CHAPTER 4

Settlement Ecodynamics in the Prehispanic Central Mesa Verde Region

Timothy A. Kohler, C. David Johnson, Mark Varien, Scott Ortman, Robert Reynolds, Ziad Kobti, Jason Cowan, Kenneth Kolm, Schauin Smith, and Lorene Yap

Many claims have been made about the influence of environment on society, settlement, and their changes through time. Environmental determinism, for example, assumes a simple one-way causation that, for extreme cases, is inarguable: “You cannot grow maize in the arctic or build igloos in the jungle” (Evans 2003:94)—at least without sophisticated technological inputs. This flow of causality is, of course, similar to that of standard evolutionary theory, in which variable organisms reproduce differentially according to their success in a given environment, which, in turn, increases their fit to that environment over time.

One problem with this perspective is obvious to social scientists, who, by training, are especially attuned to the ways in which humans modify their technology, work through their societies, and change their culture (or sometimes fail to change it) to achieve fit to an environment. But technologies, social arrangements, and cultural practices also modify the environment through a process that has recently been formalized as “niche construction” by Odling-Smee, Laland, and Feldman (2003). Therefore, humans, to an even greater extent than other animals, do not adapt to some environment given to them but are, instead, always modifying their technologies and practices to adapt to the environment they have helped create.

This chapter summarizes an on-going project that seeks to understand the given environment in southwestern Colorado between AD 600 and 1300, the niche
constructed by its resident maize farmers, and the co-evolution of their societies and their environments over seven hundred years of regionally continuous occupation. The terse descriptions of our methods and results presented here are expanded in other publications now underway (for example, Ortman, Varien, and Gripp 2007; Varien et al. 2007). In contrast to other publications on this project, which report some particular aspect of our approach (Cowan et al. n.d.; Johnson, Kohler, and Cowan 2005; Reynolds, Kohler, and Kobti 2003) or discuss a much earlier version of the investigation (Kohler et al. 2000), here we try to give a current sense for the whole project and discuss some of our preliminary conclusions.

Two major efforts define our research. In the first, we build an agent-based model in which agents representing households are loosed on a landscape that represents, with reasonable fidelity, the landscape of prehispanic southwestern Colorado. In some of our models, households are embedded within a cultural algorithm framework that allows them to learn at both an individual level and a cultural level. Each household has a plan for procuring agricultural and animal resources, as well as plans for exchanging food with other households. These plans can be adapted over time in order to adjust to changes in the environment.

Spatially, our study area is represented as 45,400 cells (pixels) that are 200 m on a side; temporally, we represent time in the model at the same annual granularity with which the tree-ring records resolve climate. Households can grow corn on this landscape, and the amounts they produce are a function of the soils in which they plant, how many 1-acre plots they plant, the weather that year, and whether those plots have been farmed long enough that their production has begun to decline. Households consume water for drinking, food preparation, and personal hygiene; we do not differentiate among these uses in our model. We can control whether they may use all known water sources or are restricted to the highest-quality, perennial sources. We present here for the first time our ongoing efforts to build a paleohydrological model for the springs in our study area, which modulates the flows for modeled springs according to a lagged relationship with reconstructed precipitation.

Our households also use wood for heating and cooking. The amount of wood available depends on the native vegetation community supported by the dominant soil in that pixel, the size of the standing crop, the weather, the amount removed by grazing or browsing by native herbivores, and whether portions of that 4-ha cell have been cleared for farming.

Finally, unfarmed portions of the landscape produce jackrabbits, cottontails, and deer, the three species of greatest importance in hunting. For the first time, we report here on how that is done and on our efforts to include hunting among our resource-use activities.

Although implementation of the model is complicated, the underlying conceptual organization is simple. We have attempted to construct agents that will learn themselves to use this rich environment in a way that maximizes their net caloric gains to the extent practical, while also meeting requirements for protein, water, and fuel.
Adapting this perspective does not mean that we believe that societies actually achieve this goal or that human agents have this goal in mind as they determine their courses of action. Rather, it is just a null hypothesis (albeit one with a special status in behavioral and evolutionary ecology) in which it is assumed that organisms behaving this way will maximize their future reproductive success (Cuthill and Houston 1997:98). This we can subtract from what we actually see to isolate those behaviors for which more complicated and subtle explanations will be found in the domains of history, political and social processes, as well as perhaps underlying cognitive metaphors or systems of meaning. Our purpose in this chapter is to demonstrate the model that will eventually enable us to attain this goal.

The second major effort in this project is to understand, as best we can, the farming societies as they are represented in the archaeological record. We are particularly interested in the very basic questions: How many people lived in our study area? Where in this area did they live? When? It has required intensive work to organize what is known about the chronology, functions, and sizes of the thousands of recorded sites in the study area, as well as a new survey to expand that knowledge for the particularly critical class of large residential sites we call “community centers.”

These archaeological data present us with two problems that provide the most important motivations for this work. First, what drives the two cycles of colonization, growth, and depopulation that we reconstruct? Second, how can we explain the general movement of people from hamlets into increasingly large community centers over the course of each cycle?

This chapter begins with three sections that discuss the major resource-availability models. Kohler first shows how we estimate maize paleoproductivity spatially and temporally. Then Kolm and Smith discuss procedures for estimating how much water was available and where it was available in our study area through time. Johnson then discusses how the model grows game and wood.

In the next major section, Varien and Ortman show how they were able to turn thousands of site forms into a high-quality database in which they divide 700 years of occupation into fourteen periods ranging from 20 to 125 years in length. We use this same database to reconstruct demographic trends for our area and determine the changing importance and size of the community centers through time.

The third major section focuses on the simulation model. Cowan, Johnson, and Kohler first discuss how the households in the model use resources. Then, they briefly report on certain dynamics that result from using resources whose availability changes both in response to use and as a result of changing climate. We are just beginning to make systematic comparisons between the output of these models and the archaeological record, so we defer most of that discussion to later publications.

Then Reynolds and Korti discuss their efforts to introduce a mechanism allowing culture change to take place as the model is running, enabling households to select those behaviors that serve them best as conditions change. The activities that can be adapted in the version of the model presented here affect only those with whom the
agents exchange maize or meat. We are just beginning to determine the effects of those exchange practices on the sizes, permanence, and locations of residences. Reynolds, Kobti, Kohler, and Yap report the state of those investigations in the section “A Sample Run of the Agent-Based Model.”

Eventually in this project, we want to determine as rigorously as we can how much of the variability in the prehispanic Pueblo settlement pattern is due to attempts by individual households to minimize costs and maximize success in an environment that changes through time because of exogenous shocks due to climate change and because of slower internal processes such as population growth, decline, or environmental depletion of various sorts. We recognize that much else of interest is going on in these societies; we also believe that no one has a good measure of how much variability can, in fact, be explained by the processes we model. The tendency in contemporary archaeology is simply to assume that most variability will be due to other factors. The unique datasets at hand will enable us to begin to evaluate assertions such as the impressively precise (yet curiously undocumented) claim by Shanks and Tilley (1992:56) that “99% of [human] action has no direct survival value in terms of conveying any definitive selective advantage. The archaeological record is, primarily, a record of style.”

**Resource-Availability Models**

We now discuss the resources produced by the model—maize, water, game, and fuel-wood—before turning to a discussion of the local archaeological record itself.

**Maize**

Macrobotanical and stable isotope data strongly suggest that, with the possible exception of some marginal areas, maize (corn) seems to have been the single most important subsistence resource in the northern Southwest from at least AD 600, if not earlier (see Kantner 2004:60–7; Matson and Chisolm 1991). In fact, in its first incarnation the simulation model being developed here achieved some success using only the predicted potential productivity of maize under dry farming to predict settlement location (Kohler et al. 1996).

Van West’s (1994) well-known estimates for maize production in our area provided our starting point in this project and still define the size and location of our study area (figure 4.1). 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). We use PDSI values calculated from historic weather records for various soil categories in our study area to see how well they predict production for maize and beans from Montezuma County from 1931 to 1960. The utility of this unique series of crop records for archaeology was first noted by Burns (1983). We modified several aspects of Van West’s approach to include portions of the study area for which soils maps did not exist when she did her work, to give temperature variability a more explicit role in production estimates, to modulate
these estimates to represent harvest rates more similar to those of maize grown prehis-
panically in our area, to restrict growth on soils reported to be unsuitable for hand
planting, and to extend the reconstructions back to AD 600. The major steps we took
to produce our current estimates (which we will elaborate and defend in a separate
publication) were as follows:

1. We determined the most appropriate proxies for local cold or short summers from
the available tree-ring data. After much work, we settled on two high-elevation
bristlecone pine sequences: one from Almagre Mountain about 350 km ENE of the
project area and one from San Francisco Peaks about 335 km SW of the project area.
Here, we use the scores on the first principal component extracted from both
sequences, which are positively correlated to recent mean monthly temperatures
of most summer months measured at the Mesa Verde, Cortez, and Yellow Jacket
weather stations, with particularly strong correlations to the mean September
temperatures (Mesa Verde: $r^2 = 0.49; p > F < 0.0001$; Yellow Jacket: $r^2 = 0.54;
$p > F = 0.01$; Cortez: $r^2 = 0.31; p > F = 0.02$).

2. We defined fourteen groups of soils within the study area that are similar in their
productivity.

3. We produced PDSI reconstructions for the years 1931 to 1960, using instrumented
data for these fourteen groups of soils and four weather stations, each representing
one of four elevation bands represented in the study area.

4. We then determined whether each of these fifty-six ($4 \times 14$) PDSI sequences has a sig-
ificant relationship with the Mesa Verde Douglas-fir indexed series, allowing it to be
retrodicted back to AD 600. All sequences, in fact, have a significant relationship with
the Mesa Verde series, with values of $r^2$ ranging from $.32$ to $.67$ (most > .5).

5. We retrodicted PDSI values to AD 600 for the fifty-six sequences, using the Mesa
Verde series as the independent variable.

6. We produced weighted, pooled PDSI values for those soils likely to have been pro-
ducing maize and beans between 1930 and 1960 in Montezuma County.

7. We regressed those values against the historic maize and bean production in
Montezuma County and against the two temperature proxies, holding “technology
trend” (year) constant, with the following results for the first principal component
(PC1) of the Almagre and San Francisco series: maize in bushels = 11.18 + 1.78
(year) + 1.33 (bean soil PDSI) + 1.28 (PC1 score) yielding an adjusted $R^2$ of 0.58
($p > F < .0001$). All independent variables were standardized before regression.

8. Because these maize production estimates apply to the average productivity of the
“bean soils,” we next adjusted the productivity for each soil class in the study area by
the ratio of the average productivity for soils in that class to the average productivity
for the bean soils, gleaned from the normal-year, total dry-weight production pub-
lished in the Cortez-area soil survey.

9. We took into account that the yields we are reconstructing are based on historic seed
varieties and planting practices. Based on historical data from Zuni and Hopi and on ethnoagricultural experiments by Muenchrath and others (2002), Adams and others (1999), and other sources, we deemed a mean yield of 500 kg/ha in our better soils (the “bean soils”) to be appropriate (though perhaps still generous). We therefore renormed the production 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 0.68.

10. We further reduced maize production on soils reported as unsuited for hand planting. The detailed soil descriptions in the soil surveys provide “Major Management Factors,” indicating the suitability of each soil complex for a variety of uses. In addition, and somewhat independently of these general land-suitability classes, the surveys report hand-planting suitability restriction codes ranging from 0 to 1.0 for each soil. (A value of 0 means “no restrictions.”) For those soils in our study area reported as “unsuitable” as to “Cropland Suitability,” we multiplied the yields from step 9 by the inverse of the hand-planting restriction value. This further reduced the yields for sixty soil complexes in our study area. These sixty soils represent 53.2 percent (by area) of the total 1,816 km² encompassed by the study area.

11. We applied a “cold correction” by disallowing any maize production above 7,900 ft elevation and by progressively discounting production in colder-than-average years in the elevation band between 7,054 ft and 7,900 ft according to a linear function that
Figure 4.2. Potential annual maize yields in kg/ha, averaged across the study area. Current (PC1) reconstruction is graphed in solid line; Van West yields for AD 900–1300, graphed in dashed line. For this figure, the Van West series has been renormed to the same mean as the PC1 series by multiplying by .516.

takes into account both the elevation and how cold it was, using the tree-ring-based cold proxy.

12. Finally, we applied a fallow factor that dictates whether and how long a field that is “in production” is allowed to rest. This fallow factor is a tunable parameter in our simulation.

The average potential yields per year in our study area resulting from this process appear in figure 4.2. (These yields are not reduced by any fallow factor.) Noteworthy periods of low potential production appear in the late 600s, the mid 700s, the late 800s and early 900s, around 1000, around 1100, from about 1130 to 1150, and in the early and 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 very cold period, when we estimate lower potential production. Van West’s estimates are higher throughout than our new estimates, though, and are renormed in figure 4.2 to illustrate their relative differences with the new estimates.
Water

The main problem we examine here is whether potable water was regionally limiting and whether changes in its availability contributed to the episodes of aggregation or depopulation outlined below. This is not a straightforward problem because groundwater quantities are controlled by complex hydrogeologic responses, in addition to direct climatic changes. The paleohydrologic model also contributes to examining community-scale dynamics because the model ultimately results in prediction of specifically located groundwater discharges directly related to the size of the local recharge areas for groundwater subsystems and to the hydrogeologic properties of Dakota and Burro Canyon sandstone. These relationships dictate that local water supply will not correlate directly to the magnitude and frequency of climate variability.

We conceptualize and characterize the modern central Mesa Verde hydrologic system using a multidisciplinary hierarchical systems analysis (HSA) approach applicable to the US Colorado plateau region, which integrates climate, surface water, groundwater, and geomorphological systems (for example, Kolm 1993, 1996). This required us to

1. Locate all groundwater discharge zones, including present springs and seeps in the study area and those possibly available from AD 600 to 1300 (a project that certainly remains incomplete, although we believe that we have now included all independently documented springs).

2. Develop a solid hydrogeologic block model to visualize and analyze the 3D framework of the groundwater flow system.

3. Develop and test mathematical models to simulate the flow paths and quantify the amount of water throughout the modern hydrologic system on a watershed–groundwater basin scale and on selected site-specific areas.

4. Develop scenarios of the paleohydrologic system based on tree-ring data, for identifying the relative roles of climate stresses on the system.

5. Compare the dynamics of this system's variations and fluctuations with the settlement dynamics of the project area. This was accomplished by incorporating the results from the dynamic paleohydrologic mathematical model into the agent-based model.

The methods and results for 2–4 are discussed below; our investigations of point 5 are now under way.

Characterization of Hydrogeology.

We first developed a 3D solid block model (plate 7) that incorporates interpretation of geologic and hydrogeologic data from Ekren and Houser (1965), Freethy (1988a, b), Hunt (1956), Thomas (1986, 1988), Weigel (1987), Whitfield and others (1983), and Wittkind (1964), as well as USGS bedrock geology maps (Haynes, Vogel, and Wyant 1972). This model was developed using the Geologic Modeling System (GMS)
software distributed by Environmental Modeling Systems, Inc. This shows the distribution of the main hydrogeologic units in our study area. On top lies an Eolian/Dakota/Burro Canyon (D) aquifer. This is underlain and isolated by a Morrison Formation confining unit. Below that lie a Morrison Formation sandstone, Junction Creek/Bluff sandstone, and the Navajo (N) aquifer unit. The block model illustrates that the D aquifer is topographically and hydrologically dissected. It is continuous in the northern and eastern parts of the study area, bounded by the Dolores River, and discontinuous in the southern and western parts of the study area, where numerous canyons and streams dissect it. The N aquifer, by contrast, is continuous throughout most of the study area but is rarely exposed for use as a water source by the prehispanic people.

Other than its relative lack of continuity, the two parameters of the Eolian/Dakota/Burro Canyon (D) aquifer that are significant for our modeling effort are its hydraulic conductivity (K) and its specific yield (Sy). Hydraulic conductivity integrates the complex effects of climate and recharge on the groundwater flow system in the aquifer, resulting in the observed spring discharges through time. Specific yield controls the quantity of water in storage that acts as the long-term reservoir of the aquifer.

*Characterization of Hydrologic System.*

The study area has regional, subregional, and local hydrologic systems. The N aquifer and lower Morrison Formation sandstones are regional and are exposed in canyon bottoms and in regional uplifts (plate 9a, b). These aquifers have limited use for prehispanic drinking water because of their locations and limited surface exposure. The spring discharge rates associated with these aquifers will not fluctuate greatly, however, because the recharge areas are located in regions far outside the study area, and groundwater travel velocities are expected to result in lags (from precipitation to discharge) on the order of hundreds to thousands of years.

By comparison, the Eolian/Dakota/Burro Canyon (D) aquifer is both subregional and local, based on topographic continuity (see plate 9a, b). Most of the dynamic groundwater discharge zones observed in the field (as springs, seeps, and phreatophyte distributions) are associated with this unit. Pueblo people utilized this dynamic D aquifer system as their primary drinking water supply.

The third type of aquifer system, stream alluvium (for example, the Dolores River and McElmo Creek alluvium; see plate 7), will respond to daily and yearly fluctuations of hydrologic stresses, both climatic and stream variations. In areas where the stream alluvium overlies impermeable geologic materials, such as shale, the stream-to-alluvial groundwater interaction is local, and the upstream variations in flow and chemistry will directly affect the alluvial aquifer at the site. In these locations, the underlying bedrock provides no new water and usually affects the water quality greatly by adding salts. In some areas, the underlying bedrock may be an aquifer (for example, the N aquifer) that provides additional water to the alluvium from below
while the stream provides the alluvium with water from the surface. This can sometimes enhance the alluvial aquifer and stream flow considerably, and water quality may vary with bedrock groundwater input. In general, even though the streams in our area may have been used for drinking water in various places, their use was likely limited by water quality, including high total dissolved solids.

The Eolian/Dakota/Burro Canyon aquifer system (D aquifer) was chosen for dynamic modeling, then, because it was apparently heavily used as a drinking-water source prehistorically and will respond dynamically to climatic stresses. The D aquifer is conceptualized as containing two major subsystems divided by the House Creek fault, whose location is approximated by the location of Yellow Jacket Creek: (1) a southeast subregional system that recharges northeast and north of the city of Cortez and either discharges to McElmo Creek at Cortez or flows into the San Juan Basin regional system (see plate 9a and figure 4.2) and (2) a northwest subregional system that recharges in the northern and northwestern part of the study area and discharges in springs, seeps, and phreatophyte locations along the western and southwestern parts of the study area (see plate 9a, b).

Local or community-scale systems are conceptualized within the regional and subregional systems, using the same hydrogeologic framework and hydrologic system parameters. Prehispanic settlements are frequently located on the mesa tops and in canyon-rim settings near where groundwater recharge and discharge are occurring in the D aquifer. Recharge by infiltration of precipitation occurs in these mesa-top environments, where much of the farming is assumed to have occurred. Groundwater flow paths are from these mesa tops to the springs observed at or below canyon rims.

**Mathematical Model of Hydrologic System—Steady-State Simulation.**

Steady-state and transient mathematical simulations of the hydrologic system were conducted using the block-centered, finite-difference MODFLOW model (McDonald and Harbaugh 1988) built upon the 3D block model and using the conceptual model outlined above. This mathematical model simulates, dynamically, the groundwater flow in the primary hydrogeologic layer, the Eolian/Dakota/Burro Canyon aquifer. A hydraulic conductivity of 0.2 m per day was applied uniformly across the layer. A constant grid cell size of 200 m by 200 m was chosen to match the spatial resolution of the agent-based settlement model.

Naturally occurring hydrogeologic and hydrologic system features such as cliff edges or rivers define boundary conditions in most places. The MODFLOW model utilizes no-flow, head-dependent flux, constant heads, and cell input/output boundary conditions. Specifically, recharge is a cell input/output flux that is regionally distributed in four zones, based on precipitation and topographic elevation across the model domain. The ranges of recharge are from $1.5 \times 10^{-5}$ to $5.0 \times 10^{-5}$ m$^3$ per day. This model incorporates seventy springs as discharge drains (head-dependent flux) within specified nodes where the springs occur. The drain discharge is allowed to vary during transient simulations, and ranges from 0 to greater than 100 cubic m per day. The out-
put of each drain, then, is the simulated drinking-water availability at that point on the landscape.

Calibration is based on water levels (heads) within the aquifer and discharge at known spring discharge sites. Our database contains fifteen springs that can be used for calibration. Calibration sensitivity is based on recharge ranges from <2 to >4 percent of precipitation. These recharge rates are equivalent to the driest and wettest five-year periods in the climate data, allowing the hydrologic model to simulate transient stresses imposed on the system by climatic (precipitation) fluctuations.

The model is designed to be highly sensitive to changes in recharge from precipitation and resulting groundwater discharge. The lag time in spring response to recharge change is minimal. However, because of the hydrogeologic characteristics (K and Sy) of the Eolian/Dakota/Burro Canyon aquifer, the actual changes in spring discharge amounts at each location are the result of a complex response to hydrogeology and hydrologic system parameters.

The potentiometric surface calculated during the steady-state model simulation indicates that three hydrologic systems can be identified in the D aquifer: (1) the SE subregional system, from the House Creek Fault to McElmo Creek at Cortez; (2) the NW subregional system, from the Dolores River Divide to the canyons in the southwest, where concentrations of sites such as Lowry Ruin and Yellow Jacket Pueblo are high; and (3) various more local systems, such as in the Sand Canyon Pueblo area. The springs, for example, in the Sand Canyon area, and streams, for example, McElmo Creek near the city of Cortez, lower the water table locally.

Two transient models that simulated stress periods of fifty- and five-year intervals were run. The calibrated steady-state simulation was the starting point for the fifty- and five-year transient simulations. Dataset results are available for each period for these two models, and the spring output, including mass balance, is available for each time interval. The drains are available as a dataset per spring (simulated in zones as a drain) per interval (figure 4.3). The annual precipitation signal used for estimating recharge is derived from the same dataset graphed by Dean and Van West (2002: 85–7). It was developed by regressing precipitation data from the National Climatic Data Center’s New Mexico Division 1 (Northwestern Plateau) on the Mesa Verde Douglas-fir ring width index series—the same series we use as a proxy for precipitation in our paleoproducivity reconstructions.

The results of the transient simulations indicate that spring discharge fluctuations may be small (Sand Canyon Pueblo) or large (Lowry Ruin) with respect to annual precipitation changes. During the fifty-year simulation, the aquifer did not show dominant drought patterns because most droughts were short (in the one-to-three-year range) and followed by wet years. The wet years that immediately followed the dry years appear to have effectively recharged the aquifer. By comparison, the five-year-interval transient simulations did show effects of drought- and wet-year variations. However, corresponding drinking water supplies, as suggested by modeled transient drain discharge results, remained generally reliable, though variable, for most locations.
Figure 4.3 compares two springs developing out of large subregional systems (near Yellow Jacket Pueblo and Lowry Ruin), with one in a small local system (at Sand Canyon Pueblo). The Lowry spring showed the most variation, with discharge values ranging from approximately 0 to 125 cubic m per day. The Yellow Jacket spring varied from about 11 to 49 cubic m per day, whereas the Sand Canyon spring varied only slightly, between about 9 and 13 cubic m per day. It is notable, though surprising, that springs supported by the two large recharge areas can vary more than the spring supported by the smaller Sand Canyon recharge area. Also interesting is the retrodiction that the Lowry spring periodically went dry, for example, in the early AD 1000s. Archaeological evidence suggests that Lowry was inhabited during this period. This may have been possible because of reliance on other springs, or it may be that further calibration of the model is needed, perhaps including some consideration of the relationship between population locations and springs in various periods. Such considerations have not been used for calibration here, and, of course, we recognize the possible dangers of circular reasoning in use of such data.

The graphs of spring discharge fluctuations (see figure 4.3) indicate a pattern of similarity in timing, but not in amplitude. For example, the Sand Canyon spring varied around 4 cubic m per day, whereas the Lowry and Yellow Jacket springs varied on
a much greater scale, at approximately 125 and 38 cubic m per day, respectively. Sand Canyon has a smaller recharge catchment area compared with the Lowry and Yellow Jacket springs. However, the Sand Canyon area has a slightly higher recharge rate because of greater precipitation associated with a higher elevation. The effect is to have a smaller magnitude of actual groundwater discharge, but also a smaller change in discharge over long-term climatic fluctuations. The Lowry and Yellow Jacket discharge zones are located towards the middle and end, respectively, of their subregional recharge areas. Apparently, the Lowry springs are more variable because they are located closer to the recharge and flow system water sources. The fluctuations of spring discharge compared with the precipitation (see figure 4.3, heavy line) illustrate the lag in the effect of precipitation, which is due to the hydraulic conductivity properties of the bedrock.

Conclusions.

Our results illustrate that time-lagged fluctuations of spring discharge did occur in response to long-term precipitation variation, based on the tree-ring climatic record. The results also indicate that the amplitude of spring-discharge variations over time is related to both the size of the groundwater recharge area and the landscape position of the spring within the groundwater flow system.

The five-year transient model results from this model serve as one input to the landscape in the agent-based simulation described below. That is, for the known springs that we modeled, as the simulation runs, flow rates are read in from an external database, with the values changing every five years. For known springs that were not modeled, primarily in the N aquifer, we used a constant estimate of flow averaged from springs in that aquifer for which flow rates were available. Households take as much water as they need from the nearest spring, up to its flow limits; if an isolated spring in a productive farming area declines significantly, this could provoke household relocation in the model.

In future work, we will try to expand our mapping of the known springs, conduct various sensitivity analyses for those we can model, and examine the possibility of refining our calibration of spring discharge, using human population distributions over time. At this point, we do not see any consistent signals across the project area that would attribute the episodes of aggregation or depopulation (which we review below) to changes in supply of potable water.

Game and Fuelwood

Any model that purports to study how prehispanic households in this area located themselves with respect to critical resources cannot consider only calories and water, although these were undeniably important. In our current models, households are also required to satisfy minimal protein requirements (Stillings 1973) by hunting rabbits, hare, and deer. In addition, households must obtain fuel for cooking and heating by harvesting woody plants (trees or shrubs). These resources were chosen—instead of,
say, lithic materials—because of evidence that they place limits on the size and locations of human groups in certain times and places in the prehispanic Southwest (Kohler and Matthews 1988; Spielmann and Angstadt-Leto 1996).

Modeling the amounts of animals and fuelwood available in the project study area starts from the same point, so these are discussed together (and by Johnson 2006, in much more detail than is possible here). Both are attributes of each of the 45,400 cells in the model, and both are derived ultimately from tree-ring-recorded climatic variability acting on production capacities specific to particular soils. So we begin with the study-area soils.

The 148 productive soil complexes within the project boundary (Pannell n.d.; Ramsey 2003, 2006) are composed of one or more soil components. Each soil component supports a native vegetation community that, every year, produces new growth for each of its constituent plant species, according to the properties of the soil and the weather that year. Annual variation in the productivity of various plant species, in turn, determines the biomass available to support the three species of herbivores that people hunt in our model.

For each soil complex, we can determine the productivity for our native plant species in a normal year through calculations that begin with data in the published soil surveys. We apply these to our 4-ha cells after determining the dominant soil within each cell. The normal-year productivity values for project-area soil complexes range from 336 to 3,360 kg/ha. Table 4.1 gives some examples for the process by which we partition the total productivity in kg/ha among the plant species reported for each soil type. These values are multiplied by 4 to determine productivity for each model cell.

Annual variation in net primary productivity (NPP) for each soil, and therefore for each cell, is derived from step 7 in the process (described above) by which we produce the maize estimates (except that the output is re-expressed in different units to provide each model cell with its appropriate NPP of native vegetation in kg). The model also partitions that NPP among each of the native vegetation species in each cell.

Of the ninety-three plant species, fifty-two are reported as commonly consumed by one or more of the animal species whose populations we model as meat sources. Fuelwood is produced by ten species of trees and thirty-nine species of woody shrubs, as well as an “other” category of each. The NPPs of these specific plants contribute to the secondary productivity of these resources.

**Modeling Game.**

In modeling potential sources of animal protein for Pueblo households, we use the modern ecology of the three wild, herbivorous species most commonly recovered from archaeological contexts in the region. These are mule deer (*Odocoileus hemionus*), black-tailed jackrabbit (*Lepus californicus*), and desert cowntail (*Sylvilagus audoboni*). The production of these protein sources is modeled on the basis of populations of each species. Each of the three populations “grows” at rates dependent on its maximum
reproductive rates ($r_{\text{max}}$), in conjunction with the availability of forage as produced by
the NPP of standing crops of its preferred foods. Population growth is generated by
the following equation:
\[
N_{t+\Delta t} = \frac{KN_t}{N_t + \gamma (K - N_t)}
\] 
Eq. 1
where $\gamma = e^{-\tau\Delta t}$ and the time step ($\Delta t$) is one year.

The $r_{\text{max}}$ values for these animal species are based on the best available data from
various sources; we use 0.4 for mule deer (McCullough 1997; Medin and Anderson
1979), 1.5 for jackrabbits (Wooster 1935), and 2.3 for cottontails (Myers 1964).

Of course, considerations of access and foraging efficiency preclude the total
harvest of new growth from any given plant; each species is restricted to a percentage of
the NPP of its preferred foods. For example, mule deer may browse up to 50 percent
of the NPP of the trees and shrubs they target. Although deer browse consists mostly
of new growth from shrubs, which is usually accessible, a significant portion comes
from trees, much of which is inaccessible. Moreover, browsing more than 50 percent
of the total new growth becomes increasingly inefficient (Wallmo et al. 1977). Black-
tailed jackrabbits and cottontails are allowed to reap 70 percent of their preferred
species, mainly because they obtain a much greater proportion of their diets from grass
species, which are assumed to be fully accessible.

For the hare and rabbit populations, plant foods are produced by the various native
plant communities supported by the dominant soil in each 4-ha model cell. In the various
native vegetation communities supported by study area soils, rabbits target
thirty-one species and hares, twenty-six. Both species of leporid are subject to carrying
 Capacities defined at the level of each 4-ha cell, based on the amounts of vegetation
available for their consumption within each cell in each year.

We “grow” deer in a similar fashion, except that deer populations are modeled in a
larger spatial frame, using 1-km cells superimposed on the original 4-ha grid of our model
world. The 45,400 4-ha model cells, therefore, are contained within 1,816 deer cells. This
is necessary because deer are much larger than either of the leporid species, consume
much more of the NPP of their preferred browse species per individual, and have much
larger home ranges. Optimal foraging theory predicts, and the archaeological record
underwrites, the probability that these large-bodied mammals were the preferred prey
of the prehispanic inhabitants of our study area to the extent that they were available
(Ugan 2005). Whereas we restrict leporid populations to particular 4-ha model cells,
deer populations are allowed to “diffuse” across deer cells. This is accomplished with
an implicit diffusion algorithm based on the iterative “preconditioned conjugate gra-
dient method” (Bulirsch and Stoer 1993:612–14) for solving large systems of linear
equations. This algorithm transfers deer from deer cells that are at carrying capacity
to adjacent deer cells that are below carrying capacity (because of depletion resulting
from hunting or climatically induced changes in carrying capacities). Cowan and oth-
ers (n.d.) describe this algorithm in detail.
### Table 4.1 Normal-Year Productivity of Natural Resources for Selected Soils

<table>
<thead>
<tr>
<th>Soil</th>
<th>Area²</th>
<th>Prod³</th>
<th>Common Name</th>
<th>% VC²</th>
<th>Kg/ha³</th>
<th>Trees²</th>
<th>Shrubs⁴</th>
<th>Fuels⁴</th>
<th>Deer⁵</th>
<th>Hare⁵</th>
<th>Rabbit⁵</th>
<th>Protein⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>105</td>
<td>5300.4</td>
<td>560.0</td>
<td>Galleta</td>
<td>21.1</td>
<td>118.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Slope: 3 – 9</td>
<td>1297.0</td>
<td>469.1</td>
<td>Indian Ricegrass</td>
<td>18.1</td>
<td>101.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rizno - .45</td>
<td></td>
<td></td>
<td>Utah Juniper</td>
<td>12.0</td>
<td>67.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piñon-Juniper</td>
<td></td>
<td></td>
<td>Blue Grama</td>
<td>11.1</td>
<td>62.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gapmesa - .35</td>
<td></td>
<td></td>
<td>Western Wheatgrass</td>
<td>11.1</td>
<td>62.0</td>
<td>89.9</td>
<td>34.0</td>
<td>25.5</td>
<td>2.8</td>
<td>4.2</td>
<td>1.4</td>
<td>2.7</td>
</tr>
<tr>
<td>Semidesert Loam</td>
<td></td>
<td></td>
<td>Needleandthread</td>
<td>9.1</td>
<td>51.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Big Sagebrush</td>
<td>6.1</td>
<td>34.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bottlebrush Squirreltail</td>
<td>6.1</td>
<td>34.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Twoneedle Piñon</td>
<td>4.0</td>
<td>22.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Winterfat</td>
<td>1.2</td>
<td>6.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>109</td>
<td>13175.0</td>
<td>392.0</td>
<td>Indian Ricegrass</td>
<td>16.7</td>
<td>65.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Slope: 6 – 25</td>
<td>3302.0</td>
<td>339.2</td>
<td>Mountain Mahogany</td>
<td>16.7</td>
<td>65.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Romberg - .45</td>
<td></td>
<td></td>
<td>Galleta</td>
<td>11.1</td>
<td>43.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crosscan - .4</td>
<td></td>
<td></td>
<td>Twoneedle Piñon</td>
<td>11.1</td>
<td>43.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piñon-Juniper</td>
<td></td>
<td></td>
<td>Utah Juniper</td>
<td>11.1</td>
<td>43.5</td>
<td>87.0</td>
<td>108.8</td>
<td>146.9</td>
<td>5.4</td>
<td>1.3</td>
<td>0.6</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Western Wheatgrass</td>
<td>11.1</td>
<td>43.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Common Snowberry</td>
<td>5.6</td>
<td>21.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Muttongrass</td>
<td>5.6</td>
<td>21.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Piñon Ricegrass</td>
<td>5.6</td>
<td>21.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Utah Serviceberry</td>
<td>5.6</td>
<td>21.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>142</td>
<td>1786.0</td>
<td>1008.0</td>
<td>Twoneedle Piñon</td>
<td>17.8</td>
<td>179.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Slope: 25 – 80</td>
<td>451.0</td>
<td>601.1</td>
<td>Western Wheatgrass</td>
<td>11.9</td>
<td>119.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wauquie - .4</td>
<td></td>
<td></td>
<td>Gambel's Oak</td>
<td>10.7</td>
<td>107.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dolcan - .3</td>
<td></td>
<td></td>
<td>Indian Ricegrass</td>
<td>10.7</td>
<td>107.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Species</td>
<td>Muttongrass</td>
<td>9.5</td>
<td>95.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td>-------------</td>
<td>-----</td>
<td>------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>True Mountain Mahogany</td>
<td>7.1</td>
<td>71.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mountain Mahogany</td>
<td>7.1</td>
<td>71.9</td>
<td>239.8</td>
<td>371.7</td>
<td>458.6</td>
<td>13.9</td>
<td>2.9</td>
<td>1.1</td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Utah Juniper</td>
<td>5.9</td>
<td>59.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galleta</td>
<td>4.8</td>
<td>47.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antelope Bitterbrush</td>
<td>3.6</td>
<td>36.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Big Sagebrush</td>
<td>3.6</td>
<td>36.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common Snowberry</td>
<td>2.4</td>
<td>24.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piñon Ricegrass</td>
<td>2.4</td>
<td>24.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Utah Serviceberry</td>
<td>2.4</td>
<td>24.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Village Project soil code; slope range; component name and proportion of complex; ecological setting
2. Number of hectares of soil complex within the study area; number of 4-ha cells represented by soil in study area
3. Normal-year NPP in kg/ha as reported for the primary component in soil surveys; mean annual productivity of model; sd
4. Components of native vegetation communities as listed in the soil surveys
5. Percent species contributes to native vegetation community, weighted by proportion component contributes to soil complex
6. Normal-year NPP per species in kg/ha
7. Total NPP of all tree species for normal year in kg/ha for soil complex
8. Total NPP of all shrub species for normal year in kg/ha for soil complex
9. Total woody biomass produced in kg/ha for soil complex, calculated as the sum of columns 7 and 8, less 25 percent for foliage lost/not developing into wood
10. Kg/ha edible meat protein provided by the three herbivore species based on NPP of their preferred plant foods supported by soil complex and 65 percent of total body weight as edible meat
11. Total kg meat protein provided by the three herbivore species based on NPP of their preferred plant foods supported by soil complex and the average amount of protein per unit edible meat weight
Modeling Fuels.

The standing crop of fuelwood also depends, indirectly, on the NPP of the woody species. Annual new growth of woody species in piñon-juniper forest is reported as 1.3 percent of standing crop (Howell 1941). Because figures for standing crop are not available for most species, we estimate them by multiplying the mean annual production of each woody species (over the full model run) by the inverse of .013 (76.9). These values are seeded as standing crop into each model cell as appropriate to its soil type and associated native vegetation community. Annual deadwood production is modeled as 6.5 percent of tree standing crop (Howell 1941) and 3.35 percent of shrub standing crop (Chojnacky 1984). At model initialization, the total standing crop of woody species includes these percentages of deadwood. In procuring fuels, households first target nearby deadwood, and then, if deadwood becomes scarce, they cut the living forest (which is calorically more costly). “Nearby” can be defined when the model is run. After harvesting has taken place within a model cell, the standing crops of the live woody species and the deadwood are replenished at a rate appropriate to the soil type and climate during each model step.

In the rulesets for household behavior that we are currently exploring, model households attempt to obtain required resources in an efficient manner. Although each resource is replenished to some degree in every model step, local overharvesting of resources is possible and is often seen during simulation, as we discuss below.

The Archaeological Record

One goal of the Village Ecodynamics Project is to compare archaeological knowledge of the settlement patterns in our project area with virtual settlement patterns created through agent-based simulation. To document the archaeological settlement patterns, we assembled a database with information on all recorded sites. Our task was to use explicit and repeatable criteria to determine site location, site function, the period or periods of occupation, and population estimates for each residential site. Creating this database forced us to devise solutions to a number of common archaeological problems; we believe that these solutions will be of use to archaeologists working in many areas. In this section, we very briefly describe the methods used to compile and analyze the database. We then apply these methods to reconstruct the demographic history of the project area and examine the appearance, use, and decline of those large sites that we interpret as community centers.

Please consult Ortman, Varien, and Gripp (2007) for details on these methods and Varien and colleagues (2007) for details on the interpretations of these data. Our methods incorporate many assumptions that influence the results. We continue to evaluate the plausibility of these assumptions, and future analyses of these data could use different assumptions and therefore produce slightly different results. The analyses that follow use what we currently believe to be the best assumptions and reflect our current understanding of these data.
The Database

The site database contains records for about nine thousand sites, most of which were recorded during one of the 336 surveys conducted in the project area (figure 4.4). Approximately 15 percent of the project area has been surveyed, including block and transect surveys. In our analysis of the database, we first assigned sites to various functional categories: isolated public architecture, single habitations, multiple habitations, field houses, and a variety of limited activity site types. Most residential sites are single habitations, and the primary features at these sites include a pitstructure, a roomblock, and a trash midden.

Determining the period of occupation was a challenge because the way sites are recorded has changed dramatically over the past fifty years. We needed a method that could be applied consistently despite differences in the type and quality of data, and we needed to detect even subtle evidence of multiple occupations. Ortman designed a
Bayesian statistical analysis (Buck, Cavanaugh, and Litton 1996; Iversen 1984; Robertson 1999) to address these issues.

We started with a calibration dataset of eighty excavated and well-dated site components, which we used to estimate the frequencies of eighteen architectural attributes and twenty-four pottery types in sites dating to each of fourteen separate periods between AD 600 and 1300. We defined these modeling periods to be as short as possible, given our current understanding of the local archaeological record. The periods vary from 20 to 125 years in length, but most span 40 years. The calibration data were used to specify the probability that each pottery type and architectural attribute dated to each of these fourteen periods. These probability distributions were scaled so that the area under the curve equals one and the probability for each period is a value between zero and one.

These probability distributions were combined with the sample data from each site to calculate composite probability density distributions for three categories of observations: architectural characteristics, undecorated pottery, and decorated pottery. A probability distribution was also created to reflect the surveyor's assessment of when a site was occupied. Finally, we weighted and combined probability density distributions, based on samples of eleven or more sherds for all sites within 7 km of each habitation site; we used this information to specify the occupational history of the “neighborhood” around each site. These neighborhood distributions are critical for our analysis because the available data for about half the sites in our database were insufficient for us to determine their most probable period of occupation. The use of neighborhood distributions to interpret when these poorly documented habitations were occupied is justified because ancestral Pueblo habitations of a given period tend to occur in spatial clusters (Adler 1990; Adler and Varien 1994; Fetterman and Honeycutt 1987; Lipe 1970; Rohn 1977).

After calculating these six probability density distributions—for architecture, plain pottery, decorated pottery, the surveyor's estimate, absolute dates, and the neighborhood—we averaged the available lines of evidence for each site (the neighborhood contributed to this average only for sites with fewer than eleven sherds) to produce a mean probability density distribution for each site.

In this project, we measure archaeological and agent populations in terms of households. Several lines of evidence indicate that each household used a single pitstructure throughout our sequence (Cater and Chenault 1988; Lightfoot 1994; Ortman 1998; Varien 1999). We therefore estimated the peak populations of habitation sites, using a two-step process. First, we estimated the total number of pitstructures present at each site, based on the number of depressions on the modern ground surface, the size of the surface roomblock, and the total site area. Then we used multiple regression trained on data from excavated sites where the peak populations were known to predict the peak populations of unexcavated sites, based on their total pitstructure estimates and various characteristics of their mean probability density distributions.

Finally, we integrated the peak population estimate with the posterior probability
distribution for each site. We know from excavation that sites with one pit structure were typically occupied during only one period (Varien, ed. 1999). For sites of this size, we simply assigned one household to the period for which the probability of occupation was highest; an additional household was also assigned to periods corresponding to secondary modes in the mean probability density distribution at these small sites. We also know, however, that larger sites were typically occupied for multiple periods (Kohler and Blinman 1987; Ortman et al. 2000). To determine the periods of occupation at these larger sites, we conducted a second multiple regression, using a dataset of thirty-five well-dated, multicomponent sites. This enabled us to predict the minimum probability value that signifies occupation. At these sites we assigned households to each of the periods that exceeded this threshold, based on the ratio of the nonpeak probability values to the peak value.

Demographic Reconstruction

Our analysis reconstructed the occupation histories of about 3,300 residential sites that have a total of 7,122 distinct components. The vast majority of these habitation components consisted of single-household farmsteads. In this section, we use these results to reconstruct the history of Pueblo occupation in the project area overall. Figure 4.5 shows momentary population estimates for these sites. This was computed using the total number of households in each period and factoring in the occupation span of sites and the number of years in each modeling period. The changing occupation spans of habitation sites over time were taken from research that uses the accumulation of cooking pottery to estimate the length of occupation at habitation sites (Varien 1999, in press; Varien and Mills 1997; Varien and Ortman 2005). As Varien and colleagues (2007) describe in detail, we have used three methods to extrapolate from the surveyed portions of our project area and estimate a range of values for the population of the total project area (see figure 4.5). We believe that the middle estimate (based on method 3) is the most accurate, but all three show that occupation of the project area occurred in two cycles: an early cycle between AD 600 and 920, with relatively low population, and a late cycle between about AD 920 and 1280, with higher population. We discuss the “settlement efficiency” estimate on figure 4.5 in the “Summary and Conclusions.”

The Development of Community Centers

The next step in our analysis examines population aggregation and the development of large sites over time. We define “large” as sites with nine or more pit structures, fifty or more total structures, or sites with civic architecture. Ninety-two sites fit one or more of these criteria (plate 10). We call these sites “community centers” because a cluster of smaller sites typically surrounds them, they are the largest site in each cluster, and they often contain public architecture, such as a great kiva (Adler and Varien 1994; Lipe and Varien 1999:345; Varien et al. 1996). In addition, these centers have the longest occupation histories of any sites in the region (Varien 1999:202–07), and
they were the location of social, economic, and political activities that did not occur at smaller habitation sites (Driver 1996; Lipe 2002). The existing records for these centers were evaluated, and new fieldwork was conducted at fifty-nine centers with relatively poor documentation. These sites were mapped to obtain better data on their size, including the number of visible pitstructure depressions, and samples of surface pottery were analyzed to yield chronological information.

The median population size of community centers is 14 households. Between AD 1225 and 1260, the range is 9–134 households at Yellow Jacket Pueblo, the largest center in the project area. The formation of centers appears to follow trends seen in the overall population: centers became increasingly common during each of the two population cycles and were most numerous at the end of the first cycle and the end of the
second cycle. There were many more people, many more centers, and larger centers in
the second cycle (Varien et al. in press). One of the most distinctive characteristics of
the community centers is their long occupation spans (Ortman et al. 2000), but all
were abandoned as a part of the migrations that emptied the region by the end of
the thirteenth century.

Community Centers and Population Trends
In our project area, we have almost a 100 percent sample of the community centers
but have identified only a small percentage of the small sites. Given this, we focus on
data from the large block surveys to summarize settlement patterns over time, because
these areas have a 100 percent sample of both centers and smaller sites. We use these
data to examine the development of centers in the context of the overall demographic
trends. Table 4.2 lists the momentary number of households living in small sites during
each modeling period and the momentary households in community centers. It is
apparent from these data that almost everyone lived in small sites during the initial
period, but during the next four periods the total households in small sites decreased
and the total households in centers increased. These trends peak at about AD 880,
when the number of households living in centers actually surpassed the number of
households in small sites. The number of households living in centers declined dra-
matically between AD 880 and the middle-to-late 1000s, when the number of house-
holds living in centers began to increase again. These two cycles of aggregation are
seen even more clearly in the next column, which lists the percent of total momentary
population of block-surveyed areas that lived in community centers during each
period. These data clearly show how the proportion of households living in centers
increased over the course of each settlement cycle.

To examine these demographic data and how they might be correlated with
drought, we compiled a database of every tree-ring cutting date in the region—a total
of about 4,600 cutting dates from 350 sites. Each cutting date tells us the year in
which that timber was harvested, and table 4.2 summarizes the number of harvested
trees in our dataset for each of the fourteen periods. We also tabulated the percent of
years in each modeling period in which precipitation was more than one standard devi-
ation below the long-term mean; we calculated the standardized mean precipitation
for the years in each modeling period. These data suggest that, in general, tree har-
vesting tended to decline during periods with a high proportion of drought years and
to increase during periods with fewer drought years. There appears, however, to be no
consistent relationship between drought and population. These data suggest that tree
harvesting and construction were curtailed during droughts but that drought did not
always result in migration and depopulation, possibly because our study area had
greater precipitation than many areas to the south and west and therefore served as a
potential refugium during drought, particularly warm droughts.

Finally, it is instructive to compare the percent of population in community cen-
ters, the overall momentary population in the block surveys, and population growth
Table 4.1: Demographic, Economic, and Environmental Characteristics of the surveyed areas.

<table>
<thead>
<tr>
<th>Population (AD)</th>
<th>Period (DD)</th>
<th>Population (HH)</th>
<th>HH/1000</th>
<th>Individuals (Total)</th>
<th>Individuals (HH)</th>
<th>Individuals (Population)</th>
<th>Individuals (HH)</th>
<th>Individuals (Population)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 - 725</td>
<td>2</td>
<td>42</td>
<td>75</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>725 - 800</td>
<td>4</td>
<td>45</td>
<td>45</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>800 - 900</td>
<td>6</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>900 - 1000</td>
<td>8</td>
<td>45</td>
<td>45</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>1000 - 1200</td>
<td>10</td>
<td>45</td>
<td>45</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>40</td>
<td>35</td>
</tr>
</tbody>
</table>

Note: Includes all data from all sites in the study area.
rates through time. Each peak in settlement aggregation corresponds to a period in which the proportion of drought years increased and emigration occurred. Apparently, community centers were especially important in the regional settlement system during these periods. We believe that this importance may be due to both ecological and social factors. For example, the centers appear to be associated with especially good soils and reliable springs. In addition, the larger populations at centers would have had more flexibility to organize labor and would have had more extensive exchange networks.

Perhaps even more important, the inhabitants in larger centers would have had more protection if conflict and warfare occurred during periods of drought and emigration. Based on recent research tabulating the local proportion of individuals with skeletal insults probably due to warfare (Cole 2006), warfare was most prevalent in our project area from the mid–late 1000s through the mid–late 1100s, and again in the late 1200s (Kuckelman 2000), both being periods when aggregation was pronounced. Aggregation in the late 1200s, though, is contrary to a microeconomic model proposed for our area by Kohler and Van West (1996), which suggested economic reasons why households should disaggregate in times of low average production accompanied by high spatial and temporal variability similar to those experienced here in the late 1200s. According to this model, households should be “risk seeking” under such conditions, taking a chance by going it alone rather than sharing with other households. One possible interpretation of our current results is that security concerns can trump any microeconomic “disaggregation signal”; risk seeking can become too risky.

Overall, our model of the settlement history of the project area suggests, first, a positive relationship between aggregation and overall population, in which aggregation appears as a continuous process during each occupational cycle. Although aggregation appears to be generally correlated with population growth, it does not clearly ebb and flow with changes in climatically induced changes in production. We suspect that the aggregation process is also related to social and historical factors, which we hope to clarify as we continue analyzing our data. Second, both periods of peak aggregation—during the late 800s and late 1200s—occurred when the local population had already begun to decline. This pattern suggests that aggregated settlements may have exerted a “gravitational pull” on their inhabitants. Perhaps aggregated settlements were more resistant to fission and abandonment than some previous models have proposed, or perhaps the probabilistic dynamics of emigration resulted in losing many more hamlets than centers during the initial phase of regional depopulation. By playing off the archaeological data against the agent-based model, we show below that interesting patterns in both depopulations are exposed.

**Resource Use and Settlement Model**

Having discussed resource availability and some of the things that the archaeological record can tell us about resource demand, we now turn back to the simulation and discuss its current structure. We begin by briefly defining how households use resources
and relocate with respect to resources, and then we discuss how agents exchange resources.

**How Resources Are Used**

Each year, agents must find and collect resources to survive. Currently, agents are required to gather both fuel and water, grow and harvest corn, and hunt. To simplify this process, all resources in the model are converted into one of two currencies, calories or protein. An agent dies if its balance of calories or protein (but see below) ever becomes negative.

**Maize.**

Agents plant, weed, and harvest maize to create a positive net balance of calories, which are then used to collect the other resources. The number of fields planted and the productivity of those fields in a given year determine the amount of maize an agent can produce. The number of fields (1-acre plots) that can be planted by model households each year is limited to either one or two greater than the number of workers it has (we have experimented with both values; children under eight years old do not work). After maize is harvested, the model determines the number of calories produced. These calories are then available to perform other types of work, such as tending next year’s crops and collecting other required resources.

**Hunting.**

We have developed two models for hunting. Here, we describe the first, developed by Kobti and Reynolds (2005); the second is described in a later publication (Cowan et al. n.d.). They differ in the granularity of their approach and in how knowledge and caloric costs are handled. In the Reynolds/Kobti model, agents store knowledge about the yields of each of the three animal populations (deer, rabbit, and hare) for visited cells. Cells with above-average performance are ordered in a best-first manner. Each of these lists constitutes a hunting plan, and each plan is processed using an approach based upon Charnov’s (1976) Marginal Value Theorem. The idea is that when a cell on the list for an animal type falls below the hunter’s average overall expectations, it is dropped from the list (figure 4.6) and replaced by a cell within a given distance from that cell. Figure 4.7 shows the process graphically. There, each of the cells currently visited according to the plan is shown. Each has an above-average expectation and is visited in order of its expectations. When one of the cells falls below the overall average for all cells, it is replaced by another within a limited radius. That radius can be set as a parameter in the model or learned by the agent.

**Fuel and Water.**

Water for domestic use and wood for fuel are also necessary for sustaining households. Each person in each household requires 1,130 kg fuelwood (Khan et al. 2001) and 3,650 liters water (Gleick 2000), although these parameters can be easily altered.
Figure 4.6. An agent maintains a dynamic list of hunting cells with above-average yields for each of the three protein resources; decreasing yields move to the right in each array.

Figure 4.7. Illustration of the cell maintenance process, based on an adaptation of the Marginal Value Theorem.

When collecting water for the year, each household locates the source nearest to its present location and determines the number of trips required to fulfill its annual requirement by dividing the amount of water needed by the cargo capacity per trip. The default capacity for transporting water is 21 liters, determined by giving an individual the ability to transport 25 kg of weight and subtracting from that the average weight (4 kg) of a local Pueblo I olla (water jar) (Lightfoot 1994). When the distance between the agent and the water source is known and the number of trips are known, these are divided by the average travel speed of an agent (a tunable parameter in the model, to which residential location turns out to be quite sensitive) to determine how many hours of work are required. This is then multiplied by the caloric cost of one hour of work by the agent to yield the resource cost (equation 2):

$$ R = \left( \frac{(2D \cdot (N/C))}{S} \right) \cdot W $$

Eq. 2
where \( R \) = resource cost; \( D \) = distance between resource and agent; \( N \) = amount of resource required; \( C \) = carrying capacity of individual; \( S \) = speed of agent; and \( W \) = caloric cost of one hour of work by an individual.

Fuel harvest is similar to water collection. For fuels, a person can carry the full 25 kg, however, because there is no container weight. When an individual reaches the resource collection location, an additional gathering cost is calculated, based on type of fuel being collected. For deadwood collection, one extra hour of work is added per trip; for standing crop harvest, two extra hours of work are added. Occasionally, the amount of resources required exceeds the amount found at a single location in the model. When this happens, the agent will collect all the available resources at that location, calculate the costs for harvesting those resources, recalculate its need, and then continue to look for resources at a new location. No fuelwood is available to agents where plots have been cleared for farming, and we assume that the plots are cleared wastefully, with none of the wood used for fuel. Although this assumption is questionable, we consider it to be approximately balanced by the fact that we do not require households to acquire wood for building or maintaining their houses or for equipment or site furniture. Moreover, we allow agents access to all woody biomass for fuel, even though some would be difficult or impossible to harvest because of limitations of stone axes.

Numerous model runs indicate that fuel harvesting by model agents often leads to local depletion (Johnson, Kohler, and Cowan 2005). In runs using various per capita fuel requirements, we typically observe the total removal of woody species from areas surrounding long-term concentrations of model households. Of course, the extent of such deforestation is linked to the size and stability of the local population, the level of demand simulated, and (less obviously) to the speed we attribute to workers traveling to obtain distant resources.

**How Resources Affect Settlement**

Settlement patterns seen in the model are a direct result of movement decisions made by the individual households. We have seen that households must keep a positive net balance of calories and protein to survive. To do this, households must maintain high maize production while keeping other resource costs low. Other than adding or subtracting local fields (plots), to the extent of their ability to do so, the only direct method that households have to keep these factors in this balance is to move their residences around the landscape.

*When a Household Moves.*

Each year, to determine how they are doing, households examine their maize production for the preceding few years, along with their rate of caloric expenditure. When this happens, a total of three states is possible. If a household is producing more calories than it needs and it has enough calories in storage to meet the next year's calorie requirements, then it is content and remains at its current location. If only one of these
criteria is met, then the household determines whether planting additional plots in its current location is feasible. If neither of these criteria is met or if only one is but the household cannot add new plots locally, it attempts to move to a new location.

How a Household Moves.
When a household moves, it tries to find a location that will allow it to maximize caloric production while minimizing resource costs. It does this by first ranking every cell within its search radius, based on how many calories that cell would produce if the household were farming in that cell during that year. If a cell already has eight or more plots planted by other agents at this time, it is excluded from this ranking. (There are nine possible 1-acre plots in each 4-ha cell, with a small amount left over for habitation.) After this ranking is done, the household calculates the expected caloric costs for collecting other resources in the top one hundred calorie-producing cells. When these costs have been calculated, the one hundred cells are reordered, based on which would produce the most calories (after subtracting anticipated caloric costs for getting water, fuels, and sufficient protein) if the household were living in that location during that year. Finally, the household moves to the location with the best prospects, based on this ranking.

The result is a move that approximately maximizes household efficiency (defined as caloric benefit–caloric cost), but with a built-in bias to be close to productive agricultural areas that are not yet fully planted. This built-in bias may be more descriptive of household preferences in the first colonization cycle than in the second cycle. Overall, within just a few years of model initiation, agents approximate an ideal free distribution, but soon, as populations rise, the distribution begins to approximate an ideal despotic distribution (Fretwell and Lucas 1970; chapter 7, this volume).

Cultural Algorithms, Networks, and Exchange
We can now discuss our initial use of cultural algorithms in the context of implementing exchange among households, because these are layered on top of everything else we have described to this point. As shown in figure 4.8, cultural algorithms (CAs) assume a social population and a belief space (Reynolds 1979). “Cultural knowledge” resides in the belief space, where it is stored and updated based on household experiences and their successes or failures. In turn, the cultural knowledge controls the evolution of the population by means of an influence function. A cultural algorithm thereby provides a framework in which to accumulate and communicate knowledge, enabling adaptation in both the population and the belief space (Chung and Reynolds 1996; Cowan and Reynolds 2003; Reynolds 1994, 1999, 2005; Reynolds and Ostrowski 2003).

At least five basic categories of cultural knowledge are important in the belief space of any cultural evolution model: situational, normative, topographic, historical or temporal, and domain knowledge (Reynolds 2005). In our model, all these knowledge sources can be represented. For example, we currently assume that agents will
have access to knowledge about the distribution of current agricultural production and topography, the distribution of rainfall over the preceding few years to the extent that it affects agricultural production (historical or temporal knowledge), and agricultural planting and harvesting techniques (domain knowledge). These latter two knowledge sources are fixed at this time.

The comprehensive cultural framework shown in figure 4.9 is proposed as a guideline for the agent’s learning strategies. The main components include the agent’s maize storage status (based on resource needs), exchange, network relations, resource generation, and movement. As new data are added to the model, they can be accommodated within this framework. The current implementation includes agriculture and hunting, along with generalized and balanced reciprocal exchange of resources among agents. No production or exchange of artifacts has yet been implemented.

**Social Networks**

As noted in the introduction, in this phase of our project a key goal is to determine as rigorously as we can how much of the variability in the archaeological settlement pattern can be attributed to the responses of individual households as they attempt to minimize costs and maximize success in a changing environment. Our introduction of cultural algorithms coupled with exchange processes, in those simulations where we
enable exchange, departs slightly from this philosophy by allowing a sort of “primitive sociality” to arise. Here, we describe the three networks developed by Korbti, Reynolds, and Kohler (2004) across which exchanges may flow.

Kinship Network.
The emergent networks in the model are developed by households, the nodes in the network. Household members live together, share their production, and are affected
Table 4.3 Connected Nodes Identified by the Kinship Social Network

<table>
<thead>
<tr>
<th>Name of Tag</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ParentHHTagA</td>
<td>A link to the parent from the mother’s side</td>
</tr>
<tr>
<td>ParentHHTagB</td>
<td>A link to the parent from the father’s side</td>
</tr>
<tr>
<td>ChildHHTag</td>
<td>One link to each child who moves away from this household and forms her or his own household</td>
</tr>
<tr>
<td>RelativeHHTag</td>
<td>One link to each extended family member</td>
</tr>
</tbody>
</table>

by the same environmental conditions. Children can grow up, marry, and move out to form their own households. Their connections to their parent households and siblings are maintained in our model. Similarly, the parents maintain ties to their children. When one of the parents in a household dies, the other can form a new household with an available single agent. If both parents die, we use the expedient process of promoting the oldest child remaining in the household (if there is one) to become the “parent,” if that child is seven years old or older. If no child that old is available, the household dies. The structure of the social network supports the notions of parents, siblings, and grandparents on both sides of the family. The layout of the generalized reciprocal network (GRN) from the perspective of a household is described in table 4.3.

The original simulation model (Kohler et al. 2000) was based on households with no social or economic interactions. The first extension to that model in the current round of development introduced gender, marriage rules, and other localized enhancements enabling individuals to co-exist and reproduce within households. Reynolds, Kohler, and Kobti (2003) have described rules for marriage and kinship dynamics. Briefly, the kinship network links each living household to its parents, siblings, children, and other relatives. We implemented generalized reciprocal exchange (Sahlins’s “generalized reciprocity” [1972:192–94]) over this network to enable agents to cooperate through resource exchange to improve their survival.

A small-world social network emerged. A small-world network is a “(large) graph with both local clustering and, on average, short distance between the nodes. Short distances promote accessibility, whereas local clustering and redundancy of edges promotes robustness to disconnection” (White and Houseman 2003:72). These distances can be measured in various ways (for example, in geographic space or kinship space). The farther away nodes are in the graph, the weaker the ties. Most nodes have many strong ties and support transitivity of exchange between nodes. Nodes with many weak ties and few strong ones are called “hub nodes.” Transmission of matter, energy, and information in small-world networks shows signs of funneling through hubs (Travers and Milgram 1969). The presence of these hub nodes allows requestors to navigate through the network looking for resources.
In our first CA models, we used just the GRN, which is based on kinship distance. The resultant system was able to support a larger population than did the system in which no resources were exchanged among kin. The small-world network gives each agent multiple paths along which to search for resources. Within the network, agents can be reliable or unreliable donors. Thus, some paths will be fruitful and lead to agents that are reliable, and others will not (see Reynolds et al. 2005).

One of the key issues was how agents can learn to navigate the existing network effectively by avoiding unreliable agents and defectors, an important problem in the effective use of such networks (White and Houseman 2003). Motivated by household-level experience and population norms, households are able to learn and make more intelligent choices in cooperating over the kinship network through the CA. For instance, a household can learn to make a better choice when it decides whom to ask for food when in need. Over time, an individual can learn to select more cooperative kin, and, indirectly, a population identifies known exemplars and establishes its acceptable norms. As a result, established households can become good donors, and those in less productive locations can depend on the social network for survival. In our simulations, we can enable a “social move” in which households are allowed to relocate closer to the productive kin and, indirectly, to more productive farmlands (such moves are not implemented in the simulations reported here). Over time, individuals cluster closer together around productive lands weakly connected by hubs in a small-world social network. When we visually compare the simulated locations of these hubs with those community centers known archaeologically, a reasonably good fit is observed. In general, however, in work to date we have not rigorously evaluated the fit of our simulated distributions to the archaeologically known settlement system.

**Economic Network.**

A second, important baseline network, the economic network, is an implementation of what Sahlins (1972:194–95) called “balanced reciprocity” (a balanced reciprocal network, or BRN, in our model). The archaeological record for our region contains a large variety of ceramics, stone tools, and other artifacts that could have been exchanged among households. This suggests the potential for economically based exchange as a mechanism for distributing resources among the agents. In our implementation of balanced reciprocity, each household maintains a list of trading partners formed from nearby households. Requiring these exchanges to be relatively local reflects the constraints of increasing costs as travel distances increase. Each household maintains a set of trading partners that can be any household within a given radius from the focal household. (In the future, we may restrict this network to non-kin.) Households adopt a strategy to decide when, and with whom, to exchange. In contrast to the reciprocal exchange model, households in this network keep balances of the amounts owed and traded. The ability of agents to repay their debts reflects their reliability, generalized here as reputation. A well-reputed household is a good producer and lives without debt. This is typical of settlers of productive lands or those with
strong social ties. Less reliable households reside on less productive lands and have weak social ties. A CA in the economic network guides the decisions that a household and the culture make in selecting reputable trading partners. The social networks produced by using both the GRN and BRN again fit a small-world pattern.

Hub Network

Also new in our current implementation is the concept of a hub network, which emerges from both the GRN and BRN networks. Our implementation of the two base networks allows households to promote themselves to the next network: the hub network. Hubs are households that are central because they have an unusual amount of connectivity in the network. Central hubs provide the network with its searchability properties and enable agents to navigate the web to locate potential partners for exchange. Here, they are operationally defined as those nodes that are of sufficient complexity in both the GRN and the BRN; we use an intersection criterion for identifying hub nodes (figure 4.10). That is, the total number of connections in the BRN and the GRN must exceed a certain constant for a node to be eligible for promotion to the hub-node network. Promotion to hub-node status is determined through a probabilistic discrete Poisson distribution, based on a household’s number of links to other hub nodes. A hub node can demote itself and remove itself from the hub network if it loses its importance in either the GRN or BRN. Hubs have the ability to exchange with one another (under the ruleset we call “coop 6”; table 4.4) and to defect on their trades. However, defection is not dealt with in detail here (see Reynolds et al. 2005 for additional discussion).

All the exchange mechanisms are incremental, and each assumes the existence of the “more primitive” mechanism. Thus, the BRN emerges from the need to address deficiencies in the GRN, and the hub net emerges from the need to address navigability issues in the BRN. In a given simulation, if the GRN is sufficient to distribute resources among agents, there is no need for the BRN to emerge. Likewise, if the GRN and BRN together can efficiently support the exchange of resources, there is no need for the hub net to emerge. The number of levels in the emergent network is, then, a function of the predictability in space and time of the resources involved.

Using Social Networks to Support Exchange

In this section, we describe how the GRN and BRN are integrated, using the example of our implementation of protein exchange. Exchange of maize takes place in a similar fashion and is discussed by Kobti, Reynolds, and Kohler (2003, 2004). A key idea is that exchange occurs when a household needs resources. After updating their networks, households try to satisfy their resource needs by calling in debts from their neighbors first, using the BRN for each needed resource. Currently, only exchange in kind is considered. If they are not successful, then they request aid from their relatives through the GRN. If they still are deficient in resources, they then go back to the economic network to initiate further exchange. The extent of an agent’s search is a func-
Table 4.4 Description of the Cooperation Methods at the Kinship Level

<table>
<thead>
<tr>
<th>Coop Number</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>When there is no cooperation, households do not exchange food.</td>
</tr>
<tr>
<td>1</td>
<td>When an agent requires food, it can select and request food from within its kinship network to survive.</td>
</tr>
<tr>
<td>2</td>
<td>When an agent has excess food, above a determined threshold amount, it can select one or more households from its kinship network and donate the excess.</td>
</tr>
<tr>
<td>3</td>
<td>Both methods 1 and 2 are enabled.</td>
</tr>
<tr>
<td>4</td>
<td>Full cooperation across the kinship and economic network (generalized and balanced reciprocal exchange simultaneously)</td>
</tr>
<tr>
<td>5</td>
<td>Hub network emergence based on the intersection of hubs from GRN and BRN networks, and accepted based on a discrete Poisson distribution</td>
</tr>
<tr>
<td>6</td>
<td>Hub nodes developed in coop 5 may exchange with other hubs</td>
</tr>
</tbody>
</table>

tion of the scarcity of the resource. If resources become scarce because of weather or soil depletion (in contrast to the case of northern Mesopotamia, described in chapter 9, we have no basis for inferring manuring of fields), dependency on all three network levels will increase. Table 4.5 shows how hunting and exchange are integrated, and table 4.6 describes the interaction of households with each of the three networks, assuming that hub-network exchange is enabled.
Table 4.5 Integration of Hunting and Exchange

<table>
<thead>
<tr>
<th>Step</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Calculate protein need for the household for the year in order to survive, based on amounts set in the parameter file.</td>
</tr>
<tr>
<td>2</td>
<td>If the first hunt, then initialize the hunting location to the current cell.</td>
</tr>
</tbody>
</table>
| 3    | If not the first hunt, then update the past hunting cell locations as follows:  
  1. Compute the average protein yield of the known cells by using the total protein yield from each cell (deer, rabbits, and hares).  
  2. If a known cell falls below the average, replace it with a nearby cell that has a better yield. This is done by searching within a hunting radius for the cell with the most yields. |
| 4    | Visit each known cell (most productive first), and hunt for deer, rabbits, and hares.  
  1. Continue hunting each cell until the household’s needed protein yield is met.  
  2. If all the known cells are hunted without obtaining sufficient protein amounts, then search for additional hunting cells in the hunting radius, up to a defined maximum number of cells. |
| 5    | Consume the protein gathered from hunting activity. |
| 6    | If the household did not satisfy its protein requirements:  
  1. Then request the needed protein from relatives, using the CA to learn whom to ask, and update knowledge accordingly.  
  2. Then call in the debt by asking the trading partners to pay back their owed balance. Update the quality criteria with each partner accordingly.  
  3. If the household is still in need, request a protein trade from known partners on the BRN. Also, seek out new partners on the BRN, if needed. (Refer to the BRN for details.)  
  4. If the household is a hub and is still in need, then request protein from another hub. |
| 7    | If the household does not meet its protein requirements, then it may die, or its probability of having additional children may decrease and probability of death for members may increase, depending on settings elsewhere in the model. |

A Sample Run of the Agent-Based Model

Here, we describe the results of a run of the simulation model, using all the resource models described above. Agents cultivate maize, hunt animals, and collect fuelwood and water. They can exchange animal and plant resources through both the GRN and BRN networks. The hub network can emerge from these networks if enabled by the simulation parameters and if needed by the population. These runs are not primarily designed to reference the archaeological record, so we do not expect a close fit between our results and the time series of local population size in figure 4.5. Here, we are interested primarily in various abstract properties of the simulated exchange systems.
Table 4.6 Exchange Actions

<table>
<thead>
<tr>
<th>Step</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Update GRN.</td>
</tr>
</tbody>
</table>
| 2    | Update BRN:  
|      | (1) Remove dead partners (and non-active/out of region/expired). |
|      | (2) Search each neighboring cell within a trade radius, get its settlers list, and add new ones to the trade list. |
| 3    | Update the hub network:  
|      | (1) Promote or demote self to or from the hub network, based on current base status. |
|      | (2) Remove dead partners, and search for new ones in range. |
| 4    | Request payback of debt from BRN and hub network partners. |
| 5    | If HUNGRY/Critical (definitions for these states, in terms of amounts in storage relative to needs, can be changed in the parameter file), request food from GRN (no payback). |
| 6    | If still HUNGRY/Critical, request food from BRN (with payback). |
| 7    | If still HUNGRY/Critical, request food from hub network (with payback). |
| 8    | If CRITICAL, agent is dead and is removed. |
| 9    | If PHILANTHROPIC/FULL:  
|      | (1) Donate surplus into GRN. |
|      | (2) Pay back debt into BRN. |
|      | (3) Pay back debt into hub net. |

Figure 4.11 gives the population of agents produced by the model from AD 600 to 1300. We started with a small initial population of fewer than two hundred households. The system is closed; no agents arrive from elsewhere in these runs, nor can active households leave.

The system is able to survive several drought periods. The number of households in each of the three networks over time is given (all households correspond to the GRN because all households participate in the kinship network). Several drops in population correspond to periods of low potential production in the productivity data planes used. One result of a drought or another environmental stress is to reduce the total number of agents. This effect then ripples through the network, first to the BRN and then to the hub network, with a slight lag at each level. Although the hub network is the last to feel the ripples, it is the hardest hit and the last to recover.

Plate 11 presents volumes for each of the three networks. The network volume is the product of the out-degrees (number of connections) of each of the nodes in the network. This allows us to observe the impact of an environmental perturbation on the overall complexity of each of the three networks. Notice that after a drought around AD 800 the volume of the BRN is very close to that of the GRN. This means that most households are involved in each network to about the same degree. Later on,
Figure 4.11. The number of agents (households) overall and participating in each of the three networks, GRN, BRN, and hub (coop 6). The total number of agents and the number participating in the GRN are the same because all agents have some kin connections to other agents. These experiments were conducted on paleoproduction data planes different from those presented in figure 4.2 and represent a proof of principle for the exchange mechanisms.

the difference between the two becomes more pronounced after each environmental perturbation. This suggests the formation of more efficient but perhaps more isolated local groups.

Figure 4.12 gives a blowup of the hub network and its volume over time, from the same set of simulations used to produce plate 11. This network is the most cyclical of the three and disappears around AD 850, 1050, and 1200 as the result of low production in the data planes utilized here. It then re-emerges, gradually recovering after each episode of low production. But each time it recovers, the volume it reaches is less than the preceding peak. This drop in peak height may be due, in part, to the fact that the hub network is produced as a nonlinear combination of parts of the GRN and BRN. Losses in either the GRN or BRN make it harder to promote individuals back up into the hub network to replace lost nodes. In fact, hub-node volume is already descending around AD 1270, after reaching a peak that is far less than any previous one. In analogy to an automobile engine, each time there is a problem, the engine never quite reaches its former level of performance. After a recovery, the newly emergent hub network is never quite as effective as the former one; its peak volume exhibits a clear monotonic decrease through time.

This is a very interesting result in the sense that archaeological evidence supports
increased populations until the mid-1200s. Because we have assumed that the system is closed and there are no incoming agents to replace the ones lost because of disruptions in the exchange network, this lack of fit with the archaeological data suggests that the system is far from closed and that, to understand the system fully, we need to understand the flow of humanity across the arbitrarily defined borders of our study region. In fact, it might be that the disruptions to our local social networks, though severe, were not as bad as those in other places. This may cause individuals from other regions to move into vacant “niches” in our system and firm up the network. (Varien et al. [2007], in fact, reconstruct four probable periods of immigration, following the initial colonization of our area by farmers.) If these immigrants were not related to current residents, they could overload the BRN because they would not be effectively integrated into the kinship structures (on which the GRN depends). Given that promotion to the hub network requires participation in both the GRN and the BRN, immigrants may not produce a resurgence in hub-net structure unless they can be integrated into the GRN. The integration of non-kin into social systems has been an important item for study in other cultures (Flannery, Marcus, and Reynolds 1989). Thus, it would be interesting in future work to model the effects of social integration on the system’s overall stability. This could be done by opening the system, in a controlled way, to enable the immigration of new households into the region, along with the ability of resident households to abandon the region.

At the moment, this discussion is purely hypothetical (follow-up experiments are
discussed in the next section), but it illustrates the power of simulation to show us alternative worlds, like so many “sandcastles,” built and rebuilt. Although these worlds might not have existed, they may be able to tell us many things about the worlds that did. Simulation is truly a “sandbox for scholars.”

**Summary and Conclusions**

As we write this chapter, we are beginning a series of runs in which we vary half-a-dozen model parameters (including type of exchange behavior, degree of soil degradation, whether households may move to protein-depleted areas, productivity of the landscape, amount of protein from hunting required per person, and which set of paleoproductivity datplanes we use). We monitor the effects of each combination of parameters on population levels through time, location of population through time, degree and location of aggregations, the amount of time or calories spent in each major modeled activity (fuel and water collection, agriculture, and hunting) through time, and so forth. For some of these outputs (especially the locations and sizes of settlements through time and the total study area population through time), we have strong archaeological evidence that will help us determine which parameter combinations provide the best fit to the archaeological data. We expect to find that the best-fitting parameters will, in fact, change through time, giving us a sense of the directions in which household-level behaviors had to change through the seven hundred years we model.

For a century now, archaeologists have been developing approaches to examine the societies of the ancient Southwest within their environments (see partial reviews in Gumerman 1988; Kohler 2004). It might surprise us that aspects of these socioenvironmental relationships still remain to be appreciated. We have been surprised, in our preliminary results, to see how depletion of fuels—and especially of deer—becomes widespread in any simulation in which the model populations approach the levels actually achieved in this area, even when we keep per person protein requirements low. Population levels higher than those seen in the Pueblo I (PI; AD 750–900) period result in a severe depression of study-area deer populations even when protein requirements from hunting are on the order of only 15 g/person. For comparison, commonly cited protein requirements averaged for different ages and sexes are around .4 g/day/lb body weight. If our average individuals weighed 90 lbs, then they needed, by this calculation, about 36 g protein/person/day. An unknown but significant part of this would come from agriculture (corn, beans, squash, and cheno-ams) and another unknown proportion from gathering, trapping, and so forth. Spielmann and Angstadt-Leito (1996:82–3) conservatively estimate that southwestern agricultural populations needed 20 g/person/day of “high-quality” protein and permit half of that to come from small mammals and plants.

Because population levels in our area were considerably higher in the Pueblo II (PII; AD 900–1140) and Pueblo III (PIII; AD 1140–1280) periods than in PI times (see
(figure 4.5), we may find that post-PI populations as high as we see in our area were unlikely without the protein supplement provided by turkey domestication. Of course, long-distance hunting, beyond the area within which we model deer populations, could have alleviated local protein shortfalls to some extent (see the expansive range mapped by Ferguson and Hart [1985:Map 15] as the traditional Zuni hunting area). It is also possible that hunting of leporids was more efficient and larger in scale than we model. Nevertheless, the ease with which local deer populations could be depleted by these populations may help us understand the degree to which hunting was subject to strong ritual regulation in historic pueblos (for example, Ferguson and Hart 1985:43; White 1962:301–05).

In this light, it is interesting to contrast the settlement patterns of the deer-dependent PI and the turkey-dependent PIII populations. In the PI case, on one hand, settlement was concentrated in and around the valley of the Dolores River, in the high northeastern portion of our study area. Because of short growing seasons, farmers could not occupy the highlands northeast of that valley, an area predicted by our model to be very productive of deer. The PI populations might have located themselves to maximize joint access to agriculture and those productive hunting territories, even at the expense of living in areas that were high enough to be risky for agriculture. The PIII populations, on the other hand, were most numerous in the mid-elevation belt that runs diagonally from the northwestern corner of our study area down towards its southeastern corner. These locations maximized access to good farming land while avoiding higher elevations, where farming was sometimes excellent but subject to failure in cold years. If the PIII populations, in essence, obtained both their calories and protein through maize, which would be the case if turkeys were fed a substantial amount of maize, then the easy access to deer so coveted by PI populations may not have been worth the risk of poor maize production—especially if deer populations were considerably depleted. A possible alternative hypothesis—that PIII populations became attracted to the relatively large springs in this belt as other water sources in our study area failed—is not supported by our paleohydrological modeling results to date.

Our estimates of momentary population size through time in the project area (see figure 4.5) show the same rapid influx of population into our study area in the mid-AD 1200s that we reconstruct for just the block surveys (see table 4.2). This, too, is an unexpected result. Much recent thinking about population history in the larger northern San Juan region (for example, Duff and Wilshusen 2000)—of which our study area is only a small part—has tended to favor a relatively gradual decline throughout the 1200s. On the basis of our productivity reconstruction (see figure 4.2), we tentatively suggest that the generally cold and dry conditions from the late 1190s through about 1235 caused populations in less favorable areas to move into the refugium that our area provides, where they occupied many relatively small community centers concentrated in the western portions of our study area. Many of these people (or at least, many people) leave our area by 1260. This marks the beginning of the final depopulation, but the high population levels, to which these recent immigrants contributed, added
to the generally hostile and resource-competitive conditions that seem to accompany the relocation of many community centers to canyon-head locations (or, on Mesa Verde itself, into alcoves) by the mid-1200s. These preliminary results lead us to suspect that the failures that cause the eventual, complete depopulation of our area began on the northern Pueblo periphery and cascaded into our study area—a possibility anticipated forty years ago (Davis 1965). It is a high priority to identify where these populations came from, to better understand their motives for leaving.

Although we have not begun a final assessment of the fit between our simulated settlement patterns and those in the archaeological record, we have generated some preliminary results relevant to the end of both population cycles, by assessing the goodness of fit through time for sixteen runs reported in detail by Cowan and colleagues (n.d.). Remembering that our agents approximate the efficient settlement pattern in each period, given the parameters under which they are operating and the patterns of productivity as they change in response to climatic variation, we can take measures of goodness of fit between the simulated and real records to assess the extent to which real populations were distributed efficiently with respect to resources. Johnson (2006:236–52) discusses how we correlate counts of real and simulated households across the landscape in each period, using unsmoothed and smoothed versions of the real household distributions, to arrive at a measure of goodness of fit.

Figure 4.5 recasts these measures of goodness of fit from those sixteen runs as a preliminary measure of settlement efficiency through time, superimposing it on our population estimates. Although we will have more to say about such measures in later publications, here we want simply to draw attention to the sharp increases in efficiency that occur at the beginning of each cycle of depopulation. At around 900 and around 1270, populations in our area were maximally aggregated, yet they were more efficiently distributed on the landscape than were populations at 860 and 1240, when population numbers in each cycle peaked. Clearly, each depopulation began with the departure or demise of those households that were least advantageously situated with respect to resources. Although households in the best locations were able to persist, they, too, ultimately left, at least at the end of the second cycle. These patterns strongly suggest that, at least in the periods of relatively high population and low production that terminate each population cycle, households risked being unable to meet their subsistence needs and their settlement decisions had direct survival ramifications and conveyed definitive selective advantages. Our preliminary measure of settlement efficiency reflects the fact that, as Robert Foley (1985:230) has noted, pressures towards optimality are always strongest when competition is most severe.

As we work more with exchange, we are beginning to understand its interactions with population size as well. Perhaps not surprisingly, agents practicing generalized reciprocity grow in number more than those with no exchange. Adding balanced reciprocity and then layering on exchange between hub nodes results in additional increases in simulated populations. (We conceptualize these hub nodes rather loosely as prosperous, influential households or lineages in community centers.) But this is a
mixed blessing because exchange of all types tends to break up in periods of subsistence shortfall and these shortfalls then become more severe to the extent that the populations have come to rely on exchange. Similarly, interruption of exchange for other reasons, for example, between hub nodes during periods of intercommunity hostility, could also cause local subsistence shortfalls due to poor distribution. The breakup of exchange networks may prove to contribute importantly to the two depopulations of our area. Certainly, we will be examining these effects closely as we begin our final analyses.

Despite its relative complexity, the Village Ecodynamics world is vastly less complex than reality. The main virtues of “Village” are that it is simpler than reality in a very disciplined manner and that we know precisely the processes it uses to produce the patterns it generates (though sometimes it takes a little work to figure out how those processes interact to produce specific changes). It is simpler than reality in a disciplined manner because we did not just use a random sample of what we believe to be the full gamut of human behavior and its social phenomenology. Instead, we have systematically dispensed with any agent actions that cannot, in Bourdieu’s (dismissive) phrase (1990:46), be reduced to a “mechanical reaction to mechanical determinations and…economic agents to indiscernible particles subjected to the laws of mechanical equilibrium.” Moreover, except for what concerns the “primitive sociality” of exchange, our agents really are particles; they do not form or take action in groups. All households behave according to the same rules, although each household may still behave differently because of varying circumstances.

The advantages of this approach are that—assuming that we have done everything correctly—anything produced by the real world but not by the model has to be explicable by some thing or combination of things that the model leaves out: we project the pure transparency of our agents onto the opacity of the archaeological record. Although this “method of residuals” still leaves numerous explanatory possibilities, it also rules out important segments of traditional archaeological explanation. To what extent would villages form in our area if they were solely the result of households responding at a household level to local economic opportunities? Do we see villages bigger than those in the archaeological record, and in different times and places? If so, their formation must not be due to the “social physics” we model, leaving us free to investigate the remaining plausibilities by using any means at our disposal.

Another advantage of this approach is the strong linkage it makes to the present. Model results do not depend on any process we cannot see acting in our own world and, most particularly, do not depend on any murky subjectivity we may want to ascribe to the actors. We can, if we like, interact with the model and pose what-if questions of it. Certain aspects of it have present value for thinking about the future. The hydrological model, for example, can be used to forecast water futures under various climatic assumptions.

Less obviously, models such as this begin to train us to think about causality in a more subtle and sophisticated fashion because what happens in these models, though
vastly simpler than life itself, is almost never a simple reaction to some specific cause. Rather, it is filtered through an interacting set of processes and circumstances. This suggests that we may never attain an explanation as completely simple as climatic deterioration for the general depopulation of the northern Southwest in the late 1200s. But this, in our view, is still preferable to abandoning the search for causal structure in human history.

**Acknowledgments**

This work is supported by the National Science Foundation (BCS-0119981). We thank many colleagues, including Kevin Cooper (Mathematics, Washington State University, Pullman), who contributed the implicit diffusion function we use for deer; Donna Glowacki (National Park Service, Mesa Verde, Colorado), who directed our Community Center Survey in 2002 and 2003; Carla Van West (SRI Foundation, Rio Rancho, New Mexico) and Jeff Dean (Laboratory of Tree-ring Research, University of Arizona, Tempe), who advised on the revisions to the maize paleoproductivity reconstructions we summarize here; Doug Ramsey (Natural Resource Conservation Service, Cortez, Colorado) for endless advice on updating soils data; Matt Salzer (Laboratory of Tree-ring Research, University of Arizona, Tempe), who allowed us to use his bristlecone pine ring-width index series from the San Francisco Peaks; Diane Curewitz, who helped with editing chores on this chapter and this volume; and William D. Lipe (Anthropology, Washington State University, Pullman), who has been a sounding board for all aspects of this project.