Understanding Anasazi Culture Change Through Agent-Based Modeling

Jeffrey S. Dean
George J. Gumerman
Joshua M. Epstein
Robert   Axtell
Alan C. Swedlund

SANTA FE INSTITUTE

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AGENT-BASED MODELING

Jeffrey S. Dean

Laboratory of Tree-Ring Research

P. O. Box 210058

The University of Arizona

Tucson, Arizona 85721-0058

George J. Gumerman

Arizona State Museum

P. O. Box 210026

The University of Arizona

Tucson, Arizona 85721-0026

Joshua M. Epstein, Robert Axtell

The Brookings Institution

1775 Massachusetts Avenue, N.W.

Washington, D. C. 20036

Alan C. Swedlund

Department of Anthropology

University of Massachusetts

Amherst, Massachusetts 01003

Miles T. Parker

The Brookings Institution

1775 Massachusetts Avenue N. W.

Washington, D. C. 20036

and

Steven McCarroll

University of California at San Francisco

1350 Seventh Avenue

San Francisco, California 94143

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INTRODUCTION

Traditional narrative explanations of prehistory have become increasingly difficult to operationalize as models and to test against archaeological data. As such models become more sophisticated and complex, they also become less amenable to objective evaluation with anthropological data. Nor is it possible to experiment with living or prehistoric human beings or societies. Agent-based modeling offers intriguing possibilities for overcoming the experimental limitations of archaeology by representing the behavior of culturally-relevant agents on landscapes. Manipulating the behavior of artificial agents on such landscapes allows us to, as it were, "rewind the tape" of sociocultural history and to experimentally examine the relative contributions of internal and external factors to sociocultural evolution.

Agent-based modeling allows the creation of variable resource (or other) landscapes that can be wholly imaginary or can capture important aspects of real-world situations. These landscapes are populated with heterogenous agents. Each agent is endowed with various attributes (e.g., life span, vision, movement capabilities, nutritional requirements, consumption and storage capacities) in order to replicate important features of individuals or relevant social units such as households, lineages, clans, and villages. A set of anthropologically plausible rules defines the ways in which agents interact with the environment and with one another. Altering the agents' attributes, their interaction rules, and features of the landscape allow experimental examination of behavioral responses to different initial conditions, relationships, and spatial and temporal parameters. The agents' repeated interactions with their social and physical landscapes reveal ways in which they respond to changing environmental and social conditions. As we will see, even relatively simple models may illuminate complex sociocultural realities.

While potentially powerful, agent-based models in archaeology remain unverified until they are evaluated against actual cases. The degree of fit between a model and real world situations allows the model's validity to be assessed. A close fit between all or part of a model and the test data indicates that the model, albeit highly simplified, has explanatory power. Lack of fit implies that the model is in some way inadequate. Such "failures" are likely to be as informative as successes because they illuminate deficiencies of explanation and indicate potentially fruitful new research approaches. Departures of real human behavior from the expectations of a model identify potential causal variables not included in the model or specify new evidence to be sought in the archaeological record of human activities.

THE ARTIFICIAL ANASAZI PROJECT

The Artificial Anasazi Project is an agent-based modeling study based on the Sugarscape model created by Joshua M. Epstein and Robert Axtell, both of The Brookings Institution and the Santa Fe Institute (Epstein and Axtell 1996). The Project was created to provide an empirical, "real world" evaluation of the principles and procedures embodied in the Sugarscape model and to explore the ways in which bottom-up, agent-based computer simulations can illuminate human behavior in a real world setting. In this case, the actual "test bed" is prehistoric Long House Valley in northeastern Arizona, which, between roughly 1000 BC and A.D. 1300, was occupied by the Kayenta Anasazi, a regionally distinct prehistoric precursor of the modern Pueblo cultures of the Colorado Plateau (Fig 1).

Archaeological information on the Kayenta Anasazi provides an empirical data set against which simulations of human behavior in Long House Valley can be evaluated. The actual spatiotemporal history is the "target" we attempt to recreate — and hence, explain — with an agent-based model. Ultimately, this target is constructed from the research of the Long House Valley Project, a multiyear research effort of the Museum of Northern Arizona and the Laboratory of Tree-Ring Research at The University of Arizona, which primarily involved a 100 percent survey of the Valley (Dean et al. 1978). Directly, however, the data were extracted from the Long House Valley

database in the computer files of the Southwestern Anthropological Research Group (SARG), an effort at large scale data accumulation and management and cooperative research (Gumerman 1971; Gumerman and Euler 1978). These data were downloaded from the SARG master file, modified through the elimination of many categories of data deemed extraneous for our purposes, and then imported into the Artificial Anasazi software. These locational and site data serve as the referents against which the simulations are evaluated.

The simulations take place on a landscape (analogous to Epstein and Axtell's Sugarscape) of annual variations in potential maize production values based on empirical reconstructions of low and high frequency paleoenvironmental variability in the area. The production values represent as closely as possible the actual production potential of various segments of the Long House Valley environment over the last 1,600 years. On this empirical landscape, the agents of the Artificial Anasazi model play out their lives, adapting to changes in their physical and social environments.

CHARACTERISTICS OF THE STUDY AREA

Long House Valley (Figure 1), a topographically discrete, 96 km^2 land form on the Navajo Indian Reservation in northeastern Arizona provides an intensively surveyed archaeological case study for the agent-based modeling of settlement and economic behavior among subsistence-level agricultural societies in marginal habitats. This area is well suited for such a test for four reasons. First, it is a topographically bounded, self-contained landscape that can be conveniently reproduced in a computer. Second, a rich paleoenvironmental record, based on alluvial geomorphology, palynology, and dendroclimatology (Gumerman 1988), permits the accurate quantitative reconstruction of annual fluctuations in potential agricultural production (in kg of maize per hectare). Combined, these factors permit the creation in the computer of a dynamic resource landscape that replicates conditions in the valley. It is on this landscape that our artificial agents move about, bring new sites under cultivation, form new households, and so on. Third, detailed regional ethnographies provide an empirical basis for generating plausible behavioral rules for the agents. Fourth, intensive archaeological research, involving a 100 percent survey of the area

supplemented by limited excavations, creates a database on human behavior during the last 2,000 years that constitutes the real-world target for the modeling outcomes (Dean et al. 1978; Gumerman and Dean 1989). Between roughly 7000 and 1000 BC, the valley was sparsely occupied by, first, Paleoindian big game hunters and, second, Archaic hunters and gatherers. The introduction of maize around 1800 B.C. initiated a long transition to a food producing economy and the beginning of the Anasazi cultural tradition, which persisted until the abandonment of the area about A.D. 1300. Long House Valley provides archaeological data on economic, settlement, social, and religious conditions among a localized western Anasazi population. The archaeological record of Anasazi farming groups from A.D. 200-1300 provides information on a millennium of sociocultural stasis, variability, change, and adaptation to which the model can be compared.

The valley's geologic history has produced seven different environmental zones (Figure 1) with vastly different productive potentials for domesticated crops and various degrees of suitability for residential occupation. One of these habitats, the Uplands Nonarable zone consists of exposed bedrock and steep, forested colluvial slopes with no farming potential. Different soil and water characteristic impart different agricultural potentials to the remaining habitats, in order of increasing potential productivity the Uplands Arable, General Valley Floor, Midvalley Floor, North Valley Floor and Canyon, and Sand Dunes zones.

Because the local environment is not temporally stable, modern conditions — which include three soil types, heterogeneous bedrock and surficial geology, sand dunes, arroyos, seeps, springs, and varied topography — are only imperfect indicators of the past environmental circumstances that influenced how and where the Anasazi lived and farmed. Accurate representations of these circumstances, however, can be achieved through paleoenvironmental reconstruction. Low- and high-frequency variations in alluvial hydrologic and depositional conditions, effective moisture, and climate have been reconstructed in unprecedented detail using surficial geomorphology, palynology, dendroclimatology, and archaeology. High-frequency climatic variability is represented by annual Palmer Drought Severity Indices (PDSI), which reflect the effects of meteorological drought (moisture and temperature) on crop production (Palmer 1965).

Low frequency environmental variability is characterized primarily by the rise and fall of alluvial ground water and the deposition and erosion of flood plain sediments. Based on relationships among these variables provided by Van West (1994), these measures of environmental variability are used to create a dynamic landscape of annual potential maize production, in kilograms, for each hectare in the study area for the period A.D. 382 to 1400.

CONSTRUCTING THE PRODUCTION LANDSCAPE

Because there are no crop yield data for any nearby or comparable areas, maize production in Long House Valley (LHV) cannot be reconstructed directly from tree growth or from dendroclimatically reconstructed PDSI values, as was done by Burns (1983) and Van West (1994) for southwestern Colorado, which possesses the only reliable dry farming crop yield data in the entire Southwest. Rather, the integration of information from several different sources was necessary to extrapolate the likely production record. The sources utilized include Burns' (1983) and Van West's (1994) dendroclimatic research and the Dolores Archaeological Project's soils work (Becker and Petersen 1987; Leonhardy and Clay 1985) in southwestern Colorado, E. and T. Karlstrom's (Karlstrom 1983, 1985; Karlstrom and Karlstrom 1986; Karlstrom 1988) soil and geomorphological studies and Lebo's (1991) dendroagricultural research on nearby Black Mesa, Bradfield's (1969, 1971) Hopi farming studies, and Soil Conservation Service (SCS) soils surveys in Apache (Miller and Larsen 1975) and Coconino (Taylor 1983) counties in Arizona.

LHV crop yields were estimated by using relationships between PDSI values and maize production worked out for southwestern Colorado by Van West. In order to employ these relationships, the existing PDSI reconstruction for the LHV area (the Tsegi Canyon reconstruction produced by the Tree-Ring Laboratory's Southwest Paleoclimate Project) had to be related to one (or more) of Van West's 113 PDSI reconstructions. Because PDSI is calculated using specific water-holding attributes of the soils involved, LHV soils had to be matched as closely as possible to one (or more) possible southwestern Colorado equivalents.

The first step in matching LHV and Colorado soils involved characterizing the former so that attributes comparable to the latter might be identified. Because there are no soils data from LHV, one or more LHV soils had to be classified in order to acquire the necessary attributes. Soils research by the Black Mesa Archaeological Project identified possible analogs to one LHV soil, that of the area defined as the General Valley Floor environmental zone, hereafter referred to as LHVgensoil. This soil and several Black Mesa soils are clayey units derived principally from the Mancos shale. Furthermore, the Black Mesa soils were equated with T. Karlstrom's x and y chronostratigraphic units, which are coeval with the prehistoric LHV soils of interest here. Using these criteria, it was possible to identify six of E. Karlstrom's profiles that contained units potentially equivalent to LHVgensoil: Profiles 3, 4, and 9 (Karlstrom 1983) and 3, 4, and 5 (Karlstrom 1985) in Moenkopi Wash and Reed Valley, respectively.

Although E. Karlstrom provides considerable information on his soil units, he does not include the critical water-holding data necessary to derive PDSIs. Therefore, we had to identify analogs to his soils that had the requisite water capacity data. This was done by using SCS surveys of Apache and Coconino counties to find shale-derived soils that fell into the same typological classes as the Black Mesa soils: soil families fine, loamy, mixed mesic Typic Camborthids, Typic Haplargids, and Ustollic Haplargids. Potential analogs with adequate water capacity data included the Clovis Soil (Ustollic Haplargid) from Apache County and the Epikom Soil (Lithic Camborthid) from Coconino County. These preliminary identifications were checked against Bradfield's data for soils along Oraibi Wash that should share most characteristics with Black Mesa soils farther up the drainage. These procedures led to the recognition of E. Karlstrom's Ustollic Haplargid x/y alluvial soils from Profiles 3 and 4 (Karlstrom 1983) and 4 and 5 (Karlstrom 1985) as satisfactory analogs for LHVgensoil.

At this point, we intended to use the typological and water capacity characteristics inferred for LHVgensoil to identify one or more analogs among the 113 soils Van West used for PDSI calculations. Two problems arose in this regard. First, the Tsegi PDSI values had been calculated using NOAA's generic soil moisture values of 1" in the first six inches of soil and 5" in the rest of

the column (the 1"/5" standard). These values clearly did not mimic the 1"/10+" attributes inferred for LHVgensoil. Two options were open: (1) recalculate PDSI using more realistic water capacity values or (2) find a Colorado analog for the 1"/5" default PDSIs. Lacking resources to do the former, we opted for the latter.

Finding a Colorado analog for the default PDSIs involved identifying a soil (or soils) with attributes that mimicked those of the postulated LHVgensoil. Potential analogs had to have the following characteristics: (1) they had to duplicate the LHV soil families, (2) they had to represent the same elevational range as the floor of LHV, roughly 6,000 to 7,000 feet, (3) they had to have a comparable silt-loam-sand composition and shale derivation, and (4) they had to exhibit the default 1"/5" water capacity used in calculating the Tsegi PDSIs. We hit a snag on the first criterion because, although Van West gives the series names for the 113 soils she used, she does not give their family assignments. Luckily, the Dolores Archaeological Project provided both series and family names and allowed us to assign family designations to Van West's series names. With this information, it was a simple matter to identify soils that had the four characteristics listed above. Two soils came closest to meeting the criteria: Sharps-Pulpit Loam (R7C) and Pulpit Loam (ROHC), both fine, loamy, mixed mesic Ustollic Haplargids that occurred between 6,000 and 7,000 feet in elevation. Fortunately, Van West had chosen each of these soils to represent one of eleven soil moisture classes. The ROHC class came closest to LHVgensoil and was chosen as the Colorado analog for that taxon.

The selection of ROHC as the working analog for LHVgensoil permitted the use of PDSI to estimate annual maize crop yields in LHV. Through a series of statistical operations, Van West calculated the yield of maize in pounds per acre or kilograms per hectare for each representative soil type, including ROHC, under five different growing season conditions: Favorable, Favorable-to-Normal, Normal, Normal-to-Unfavorable, and Unfavorable. She also assigned each yield category a range of PDSI values: Favorable (PDSI 3.000), Favorable-to-Normal (1.000 to 2.999), Normal (-0.999 to 0.999), Normal-to-Unfavorable (-2.999 to -1.000), Unfavorable (-3.000). These

concordances allow crop yields to be estimated for each PDSI category. It then becomes a relatively "simple" matter to convert the Tsegi PDSI values to LHV maize crop yields.

Before conversion can begin, some way of integrating the LHV PDSI, Hydrologic Curve (HC), and Aggradation Curve (AC) representations of past environmental variability into a single measure useful for estimating crop yield had to be devised. This was necessary because during periods of rising and stable high water tables, groundwater basically supports crop production and overrides climatic fluctuations. Therefore, there are long periods when PDSI does not adequately represent environmental potential for farming. We handled this issue by generating Adjusted PDSI values that incorporate HC and AC effects on crop production. This was done by assigning arbitrary PDSI values corresponding to Favorable or Favorable-to-Normal conditions during periods of deposition and rising or stable high water tables. At other times, climate is the primary control on crop yield, and straight PDSI values express environmental input. The new series of Adjusted PDSI values reflects this operation. But, this procedure applies only to the General Valley Floor zone of LHV and not to the five other farmable environments in the valley, the North Valley Floor, Midvalley Floor, Canyon, Uplands Arable, and Sand Dunes zones (Figure 1). Because the HC and AC are different for each of the environmental zones, a set of Adjusted PDSI values was created for each of four groups of zones: (1) General Valley Floor, (2) North Valley Floor East and West and Canyons (3) Midvalley Floor East and West, (4) Shonto Plateau-Black Mesa Uplands Arable, and (5) the Sand Dunes along the northeastern margins of the Valley. Each set of Adjusted PDSI values is used for its corresponding environmental zone. The four series of Adjusted PDSI values are then converted to maize crop yields for each hectare in each zone.

The conversion takes place by equating specific crop yields in kg/hec with specific PDSI ranges as indicated in Table 1. Thus, for example, on the General Valley Floor and Midvalley Floor East, a PDSI between 1.000 and 2.999 equals a yield of 824 kg/hec of shelled corn, a PDSI greater than or equal to 3.000 equals a yield of 961 kg/hec, and so forth. This transformation applies only to General Valley Floor and Midvalley Floor East, however, because the other environmental zones have different productivities. For example, the North Valley Floor, Midvalley

Floor West, and Canyon zones produce higher yields under identical climatic, hydrologic, and aggradational conditions, while the Arable Uplands produce less. These differences are expressed by increasing the yield for the North Valley Floor-Midvalley Floor West--Canyons zones by 20 percent and decreasing the yield of the Uplands zones by 20 percent relative to the General Valley Floor yield as shown in Table 1. Thus, a PDSI between 1.000 and 2.999 equals crop yields of 988 (North Valley Floor) and 659 (Uplands) kg/hec, and a PDSI 3.000 produces yields of 1153 and 769 kg/hec, respectively. Yields for the particularly favorable dune areas in the North Valley and Midvalley Floor West zones are calculated by increasing the General Valley Floor yields by 25 percent as shown in Table 1. Here, a PDSI between 1.000 and 2.999 equals a crop yield of 1030 kg/hec, and a PDSI 3.000 equals a yield of 1201 kg/hec. Carrying these conversions of Adjusted PDSI values through for each of the environmental zones produces five series of annual crop yield estimates in kg/hec. Multiplying these by the hectarage of each zone produces estimates of total potential crop yield if every bit of land is farmed.

AGENT (HOUSEHOLD) ATTRIBUTES

The constructed physical and resource landscape of the virtual Long House Valley is the changing environment on which the agents described here act. Artificial agents representing individual households, the smallest social unit consistently definable in the archaeological record, populate the reconstructed production landscape. These household agents have independent characteristics such as age, location, and grain stocks, and shared characteristics such as death age and nutritional need. Distinctions between independent and shared characteristics are not always certain. For example, in the current model, nutritional need is the same for all agents, but in other models, nutritional need might be varied stochastically across agents. Agent demographics, nutritional requirements, and marriage characteristics were derived from ethnographic and biological anthropological studies of historic Pueblo groups and other subsistence agriculturalists throughout the world (Hassan 1981; Nelson et al. 1994; Swedlund 1994; Weiss 1973; Wood 1994).

In the archaeological view of Long House Valley, five surface rooms or one pithouse are considered to represent a single household, which, based on numerous archaeological and ethnographic analyses, is assumed to comprise five individuals. In our Artificial Anasazi model, household size is fixed at this number for all households at all times. Each simulated household is conceived to be both matrilineal and matrilocal, and so assumptions governing household formation and movement are centered on females. Males are included in maize consumption calculations.

Every year, household agents harvest the grain that is available at the location they have chosen to farm, as determined by environmental data and modified by stochastic factors. These factors are intended to grossly approximate location-to-location soil quality variation, as well as year-to-year fluctuations caused by weather, blight, and other factors not available in the data.

The agents then consume their nutritional requirements, 800 kg of maize per year, based on an approximation of individual consumption of 160 kg (560 kcal) per year. Households can store any remaining grain for later consumption, but grain that is not consumed within two years of harvest is lost.

At this point households may cease to exist, either because they do not have enough grain to satisfy their nutritional needs or because they have aged beyond a certain maximum, 30 years in the current model. Note that a household "death" is not imagined to represent the literal death of all household members. Instead, it represents that a given household no longer exists as a single unit in the valley. Members might die, but they also might be absorbed by other households or simply migrate out of the valley altogether.

Next, household agents estimate the amount of grain that will be available the following year, based on current year harvest and grain stores. If this amount will not satisfy minimum requirements for a given household, the household moves. Determining how, and thus where, a household moves is a critical factor in designing a model that has a meaningful relationship to the historical record.

First, the agent finds a new location to farm. In the current model, agents simply search for the most productive land that is available and within 1600m of a water source. Household

farmlands each occupy one cell in the model, with each cell comprising one hectare. Household residential locations, or settlements, also occupy one cell. To be considered available, land must be unfarmed and unsettled.

Second, the agent looks for a settlement location. The agent finds and settles on the location nearest the farmland that contains a water source. In the current model, if the closest water source is located in a floodplain, the agent instead occupies the closest location to the water source that is on the border of or outside of the floodplain area.

Note that the requirement that a farmland site be within 1600m of a water source is not dictated by an overriding need to farm near a water source; water sources in the context of the model provide potable water suitable for household consumption, and they are not important to agriculture. Rather, the farmland must be near water because proximity to water sources is a critical factor in choosing residence locations and because farmplots must be located within reasonable distances of residences. In fact, farm and residence siting searches are really inseparable parts of single decisions on residence and farm locations. This is one reason households are not initially assigned historical settlement locations. As historical farmland locations are not known, they cannot be supplied as initial conditions for running the model and have to be selected by the agents according to the rules of the model. To attempt to constrain farming location choice by using contextually meaningless and predetermined residence locations would be arbitrary and inconsistent.

Finally, household agents may fission. If a household is older than a specified fission age (16 years), it has a defined probability (0.125) of triggering the formation of a new household through the "marriage" of a female child. This summary value is derived from the combined demographic inputs. The use of a minimum fission age combined with fission probability is designed to approximate the probability a household would have daughters, the time it would take such daughters to reach maturity, and the chances of their finding a mate, conceiving a child, and forming a new household. As discussed for household deaths above, the fission process is not

meant to be a strict measure of new births within a household. For instance, fission might partially represent immigration, as new arrivals to the valley combine with existing households.

The above completes the specification of agent attributes. Artificial Anasazi household agents are endowed with behavioral rules governing consumption, reproduction ("fissioning"), movement, the selection of farm and residential sites, and ultimately decisions to abandon LHV, which the actual Anasazi did around 1300. Can we explain all or part of local Anasazi history — including the departure — with agents that recognize no social institutions or property rights (rules of land inheritance), or must such factors be built into the model? At present, our agents do not invoke such considerations; rather, they respond purely to environmental stimuli. These are the simplest plausible rules that we could devise. Both the strengths and weaknesses of these rules will prove revealing.

RUNNING THE MODEL

Although the LHV production landscape has been reconstructed for the period A.D. 200 to 1450, our study period runs from A.D. 800 to 1350. The initial agent configuration for each run uses the historically known number of agents but, to be consistent with the agent design, does not use historical settlement locations. Each household executes its full behavioral repertoire (e.g., moving, consuming, reproducing, storing food, and, if need be, leaving) each year. The program tracks household fissions, deaths, grain stocks, and internal demographics. If felicitous decisions are made, the household produces enough food to get through another year; if not, the household runs out of food and is removed from the simulation as a case of either death or emigration.

While a single simulation run may produce plausible and interesting outcomes, many iterations involving altered initial conditions, parameters, and random number generators must be performed in order to assess the model's robustness. Some model outputs (e.g., total population) can be characterized statistically across runs and can be compared to LHV data. Other outputs (e.g., spatial distributions of agents) are not easily characterized statistically, but can be visually compared to real world patterns.

COMPARING THE SIMULATION WITH THE ARCHAEOLOGICAL DATA

Graphical output of the model includes a map for each year of simulated household residence and field locations, which runs simultaneously with a map of the corresponding archaeological and environmental data. These paired maps facilitate comparison of historical and simulated population dynamics and residence locations. Simultaneously, "real time" histograms and time series plots illustrate annual simulated and historical population numbers, aggregation of population, location and size of residences by environmental zone, the simulated amounts of maize stored and harvested, the zonal distribution of simulated field locations, and the number of simulated households that fission, die out, or leave the valley. Figures 2 through 5 illustrate representative results for many simulations, all using the parameter values listed in Table 2. Unless otherwise indicated, the graphs represent mean values for 35 runs, a procedure that characterizes general trends across a number of iterations rather than the idiosyncracies of individual runs.

Population size curves representing iterations of the model and archaeological estimates are shown in Figure 2a and 2b, respectively, at different scales to facilitate comparison. The stepped appearance of the archaeological population graph is an artifact of the estimation procedure in which ceramic dates for sites begin and end on full, half, or quarter centuries (e.g., 1000, 1150, or 1275). Simulated population typically tracks the archaeological population trajectory; that is, both exhibit similar relative variation. If it were smoothed, the archaeological curve would even more closely resemble the simulated graph. Both show an increase up to about 900, a leveling off in the tenth century, a major growth surge between 1000 and 1050, another leveling from 1050 to 1150, a drop in the late 1100s, resurgence in the early 1200s to a peak in midcentury, and a major crash in the late 1200s. The simulated and archaeological curves also exhibit important qualitative differences including a greater and more prolonged simulated population decline in the twelfth century, a more immediate, more gradual, and relatively higher post-1150 recovery in the archaeological population, a slightly earlier thirteenth century decline in the simulated curve, and the failure of the simulated curve to drop to zero at 1300. While there is general qualitative agreement between these two

curves, there are significant quantitative disparities in the household numbers and settlement sizes. Both total population (Figure 2) and individual settlement sizes (Figure 3) are much larger in the typical simulation than what we infer to have been the actual case. Population aggregation occurs earlier and with greater frequency in the typical simulation than in the historical record (Figure 3).

Although simulated Long House Valley population aggregation (Figure 3) departs quantitatively from the archaeological situation, it is nonetheless quite revealing about settlement dynamics. The simulation's tendency to generate aggregation of greater magnitude than in the study area is evident in the large number of households distributed across settlements larger than 40 households beginning in the early 1100s. This pattern varies considerably from the real situation in which a few large sites appeared only after 1200. The peak at 1180 means that nearly 800 simulated households were living in fewer than 20 sites of 40 or more households, when during that period in the real valley there were no sites of the requisite size (200 rooms). The peak around 1260, with 600 households in fewer than 15 sites of more than 40 households, conforms more closely to archaeological reality. Although only one or two individual sites had as many as 200 rooms during the 1250-1300 period (Long House had more than 300), there were at least four *clusters* of sites each of whose total room count equaled or exceeded that number. Clearly, the simulation packs more households into single residential loci than did the real Anasazi who tended to distribute members of a residential unit across a number of discrete but spatially clustered habitation sites (Dean et al. 1978).

On a larger scale, the qualitative aspects of the aggregation graphs (Figure 3) replicate important aspects of the settlement history of Long House Valley and the surrounding region with uncanny accuracy. Fluctuations in the numbers of simulated households in the two smaller site categories (1-9 and 10-39 households) parallel one another and, together, exhibit a strong reciprocal relationship with the largest sites (40 and more households). When the simulated population is concentrated in large aggregated sites, there are few small-to-medium sized sites, and when most of the population is distributed among small-to-medium sites, there are few large sites. Thus, from 900 to 1000, the population was concentrated in large and medium sites and from 1150 to 1200 and

1260 to 1300 it was concentrated in large sites. Conversely, from 1000 to 1150 and 1200 to 1260 it was distributed among small and medium sites. These patterns of aggregation and dispersal virtually duplicate the settlement history of the eastern Kayenta Anasazi area, which includes Long House Valley (Dean 1996). During Pueblo I times (850-1000), the real population was aggregated into medium-to-large pithouse villages. Large villages disappeared abruptly after 1000, and, in the Pueblo II period (1000-1150), the population dispersed widely across the landscape, living in small-to-medium sized unit pueblos that rarely comprised more than 30 rooms. During the Transition period (1150-1250), settlements once again exhibited a tendency toward aggregation, although not nearly as strong as that produced by the simulation between 1150 and 1200. After 1150, people began moving out of upland and outlying areas and concentrating in lowland localities like Long House Valley. Although they did not yet aggregate into extremely large sites or unified clusters of sites, site size tended to be larger than that of the Pueblo II period. The magnitude of the simulated return to a dispersed small-to-medium site distribution from 1200 to 1260 also far exceeds the archaeological situation during the second half of the Transition period in which there were minor settlement adjustments toward a more dispersed pattern in the valley (Effland 1979). The simulated shift to residence in large sites between 1260 and 1300 duplicates the Tsegi phase (1250-1300) pattern of aggregation into fewer but larger sites and into organized site clusters throughout Kayenta Anasazi territory.

Eastern Kayenta Anasazi settlement shifts between 800 and 1300 are related to low and high frequency environmental fluctuations (Dean et al. 1985:Figure 1). During periods of depressed alluvial water tables and channel incision (750-925, 1130-1180, 1250-1450) populations tended to aggregate in the few localities where intensive floodplain agriculture was possible under these conditions, a process of compaction that produced large sites or site clusters. During intervals of high groundwater levels and floodplain deposition (925-1130, 1180-1250), farming was possible nearly everywhere, and people were not constrained to live in a few favored localities. In the 1000-1130 period, a combination of salubrious floodplain circumstances and unusually favorable high-frequency climatic conditions allowed the population to disperse widely across the

landscape. Given the simulation outcomes illustrated in Figure 3, it seems clear that the Artificial Anasazi Project has successfully captured the dynamic relationship between settlement aggregation-dispersal and low and high frequency environmental variability in the study area.

After 1250, the area was afflicted with simultaneous low and high frequency environmental degradations. Falling alluvial water tables, rapid arroyo cutting, the Great Drought of 1276-1299, and a breakdown in the spatial coherence of seasonal precipitation (Dean and Funkhouser 1995) combined to create the most severe subsistence crisis of the nearly 2000 years of paleoenvironmental record, an event that was accompanied by the abandonment of the entire Kayenta region. As was the case with population, simulated aggregation does not duplicate the Anasazi abandonment of the valley after 1300. Nonetheless, the behavior of artificial aggregation after 1250 is extremely instructive about the possibilities of human occupancy of the area during intervals of environmental deterioration and high population densities. The number of large settlements (more than 40 households) drops precipitously, but they do not disappear entirely. Conversely, the numbers of small and medium settlements continue unchanged through the period of greatest stress and increase noticeably after 1300. These results, coupled with paleoenvironmental evidence that the valley environment could have supported a reduced population, clearly indicate that many Anasazi could have remained in the area had they disaggregated into smaller communities dispersed into favorable habitats, especially the North Valley Floor. Thus, the model supports extant ideas that environmental factors account for only part of the exodus from the study area and that the total abandonment must be attributed to a combination of environmental and nonenvironmental causes (Dean 1966, 1969). The delicate balance between environmental "push" factors and nonenvironmental (cultural) "pull" factors suggested by the artificial Long House Valley results is compatible with long-standing, archaeologically untestable hypotheses (Dean 1966; Lipe 1995) about the real Anasazi world. The failure of this aspect of the simulation to quantitatively replicate the case study results provides valuable insights into what humans might have done in the real Long House Valley but did not.

The similarities between the simulated and real Long House Valley settlement patterns far outweigh the differences. Figure 4a-c gives side-by-side comparisons of simulated and archaeological site distributions for three years (1000, 1144, and 1261) selected to illustrate relationships between the simulated and known distributions of sites against the backdrop of increasing hydrologic potential represented by progressively darker shades of gray. Figure 4a shows the paired situations at 1000 when there was considerable hydrologic variability coupled with high corn production potential across the landscape. While the number of simulated sites far exceeds the actual numbers, the simulation accurately reflects the distribution of real sites along the periphery of the floodplain throughout the entire valley. Although crowded, the simulated distribution is what would be expected given the relatively uniform productive potentials across all farmable zones. The large simulated sites along the northeastern margin of the valley represent population aggregates held over from the Pueblo I interval (850-1000) of low alluvial water tables and floodplain erosion. Apart from these similarities, however, the model performs only moderately well for this period.

Figure 4b represents a year (1144) in which both hydrologic conditions and potential crop production varied across the landscape. The simulation mimics the spread of sites throughout the valley, particularly along the margins of the floodplain, and captures the initial shift in settlement density toward the north end of the valley that occurred during the environmental degradation of the middle twelfth century. The simulation replicates the twelfth-century clustering of settlements into five groups, one at the southwestern extremity of the valley, one in each of the Midvalley Floor localities, one at the mouth of Kin Biko on the northwestern margin of the valley floor, and one at the northeastern corner of the valley. The southwestern group is notable because the simulation accurately depicts the mix of one large, one medium, and several small sites that characterize the real group. In the northeastern corner of the valley, a real group of eight sites is matched in the simulation by two aggregated sites. In addition, the simulation reproduces the scatter of sites in the nonagricultural uplands on the western and northern sides of the valley. Finally, the simulation accurately locates settlements in the appropriate environmental zones, with the heaviest

concentrations in the Midvalley Floor and the North Valley Floor. Major differences between the simulated and real situations are the greater size and number of simulated settlements in the north-central uplands and upper Kin Biko.

Figure 4c depicts a year (1261) near the beginning of the period of severe environmental stress that began about 1250. This year was characterized by extremely high spatial differentials in hydrologic conditions and crop production potential. The model spectacularly duplicates the abandonment of the southern half of the valley as a place of residence and the concentration of the population along the northwestern edge of the floodplain near the remaining patches of productive farmland. The simulation also reproduces four of the five settlement clusters that characterized Tsegi phase settlement. An upland cluster of four sites at the northeastern end of the valley is represented in the simulation by two aggregated sites. A larger cluster of large and small sites along the northern margin of the floodplain is matched by a single very large site and a row of small to large sites. The Long House cluster at the mouth of Kin Biko is represented in the simulation by a couple of large sites. The simulated Midvalley Floor West settlement group, consisting of three aggregated and one small site, is displaced into the uplands compared to the actual cluster of nine sites, which adjoins the farmland. In three of the clusters, the simulation reproduces the site size distribution of the actual situation in which the cluster comprises one or two large pueblos and a few smaller sites. In addition, the model located a large site in exactly the same positions as the Anasazi situated Long House in the cluster at the mouth of Kin Biko and Tower House in the cluster along the northern margin of the valley. Significant discrepancies between the artificial and real site distributions are the absence of a Midvalley Floor East group from the simulation and the model's placement of too many settlements in Kin Biko.

Another aspect of the simulation reveals much about general patterns of subsistence farming in the valley, even though real-world information on the utilization of farmland for detailed testing of the simulation is unattainable. The order in which different environmental zones are exploited by the Artificial Anasazi (Figure 5) is in exact accordance with expectations of the real world (Dean et al. 1978). The simulation begins during a period of low frequency environmental

stress, and most fields are located in the zones that are productive during episodes of depressed alluvial water tables and arroyo cutting: the North Valley Floor, Kin Biko, and, to a lesser degree, the Midvalley Floor. Fields saturate the North Valley Floor and Kin Biko by 1000, and farming of these areas fluctuates only slightly thereafter. The Midvalley Floor reaches capacity by 1030. During the 800-1000 period, use of the Uplands Arable and General Valley Floor zones remains low because neither area has groundwater available to support crop production, which would have depended solely on the unreliable and generally deficient rainfall. This dependency is indicated by the high variability in farmland use on the General Valley Floor before 1000. By 1000, changes in floodplain processes that begin early in the tenth century enhance productivity in the General Valley Floor and impact the agricultural decisions made by the agents. Rising alluvial water tables and floodplain deposition provide a stable water supply for crops in the General Valley Floor and replace precipitation as the primary control on production. The result is a major "land rush" to establish fields in the newly productive General Valley Floor that begins around 980 and approaches the zone's carrying capacity within 50 years. Again as would be expected, large scale use of the Upland Arable Zone, where production is controlled primarily by rainfall, does not begin until after 1020 when all the other zones have achieved virtual saturation. The salubrious agricultural conditions that began around 1000 supported the huge population growth and settlement expansions of the 1000-1120 period in both the artificial and real Long House Valleys.

After about 1030, Figure 5 reflects varying use of different farming environments by a population of agents that approaches the carrying capacity of the simulated area. The North Valley Floor, General Valley Floor, Midvalley Floor, and Kin Biko were fully occupied by fields, and because crop production was controlled by stable floodplain conditions, use of these areas exhibits minimal variability. In contrast, field use in the Upland zone varies considerably because production there depends on precipitation rather than hydrologic conditions. Fields in both the General Valley Floor and Upland zones are severely reduced by the secondary fluvial degradation and drought of the middle twelfth century. The greater sensitivity of the Upland farms to environmental perturbations is indicated by the facts that farming in these areas begins to decline

before that on the General Valley Floor and that Upland farmland is abandoned during the depth of the crisis. Upward blips in Midvalley Floor and North Valley Floor field numbers reflect the establishment of fields in these more productive areas by a small number of agents forced out of the General Valley Floor and Uplands. Displaced agents that cannot be accommodated in the favorable areas are removed from the simulation (through death or emigration), which accounts for the decline in simulated population during this interval (Figure 2a). When favorable groundwater conditions return, more fields are once again established in the General Valley Floor and Uplands. Once again, the inferior quality of Upland farmland is indicated by the fact that it was not reoccupied until all other zones had been filled to capacity. The Uplands' continued sensitivity to environmental variation is shown by the fluctuations in use between 1190 and 1230 and its abandonment well before the effects of the next environmental degradation are felt in the other zones.

The major low and high frequency environmental crisis of the last half of the thirteenth century has major repercussions for Artificial Anasazi field selection. Groundwater depletion and arroyo cutting virtually destroy the farming potential of the General Valley Floor and make production there totally dependent on precipitation, which itself is depressed by the Great Drought of 1279-1299. Upland fields are abandoned by 1240, the number of fields on the Midvalley Floor decreases after 1270, and the General Valley Floor is virtually abandoned as a farming area by 1280. Only the North Valley Floor and Kin Biko, where local topographic and depositional factors mitigate the effects of fluvial degradation, retain their farming potential. These areas, already completely filled, remain fully utilized but lack the capacity to absorb agents displaced from the General Valley Floor, Midvalley Floor, and Uplands zones. The disappearance of these agents from the simulation accounts for the major population decline of this period (Figure 2a). Unlike the real Anasazi, simulated agents continue to locate fields in Long House Valley after 1300 but under vastly altered environmental conditions. Far fewer fields are located on the General Valley Floor and, as shown by the rapid fluctuations after 1270, this area is far less productive and far more vulnerable to high frequency productivity fluctuations caused by the greater control exercised by

precipitation. The North Valley Floor continues to be highly productive but, even there after about 1280, high frequency climatic variability becomes a more important factor in productivity. The decline in field locations on the North Valley Floor after 1320 is due to the depopulation of the virtual valley; for the first time in about 200 years, the population of agents falls below what can be supported on the landscape.

As was the case with simulated population (Figure 2a) and aggregation (Figure 3), the simulated distribution of farmland clearly shows that the Anasazi need not have totally abandoned Long House Valley as a result of environmental deterioration comparable to that presently built into the model. Instead, a substantial fraction of the population could have stayed behind in small settlements dispersed across suitable farming habitats located in areas (primarily in the North Valley Floor zone) still suitable for agriculture given the detrimental environmental conditions of the post-1250 period. The fact that in the real Long House Valley, that fraction of the population chose *not* to stay behind but to participate in the exodus from the area, supports the assertion that sociocultural "pull" factors were drawing them away from their homeland.

All runs described above use the parameter estimates of Table 2. These were deemed the most plausible values. But they are not the only possibilities. In research to be presented elsewhere, these values are systematically varied over a range in which the Table 2 values are intermediate. It is striking that over that entire range of plausible environments — including some severely degraded ones — we have not observed the complete abandonment of the real Long House Valley that occurred after A.D. 1300. This outcome strongly reinforces the idea that the valley could have supported a reduced, but still viable, population. Thus, the comparison of the results of the simulation with the real world helps differentiate external (environmental) from internal (cultural) causation in cultural variation and change and even provides a clue, in the form of the proportion of the population that could have stayed but elected to go, as to the relative magnitude of these factors. This finding highlights the utility of agent-based modeling in archaeology by demonstrating a predicted response (Dean 1966) that never could be tested with archaeological data. Because the purely environmental rules explored thus far do not fully account

for the Anasazi's disappearance from LHV, it could be argued that predominantly nonenvironmental sociological and ideological factors were responsible for the complete abandonment of an area still capable of supporting a substantial population.

CONCLUSIONS

How has agent-based modeling improved understanding of culture change in Anasazi country? First, it allows us to test hypotheses about the past for which we have only indirect evidence. For example, the simulations support predictions about the use of different kinds of farmland under different low and high frequency environmental conditions. Second, it illuminates the relative importance of and interactions among various demographic and environmental factors in the processes of sociocultural stability, variation, and change. Third, the generation of similar macroscale results from different microscale specifications elucidates the role of equifinality in sociocultural processes and archaeological analysis. Fourth, progressively augmenting agent specifications allows the experimental manipulation of behavioral modes and assessment of their incremental effects on agent responses to environmental variability.

Finally, agent-based modeling encourages the consideration of previously unspecified, ignored, or discounted factors as consequential mechanisms of cultural adaptation and change. In this regard, Steven Jay Gould (1989) among others has emphasized that a problem with historical sciences — such as astronomy, geology, paleontology, and archaeology — is that we cannot rewind and rerun the tape of history. While this may be literally true, with agent-based modeling, we can execute numerous simulations to investigate alternative outcomes of sociocultural processes under different initial conditions and operational procedures. We can systematically alter the quantitative parameters of a model or make qualitative changes that introduce completely new, and even unlikely, elements into the artificial world of the simulation. Thus, in terms of the Artificial Anasazi model, we could change agent attributes, such as fecundity or food consumption, or introduce new elements, such as mobile raiders, environmental catastrophes, or epidemics.

Ultimately, "to explain" the settlement and farming dynamics of Anasazi society in Long House Valley is to identify rules of agent behavior that account for those dynamics, that generate the target spatiotemporal history. Agent-based models are laboratories where competing explanations — hypotheses about Anasazi behavior — can be tested and judged in a disciplined empirical way. The simple agents posited here explain important aspects of Anasazi history while leaving other important aspects unaccounted for. Our future research will attempt to extend and improve the modeling, and we invite colleagues to posit alternative rules, suggest different system parameters, or recommend operational improvements. Agent-based models may never fully explain the real history — these, after all, are simple instruments — but they enable us to make scientific progress in a replicable, cumulative way that does not seem possible with other modeling techniques or through narrative methods alone, as crucial as these are in formulating the principles, hypotheses, and experiments that can carry us forward.

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FIGURE CAPTIONS

Figure 1. Long House Valley, northeastern Arizona, showing the seven potential production zones.

Figure 2. Simulated population (**a**) compared to archaeologically estimated population (**b**) in numbers of households through time, A.D. 800 to 1360. Numbers of households are graphed at different scales to allow easier comparison of time series.

Figure 3. Simulated household aggregation represented by the number of households grouped into settlements of 1-9 rooms, 10-39 rooms, and more than 40 rooms.

Figure 4. Digitized maps of Long House Valley showing simulated site size and spatial distributions at three selected years: **a.** A.D. 1000, **b.** A.D.1144, **c.** A.D. 1261. Sites are represented by circles; the darker the circle, the greater the number of households in the settlement.

Figure 5. Distribution of simulated Artificial Anasazi farms among five arable environmental zones expressed as the number of hectares under cultivation in each zone from A.D. 800 to 1360.