In a recent paper in *American Antiquity*, van der Leeuw and Redman (2002) call for archaeology to situate itself at the center of socio-natural studies, by which they mean the study of long-term interactions among components of ecosystems that include human populations (see also Fisher and Feinman 2005; Redman 1999). This is a timely and important challenge for which archaeology is well suited. It is also a line of research that archaeologists in the American Southwest have been addressing, in one form or another, ever since A. E. Douglass discovered that the history of south-
western climate could be read from tree-rings (Douglas 1929).

Research on human ecology in the Southwest is extensive and often implicit, and we could not hope to accomplish our goals for this paper if we were to review it properly here. However, based on our knowledge of the literature that focuses explicitly on human-environment relations we find it productive to characterize recent studies as following one of three courses of a braided stream. The first and most venerable focuses on the effects of long- and short-term climatic fluctuations for agricultural success and population movement (Berry 1982; Dean 1985, 1988; Dean et al. 1985; Euler et al. 1979; Jett 1964; Lipe 1970; Petersen 1988). A second, more recent course models agricultural productivity on specific landscapes by integrating climate information with geomorphology, soils, and likely agricultural strategies (Hill 1998; Huckleberry and Billman 1998; Kohler et al. 2000; Stone and Downum 1999; Tuggle et al. 1984; Van West 1994). The third and perhaps least-developed course considers anthropogenic changes in past southwestern environments and the impact of these changes for humans (Diamond 2005:Chpt. 4; Kohler 1992, 2004; Kohler and Matthews 1988).

In this paper we weave these branches together to consider impacts of climatic variation, agricultural productivity, and anthropogenic change simultaneously using data generated by the Village Ecodynamics Project (Kohler et al. 2007). We present results of several studies. First is an assessment of the occupation histories of the 3,176 habitation sites in our project study area. Second is a new reconstruction of potential maize productivity for the project area. This in turn makes possible an analysis of settlement dynamics using the Village Project archaeological site database incorporating comparisons with the productivity data. Finally, we analyze a database of wood samples from sites in the project study area for which year of harvest could be determined through tree-ring analysis. This dataset includes the year in which each dated timber was harvested and the species of tree. Nearly all of these come from structural contexts, and we assume they represent timbers harvested for construction. We also examine the number of rings in the specimens when both the pith and the outside ring is present, which gives the age of the section of the tree that was sampled and analyzed by analysts at the Laboratory of Tree-Ring Research. We use these data to address how the Pueblo populations affected study-area woodlands through centuries of harvesting timbers.

We begin this new synthesis of settlement history in the central Mesa Verde region by describing these three datasets and the methods used to analyze them. Then we present our results and consider their implications for the historical ecology of Pueblo peoples in the northern Southwest.

**Site Data**

The site database for our study contains information on 8,948 sites. Most were recorded during the many archaeological surveys conducted within the project study area in the context of problem-oriented research or cultural resource management work. These surveys cover approximately 15 percent of the study area and include large, block surveys (which were used in many of the settlement analyses that follow), transect surveys, and a variety of smaller surveys (Figure 1). Although resurvey would undoubtedly discover additional sites within certain of these blocks, we will assume here that all habitation sites within the surveyed areas...
have been recorded and that only a small portion of the total has been recorded outside these surveyed areas.

In Table 1 we present the general time periods and primary functions inferred for all sites in the Village Project database. The project study area has been used by humans from Paleoindian to historic times, but 97 percent of all sites for which period of occupation could be inferred date from the occupation of the study area by Pueblo peoples, between about A.D. 600 and 1280. Most sites for which a primary function has been recorded are habitation sites. We used the presence of a trash midden and one or more pit structure depressions as evidence that a given settlement was a year-round residence for at least one household; the analysis of features and assemblages at excavated sites with these characteristics supports this interpretation (Varien 1999a; Varien, ed. 1999). A total of 3,176 sites in the database possess these features and are accordingly interpreted as single habitations, multiple habitations, or community centers. The occupational histories of these settlements, reconstructed using the methods outlined by Ortman and others (this issue), suggest that some of these habitations were occupied for more than one of the 14 modeling periods into which we have subdivided our sequence.

Based on recent research in our study area (Cater and Chenault 1988; Lightfoot 1994; Lipe 1989; Ortman 1998; Varien, ed. 1999) we infer that each pit structure was the central building used by a single household consisting of individuals related by lineage or marriage, two to three generations deep. About two-thirds of the habitation sites in the database contain only one pit structure, and thus represent farmsteads occupied by a single household. Approximately 850 sites contain evidence of between 2–8 pit structures and are termed multiple habitations. Finally, the largest sites are called community centers. For the purpose of these analyses, community centers are defined as settlements with

Figure 1. Digital elevation model showing the study area boundary and the location of archaeological surveys.
nine or more pit structures, 50 or more total structures, or sites with public architecture.

We interpret these large sites as community centers because their inhabitants could not have all been lineally related, they often contain public architecture such as a great kiva or plaza, and they are typically the largest site within a cluster of sites (Adler and Varien 1994; Lipe and Varien 1999:345; Ortman and Varien 2007; Varien et al. 1996). These centers generally have longer histories than most of the smaller habitations in the region (Varien 1999:202–207; Varien and Ortman 2005). Finally, excavations at these centers indicate that they were locations of social, economic, and political activities not occurring at smaller habitations (Adler 1994; Bradley 1988, 1993, 1996; Driver 1996; Lipe 2002; Muir 1999; Muir and Driver 2002; Ortman and Bradley 2002; Potter 1997, 2000; Potter and Ortman 2004).

As a result of 15 years’ effort to document large settlements in the greater Mesa Verde region (see Varien et al. 1996; Varien 1999a), we have identified 106 community centers in the Village Project study area. As we compiled the database we evaluated existing records for these centers and conducted new fieldwork at 59 poorly documented centers. A team led by Glowacki mapped these sites and obtained size data (site area, number of pit structures, size of the roomblock area, and the estimated number of rooms), compiled an inventory of cultural features, and analyzed the surface pottery to collect new chronological information. As a result, we believe that we have a relatively complete dataset of all community center sites in the Village Project study area, regardless of whether or not the center occurs within a survey block as defined in Figure 1. This assumption will play an important role in our efforts to model population dynamics below.

### Paleoproductivity Estimates

Macrobotanical and stable isotope data suggest that in the northern Southwest maize was the single-most important subsistence resource by at least A.D. 600, and perhaps even earlier in the Basketmaker sequence (Kantner 2004:60–67; Matson 1991:90–101; Matson and Chisholm 1991). Van West’s (1994) well-known estimates for maize production in our project study area provided the starting point for modeling paleoproductivity in the Village Project. Following Van West, we use the Palmer Drought Severity Index (PDSI) as a basis for our maize productivity calculations. The PDSI is a relative measure of soil moisture developed by Palmer (1965); Burns (1983) was the first to note

<table>
<thead>
<tr>
<th>Primary Function</th>
<th>Paleo-indian</th>
<th>Archaic through Basket-maker II (A.D. 600-1280)</th>
<th>Ancestral Pueblo</th>
<th>Numic / Historic</th>
<th>Unknown</th>
<th>Not recorded</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not recorded</td>
<td>4</td>
<td>48</td>
<td>740</td>
<td>9</td>
<td>27</td>
<td>1</td>
<td>1642</td>
</tr>
<tr>
<td>Indeterminate</td>
<td>4</td>
<td>174</td>
<td>24</td>
<td>4</td>
<td>24</td>
<td>17</td>
<td>223</td>
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<tr>
<td>Isolated Find</td>
<td>3</td>
<td>9</td>
<td>1</td>
<td>18</td>
<td>9</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Artifact scatter</td>
<td>1</td>
<td>56</td>
<td>546</td>
<td>3</td>
<td>154</td>
<td>66</td>
<td>827</td>
</tr>
<tr>
<td>Ceremonial site</td>
<td>15</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay quarry</td>
<td>2</td>
<td></td>
<td>1</td>
<td>6</td>
<td>3</td>
<td>268</td>
<td></td>
</tr>
<tr>
<td>Field house</td>
<td>1</td>
<td>618</td>
<td>1</td>
<td>20</td>
<td>640</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiln</td>
<td></td>
<td>259</td>
<td></td>
<td>6</td>
<td>3</td>
<td>268</td>
<td></td>
</tr>
<tr>
<td>Limited activity</td>
<td>1</td>
<td>10</td>
<td>565</td>
<td>5</td>
<td>8</td>
<td>73</td>
<td>200</td>
</tr>
<tr>
<td>Reservoir</td>
<td></td>
<td>14</td>
<td></td>
<td>2</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock art</td>
<td></td>
<td>15</td>
<td>2</td>
<td>6</td>
<td>13</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Stone quarry</td>
<td>1</td>
<td>12</td>
<td></td>
<td>10</td>
<td>36</td>
<td>59</td>
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<td>Storage</td>
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<td>107</td>
<td></td>
<td>8</td>
<td>116</td>
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<td></td>
</tr>
<tr>
<td>Water control</td>
<td></td>
<td></td>
<td>45</td>
<td>11</td>
<td>9</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>Single habitation</td>
<td>8</td>
<td>1991</td>
<td>5</td>
<td>75</td>
<td>2079</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple habitation</td>
<td>3</td>
<td>852</td>
<td>1</td>
<td>16</td>
<td>872</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indeterminate habitation</td>
<td>4</td>
<td>227</td>
<td></td>
<td>11</td>
<td>242</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Community center</td>
<td></td>
<td>106</td>
<td></td>
<td>106</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Total                            | 6            | 139                                           | 6297            | 19             | 52      | 313          | 2122  | 8948

Table 1. Primary Temporal and Functional Classification of Sites in the Village Project Database.
its utility for archaeology. Our studies show that PDSI values, calculated from historic weather records, are reasonably well correlated with records of maize-and-bean production in our study area from 1931–1960. Moreover, we can estimate the PDSI values from tree-ring data relatively accurately and thus project them into the prehispanic period.

Our study modifies Van West’s approach by (1) including portions of the study area for which soils maps did not exist when she did her work, (2) giving temperature variability a more explicit role in developing production estimates, (3) modifying these estimates to represent harvest rates more similar to those of maize grown prehispanically in our area, (4) reducing estimates of production based on soils that are evaluated as unsuitable for hand planting (Ramsey 2003), and (5) extending the reconstructions back to A.D. 600.

This work was accomplished in a series of steps; here we give a general overview with additional details deferred to other publications. The first step was to use the available tree-ring data to develop proxies for temperature and identify local cold or short summers. We eventually settled on two high-elevation bristlecone pine sequences, one from Almagre Mountain about 350 km east-northeast of the project area (Graybill 1984), and one from San Francisco Peaks about 335 km southwest of the project area (Figure 2). We used the scores on the first principal component extracted from both sequences (Table 2) as an independent variable in a regression formula retrodicting productivity, as explained below. These scores are positively related to average temperatures for local weather stations during the summer months, with the correlations strongest and most significant for late summer (e.g., in September, when the $r$ at Mesa Verde is .49 [p < .0001], at Yellowjacket, .53 [p = .01], and .31 in Cortez [p = .02]). Although these correlations are not terribly strong, their only purpose is to assure us that these sequences are sensitive to local late summer temperatures. We also produced a rather similar reconstruction in which the Almagre sequence by itself provided the temperature proxy, but that will not be discussed further here.

In the second step we assessed differences in soils in the study area and defined 14 groups of soils that are similar with respect to their productivity. Third, using instrumented data from four weather stations, each representing a different elevational band, we produced PDSI reconstructions for these 14 groups of soils for the years between 1931 and 1960. This produced 56 (4 x 14) PDSI sequences
for the study area. Fourth, we determined that each of these 56 PDSI sequences had a significant relationship with the Mesa Verde Douglas-fir indexed series, with values of $r^2$ ranging from .32 – .67 (mean = .54, s = .11; all with $p > F < .001$ and all but three with $p > F < .0001$). Fifth, using these regression relationships we retrodicted PDSI values to A.D. 600, using the Mesa Verde series as the independent variable for each of the 56 combinations of soil/elevation.

In the sixth step, we produced a weighted average of the PDSI values for those soils producing maize and beans between 1930 and 1960 in Montezuma County, which we call the “bean soils,” below. The seventh step regressed those values against the historic maize and bean production in Montezuma County, and against the two temperature proxies, introducing a third independent variable, year, which would allow us to assess and hold constant the “technology trend” (Burns 1983:70) that this represented. This produced the following results for the first principal component (PC1) of the Almagre and San Francisco series:

We standardized all independent variables prior to regression, so the partial slopes associated with each may be considered beta weights. Therefore, the single-most important variable affecting maize yields during the calibration period was “year,” a variable standing in for the technology trend (increasing use of fertilizer, mechanized equipment, more productive varieties, and so on). Following that, the PDSI, affected mostly by precipitation, and the PC1 score, affected mostly by temperature, are approximately equal in importance.

Because these maize production estimates apply to the average productivity of the soils farmed historically (the bean soils), the eighth step was to adjust the productivity for each soil class in the study area relative to the bean soils. We did this by calculating the ratio of the average productivity for soils in that class to the average productivity of the bean soils, which was gleaned from the normal-year total dry weight production published in the Cortez-area soil survey (Ramsey 2003:Table 7).

The ninth step takes into account the fact that the farming practices of Pueblo peoples in the study area likely produced lower yields than those obtained using historic seed varieties and planting practices. We used historical data from Zuni and Hopi and ethnoagricultural experiments by Muenchrath et al. (2002), Adams et al. (1999), and other sources, to adjust the yields. Using these sources, we determined that 500 kg/ha was a reasonable estimate for the mean yield in our best soils (i.e., the bean soils). We then renormed our production figures so that the mean production in the bean-field soils is 500 kg/ha by multiplying the yields from step 8 by a factor of .68.

The tenth step further reduced maize production on soils reported as unsuited for hand planting. The detailed soil descriptions in the soil surveys provide “major management factors” that indicate the

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Table 2. Principal Components Analysis Used to Generate Temperature Proxy for Paleoproductivity Reconstruction.

<table>
<thead>
<tr>
<th>Ring-Width Index Series (Abbreviation)</th>
<th>Reference</th>
<th>Species</th>
<th>Approx. Elevation (m)</th>
<th>Years Used (A.D.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Francisco Peaks (SFP)</td>
<td>Salzer (2000) and personal communication</td>
<td>bristlecone pine</td>
<td>3535</td>
<td>560–1983</td>
</tr>
</tbody>
</table>

Eigenvalues of the Correlation Matrix

<table>
<thead>
<tr>
<th>n</th>
<th>Eigenvalue</th>
<th>Proportion</th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.233</td>
<td>0.617</td>
<td>0.617</td>
</tr>
<tr>
<td>2</td>
<td>0.767</td>
<td>0.383</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Eigenvectors

<table>
<thead>
<tr>
<th>n</th>
<th>Eigenvectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Prin1</td>
</tr>
<tr>
<td>2</td>
<td>Prin2</td>
</tr>
<tr>
<td>SFP</td>
<td>0.707</td>
</tr>
<tr>
<td>ALM519</td>
<td>0.707</td>
</tr>
</tbody>
</table>
suitability of each soil complex for a variety of uses. In addition, and somewhat independently of these general land suitability classes, for each soil the surveys report hand-planting suitability restriction codes ranging from 0 to 1.0. (A value of 0 means no restrictions; 1 indicates the soil to be completely unsuitable, even for hand planting.) For those soils in our study area reported as “unsuitable” in the “cropland suitability” field, we multiply the yields from step 9 by the inverse of the hand-planting restriction value. This further reduces the yields for soil complexes that in our study area for the most part represent off-mesa, steep, stony soils. In a few places there are also bogs or highly alkaline soils that have their potential yields reduced through this correction. Altogether these soils represent 53.2 percent (by area) of the 1817-km² study area.

The eleventh step applied a “cold correction” factor. This factor disallowed any maize production above 7,900 feet (2,400 m) and progressively reduced production in colder-than-average years in the elevational band between 7,054 and 7,900 feet. Discounting production in this elevational band was accomplished using a formula that takes into account both the elevation and how cold it was, using the tree-ring-based temperature proxy.

Figure 3 displays the average potential yields per year in our study area that result from this process. These estimates are not affected by any fallow factor, possible land degradation, or improvements in agricultural productivity over time due to innovations in farming practices or the evolution of more productive maize varieties through human selection. These estimates are spatial and provide a yearly estimate for each 4-ha plot of land in the study area, but for Figure 3 we have averaged those values across the study area to provide a measure of average annual agricultural potential. Of course, we can also estimate the potential productivity of land adjacent to known sites that was likely farmed when those sites were occupied.

We emphasize that what we have produced is only a model for paleoproductivity. Our claim, in
constructing the model this way, is that soil moisture, length of growing season, elevation, and local soil characteristics are the most important factors affecting production. Future refinements could attempt to take into account other variables of probable local importance, including patterns of cold-air drainage and aspect, but we have been unable to locate data that would allow us to calibrate the importance of these factors. The final strength of the fit we obtain with the historical data on crop yields (adjusted $R^2 = .58$) compares favorably with that obtained by Van West in her widely cited and accepted reconstruction (unadjusted $R^2 = .49$; Van West 1994:101–102) and is incomparably better than the traditional archaeological technique of estimating maize production by inspecting a graph of tree-ring departures through time (which implicitly, and surely incorrectly, assumes a perfect correlation). The essence of our approach—and also that of Van West—is to try to understand what effects these tree-ring departures have on maize production on a specific landscape. Therefore, our reconstruction does not necessarily apply to neighboring regions.

We reconstruct noteworthy periods of low potential production in the late 600s, the middle 700s, the late 800s and early 900s, around 1000, around 1100, from about 1130–1150, in the early 1200s, and in the late 1200s. Our reconstruction differs from Van West’s most dramatically in the late 1160s and early 1170s, when we estimate relatively higher potential production, and in the early 1200s, a cold period when we estimate lower potential production. Van West’s estimates are relatively higher throughout than these new estimates.

Tree-Ring Database

The tree-ring database for the central Mesa Verde region was compiled by archaeologists at the Crow Canyon Archaeological Center from records at the Laboratory of Tree-Ring Research at the University of Arizona. The database includes 1,784 cutting dates from 91 sites in the study area. The vast majority of these samples with cutting dates were collected from burned deposits near the floors of collapsed structures, and therefore we assume they represent timbers harvested for use in construction. Because large timbers are difficult to cut and shape when dry, we also infer the date recorded for most cutting dates not only represents the year that tree or limb died, but also the year in which the tree or limb was harvested for eventual use in construction. The species of tree recorded for each date also provides information on species selection and availability. We therefore believe our database provides a record of a specific cultural practice through time.

Sampling issues, however, prevent us from viewing this sample as representative of the rate of construction-timber harvesting through time. The available sample is biased in favor of periods that archaeologists have studied most intensively and contexts where preservation is most likely. This includes periods when open sites were burned, when cliff dwellings were built, and when there was a large amount of construction generally. The sample is biased against periods in which large numbers of recycled timbers were used (Bradley 1993; Varien 1999a; Varien and Kuckelman 1999). For these reasons we do not take the numbers of cutting dates through time as a proxy for population, and consider them to offer only a general indication of construction activity. Because we believe cutting dates indicate the year when timbers were harvested for construction, we do believe our sample conclusively identifies years when construction occurred and characterizes patterns in the species of timbers harvested. The age of the particular sample can also be determined when both pith and cutting dates are present. These data are interpreted cautiously to examine changing patterns in wood procurement.

Momentary and Total Population Estimates

In this section we reconstruct the overall population history of the study area. We begin by calculating the momentary population, in households, of sites in our database for each of our 14 modeling periods. Then we use average momentary household estimates for sites in the database to estimate the total momentary population for the entire study area.

Ortman and others (this issue) describe the probability density analysis we used to reconstruct the occupational histories of habitation sites and thus estimate the total number of households that occupied these sites at some point during each period. Here, we use these estimates of total households to
calculate the average momentary population of households in our sample. Momentary household estimates take into consideration the use-lives of houses in small sites and community centers vis-à-vis the lengths of our modeling periods. During the final few centuries of our sequence the average use-life of a house in both small sites and community centers was equal to or greater than the length of our modeling periods, so for these periods the use-lives of houses in small sites and centers are effectively subsumed by the probability density analysis (Ortman et al. 2007) and have no effect on momentary household calculations. For earlier periods, however, the average use-life of a house was shorter than the length of the modeling period within which our analysis suggests a house was occupied, so for these periods we need to take into account the variable use-lives of houses in small sites and centers, and the length of the corresponding modeling period.

House use-life estimates for early small sites were calculated by measuring the accumulation of cooking pottery, following the methods developed by Varien and others (Varien 1999a; Varien and Mills 1997; Varien and Ortman 2005). Excavations and the analysis of pottery assemblages indicate that houses in community centers were used for longer periods than houses in small sites (Kohler and Blinman 1987; Ortman et al. 2000), so we developed a new method for estimating the use-life of houses in early community centers. This method uses the probability density analysis and point estimates for the total accumulation of cooking pottery at two early community centers excavated using stratified random samples: Grass Mesa (Kohler 1988) and Rio Vista villages (Wilshusen 1986). To calculate the average use-life of houses in these two centers we divided the total households inferred for all periods from the probability density analysis by the total household-years of occupation, based on point estimates of the total cooking pottery accumulation and Varien’s (1999a:107) accumulation rate per household year.

With these use-life estimates in hand, we obtain momentary household estimates by dividing the mean house use-life for a given site type and period by the length of that period, and multiply the result by the corresponding total household estimate for sites of that type and period in the site database. These calculations are presented in Table 3. Again, note that total and momentary household estimates differ for the years between A.D. 600 and 1100 because the length of our modeling periods in this interval exceed our estimates of house use-life. From A.D. 1100 to 1280, however, house use-life was equal to or greater than the length of the periods, so the total and momentary population estimates are the same.

The average momentary household estimates for habitations in the database form the basis for estimating the total momentary population for the entire study area. Estimating population from archaeological evidence is notoriously difficult (Powell 1988), and a variety of different methods can be used, each of which produces different results. We estimated total population using three methods, the results of which are compared in Figure 4. Method 3 produces middle-range estimates that we believe are most reasonable, so we present the details of these calculations in Table 4. Under our preferred method we make two assumptions: (1) that the small-site momentary household density for the block-surveyed area is representative of the entire study area, and (2) we have a 100 percent sample of community centers. We first determine the proportion of the study area covered by block survey, and the momentary household density of small sites in this surveyed area. Then, we multiply the small-site momentary household density in the surveyed areas by the inverse of the sampling fraction to get total momentary household estimates for small sites. We then add the total momentary households in centers and the estimates for small sites to estimate the total momentary households in the study area. Then, we convert total momentary households into estimates of the momentary total persons who resided in the study area during each period by multiplying the total momentary household figure for each period by six, based on Lightfoot’s (1994) ethnographic review of household sizes in historic Pueblo groups. Finally, we use these total population figures to calculate the population density of humans per square kilometer of potentially arable land in the study area. These estimates indicate that population peaked during the A.D. 1225–1260 period, when approximately 19,500 persons, nearly 11 persons per square kilometer of land below 2,400 m elevation, lived in the Village Project study area.
### Table 3. Calculation of Momentary Populations of Pueblo Habitation Sites in the Village Project Site Database.

<table>
<thead>
<tr>
<th>Period</th>
<th>Occupation Span (years)</th>
<th>Span / Period Length</th>
<th>Total Households</th>
<th>Momentary Households</th>
</tr>
</thead>
<tbody>
<tr>
<td>Begin (A.D.)</td>
<td>End (A.D.)</td>
<td>Length (years)</td>
<td>Small sites</td>
<td>Community centers</td>
</tr>
<tr>
<td>600</td>
<td>725</td>
<td>125</td>
<td>8</td>
<td>28</td>
</tr>
<tr>
<td>725</td>
<td>800</td>
<td>75</td>
<td>13</td>
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<td>800</td>
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<td>1140</td>
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<td>1225</td>
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<td>1260</td>
<td>1280</td>
<td>20</td>
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</table>


\(b\) Community-center occupation spans for modeling periods prior to A.D. 1020 based on the ratio of total household years from the Bayesian analysis and the accumulation of cooking pottery at Grass Mesa (Kohler 1988) and Rio Vista (Wilshusen 1986) villages.
Settlement History

In this section, we use the total momentary population estimates to examine population dynamics and settlement ecology in the project study area. The results of these analyses are presented in Figure 5 as a series of line charts.

Population Dynamics

Figure 5A presents total momentary population estimates for the study area. This population reconstruction shows that occupation of the region occurred in two general cycles. The early cycle spans A.D. 600 to 920 and the late cycle 920 to 1280. Population density became much higher during the late cycle than at any point in the earlier cycle, and peaked in the mid-A.D. 1200s.

Figure 5B translates the total momentary population estimates into population growth rates for each period. The dashed lines on this chart reference positive or negative annual growth rates of .7 percent (an intrinsic rate of natural increase of .007). Based on Cowgill’s (1975) work, we interpret points above and below the dashed lines as periods when growth or decline may have included either immigration or emigration. Using this guideline, settlement in the region included four probable periods of immigration and two of emigration (Figure 5B). Since habitation sites prior to A.D. 600 are nearly absent in the study area (Table 1), there was actually a fifth episode of immigration not shown on Figure 5B, when the study area was first colonized by Pueblo farmers around A.D. 600.

This reconstruction presents a dynamic picture of regional population history that contrasts markedly with the view of gradual population growth and culture change over the seven centuries when Pueblo groups occupied the area (e.g., Rohn 1989). The probability that people moved into and out of the study area so often makes it likely that inhabitants of the region came from different areas and had distinct histories (Glowacki 2006; Wilshusen and Ortman 1999). As discussed below, many important events in the Pueblo Indian history of the Mesa Verde region occurred in the context of these dramatic swings in population.

Population Aggregation

Figure 5C examines settlement aggregation and the development of community centers. It uses data from block surveys within the study area, where we have a 100 percent sample of both centers and smaller habitation sites, to calculate the portion of households living in larger centers during each period. This chart shows that the formation of centers also occurred in two cycles, with peak aggregation at the end of each cycle, during the A.D. 880–920 and 1260–1280 periods. Perhaps the most
interesting and unexpected outcome of this analysis is that aggregation peaked during periods of population decline at the end of each cycle, and not during the period of peak population in each cycle. We examine this pattern in more depth in our summary discussion.

Figure 5D examines the formation of centers, summarizing the number of new centers founded during each period, and the total number of centers occupied in each period. From these data we can infer that centers tended to remain occupied for several periods after their initial founding. The persistence of centers over time in our reconstruction contrasts with views suggesting that villages in the northern Southwest were ephemeral and unstable (Adams 1989, 1991; Lekson and Cameron 1995; Schlanger and Wilshusen 1993).

Community Centers and Agricultural Potential

Figure 5E integrates our new potential paleopродucitivity estimates into our settlement pattern reconstruction. The solid line shows the mean potential productivity of the two-kilometer catchments around community centers founded in each period, during that period. We chose a two-kilometer radius as the size of a community center catchment based on both ethnographic research, which suggests this radius approximates the area within which community members would have interacted most regularly and farmed most intensively (Varien 1999a:153–155; Varien et al. 2000:51–52), and also archaeological research, which demonstrates that clusters of residential settlements, centered on villages and/or public architecture, tend to have a radius of two kilometers in our study area (Adler and Varien 1994; Ortman and Varien 2007). The thin line in Figure 5E shows the mean paleopродucitivity of the study area overall during each period.8 This chart thus incorporates both spatial and temporal variability in agricultural potential in a catchment analysis.

For most of the early demographic cycle the agricultural potential of community-center catchments was well above the mean. This is not surprising, as one would expect the earliest villages in a sparsely populated landscape to emerge in highly productive catchments. There is an interlude of low population density at the beginning of the second settlement cycle, between A.D. 920 and 1060. During this interlude the agricultural potential of catchments surrounding new centers was about average for the study area overall. Why these new centers were not founded in the high-potential catchments of the early-cycle centers is puzzling, and invites speculation that the catchments on which early-cycle centers were founded had been so degraded by the end of the cycle that they were unattractive places to live and farm for a period of time (Kohler

<table>
<thead>
<tr>
<th>Period (A.D.)</th>
<th>Database momentary households</th>
<th>Study area momentary households</th>
</tr>
</thead>
<tbody>
<tr>
<td>Begin</td>
<td>End</td>
<td>Small sites in block surveys</td>
</tr>
<tr>
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<tr>
<td>1260</td>
<td>1280</td>
<td>123.0</td>
</tr>
</tbody>
</table>

Table 4. Best Estimate for Total Population in the Village Project Study Area.

4Block survey small sites / proportion of study area surveyed.

5Total households x 6, after Lightfoot (1984).

6Total persons / 1776 km2 of land below 2400 m (7900 ft.) in study area.
Figure 5. Population and settlement dynamics in the Village Project study area. Notes: Points in all graphs represent the initial date of a modeling period. A) Total population (individuals); B) Rate of population change (per 1000 per year, dashed lines mark limits of in situ growth/decline); C) Proportion of block-survey households in centers; D) Number of newly-constructed and occupied centers; E) Mean productivity (kg maize/ha); F) Tree-ring cutting dates/years in period; G) Mean and standard deviation of construction timber age.
This possibility reminds us that our paleoproductivity reconstruction provides estimates of agricultural potential that are unaffected by historically contingent human impacts, either positive or negative. This is clearly an area where subsequent phases of this research could focus.

There was a burst of new center construction associated with immigration during the late A.D. 1000s, the early years of the late cycle. These centers were once again located on better-than-average catchments at the time they were founded. But as population increased over the course of the late cycle, the productivity of new community center catchments fell below the study area mean. This cannot be due to abandonment of centers founded earlier in this cycle, for example due to local soil degradation, because many centers founded on relatively good catchments early in the late cycle were still occupied even as new centers were built in less-optimal catchments over time.

However, other factors may explain the declining potential of new center catchments over the course of the late cycle. First, new centers founded relatively early in this cycle continued to occupy their high-productivity catchments, so these were not available to subsequent communities. In addition, the population density of the study area reached unprecedented heights during the final century of occupation, and it may well be that this forced people to build new centers on less-productive catchments. It is also possible that agricultural potential came to have a lower priority, relative to other factors, in choosing center locations. For example, centers founded early in the late cycle, such as Yellow Jacket and Albert Porter pueblos, were located on and adjacent to deep soils that were ideal for farming, whereas centers founded later in the cycle, such as Sand Canyon and Woods Canyon pueblos, were in canyon settings close to domestic water, building stone, and construction timber, but further from the best agricultural soils (Varien et al. 1996). It may be that farming these localities for centuries had resulted in land tenure systems that were widely acknowledged such that people no longer had to claim fields by living directly on these lands (Adler 1996; Varien 1999a). So as the late cycle progressed, people who had initially lived near fields and walked to water increasingly came to live near their water, stone, and timber resources and walked to their fields. One can also characterize these new center locations as being more defensible than earlier locations (e.g., Kuckelman, ed. 2000), and conflict and warfare have been documented during this period (Kuckelman 2002; Kuckelman et al. 2000, 2002; Lightfoot and Kuckelman 2001). However, safety at the latest centers could have been found in numbers as well as in the physiographic setting.

Construction-Timber Procurement

Figure 5F presents the number of tree-ring cutting dates recovered from sites in the study area during each period, standardized according to the length of the period. There are at least a few cutting dates for every period, demonstrating that the study area was occupied virtually continuously for 700 years. In addition, the number of cutting dates per year during the three periods from A.D. 880 to 1020 is consistently low. This is the period of low population density at the start of the second demographic cycle.

In other respects, however, the corpus of tree-ring dates does not provide a reliable record of population dynamics; the \( r^2 \) value for the regression between numbers of tree-ring cutting dates and population by period is .008. The current distribution of dates appears to represent a complex combination of ancient practices—including construction activity, recycling of timbers, and burning—and modern archaeological practices, such as differential intensity of sampling for datable timbers and the research foci of major excavation projects. As an example, tree-ring cutting dates are especially abundant for A.D. 840–880 because excavations by the Dolores Archaeological Program focused on community centers of this period, and many sites constructed during this period burned at abandonment. Likewise, cutting dates are especially abundant for the A.D. 1200s because several major projects have focused on this century, and many sites constructed during this period were also burned at abandonment.

Although we do not consider it productive to make specific comparisons between cutting dates and our demographic reconstruction, these data can be used for other purposes. Figure 5G summarizes the age distribution of the archaeological samples that have both pith and cutting dates. These data
must be interpreted with caution because many factors affect the age of the sample, including the portion of the tree that was harvested and the portion of the sample that was analyzed. But these data indicate that the mean age of the archaeological samples, and their standard deviation, decreased gradually over the course of the early settlement cycle. The local woodlands were relatively unaffected by human impacts when occupation of the study area began about A.D. 600, due to limited use by humans prior to that time. During subsequent use of the area, however, pueblo agriculturalists cleared forested areas for fields, collected wood for fuel, and harvested suitable timbers for support posts, walls, and roofs of their houses. The fact that the mean age of timbers and the standard deviation of timber ages decreased during the first occupational cycle may indicate that the use of woodlands surrounding sites created stands of younger, and more even-aged, trees. Forests may have recovered somewhat during the period of low population at the onset of the second cycle, as reflected by the increasing age of archaeological samples during the course of the A.D. 900s. During the late cycle, it appears that the mean age of utilized timbers once again gradually declined, but the standard deviation of these ages did not decline as it had during the early cycle. This suggests that the late-cycle population, despite its larger size, did not impact the local forests as dramatically as the early cycle population.

This interpretation of tree-ring sample age distributions is supported by the archaeobotanical analysis of wood used for fuel. Kohler and Matthews (1988) demonstrate a pervasive shift from high-quality fuel woods such as pinyon and juniper to low-quality fuel woods like *Populus* and rosaceous shrubs among the Dolores Pueblo I villages. By contrast, Adams and Bowyer (2002:134, 141–142) demonstrate relative stability in use of juniper and pinyon for fuels throughout the thirteenth century in our study area. Although their archaeobotanical evidence indicates some landscape disturbance by the end of the thirteenth century, the presence of small juniper and pinyon plant parts such as twigs, needles, and bark suggests that intact pinyon-juniper woodland was never absent from the landscape or at a great distance from sites (Adams and Bowyer 2002:141). Perhaps, then, thirteenth-century communities did not impact their local woodlands to the same extent as did nineteenth-century communities in the Dolores River valley.

Figure 6 summarizes proportions of ponderosa pine, juniper, and pinyon pine among cutting dates for each period. These are the three species used most commonly in construction. Although Ponderosa pines produce large, straight timbers ideal for support posts and primary beams, this species is rare in the study area, occurring primarily at elevations that are too high for maize agriculture, such as the upper slopes of Ute Mountain and the uplands adjacent to the Dolores River. Most Ponderosa timbers date from A.D. 600 and 880 and come from sites in the Dolores River valley, where they were likely used as posts and beams in pit structures. During the late cycle the Dolores River valley was largely unoccupied, and pit structure roofs were supported by masonry walls instead of posts, so there was little incentive to procure Ponderosa timbers from a distance. The one exception to this rule appears to have occurred during the era of Chacoan influence when Ponderosa timbers were used to roof great houses. All 32 Ponderosa cutting dates from the late cycle come from great houses exhibiting Bonito-style architecture, including Ida Jean, Wallace Ruin, Escalante Ruin, and Lowry Ruin. A hallmark of Bonito-style architecture in the San Juan basin is roof construction using Ponderosa pine vigas, often imported from a substantial distance (Betancourt et al. 1986; Durand 1999; Reynolds et al. 2005; Windes and Ford 1996:303–306). Thus the restriction of Ponderosa timbers to great houses in the second cycle probably reflects the energy expended in construction of these structures and not depletion of local Ponderosa forests.

Juniper occurs throughout the study area, and was the most commonly used species overall. Pinyon also occurs throughout the study area but was little used after A.D. 880. Juniper was always preferred over pinyon for construction, perhaps because it is stronger and more rot resistant. So the decline in pinyon over time may be due in part to the increasing use-life of houses in the late cycle, which led to an even stronger preference for juniper. The decline in juniper over the course of the early cycle therefore may indicate that land-use practices led to a shortage of suitable junipers within a reasonable distance of settlements. In contrast, nearly all dated construction timbers were of
juniper throughout the late cycle, indicating either that land use did not deplete local woodlands to the point that builders were forced to use the less-desirable species, or that traveling farther to obtain desirable construction timber was an accepted cost of building more durably. In sum, both sample age and species distributions suggest that the larger populations of the late cycle degraded local woodlands to a lesser degree than did the smaller populations of the early cycle. We will consider the importance of this for the study of human-environment relations in our concluding discussion.

**Implications for Pueblo History**

The reconstruction presented in this paper contributes to our understanding of the long history of Pueblo peoples in the Mesa Verde region. First, it provides new population estimates for a densely occupied portion of the northern Southwest. One estimate that is intrinsically interesting, especially to Pueblo people we work with, is that cumulatively about 197,000 people lived in the study area during the seven centuries between A.D. 600 and 1300.\(^9\) A second figure that is especially useful for comparative studies is our estimate of the peak population of the Village Project study area. Based on the methods presented in this paper and in the previous paper by Ortman and others (2007), we estimate that approximately 19,500 persons, or 11 persons per square kilometer of land below 2400 m elevation, inhabited the study area during the mid-thirteenth century. This new estimate is within the range (15,000 to 30,000) suggested by Rohn (1983:176; 1989:166) for the entire Mesa Verde region, but is higher than estimates produced by Duff and Wilshusen (2000:173–184); they calculated 23,000 people as a maximum estimate for the portion of the Mesa Verde region in southwestern Colorado, but argued that a peak population of between about 6,000 and 11,000 people is more likely. Our figure is also higher than the estimate of about 12,700 people produced by Wilshusen (2002) in a follow-up study. Our peak population estimate for the Village Project study area covers only a portion of the larger areas considered in these studies, and thus suggests a still higher regional population. We nevertheless prefer our new estimate because it is based on a more thorough analysis of a larger body of data, building up from the original site forms, and profiting from years of excavation to calibrate the surface pottery and architectural data.

A second important feature of our reconstruction is the dynamic population history it suggests. In contrast to traditional views of population continuity, in situ growth, and gradual culture change in the Mesa Verde region, our work suggests up to five episodes of immigration and two periods of emigration, each of which is tied to important events in Pueblo Indian history. In this sense our reconstruction offers support for the contention that population movements played a central role in cultural transitions throughout Pueblo history (e.g., Berry 1982; Wilshusen and Van Dyke 2006).

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**Figure 6. Species distribution of harvested timbers through time (N = 1,784).**

<table>
<thead>
<tr>
<th>Modeling period (A.D.)</th>
<th>Juniper</th>
<th>Ponderosa</th>
<th>Pinyon</th>
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<tbody>
<tr>
<td>600-725</td>
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<tr>
<td>725-800</td>
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<tr>
<td>1240-1280</td>
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\(^9\) Estimate is within the range (15,000 to 30,000) suggested by Rohn (1983:176; 1989:166) for the entire Mesa Verde region, but is higher than estimates produced by Duff and Wilshusen (2000:173–184); they calculated 23,000 people as a maximum estimate for the portion of the Mesa Verde region in southwestern Colorado, but argued that a peak population of between about 6,000 and 11,000 people is more likely. Our figure is also higher than the estimate of about 12,700 people produced by Wilshusen (2002) in a follow-up study. Our peak population estimate for the Village Project study area covers only a portion of the larger areas considered in these studies, and thus suggests a still higher regional population. We nevertheless prefer our new estimate because it is based on a more thorough analysis of a larger body of data, building up from the original site forms, and profiting from years of excavation to calibrate the surface pottery and architectural data.
The first episode of immigration in our study area occurred when it was initially settled by a substantial population of year-round residents, in the A.D. 600–725 period. We know little about the reasons for this migration or the source of the migrants; these remain important problems for future research. The second episode occurred as the well-documented villages of the Dolores River valley formed in the northeast corner of our study area (Kane 1986, 1989; Kohler 1992; Orcutt et al. 1990; Potter 1997; Schlanger 1988). Schlanger (1988:787) was the first to argue for large-scale migration into the Dolores River valley during the mid-ninth century to which Wilshusen and Ortman (1999) added the suggestion that these villages were created by people with distinct cultural and historical backgrounds, with one source in the upper reaches of the San Juan drainage to the east and another in southeastern Utah to the west. Our reconstruction, in agreement with Wilshusen and Ortman (1999:380, 389), suggests that these groups moved into the study area primarily during the A.D. 800–840 period and then coalesced into the large villages of the Dolores River valley in the subsequent period.

This period of village formation was followed by the first large-scale emigration from the study area between A.D. 880 and 920. It now appears that many of these migrants went south into northwestern New Mexico (Wilshusen and Wilson 1995) and the San Juan geologic basin (Judge 1989:216; Windes 2005). Several recent studies have argued this movement from north to south contributed to the initial development of the Chacoan regional system (Varien 2001:53; Varien et al. 2007; Wilshusen and Van Dyke 2006; Windes 2005). Despite a third episode of possible immigration in the late tenth century, population levels remained low until the fourth episode of immigration in A.D. 1060 to 1100. This increase in population density has been largely unrecognized in previous studies, and it is associated with other important changes in settlement patterns (Glowacki 2006). First, both the number of community centers and the proportion of people who lived in centers increased. Second, these new centers were built in settings that had less-productive catchments than established centers in the uplands, but did contain domestic water sources, especially springs, and ready access to stone for masonry buildings (Fettermann and Honeycutt 1987) and timber for construction and fuel.

These changes in settlement pattern, unparalleled in their scope and swiftness, anticipate the largest change of all: the complete depopulation of the region during the late thirteenth century. Duff and Wilshusen (2000) argued that emigration from the region was a long-term process that began in the late A.D. 1100s or the early 1200s, and they note that robust intrinsic growth could increase the overall population of an area even in the context of limited emigration. But in a separate study, Wilshusen (2002:118–119) argued that population levels remained high until the middle-to-late 1200s. Although it may not apply to the entirety of the larger areas studied by Duff and Wilshusen, our reconstruction supports elements of both models. It suggests that emigration from the Village Project study area began at least two decades prior to final depopulation, but it also suggests that more than 10,000 individuals remained in our study area after A.D. 1260. These people either emigrated or died over the following two decades. The latest tree-ring cutting-date from the Mesa Verde region in our database is A.D. 1280, and it is likely that the entire region was devoid of Pueblo people by a few years later.

Implications for Historical Ecology

In this final section we discuss several findings in greater depth and consider their implications for the study of historical ecology. The first finding of general importance is that one cannot account for the history of aggregated settlements in our study area without considering both ecological and social factors. This conclusion is supported by several lines of evidence. First, Figure 5D shows that community centers were relatively resilient in our study area.
area and tended to persist for several successive periods after their initial founding. Second, Figure 5B shows that the proportion of population living in centers grew over the course of each settlement cycle, reaching a peak during the phase of emigration that occurred at the end of each cycle. This indicates that most of the initial emigrants at the end of each settlement cycle moved out of small sites rather than centers. Evidently, centers, especially the largest centers, exerted a stronger hold on their inhabitants than did isolated farmsteads. This might be explainable through the differing “sunk costs” in these two settlement types (Janssen et al. 2003); it could be due to the threat level on the landscape (Haas and Creamer 1996; Kuckelman 2002; Kuckelman et al. 2002; LeBlanc 1999; Lightfoot and Kuckelman 2001; Wilcox and Haas 1994); or perhaps due to some other factor that needs to be adduced. In any case, this is an interesting topic for future research.

Figure 7 presents a series of scatterplots that illustrate our general point in greater detail. Each of these plots contains one or two series of 14 points, and each of these points characterizes one of our 14 modeling periods using two summary variables generated from our settlement or paleo-productivity reconstructions. Regression lines and correlations are also given for each series. Figure 7A illustrates that there is practically zero correlation between long-term climatic fluctuations, as measured by mean potential productivity of the study area across the years in each period, and the proportion of households that lived in community centers during that period. This evidence suggests that agriculture was not as marginal in our study area as is often assumed. Instead, these data indicate that the landscape was productive enough on a per hectare basis that people could live in villages during any of these periods. These data also indicate that aggregation was not particularly responsive to climatic variation on an annual basis, at least as averaged within periods.

Figure 7B shows that the number of occupied centers was proportional to the overall population...
of the study area, but that the proportion of population actually living in these centers was not closely related to these same population levels. This is because aggregation peaked during the initial period of population decline at the end of each cycle, as mentioned previously.

Figure 7C shows that the proportion of households living in centers during a given period correlates more strongly with the elapsed time in the relevant settlement cycle than with either average maize productivity (7A) or overall population density (7B). This scatterplot compares the percent of households living in community centers with the total years elapsed in each occupational cycle; the first cycle begins at A.D. 600, the second at A.D. 920. The number of years elapsed is the cumulative years passed in a given occupational cycle at the end of each period within that cycle. So there was something about the passage of time that promoted population aggregation on this landscape. Based on initial results of Village Project modeling efforts (Reynolds et al. 2003), we suspect that social factors, such as the growth of exchange networks with “hub-nodes” at community centers, are important to this pattern.

Figure 7D, however, suggests that ecological and sociopolitical factors limited the growth of centers inhabited by subsistence-farming households on this landscape. As population grew, people built new centers (Figure 7B), but the size of the largest centers (Figure 7D)—primarily Grass Mesa Village (Kohler 1988) during the early cycle and Yellow Jacket Pueblo (Kuckelman 2003) during the late cycle—did not keep pace with rising population density. As can be seen in 7D, the size of the largest centers did not increase in direct proportion with the total study area population. One factor that may have limited center growth was the increasing distance new arrivals had to travel to fields, which would encourage the establishment of new centers over the continued growth of existing centers. Sociopolitical factors may also have played a limiting role. Cross-culturally, there appears to be a major threshold of sociopolitical organization at roughly 500 members in the “largest organizational unit” (Johnson 1982). Johnson and Earle (1987:314) consider this a transition from “local groups” (roughly, autonomous villages and communities) to larger polities of various sorts. The relative difficulty of crossing this threshold with available models of sociopolitical organization may contribute to the flattening out of the best-fit curve (Figure 7D) as it begins to approach 500.

A second general conclusion of our study is that although increasing population strongly influenced the size of aggregates, it did not necessarily lead to increased environmental impacts. An intriguing finding from our analysis of construction timber use is that both the minimum-age distributions of harvested timbers and species-distributions of cutting dates through time suggest that the early-cycle population did far more damage to the woodlands surrounding settlements than did the late-cycle population, despite being only one-third its size. This interpretation is supported by archaeobotanical analysis of fuel use. This is striking evidence that anthropogenic impacts to ecosystems need not increase in lockstep with population density, an encouraging finding for our contemporary world.

We can think of two factors that may be responsible for the lowered impact of the larger late-cycle population on local woodlands. First, changes in architecture may have made it easier to conserve and recycle construction timbers. During the early cycle both roofs and walls of houses were built of wood and earth, and a variety of lines of evidence (Ahlstrom 1985; Cameron 1990; McIntosh 1974; Schlanger 1987; Varien 1999b, 2006) suggests that construction timbers in contact with the ground were used only for 8–12 years, a length of time that corresponds to the average use-life of houses based on pottery accumulations. In contrast, during the late cycle load-bearing walls were constructed of stone masonry, so wood was used almost exclusively for roofing. The roof timbers in late-cycle houses did not contact the ground and were less prone to rot and decay; as a result, these timbers lasted much longer (Ahlstrom 1985:642; Varien 1999b). Thus, a higher proportion of timbers were salvageable when an old house was demolished and a new one built during the late cycle than during the early cycle. Both factors, longer use life and increased recycling, would have lowered the demand for construction timber.

A comparison of recycling rates at two sites in our database with similar occupation spans, and at which complete houses were excavated, supports this view. The Duckfoot site was occupied between A.D. 850–880 at the end of the early cycle; only 16 percent of the 215 cutting dates recovered from
it date prior to A.D. 850, the approximate year of initial construction (Lightfoot 1992, 1994). In contrast, 68 percent of the 275 cutting dates from Sand Canyon Pueblo, a late-cycle village occupied between A.D. 1260–1280, date prior to the construction date of the earliest dated house (Ortman and Bradley 2002:48–53). In fact, 30 percent of these dates are prior to A.D. 1225, and stem-and-leaf plots of the dates from specific roofs exhibit multiple date clusters that Bradley (1993) interprets as groups of recycled timbers from several previous generations of houses. Excavations at small family farmsteads surrounding Sand Canyon Pueblo (Varien, ed. 1999) suggest that many of these recycled timbers were originally cut down to build earlier houses in the area. This dramatic increase in recycling may have compensated for the larger population of the late cycle and mitigated impacts of construction on local woodlands.

A second factor that may have lowered the impact of the late-cycle population on local woodlands is changing land-use practices. During the early cycle houses were short-lived and population density was low, indicating that households relocated often and had ample opportunity to claim previously unfarmed land (Varien 1999a, 2006). The easiest way for Pueblo farmers to clear new land for agriculture was to burn it (Kohler 1992; Matson 1991), but in the process large numbers of trees that could provide construction timbers would be destroyed. Thus, swidden agriculture, even by a relatively small population, could have had a significant negative impact on the slow-growing forests of this high-desert environment over three centuries. In contrast, during the late cycle population density was high and houses came to be occupied by multiple generations, and farmland was likely inherited from one generation to the next (Varien 1999a; Varien and Ortman 2005). This change from swidden to more settled, intensive agriculture may also have moderated the impact of this larger population on the woodlands surrounding settlements.

This scenario appears broadly consistent with findings from cultural ecology. Although several studies have argued that swidden agriculture produces a stable mosaic forest in tropical environments (Robbins 2004:33), Netting (1993) has found that intensive, settled, smallholder agriculture is the dominant, and apparently more sustainable, form in drier or more temperate environments. These findings suggest that a key variable affecting the relative sustainability of swidden versus settled agriculture is the rate of forest succession and regrowth: somewhat obviously, forests that regenerate slowly are more prone to degradation from swidden agriculture than are forests that regenerate quickly. Data from the Village Project support this view in suggesting that, over a comparable length of time and in the same environment, settled, intensive agriculture by a large population impacted local woodlands less extensively than did swidden agriculture by a smaller population. Regardless of whether recycling, agricultural strategies, or both are responsible, the patterns we observe in construction timber age and species distributions support the conclusion that resource-use practices have the ability to moderate the per person impact of humans on their sustaining environments. Fisher (2005) has documented this same phenomenon in the Tarascan region of Postclassic Mesoamerica.

Our third general conclusion is that the notion of carrying capacity cannot account for the collapse of our settlement system. The peak population of the Village Project study area was reached in the mid-thirteenth century, when it was inhabited by 11 persons per square kilometer of arable land. Within a generation of reaching this peak population, the settlement system had collapsed and the region was totally depopulated. Despite the population increase, we do not believe this collapse can be explained as a population exceeding the absolute carrying capacity of its local environment.

Our paleoproductivity reconstruction suggests that, absent significant anthropogenic impacts, the study area was amenable to additional intensification at the end of the late cycle. The mean annual productivity of all hectares in the study area during the thirteenth century was 235 kg maize per hectare, with a standard deviation of 41 kg maize per hectare. If our paleoproductivity reconstruction is roughly accurate, it indicates that about 35 percent of the land below 2400 m in the study area could produce a two-year supply of the daily caloric needs of the mid-thirteenth-century population during a year that was one standard deviation below the long-term mean for annual productivity (nutritional needs and caloric yield of cornmeal provided by the US Department of Agriculture).
This rough calculation assumes that people can make use of large areas of low production that contribute to the mean production, and it ignores the limiting effect of runs of bad years. Nevertheless, these figures do suggest that total potential agricultural productivity did not directly limit this population and highlight the fact that local populations in the thirteenth century did not use much apparently productive land in the eastern third of the project area (see also Kohler 2000). Pueblo farmers in our study area thus could have put more land into production as one means of addressing shortfalls, unless this option was impossible for security reasons; or they could have intensified production by capturing more of the available moisture (e.g., through more use of check dams and terraces), or by extending the growing season (e.g., through the use of rock mulches). This finding focuses our attention on the need to better understand why populations did not use all the apparently productive land available: was use limited by more severe and durable anthropogenic impacts to the study area than we currently recognize? Did conflict and warfare, which has been documented during the thirteenth century (Kuckelman, ed. 2000, 2002; Kuckelman et al. 2002), restrict settlement to specific areas? Was it the relative indefensibility of the rather flat “eastern marches” of the project area that prevented its use?

Another point which bears on this discussion is that the population density of the project study area near the end of our late cycle approached levels that preceded the emergence of regional polities and hereditary ranking in formative Mesoamerica. For example, it was similar to the population density of the Valley of Mexico between 900–650 B.C., about 600 years after initial colonization of the valley by farmers, and immediately prior to the appearance of the first regional polities (Sanders et al. 1979:217). Likewise, the population density of the Valley of Oaxaca increased to 15 persons per square kilometer of prime agricultural land between 1150–850 B.C., about 750 years after the earliest agricultural settlements, and during the period in which hereditary rank society emerged (Marcus and Flannery 1996:106). Similar population densities were reached in the Village Project study area about the same length of time after its initial colonization by people who lived in year-round habitations, made pottery, and grew maize as a dietary staple. But in this case—instead of the emergence of hereditary ranking, regional polities, and ultimately archaic state polities—we have regional depopulation and the disintegration of the settlement system. Perhaps the population density of the mid-thirteenth century did exceed the carrying capacity for a society comprised of politically autonomous villages, but since additional intensification and increased production on this landscape appears to have been possible at the time of the final depopulation, we must ask why Pueblo peoples in our region did not follow the path of societies in Mesoamerica when confronted with similar population pressures.

Our final conclusion for the study of historical ecology is that issues of scale loom large. Figure 8 illustrates our reconstruction of agricultural productivity for each year of the thirteenth century relative to mean productivity for the A.D. 600–1300 period. This graph shows that the 1200s were plagued by drought and cooler-than-normal temperatures, which resulted in poor harvests. There were 69 years when agricultural potential was below the long-term average and only 31 years that were above average. Yet this was a period when population grew, including growth that may have been due to immigration. This finding cautions us to recognize that climatic fluctuations occurred over large areas on an annual basis, and variation in rainfall and especially temperature would have affected the relative agricultural potential of lands beyond our study area in complex ways. The best lands during a warm and dry period would have been different than the best lands when it was cool and dry, warm and wet, or cool and wet. The amount of population movement into and out of our study area over time (Figure 5B) suggests that the scale of the effective environment that Pueblo people responded to was much larger than our project study area. This is an important point that one must consider in studying historical ecology.

Although our paleoproduction reconstruction deals with a much smaller area than the effective environment that Pueblo people responded to in locational decision-making, we do not think this undermines the utility of our endeavor. We have learned a great deal about human-environment relationships and Pueblo Indian history in the central Mesa Verde region through the Village Project, despite modeling the environment only within our
But to tackle the larger problems of the historical ecology of Pueblo peoples, we will eventually need to work at larger scales. We believe our study illustrates that the methods needed to accomplish this effort are at hand, and applying these methods to a larger region would produce exciting and substantive results.

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These correction factors were derived in a semi-quantitative fashion using data on production from the high-elevation San Juan Basin Branch Station at Hesperus, Colorado, and observations on local dryland farming by experienced local gardeners (and archaeologists, e.g., Honeycutt 1995).

The laboratory of tree-ring research has developed a number of suffix codes to distinguish various factors affecting the interpretation of a date relative to the year of death of the tree from which the sample was taken. In this study we consider all dates except those associated with “wv” or “++” suffixes as cutting dates. The former case indicates that an unknown number of rings is missing from the outermost ring of the sample to the last growth ring of the tree, and the latter case that the date of the outermost ring was estimated by counting from the last datable ring. This latter situation is problematic because certain species, especially juniper (the most common species used for construction in our study), have a higher proportion of small sites relative to centers that lie outside block survey areas. We calculate the momentary household estimates for centers and the proportion of momentary households in centers versus small sites in the areas covered by block survey, and then multiply the momentary household estimate for community centers by the inverse of this proportion to obtain the total momentary households for the entire study area. Method 1 probably underestimates total momentary households because the proportion of households in centers varies across block-survey areas, and several of the largest surveys surround clusters of large community centers. The unsurveyed portion of the study area may therefore have a higher proportion of small sites relative to centers than is suggested by the block survey sample.

For Method 2, we divide the study area into four spatial quadrants and four elevational zones to create 16 discrete strata. We then determine the proportion of block survey within each stratum (the sampling fraction), the momentary household density in block survey areas in each stratum, and multiply the population density by the inverse of the sampling fraction to estimate the population for each stratum. Finally, we sum the stratum estimates to estimate the total population for the study area. Method 2 produces the highest estimates, and may overestimate total momentary households somewhat because it assumes that the block survey sample in each stratum is representative of the population density of the entire stratum. This approach neglects the distribution of other critical resources, such as fresh water from springs, and does not reflect the known distribution of community centers very well.

We recognize that this is a very conservative estimate. Richerson et al. (2001:396–397), for example, consider .01 (1 percent per year) to be a conservative estimate for the obtainable $r$ (the intrinsic rate of natural increase).

Note that neither set of lines tracks year-to-year variability; period means are joined by straight lines.

This was calculated by taking the total households in small sites in block surveys / surveyed portion, and adding this to the total households in all community centers to get total households by period in the study area. These estimates were multiplied by 6 to get the total persons by period. This figure was multiplied by 50/modeling period length (account for lifespan of a person and length of modeling period, as we do for calculating momentary households). The results for each period were summed to get a grand total.

It also appears that population decreases in smaller centers before it decreases in larger centers (Glowacki 2006).
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