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Modeling Prehistoric Climate and Agriculture in Southwestern Colorado

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Introduction

The Anasazi abandonment of the northern San Juan area at the end of the Pueblo III period poses one of the classic problems in Southwestern archaeology. That these people left the area in the late thirteenth century A.D. is well known; what is not known with certainty, however, is why they left. It has long been suspected that such a widespread and seemingly sudden depopulation of this large area must have had its roots in an environmental crisis caused by natural climatic fluctuations, such as the “Great Drought” of A.D. 1276–1299 (Douglass 1929).

This chapter partially summarizes a larger work (Van West 1990) in which an attempt was made to reconstruct the agricultural environment available to Anasazi farmers in the heartland of the northern San Juan area before and during the period of abandonment. To approach this problem, Van West (1990) created a quantitative, high-resolution model of potential prehistoric agricultural productivity and sustainable population for an 1816-km² (701-mi²) area in the dry-farming region of southwestern Colorado (Figure 9.1). Although the results are applicable to the entire study area, they are actually based on the portion of it for which good soils data were available—approximately 1470 km².

While efforts to reconstruct climatic variation and its influence on agricultural productivity and population or settlement in the Mesa Verde area have been made before (e.g., Herold 1961; Cordell 1975; Burns 1983; Schlanger 1985; Petersen 1988), none to date has had the opportunity to use both the high-quality environmental data and the spatial data-management systems now available. Without these recently derived environmental data and state-of-the-art computing technology, this research could not have been done. The data are too many, the calculations too complex, and the accurate evaluations of the options too numerous to be processed or displayed in a single lifetime. Thus, computer technology, especially Geographic Information Systems (GIS) hardware and software, plays an important role in this research. This chapter briefly summarizes the methods used to build the model that integrates climatic and soils data to produce estimates of agricultural productivity and population, then focuses on the results of the modeling effort and on their implications for understanding the Anasazi abandonment of southwestern Colorado. In the longer presentation of the model (Van West 1990), three scales of analysis are used. These are (1) the entire study area; (2) two small areas (18 km² and 26 km²) where complete archaeological surveys have been done, so that estimates of actual prehistoric population can be compared with estimates of carrying capacity generated by the model; and (3) eight individual site catchments, where patterns of tree-ring-dated occupation and abandonment can be compared with modeled variation in agricultural productivity for those catchments. In this chapter, the results of only the first two approaches are summarized.

The methods employed to build the model are fully described elsewhere (Van West 1990). Below, the principal elements of the model are summarized.

Modeling Climate, Agriculture and Population

The model (Figure 9.2) integrates climatic data derived from tree-ring series with data on the water-holding capacity of soil classes to calculate Palmer Drought Severity Indices (PDSI). These indices are calculated for June of each year from A.D. 901 to 1300 for each of 36,759 4-ha cells that make up the actual spatial database for the model.
Calibrations of natural plant productivity estimates and historic agricultural yield values for specific soil types under varying soil moisture conditions are used to retrodict potential prehistoric agricultural yields under reconstructed moisture conditions for all 4-ha cells in the database. From the cumulated prehistoric agricultural production estimates, potential population sizes and densities are calculated, using a variety of assumptions about levels of maize cultivation, consumption, and storage.

**Soil Data**

The study area (Figure 9.1) includes 45,400 4-ha cells, but as noted above, adequate soils data were not available for some of them. The USDA Soil Conservation Service (SCS) had mapped 98 soil types in the study area as of 1988. Each 4-ha cell was considered to have a single soil type, based on the dominant soil type by area in the unit. The 98 soil types were grouped into 11 soil classes based on available water-holding capacity (AWC), for the purpose of calculating PDSI values. Later, estimated agricultural yields for each of the original 98 soil types under five different growing-season conditions were used to “translate” spatially and temporally sensitive PDSI values into quantitative estimates of bean and maize production for each of the 4-ha cells. The sum of the individual values for all cells in the study area provided estimates of yields for the total study area.

**The Palmer Drought Severity Index**

The Palmer Drought Severity Index (Palmer 1965) was used as a way of quantifying variation in effective soil moisture. The PDSI has been shown to have a higher correlation with variation in tree-ring series than do annual and seasonal precipitation or temperature per se (Rose et al. 1982). This is undoubtedly because the PDSI integrates both moisture and temperature conditions, as in effect do trees when they add growth rings. The PDSI was designed to be an index of meteorological drought, defined
Figure 9.2. The conceptual model for reconstructing prehistoric agricultural productivity.
as "a period of prolonged and abnormal moisture deficiency" (Palmer 1965:1). The index is based on a waterbalance, or hydrological accounting, approach to modeling soil moisture conditions (Palmer 1965:6) that takes the water holding capacities of particular soils into consideration. The PDSI value for a particular soil will vary depending on the cumulated balance of water added monthly by precipitation and subtracted monthly by evapotranspiration, which varies with temperature.

Because the PDSI values represent departures from the long-term mean condition of a given place, they do not provide a basis for comparing the absolute amounts of water in soils at different places having differing climatic regimes. Thus, a PDSI indicating moderate drought for a soil in Iowa may be based on more actual soil moisture than a PDSI indicating a wet period for a soil in southwestern Colorado.

The 1470-km² portion of the study area for which good soils data are available ranges in elevation from approximately 1500 m at the lowest to 2365 m at the highest. This results in a substantial range of elevation-related differences in annual precipitation and temperature. Consequently, PDSI values for the 11 AWC soil classes were calculated separately for five elevation zones, each of which could be characterized by historic climatic data from a weather station located in or near the study area. The weather stations are Bluff, Utah; and Cortez, Ignacio, Mesa Verde, and Ft. Lewis, in Colorado. These calculations resulted in the production of 55 long-term reconstructions of PDSI representing the full length of the tree-ring record (A.D. 901 to 1970), including the 400-year period of interest. The 55 reconstructions insured that the climatic variation characteristic of different elevation zones would be taken into account, and that PDSI values for particular soils would be expressed in relation to the long-term mean soil moisture condition for that soil in that elevation zone. Thus, soils with different water-holding capacities from different elevation zones could be characterized on a scale ranging from extreme drought to extreme wetness, relative to the long-term norms for each soil in its elevation zone.

Tree-Ring Data and Calibration of PDSI Values

The tree-ring data used to model past climate were eigenvector amplitudes (i.e., factor scores) that resulted from a principal components analysis of seven tree-ring chronologies from the southern Colorado Plateau. The data set was created by Martin Rose in conjunction with research undertaken by the Laboratory of Tree-Ring Research (Rose et al. 1982).

The reconstruction of PDSI values for representative soils in the study area by using modern precipitation and temperature data and tree-ring chronologies was a multistep process (Fritts 1976; Meko et al. 1980; Hughes et al. 1982; Rose et al. 1982; Graybill 1989). The process began with calculation of PDSI values for specific soils using historic climatic data from a specific weather station. In this step, actual PDSI values were determined for every month and every year in the instrumented series.

Second, PDSI values from a selected month were correlated with tree-ring values for a common period of time in order to generate an initial multiple regression equation that could be used as a transfer function to predict (or in this case, to retrodict) PDSI values in the prehistoric and preinstrumented time period. Here the tree-ring data were treated as independent variables and the PDSI values as the dependent variable. In this "initial calibration," a portion of the historic record was used to build the initial regression equation, and another portion was used to test it.

Third, "verification" of the initial calibration equation took place. Correlation coefficients and probability tests were used to assess the strength of the initial equations to faithfully predict the actual values generated by the original instrumented PDSI data for years not used in the creation of the original calibration equations.

Fourth, a "full calibration" period regression equation was created for the entire period of instrumented record that overlaps with the modern end of the tree-ring data. The product of this step was the final transfer function to be used to retrodict the preinstrumented PDSI values.

Last, the retrodiction of the entire PDSI series was accomplished by applying the transfer function to the full set of tree-ring values. In this step, the tree-ring data were used as the predictor, or independent, variables and the PDSI was the predicted, or dependent, variable.

In modeling PDSI values for southwestern Colorado, the above process was repeated 55 times, once for each of the data sets (the 11 AWC types occurring in each of the five elevation zones). The conservative estimate of the explained variance (the adjusted $r^2$) for the 55 regression equations ranged from 32 to 62 percent, with an overall mean of 50 percent. This indicates that about 50 percent of the variation in a PDSI value can be explained by the tree-ring data, used here as a proxy for stochastic variation in climate. The adjusted $r^2$ values for the project compared favorably with those obtained by Rose in a reconstruction of PDSI values for the Zuni area (Martin Rose, personal communication 1989) and for southwestern Colorado (Rose et al. 1982). The program that reconstructed the entire time series for PDSI values in the study area was written by Robert Lofgren of the Laboratory of Tree-Ring Research at the University of Arizona.

Use of Geographic Information System Technology

GIS hardware and software were used to manage and analyze these large data sets and to display results. This technology has the ability to interrelate multiple spatial and...
nonspatial data sets concurrently, to create new information through combinations or transformations of original data, and to produce analytic products (e.g., tables, charts, graphs) in addition to map-like images.

Without GIS it would have been impossible to integrate the reconstructed drought indices and estimated agricultural yields from the actual soil classes with the locations of these soils, as mapped by the 4-ha cells used to partition the study area. By capturing, coregistering, and evaluating all data layers, as well as by creating new data layers from reclassifications and transformations of the original data, GIS technology made the fast, accurate, and consistent assignments necessary to create the model, display the results, and assess patterning across space and through time. Figure 9.3 provides an example of a GIS-generated map of potential agricultural productivity for one year—A.D. 902. To produce this map, equations were required that related agricultural productivity to soil class characteristics at differing PDSI states (see discussion below of how agricultural productivity was estimated). With GIS technology, such maps can be generated year by year for PDSI values, potential agricultural production, or potential population density.

In the GIS applications for this project, two raster (grid cell-based) programs were used to capture, store, manipulate, and display the spatially distributed data of the model. The programs—mainframe software called VICAR/IBIS and microcomputer software called EPPL7—made possible the investigation of the study area at a relatively high level of spatial resolution (4-ha cellular units). Input to the GIS was in the form of previously generated computer values entered through floppy disks, digital elevation data (DEM's) purchased from the U.S. Geological Survey on magnetic tape, and newly digitized spatial data and keyboard-entered tabular data entered directly into GIS programs. Output from the GIS consisted of color graphic displays on video monitors, black-and-white image output on dot matrix printers (e.g., Figure 9.3), and tabular data that were transferred to mainframe programs for further analysis.

Estimation of Potential Agricultural Productivity

Information on historic yields of nonirrigated bean and maize cultivation in southwestern Colorado was gathered in order to address two methodological problems that had to be solved before data on soil quality and PDSI values could be used to generate estimates of both relative agricultural productivity and actual agricultural yields. The first problem was to establish the nature and strength of the relationship between modern crop yield and modern soil moisture conditions as modeled by the Palmer Drought Severity Index—that is, the extent to which crop yields in the historic period have varied with PDSI. This would provide a basis for calibrating moisture-related variation in prehistoric crop yields. The second problem was to develop a method whereby specific yield values could be estimated for soil types and AWC classes in the study area.

For the first problem—calibrating historic crop-yield response with PDSI variation—data gathered by Burns (1983) were consulted. Burns compiled historic yield values for pinto beans and maize grown by dry-farming techniques for five counties in southwestern Colorado. Only the records for Montezuma County for the period A.D. 1931–1960 were considered in our study. This 30-year period was selected because monthly precipitation and temperature data (necessary for calculating PDSI values) were available for the Cortez, Colorado, weather station starting in 1931, and because too few maize yield data were available after A.D. 1960.

Regression analysis was used to determine the relationship between crop yields and PDSI values. The best results were obtained with partial linear regression, with time also considered as an independent variable. With partial regression techniques, the contribution to crop production of the first independent variable—time—could be controlled for and the unique contribution made by the second independent variable—soil moisture—could be assessed. This approach was taken because it was thought that time might be a proxy for the cumulative influence of modern technological changes on crop yields, or what Burns (1983) referred to as the “technology trend.” Although crop production in Montezuma County prior to 1960 did not involve much use of chemical fertilizers, herbicides, or pesticides, these inputs were more likely to be used later rather than earlier. In addition, tractors and other mechanized farm equipment were increasingly employed during the 30-year period of interest.

The use of partial regression was successful in increasing the correlation coefficient (r) and index of determination (r²) for PDSI values and crop yields. The partial regression demonstrated a significant relationship between soil moisture and maize yield (r = .70; r² = .49; significant at .001), but it also provided the shape of the function that needed to be fitted to the model—linear and positive.

With regard to the second problem—establishing approximate yields of nonirrigated beans and maize for the numerous soil types—several approaches were used. Estimates of average bean yield for 44 of the 98 soil types in the study area were available from the Soil Conservation Service. Using linear regression, these data were related to estimates of natural plant productivity under “average” growing-season conditions for the same soil types, also available from the SCS. The regression equation then permitted extrapolation of bean yields to the remaining 54 soil types for which only the natural productivity estimates were available. Furthermore, estimates of bean yield under notably “favorable” and “unfavorable” growing-season conditions were calculated from SCS values of natural plant
productivity also recorded for the 98 soils in the study area. The historic data on bean and maize yield were then used to obtain a relationship between historic bean and maize yields, so that the bean yield data for various soils and moisture conditions could be used to estimate maize yields for the same soils and conditions. As a result, both soil quality and amount of stored soil moisture were taken into account when potential production of beans or maize was calculated for a given soil class in a given year.

For example, under these calibrations, a good mesa-top agricultural soil (ROB, Witt loam, 1–3 percent slopes) was estimated to produce 514 lbs/ac of beans and 1087 lbs/ac of maize, or roughly 19.4 bu/ac of maize in a favorable year, where a bushel equals 56 lbs. In metric figures, this is 576 kg/ha of beans and 1217 kg/ha of maize. In an unfavorable year, the same soil was estimated to produce 307 kg/ha of beans and 649 kg/ha of maize. This particular soil type is one of the most commonly used in dry farming today, and very likely was an important soil in prehistoric times as well.

For a poor soil, the estimated yields would be much lower. Soil type M2C (Romberg-Cragola complex) is stony, with 6 to 25 percent slopes. This soil is common in and near canyons in the study area. In a favorable year, bean production was estimated at 228 kg/ha, and maize at 483 kg/ha. In an unfavorable year, this soil was estimated to produce 72 kg/ha of beans and 152 kg/ha of maize.

Although these estimates were calibrated on the basis of historic-period crop production in southwestern Colorado, they appear to be reasonable as proxies for subsistence production by Anasazi farmers using dry-farming techniques. For example, Bradfield (1971) estimated that Hopi maize production averaged approximately 12 bu/ac (753 kg/ha) in normal years, on commonly used arable soils, in an area where both rainfall and soil quality appear consistently lower than in our southwestern Colorado study area. Bradfield (1971) also notes earlier reports that Hopi maize production averaged 10 to 12 bu/ac but reached approximately 15 bu/ac (941 kg/ha) on the best lands in the best years.

Relative agricultural productivity (e.g., low to high) for each cell was aggregated by GIS means and displayed as a map-like image (Figure 9.3) providing a visual assessment of which parts of the study area, of a locality, or of a site catchment were most and least productive in a given year. These images also permitted visual comparison of the location of productive and unproductive areas from year to year. The actual estimated yields of beans or maize were also summed by the GIS at scales ranging from a few 4-ha cells to the entire study area. Figure 9.4, for example, graphs the estimated potential annual maize production for
the study area for the period A.D. 901-1300. When these aggregated estimates were compiled, all yields that fell below a certain threshold of productivity—212 kg/ha for beans and 448 kg/ha for maize—were excluded. This is not to say that Anasazi farmers never used areas with low-yielding soils. It was felt that these areas were much less likely to be used, however, and that it was desirable to err on the side of conservatism in estimating the potential agricultural yields of the study area.

Estimation of Potential Human Population

Once an estimate of the potential annual supply of maize was obtained (excluding the contribution of the lowest-yielding cells, as noted above), a method for determining the maximum annual demand for that potential yield had to be devised. Human demand for the supply necessarily included consideration of land use and cultivation practices, predictable postharvest crop losses, seed-retention rates, storage levels, and human consumption rates. Consequently, a number of assumptions were made so that these parameters could be modeled. These six assumptions are outlined below.

First, it was assumed that only 50 percent of the lands potentially usable for raising crops were ever cultivated in any year. This estimate was also used by Kohler et al. (1986:528) in a recent attempt to model agricultural productivity in the vicinity of the Dolores Archaeological Project, and it reflects ethnographic observations of land use by the Hopi (Forde 1931:370), San Juan Pueblo (Ford 1968:157), and maize-growing Mexican peasants (Sanders 1976:141-143).

Second, although it is not known precisely in what proportions the major prehistoric cultigens of maize, beans, and squash were grown, it seems clear from a variety of archaeological evidence that maize was the major food crop grown by Pueblo III Anasazi in the Mesa Verde region. In this study, it is assumed that 80 percent of the lands that were cultivated were devoted to maize. This value is supported ethnographically by Hack (1942), who reports that Hopi farmers of the early twentieth century devoted 72 percent of their farmland to growing maize. Williams (1989) uses an estimate of 80 percent for a sixteenth-century Aztec community, and Sanders (1976) uses the same figure in the prehistoric Basin of Mexico.

Third, not all maize harvested was available for consumption. Some would have been lost in transport, or to pests and spoilage. In this study, we followed Williams (1989) and Hassan (1981) in reducing the annual estimated gross maize yield by 10 percent to account for losses.

Fourth, of what is harvested, stored, and potentially available for consumption, a percentage must have been reserved for seed for the following year, and perhaps also for replanting in the same season or subsequent seasons if there is a crop failure. It is assumed here that 10 percent of the potential net yield was reserved for planting subsequent crops.
Fifth, although minimum daily caloric requirements vary from person to person and depend on factors such as age, gender, metabolism, and level of activity, it is assumed here that an average of 160 kg of maize was used to sustain the average person in the prehistoric populations of the study area. This value is equal to .4384 kg per day, or 1534 calories per day, where 1 kg of maize yields 3500 calories (Cook and Borah 1979:164). The estimate of 160 kg per person per year was used by Sanders (1976:145) as an aggregate statistic based on a range of ethnographic data on preindustrial maize farmers. Assumptions about average caloric needs per person per day vary but generally fall in the range of 2000 to 2500 (e.g., Schlanger 1985; Kohler et al. 1986; Hassan 1981). The estimate of 1534 calories per day from maize that is used here implies a diet based from 61 to 77 percent on maize, similar to recent estimates for Pueblo-period Anasazi (e.g., Kohler et al. 1986; Decker and Tieszen 1989).

Sixth, this study considers the possibility of storing a portion of edible harvest for one or even two years beyond the needs of the current year (cf. Burns 1983). The goal of attempting annually to grow enough maize to last two years is often cited by ethnographers as the Pueblo ideal (e.g., Hough 1915; Forde 1931; Parsons 1936; Whiting 1939; Titiev 1944; Ford 1968; Bradfield 1971). Incorporating these goals in the model results in substantially reduced estimates of potential population size and density, as compared with modeling population on the assumption that people only wished to grow enough to have one year’s supply of maize on hand at the end of harvest. One way to visualize the implications of increased storage goals is to relate production goals to amount of land cultivated. If it was necessary from time to time to harvest greater amounts of maize in order to have a two- or three-year supply of maize at the end of harvest, the household would have had to control a greater amount of arable land than if planting was always designed to yield just one year’s supply at harvest. Hence, maximum population density decreases as storage goals increase.

In this study, three estimates of population size were made, based on differing assumptions about storage goals and, hence, about amount of agricultural production desired. The first estimate (POP1YR) assumed that the adjusted net yield was fully consumed by the next harvest, and that long-term storage was not a goal. The second estimate (POP2YR) assumed that planting was sufficient ordinarily to produce enough maize for consumption both in the current harvest year and for one additional year. The third estimate (POP3YR) assumed a goal of obtaining enough maize for the current harvest year and for two additional years.

Even if the amount of production was not governed by explicit storage goals, it seems likely that more maize was typically grown than would have been needed to support the producers just for the current harvest year. Maize was grown not only for household consumption but to fulfill kin reciprocity and ceremonial obligations within the community, as well as for trade and exchange transactions (Kavena 1980; Bradfield 1971). In addition, the hazards faced by farmers in a semiarid environment (e.g., drought, pests, storms) may have promoted planting enough maize to provide adequate food in a bad, rather than normal, year. This strategy would ordinarily result in production beyond the needs for the year succeeding the harvest. Consequently, it seems likely that the POP2YR estimates, or even the POP3YR estimates, are likely to be more realistic than the POP1YR.

Results

The Study Area

Annual values for total maize yield for the study area were estimated (Figure 9.4). From these figures, estimates can be made of the maximum number and maximum density of people who could be supported by that yield for a population requiring one year, two years, or three years of maize in storage at the end of harvest (Figure 9.5). By definition, population size varies directly with maize production in these estimates. In some years, maximum potential yield and maximum potential population are quite high, and in some years they are much lower; this shift often happens quickly. It is clear, however, that the size of a real population could not vary from year to year in this manner. Rather, longer-term trends in productivity control the real size of a population that can be sustained in a given place. Consequently, long-term trends were derived from the 400-year series of values.

The 400-year mean value, the 400-year minimum value, and a range of values equivalent to 20 percent through 60 percent of the 400-year mean value were taken for POP1YR, POP2YR, and POP3YR to represent the maximum carrying capacity, the critical carrying capacity, and the optimal carrying capacity, respectively (Table 9.1). These data better approximate a sustainable population size than do productivity estimates from any individual year.

In this study, the concepts of maximum, critical, and optimal carrying capacity have been adapted from Hassan (1981: 166-168) to estimate sustainable population levels over extended periods of time. Maximum carrying capacity is a population size estimate that is equivalent to the long-term mean value of the estimated yearly maximum population for the total period of 400 years. For a POP2YR agricultural strategy, the maximum carrying capacity for the study area as a whole is 35 ± 7 persons per km² (Table 9.1). This value is the upper limit on population size and represents a regional population that would frequently experience yield shortfalls when annual production fell noticeably below the mean.
Critical carrying capacity is a population size estimate that is equivalent to the minimum annual population value in the 400-year period. It is a value below the maximum carrying capacity (the long-term mean) and represents the largest population that would exist throughout the entire period without experiencing significant crop shortages.

Hassan (1981) has suggested, on the basis of cross-cultural data, that groups that are able to maintain their numbers over an extended period of time usually have population sizes well below the limit of fluctuating productivity. The range of values within which such populations fall can be referred to as the optimal carrying capacity. Its upper limit is roughly equivalent to the critical carrying capacity. Its lower limit is not specified, but the populations studied by Hassan (1981) fell between 20 percent and 60 percent (and most commonly, between 40 and 60 percent) of the long-term mean population level that can be calculated for their sustaining area (Hassan 1981:175).

In Table 9.1, critical carrying capacity is set at the minimum population value modeled during the 400-year period from A.D. 901 to 1300. Using the POP2YR set of values, the low of 21 persons/km$^2$ occurs 15 times during this period. Values nearly as low—22 and 23 persons per km$^2$—occur an additional 12 times. Occasionally two (but never three) of these population lows occur two years in a row (A.D. 906-907; 980-981). Other lows occur at close intervals (e.g., A.D. 901 and 906-907; A.D. 972 and 980-981; A.D. 1062 and 1067; A.D. 1146, 1150, 1156, and 1161; and A.D. 1254 and 1258). By contrast, there are a few fairly long intervals when the three lowest population values do not occur (A.D. 1020-1061; A.D. 1091-1130; A.D. 1187-1216; A.D. 1228-1253) and a number of periods of 15 or more years when the minimum population supportable was, in fact, reasonably high (Figure 9.5). Generally, however, the very low values occur once every 10 to 25 years, a time likely to be recalled by adults in the population.

The long-term minimum value, or critical carrying capacity, thus represents the long-term maximum number of people whose demands for maize could always have been met from the resources of the study area, under the assumptions about land use, consumption rate, etc., described previously. The maximum carrying capacity—the long-term mean—is theoretically the highest long-term population size that could have been sustained most, but...
Table 9.1. Comparison of Population and Carrying Capacity Values for the Study Area, Sand Canyon Upland Survey Area, and Mockingbird Mesa Survey Area, A.D. 901-1300

<table>
<thead>
<tr>
<th></th>
<th>Study Area</th>
<th>Sand Canyon Upland Survey Area</th>
<th>Mockingbird Mesa Survey Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (km²)</td>
<td>1470.36</td>
<td>26.08</td>
<td>17.96</td>
</tr>
<tr>
<td>TOTPROD (kg)</td>
<td>64,925,217 ± 13,936,845</td>
<td>1,779,087 ± 337,524</td>
<td>801,336 ± 204,994</td>
</tr>
<tr>
<td>c.v.</td>
<td>21.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>POP1YR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean and s.d.</td>
<td>88 ± 19</td>
<td>137 ± 26</td>
<td>89 ± 23</td>
</tr>
<tr>
<td>Range</td>
<td>52-141</td>
<td>93-198</td>
<td>46-142</td>
</tr>
<tr>
<td>POP2YR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean and s.d.</td>
<td>35 ± 7</td>
<td>55 ± 10</td>
<td>36 ± 9</td>
</tr>
<tr>
<td>Range</td>
<td>21-57</td>
<td>37-80</td>
<td>18-57</td>
</tr>
<tr>
<td>POP3YR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean and s.d.</td>
<td>19 ± 4</td>
<td>29 ± 5</td>
<td>19 ± 5</td>
</tr>
<tr>
<td>Range</td>
<td>11-30</td>
<td>20-43</td>
<td>10-31</td>
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<tr>
<td>Maximum value</td>
<td>57</td>
<td>80</td>
<td>57</td>
</tr>
<tr>
<td>Maximum CC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Mean value)</td>
<td>35</td>
<td>55</td>
<td>36</td>
</tr>
<tr>
<td>Critical CC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Minimum value)</td>
<td>21 (60%)⁴</td>
<td>37 (67%)⁴</td>
<td>18 (50%)⁴</td>
</tr>
<tr>
<td>Optimal CC</td>
<td>60% of mean</td>
<td>21 (60%)⁴</td>
<td>22</td>
</tr>
<tr>
<td>40% of mean</td>
<td>14</td>
<td>22</td>
<td>14</td>
</tr>
<tr>
<td>20% of mean</td>
<td>7</td>
<td>11</td>
<td>7</td>
</tr>
</tbody>
</table>

NOTE: All population values (POP1YR, POP2YR, POP3YR) and carrying capacity estimates are truncated integers.

Carrying capacity values in the lower part of the table are persons/km² and assume POP2YR levels of production.

cc = Carrying capacity.
c.v. = Coefficient of variation (the ratio of the standard deviation to the mean multiplied by 100 and rounded to the nearest tenth).
s.d. = Standard deviation.
TOTPROD = Total mean productivity of maize rounded to the nearest whole number.
POPKM = Number of persons per km².
POPNUM = Number of persons per study area or locality.

not all, of the time without change in the parameters of maize production and consumption. It is the least realistic of the three levels of carrying capacity, but it does provide an upper threshold for estimating aggregate population for the study area as a whole.

The population density and size values provided in Table 9.1 are high—higher than some researchers might think possible, particularly toward the end of the thirteenth century, when the Mesa Verde area was permanently abandoned by Anasazi populations. The estimates for POP1YR are probably the least realistic because we suspect that prehistoric Puebloans did attempt to store at least two years of maize at the end of harvest, in case production was low or failed the following season. Consequently, POP2YR is likely to be a better estimator of sustainable population. We suggest that the POP3YR values also represent a more likely estimate than POP3YR, since they seem to reflect the ethnographically reported attempts by historic Puebloan farmers to buffer risk, while acknowledging that most people do what is minimally required to protect themselves against disaster.

Thus, some 21,300 to 31,360 persons, representing an optimal density of some 14 to 21 persons per km² for the 1470-km² study area, could have been supported in any given year within the A.D. 901-1300 time period. For both number and density, the lower value represents 40 percent of the long-term mean, or maximum carrying capacity, and hence falls within the optimal carrying capacity range (20 to 60 percent of the mean). The upper value also represents critical carrying capacity. The upper value for the study area is similar to the value recently suggested by Rohn (1989) for the population of the Montezuma Valley in the Pueblo III period. As he defines it, however, the Montezuma Valley is more extensive than the study area; it extends from the east slopes of the Abajo Mountains in southeastern Utah to the valley bottom drained by upper
McElmo Creek, below the northern escarpment of the Mesa Verde in southwestern Colorado. Rohn asserts that 30,000 people is a conservative estimate of the number of people who lived in the Montezuma Valley in the thirteenth century (Rohn 1989:166), an estimate derived from his knowledge of archaeological survey data in the Montezuma and Dolores county areas. Further, this estimate of 30,000 does not include the numbers of people he estimates for nearby Mesa Verde and the Mancos valley. Therefore, it would seem that the POP2YR estimates are generally in line with the only recent general estimates of Pueblo III period population for the heartland of the Mesa Verde Anasazi.

Several tentative conclusions can be drawn from this preliminary analysis of the data for the study area as a whole. First, climatically induced variation in soil moisture and its effects on agricultural productivity do not present a sufficient cause for the depopulation of the Mesa Verde Anasazi region in the late thirteenth century A.D. Within the parameters of the model, there was always enough productive land to support thousands of people in the study area, even during the difficult times of the middle A.D. 1100s, which coincide with the collapse of the Chacoan system, and during the so-called Great Drought of the late 1200s, which coincides with the major and final depopulation of the area. It is possible, of course, that other climatic or environmental variables, such as cooling temperatures related to the onset of the Little Ice Age (Petersen 1988; Damon 1990) or arroyo cutting in alluvial valleys (Hack 1942; Karlstrom 1988), might have operated independently or in concert with reduced soil moisture to cause or contribute to depopulation. Furthermore, crop failures due to plant disease or pests are not addressed by the model, nor is the possibility of human-induced decline in agricultural productivity due to depletion of soil fertility or erosion of cropland (e.g., Stiger 1979).

Second, the modeling effort demonstrates that the distribution of the most productive land changed somewhat from year to year, but that there were locations in the study area that were consistently productive and some that were consistently unproductive. Therefore, it may be concluded that guaranteed access to consistently productive land, or at least to the crops grown on such land, was essential as the landscape “filled up” with people (cf. Kohler 1989; Adler 1990). If mobility and access to consistently productive lands were restricted, or if redistribution systems were not in place to support populations living in less productive and reliable areas, then the potential aggregate population figures would overestimate the actual regional population that could have been supported. These issues fall as much in the sociopolitical realm of human cultural systems as in the environmental realm and force us to consider seriously the complex interactions of climatic variation, environment, and human behavioral systems (Dean 1988; Gumerman 1988).

Locality Block-Survey Areas

The agricultural productivity model was also applied to recently surveyed portions of two localities within the study area—the Sand Canyon and Mockingbird Mesa localities. Demographic reconstructions have been made for both block-survey areas; these provide a basis for comparing modeled carrying capacity with actual (or at least estimated actual) population sizes.

The upland block survey in the Sand Canyon locality, as digitized in this study, covers a 26-km² area surrounding two large Pueblo III sites: Sand Canyon Pueblo and Goodman Point Ruin (Figure 1.3). The survey was carried out by the Crow Canyon Archaeological Center in 1986 and 1987 (Adler, this volume; Van West et al. 1987; Adler 1988, 1990). The Mockingbird Mesa block survey, as digitized for this study, covers an area of approximately 18-km², coterminous with the mesa-top surface of Mockingbird Mesa (Figure 9.1). The Bureau of Land Management conducted a block survey of this area between 1981 and 1984; the work was reported by Fetterman and Honeycutt (1987).

Adler developed average momentary population estimates for several time periods in the Sand Canyon upland survey (Adler, this volume; Adler 1988, 1990). He proposed two series of estimates—one based on an assumption of a 20-year habitation-site use life and one based on an assumed 50-year use life. Using the Mockingbird Mesa survey data, Fetterman and Honeycutt (1987) estimated population on the basis of 12-year and 100-year use-life estimates for all Anasazi habitations. Schlanger (1985, 1988) also used a sample of the Mockingbird Mesa site data to make estimates of average momentary population for a number of time periods, on the assumption that habitation sites were occupied for 20 years. Although Schlanger’s assumptions and methods of estimating population were not identical to those used by Adler, they were closer than those used by Fetterman and Honeycutt (1987). Consequently, Schlanger’s population estimates for Mockingbird Mesa were used here, as were Adler’s for the Sand Canyon upland survey area.

Table 9.1 summarizes and compares the 400-year mean maize yield and estimated potential population values for the two block survey areas with those of the study area as a whole. The POP2YR density values predicted by the productivity model for the Mockingbird Mesa survey area are nearly identical with those for the study area as a whole, but the POP2YR density values predicted for the Sand Canyon upland survey area are markedly higher. This suggests that Mockingbird Mesa is generally representative of average conditions in the study area as a whole, although it does not include the extremes of elevation and soil productivity that are found in the larger area.

It also demonstrates that there are places within the study area that are better than others insofar as productive land...
is concerned. The Sand Canyon upland survey area is a more productive and more predictable location in which to farm than is the area that was surveyed on Mockingbird Mesa. The higher coefficient of variation for maize yields on Mockingbird Mesa indicates there is more overall variation associated with this area than with the Sand Canyon uplands.

Table 9.1 provides the maximum, critical, and optimal carrying capacity values for the three areas expressed as persons/km² for a population requiring two years' maize at the end of harvest (POP2YR). At any time within the A.D. 901-1300 period, Mockingbird Mesa could have supported a population density of at least 18 persons/km². This minimum value, or critical carrying capacity, is equal to 50 percent of the long-term mean value of 36 persons/km². The critical carrying capacity value occurs 16 times over the 400-year time span, in a pattern similar to that of the study area as a whole.

By contrast, the data indicate that the Sand Canyon upland survey area could have always supported at least 37 persons/km² at any time during the 400-year period, a value equal to 67 percent of the long-term mean of 55 persons/km². This minimum, or critical carrying capacity, value occurs 29 times in the period A.D. 901-1300, nearly twice as often as the minimum value occurred in the modeled Mockingbird Mesa population. In absolute terms, the long-term critical carrying capacity of the Sand Canyon upland area is twice as high as the comparable figure for Mockingbird Mesa. This is a good indicator of the higher long-term agricultural productivity of the Sand Canyon area.

Figure 9.6 plots estimated actual momentary population densities for the Sand Canyon upland survey area for each of the archaeological time periods established by Adler (this volume; Adler 1990). Two series of estimates are given, based on assumptions of 20- and 50-year use lives for habitation sites. Varien's data (Varien et al., this volume) suggest that the shorter use life is probably the more realistic.

In Figure 9.6, the population estimates for the Sand Canyon area are overlaid on a plot of the maximum value, the long-term mean value (maximum carrying capacity), and the minimum value (critical carrying capacity) calculated for the 400-year period from the annual population density values associated with the POP2YR assumptions. Also depicted are those intervals when the minimum value (critical carrying capacity) "lifts" for a period of time from its low of 37 persons/km² to some greater value.

These episodes of higher minimum values were identified and plotted as follows. Using population density data for POP2YR, the minimum potential population value for a consecutive series of 10 years was recorded for each 10-year period beginning in A.D. 901. For example, the minimum potential population value for A.D. 901-910 is 37 persons/km². Similarly, the minimum value for each run-
could have lived well below the limits imposed by the productive environment.

Figure 9.6 also plots Schlanger's (1985) estimates of average momentary population density estimates for Mockingbird Mesa, using the assumption of a 20-year habitation-site use life. Estimates based on a 50-year span were not made. As with the Sand Canyon locality, the estimates of actual population are overlaid on a plot of the long-term mean value of potential population (the maximum carrying capacity), the maximum value, and the minimum value (critical carrying capacity), calculated for the 400-year period using POP2YR assumptions. Again, periods of elevated critical carrying capacity are depicted.

A comparison of Schlanger's population estimates for Mockingbird Mesa with the long-term estimates generated by the model reveals a different scenario than that reconstructed for the Sand Canyon uplands. Schlanger's estimates indicate that two periods of major population growth were followed by two periods of major population decline. In both cases, in the periods of major growth—A.D. 980-1025 and A.D. 1175-1250—the population (estimated from the archaeological data to average 28.5 and 53 persons/km² for the periods, respectively) exceeded the POP2YR productive capabilities of the Mockingbird Mesa survey area. This area has a 400-year critical carrying capacity of only 18 persons/km² and a variable 10-year critical carrying capacity that was always less than 35 persons/km². The earlier period of high population density was followed by a period (A.D. 1025-1100) of very low density, whereas the later high population period (A.D. 1175-1250) was followed by a time of unknown population density (A.D. 1250-1300), during which the Mesa Verde and Four Corners regions are known to have been abandoned. These data suggest a

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**Figure 9.6.** Estimates of carrying capacity for Sand Canyon upland survey area (above) and Mockingbird Mesa survey area (below).
repeated history of population overshoot and collapse when human demand exceeded agricultural supply.

In summary, comparison of modeled with estimated actual population in these two survey areas suggests two quite different histories of population in the 400 years examined. This is particularly interesting, since the areas are relatively close to each other (about 15 km apart from center to center) and both possess excellent soils with relatively high available water capacities. However, the Sand Canyon upland survey area is 124 to 385 m higher in elevation than the Mockingbird Mesa area and is not as circumscribed by canyon topography. This preliminary comparative study at the scale of small localities indicates that there are places within the study area that are more productive and predictable than others, and that even among the better locations there are some that are consistently superior.

A number of issues remain to be researched if this type of study is to be pursued further. First, pottery chronologies need to be improved, so that the survey data can be better compared with the more finely controlled environmental chronology. Second, we need sounder estimates of habitation-site use life. We hope that Varien’s work with the Site Testing Program (Varien et al., this volume) will put this aspect of demographic estimation on a sounder footing. Third, survey coverage needs to be expanded around both the existing Sand Canyon upland and Mockingbird Mesa block survey areas. Both have heavy Pueblo III occupation that extends essentially to the edge of the survey block. If Pueblo III (or any other period) population density falls off rapidly outside the present survey area, the populations we have been discussing may have had a larger agricultural sustaining area available to them, and hence have had lower population density relative to this sustaining area. If, on the other hand, high density population continues outside the existing survey areas, the estimates discussed above will be supported.

Conclusions

The modeling effort described above indicates that within the study area agricultural productivity varied considerably from place to place and from year to year. It also is clear that there was always enough productive land to produce sufficient maize to support a very large population (for example, an estimated 31,360 persons at a density of 21 persons/km² over the 400-year period), even in the relatively dry times of the middle twelfth and late thirteenth centuries. If mobility and access to productive land were not restricted, or if redistribution systems were in place to support dispersed populations or uneven production, then the prehistoric productive environment could have always sustained many people, even during the so-called Great Drought of A.D. 1276–1299. If, however, mobility and access to productive resources were severely restricted and extensive intercommunity food sharing was not regularly practiced, then there would have been times when the demand for maize by some populations that were confined to living in certain places might not have been met by their agricultural production. Nevertheless, it is important to emphasize that there were always locations somewhere within the study area that could produce adequate maize crops, and at no time was the “potential dry-farming belt” (Petersen 1988) completely pinched out due to fluctuations in moisture supply. In other words, rainfall and soil moisture fluctuations as they affected crop production in and of themselves cannot be used as a sole and sufficient cause for the total abandonment of the northern San Juan region at the end of the thirteenth century.

Studies at the level of individual site catchments (reported in Van West 1990, but not reviewed in this chapter) suggest that Anasazi populations were aware of the differential productivity of places on the landscape and tended to select those locations that would consistently produce good yields of maize. This may indicate that populations considered only the most arable soils as worth farming. Perhaps as their populations increased in a given area, the prehistoric Puebloan farmers of the study area were unwilling to meet their annual maize requirements by working more land of lower productive potential—that is, by lowering their cost-benefit ratio. Instead of turning to less productive soils or intensifying production on the better soils (e.g., by decreasing fallow, increasing cultivation effort, or building water and soil control features), they may have moved to places where high productivity was more predictable. This would have occasioned both local abandonments and relocations within the region and ultimately, perhaps, the abandonment of the northern San Juan region itself. The model described above can generate precise characterizations of the most productive soils for given periods. Focused survey could then determine whether prehistoric land use patterns indicate that Anasazi farmers were concentrating just on these soils or were less selective in their land use.

An alternative to the scenarios sketched above is that environmental factors other than soil quality and soil moisture were the limiting factors in sustaining a large population in the study area. Environmental resources suggested elsewhere as potentially limiting include scarcity of potable water relative to population size (Hérald 1961), wood resource depletion (Kohler and Matthews 1988), soil nutrient depletion in pinyon-juniper woodland zones (Mason et al. 1988), animal protein deficiency (Sneath and Scott 1985, 1989), and cooling temperatures, resulting in growing seasons that were too short for agriculture in upland locations (Petersen 1988). While possible shortages of drinking water and reduced growing seasons are linked to meteorological conditions, the other factors—shortages of wood for construction and fuel, shortages of animal pro-
tein, and depletion of soil nutrients—appear more closely linked to human overuse of the environment and poor resource management practices than to limits imposed by the natural environment as such. It is possible, of course, that several of these factors, including meteorological drought, acted together in the late thirteenth century. If so, the estimates of potential population currently generated by the model would be too high. Survey data suggest that in at least two relatively favorable localities, thirteenth-century populations were well into the zone of optimal carrying capacity. Hence lesser carrying capacities than those modeled may well have put a number of populations at risk.

Unless there was a truly large drop in temperature in the late 1200s, it would appear that environmental factors were incapable of causing a complete and rapid depopulation of the entire region, as evidently happened. That is, if populations were having problems because their numbers exceeded optimal or critical carrying capacity, then death or emigration of some portion of those populations should have enabled those remaining to adapt. There is no evidence that the high populations of the Pueblo III period resulted in irreversible soil erosion or depletion. There is abundant, uneroded soil in the area today, and it supports commercial dry-farm agriculture over large areas in the northern San Juan drainage.

Another possibility is that social or cultural factors were responsible for the ultimate abandonment of the region—either alone or in combination with environmental factors. Comparison of the Mockingbird Mesa and upper Sand Canyon areas suggests that, in some locations, the growing populations of the thirteenth century may have "overshot" the productive capacity of their local environment. If the best alternative locations were already occupied because of regional population growth, the populations that were having difficulty would have had to join existing groups—either alone or in combination with environmental factors—or move out of the area. There is evidence that large Pueblo settlements were forming in the Rio Grande and in the Western Pueblo area during the late 1200s and early 1300s (Dickson 1979; Crown and Kohler 1990; E. C. Adams 1989; Lipe and Lekson 1990). Some of these settlements appear to be on "new lands" having little previous occupation, suggesting that land was available. In other cases, existing settlements appear to have increased substantially at this time, perhaps in part by absorbing immigrants. There are hints in architectural and community pattern changes (e.g., the increasing prominence of the central plaza and the decreasing ratio of kivas to rooms [Lipe 1989; E. C. Adams 1989]) that new forms of community integration, probably employing new or elaborated forms of religious ritual, may have characterized these growing Puebloan communities to the south. Perhaps new lands and dynamic new communities to the south provided a "pull" on northern San Juan populations that reinforced whatever "push" was being exerted by environmental or other problems in their homeland.