictor data, we cannot identify nonclimatic tree-growth effects that could indicate anthropogenic environmental degradation. Although a dendrochronological resolution of this problem is beyond the scope of this study, the synchronicity of geomorphic fluctuations across the entire southern Colorado Plateau (Karlstrom 1988) argues against local behavioral causes for the episodes of arroyo cutting noted in Chaco Canyon.

The idea that the climate was characterized by alternating summer-dominant and winter-dominant precipitation regimes is not supported by this analysis. Our modeling indicates that summer-dominant rainfall, with a concomitant reduction in winter precipitation, should markedly reduce tree growth, particularly that of Douglas-fir, compared to growth under winter-dominant precipitation conditions. The increase in average ring width that should have accompanied a transformation from summer- to winter-dominant conditions around A.D. 1100 is absent from the Chaco area tree-ring record (Figure 6). Furthermore, local tree-ring samples fail to exhibit the increased incidence of intra-annual growth bands ("false rings") that should accompany summer-dominant precipitation. These results support other paleoenvironmental evidence that such long-term shifts in the seasonal patterning of precipitation did not occur (Hevly 1988).

With regard to the hypotheses involving variations in annual precipitation, large rings should reflect climatic conditions favorable to crop production and narrow rings should specify conditions limiting to crop growth. Therefore, the average-to-high tree-growth characteristic of the 10th and 11th centuries indicates climatic conditions that, at least, did not inhibit the
large-scale occupation of Chaco Canyon and the expansion of the Chacoan system.

Narrow tree rings between A.D. 1130-1160 (Figure 6) reflect deficient moisture conditions that may have contributed to the demise of the Chacoan system. The modeling indicates that narrow rings such as these indicate decreased autumn and winter precipitation. The effects of precipitation are sometimes interactive so that low precipitation during several winter months would produce narrower rings than would be indicated by the sum of the linear effects. Decreased summer moisture may also be associated with narrow ring development, but we find no evidence in any tree-ring chronology from the area that low summer temperature or high summer precipitation could have produced narrow rings. Except for winter, cool temperatures in these arid sites enhance growth by reducing evapotranspiration.

Although we lack conclusive evidence that either summer moisture or summer drought was a factor in the Chacoan decline, precipitation any time in the year probably would help replenish soil moisture storage in fallow or cultivated ground, contribute to stream discharge in the growing season, favor regeneration of forests in heavily impacted areas, and enhance the growth of crops during the summer. The simulations, however, do make it clear that the autumn-winter drought of A.D. 1130-1160 could not have been ameliorated by wet summers. Indeed, the modeled growth response of the two pine species suggests that summer conditions during this period could have been dryer than normal. A combined winter-summer drought would have devastated the agricultural system of the Chaco Canyon by reducing stored soil moisture, on which germination depends, and reducing the amounts of soil moisture and rainfall available for the direct watering of crops and the operation of the irrigation systems, which are necessary for crop maturation.
Finally, the dendroclimatic modeling indicates that Petersen’s (1988:115-119, Figures 55-60) hypothesized shifts from dry winters to wet winters around A.D. 1000 and from wet winters to dry year-round conditions around A.D. 1100 should be accompanied by, respectively, a long-term increase and a long-term decrease in ring-width indices in the Chaco Canyon tree-ring chronology. The absence of these expected dendrochronological changes (Figure 6) suggests that the shifts in the potential dry farming belt in southern Colorado do not represent regional-scale low frequency environmental processes that also affected the Chaco Canyon area to the south. On the other hand, the narrow rings between A.D. 1130 and 1160 in the Chaco ring chronology strongly support Petersen’s inference that this period was characterized by low winter precipitation, unreliable summer rainfall, and elevated temperatures.

In conclusion, when examined in light of the dendroclimatic modeling results, the Chaco Canyon tree-ring chronology illuminates several of the hypotheses concerning the role of environmental factors in the history of the Chacoan regional system. As might be expected, tree-ring variability supports ideas involving annual or seasonal climate, including the notions that equable conditions in the 10th and 11th centuries favored development of the system and that a severe and prolonged autumn-winter and probably summer dry spell in the middle 1100s contributed to the downfall of the system and the collapse of the Chaco Canyon core. In contrast, the dendrochronological data do not support hypotheses that involve long-term shifts in the seasonal patterning of precipitation, that is, alternating summer-dominant and winter-dominant precipitation regimes. The modeling also indicates that the environmental factors involved in changes in the potential dry farming zone in southwestern Colorado had little direct affect in Chaco Canyon, probably because a different combination of environmental variables controls agricultural potential in this low lying area. Finally, the current study does little to elucidate the role of anthropogenic environmental degradation in the demise of the Chacoan system.

Dendrochronology and dendroclimatic modeling still have much to contribute to resolving the environmental component of the Chacoan problem. Further research focused on specific problems could illuminate several unresolved issues including the roles of temperature, summer rainfall, and human-induced environmental change. It may be possible to use modeling of the climatic component of tree growth to identify ring-width variability caused by non-climatic, perhaps human, factors. Additional evidence could be generated to clarify temperature and summer rainfall effects on tree growth. Cleaveland (1986) shows that the density and size of latewood might contain the required information, but density and latewood widths would have to be acquired from Chaco wood of the crucial time period. A process model using daily precipitation, temperature, and day length to model the cellular structure of rings that is now being developed (Fritts et al. 1991, 1992; Fritts and Shashkin, in press; Shashkin and Fritts 1992) could help resolve these questions. When this model is sufficiently well parameterized and validated for species in the Chaco area, the structure of wood cells formed late in the growing season can be simulated using different regimes of daily precipitation and temperature. Then the ring structure of trees growing during the Chacoan period can be examined for their consistency or lack of it with the simulated cell features modeled under various climatic conditions.

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