Colloquium

Population growth and collapse in a multiagent model of the Kayenta Anasazi in Long House Valley

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Long House Valley in the Black Mesa area of northeastern Arizona (U.S.) was inhabited by the Kayenta Anasazi from about 1800 before Christ to about *anno Domini* 1300. These people were prehistoric ancestors of the modern Pueblo cultures of the Colorado Plateau. Paleoenvironmental research based on alluvial geomorphology, palynology, and dendroclimatology permits accurate quantitative reconstruction of annual fluctuations in potential agricultural production (kg of maize per hectare). The archaeological record of Anasazi farming groups from *anno Domini* 200-1300 provides information on a millennium of sociocultural stasis, variability, change, and adaptation. We report on a multiagent computational model of this society that closely reproduces the main features of its actual history, including population ebb and flow, changing spatial settlement patterns, and eventual rapid decline. The agents in the model are monoagriculturalists, who decide both where to situate their fields as well as the location of their settlements. Nutritional needs constrain fertility. Agent heterogeneity, difficult to model mathematically, is demonstrated to be crucial to the high fidelity of the model.

As the only social science that has access to data of sufficient duration to reveal long-term changes in patterned human behavior, archaeology traditionally has been concerned with describing and explaining how societies adapt and evolve in response to changing conditions. A major impediment to rigorous investigation in archaeology—the inability to conduct reproducible experiments—is one shared with certain other sciences, such as astronomy, geophysics, and paleontology. Computational modeling is providing a way around these difficulties.[k]

Within anthropology and archaeology there has been a rapidly growing interest in so-called agent-based computational models (4–6). Such models consist of populations of artificial, autonomous "agents" who live on spatial landscapes (8). Each agent is an indivisible social unit—an individual, a household, a clan—endowed with specific attributes (e.g., life span, nutritional requirements, movement capabilities, family ties). A set of anthropologically plausible rules of behavior defines the ways in which agents interact with their physical environment and with one another. Social histories unfold in such models by "turning on" each agent periodically and permitting it to interact. Agent models offer intriguing possibilities for overcoming the experimental limitations of archaeology through systematic analyses of alternative histories. Changing the agents' attributes, their rules, and features of the landscape yields alternative behavioral responses to initial conditions, social relationships, and environmental forcing.

Long House Valley, a topographically discrete, 96-km^2 land form (Fig. 1) on the Navajo Indian Reservation in northeastern Arizona (8), provides a realistic archaeological test of the ability of agent-based computational models to explain settlement patterns and demographic behavior among subsistence-level agricultural societies in marginal habitats. Between roughly 7000 and 1000 years before Christ (B.C.), the valley was sparsely occupied, first by Paleo-Indian big game hunters and second by Archaic hunters and gatherers. The introduction of maize around 1800 B.C. initiated a long transition to a food producing economy and began the Anasazi cultural tradition (7), which persisted until the abandonment of the region around *anno Domini* (A.D.) 1300 (9). Anasazi is the term applied to a distinctive archaeological pattern and sequence that is confined to the southern Colorado Plateau and that has given rise to the cultural configurations that characterize the modern Pueblo people of the Southwest. The Anasazi pattern is defined by an emphasis on black-on-white painted ceramics, plain and textured gray cooking pottery, the development from pithouses to stone masonry and adobe pueblos, and the kiva as the principal ceremonial structure. Considerable spatial variability within the general pattern has led to the recognition of several geographic variants of Anasazi. Long House Valley falls within one of the western Anasazi configurations.

Long House Valley is well suited for application of multiagent modeling for a variety of reasons (10). Its bounded topography combined with the rich paleoenvironmental record permits the creation in the computer of a dynamic resource landscape that accurately replicates actual conditions in the valley from A.D. 200 to 1500. Low- and high-frequency variations in alluvial hydrologic and depositional conditions, effective moisture, and climate have been reconstructed in unprecedented detail with dendroclimatology, surficial geomorphology, palynology, and archaeology (11–12). High-frequency climatic variability is represented by annual June Palmer Drought Severity Indices (PDSI), which reflect the effects of meteorological drought (moisture and temperature) on crop production (13). Low-frequency environmental variability is characterized primarily by

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Abbreviation: A.D., *anno Domini*.

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[k]For example, because large-scale experiments on the Earth's tectonic structure (e.g., mantle and core) are impossible, numerical models play a crucial role in geophysics (1). An essentially identical situation exists in planetology, where progress on the origin of the moon, for instance, is achieved numerically (2). Computational models are increasingly common in paleontology (3).

Fig. 1. Long House Valley, looking to the South.

the rise and fall of alluvial groundwater and the deposition and erosion of flood plain sediments. Based on statistical relationships between PDSI and annual crop yields in southwestern Colorado provided by Van West (14), 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. 400-1400. Intensive archaeological research provides a database on human settlement in the valley (8, 15).[l] Finally, detailed regional ethnographies provide an empirical basis for generating plausible behavioral rules for the agents (17–19).

The multiagent model is created by instantiating the landscape, reconstructed from paleoenvironmental variables, and then populating it with artificial agents that represent individual families, or households, the smallest social unit consistently definable in the archaeological record (20, 21).[m] Each household agent is initialized based on demographic characteristics and nutritional requirements derived from ethnographic studies of historic Pueblo groups and from other subsistence agriculturists.[n] Each family agent is defined by certain attributes (Table 1), including its age, size, composition, and amount of maize storage. Similarly, each agent has specific rules of behavior (Table 2). These rules determine how the households select their planting and dwelling locations.

Once all agents are initialized, the model proceeds according to internal clocks (Table 3). Essentially, all agents engage in agricultural activity during each period (1 calendar year) and move their plots or dwellings or both based on their success in meeting nutritional needs. Simulated household and field locations, as well as the size of each community (the number of households at each site), are updated annually. A map of annual simulated field locations and household residence locations and sizes runs simultaneously with a map of the actual archaeological and environmental data so that the real and simulated population dynamics and residence locations can be visually compared. Time series plots and histograms illustrate annual simulated and actual population numbers, aggregation of population, location and size of residences by environmental zone, the simulated

Table 1. Household (agent) attributes

1. Five surface rooms or one pithouse is considered to represent a single household.
2. Each household that is both matrilineal and matrilocal consists of 5 individuals. Only female marriage and residence location are tracked, although males are included in maize-consumption calculations.
3. Each household consumes 160 kg of maize per year per individual.
4. Each household can store a maximum of 2 years' total corn consumption (1,600 kg), i.e., if at harvest 800 kg of corn remains in storage and additional 800 kg can be added to that from the current crop.
5. Households use only 64% of the total potential maize yield. (The unutilized production is attributed to fallow, loss to rodents, insects, and mildew, and seed for the next planting.)

[l]The archaeological survey data were generated by the Long House Valley Project, a joint venture of the Museum of Northern Arizona and the Laboratory of Tree-Ring Research at the University of Arizona (8). The availability of the Long House Valley data in the Southwestern Anthropological Research Group (16) automated database greatly facilitated the development of the model.

[m]The model is written in JAVA and utilizes the ASCAPE framework (see the article by Inchosa and Parker, this issue of PNAS). It is available at www.brookings.edu/dynamics/models.

[n]Although our agents' nutritional requirements are denominated in terms of corn production and set to reflect the average human requirements for calories (22), we do not infer that the Anasazi met all their caloric requirements with corn. We know that they had a diverse diet, including cultivated corn, squash, and beans, and a host of wild plants and animals, and that an exclusive corn diet could lead to several nutritional problems. For modeling purposes, however, we can subsume these resources and their distribution under a simplified resource space and single proxy (corn) for the agents' nutritional requirements.

Table 2. Household (agent) rules

1. A household fissions when a daughter reaches the age of 15.
2. A household moves when the amount of grain in storage in April plus the current year's expected yield (based on last year's harvest total) falls below the amount necessary to sustain the household through the coming year.
   A. Identification of agricultural location:
      The location must be currently unfarmed and uninhabited.
      The location must have potential maize production sufficient for a minimum harvest of 160 kg per person per year (22). Future maize production is estimated from that of neighboring sites.
      If multiple sites satisfy these criteria the location closest to the current residence is selected.
      If no site meets the criteria the household leaves the valley.
   B. Identification of a residential location:
      i. The residence must be within 1 km of the agricultural plot.
      ii. The residential location must be unfarmed (although it may be inhabited, i.e., multihousehold sites permitted).
      iii. The residence must be in a less productive zone than the agricultural land identified in A.
      If multiple sites satisfy these above criteria the location closest to the water resources is selected.
      If no site meets these criteria they are relaxed in order of iii then i.

amounts of maize stored and harvested, and the number of households that fission, die out, or leave the valley.

In previous work (10) we characterized the performance of this model with respect to a "base case" parameterization (Table 4). Although closely reproducing the qualitative features of the history of demographic changes and settlement patterns in Long House Valley, that model yielded populations that were substantially too large. All attempts to reduce the population in that model by changing agent parameters resulted in premature population collapse.

We modified this earlier model (10) to incorporate greater levels of both agent and landscape heterogeneity. In the previous model all agents had the same ages for the onset of fertility and death. Here, each agent gets a specific value for these ages when it is born, based on sampling from a uniform distribution. A similar procedure was applied to the household fission rate. These changes introduce six adjustable parameters, namely the endpoints of these uniform distributions. For the production landscape**,** we treated two parameters as variable, the average harvest per hectare and the variance in this harvest.[o]

A systematic search of this eight-dimensional space of parameters yields values that generate model realizations having total populations closest to the historical data, according to several criteria. At each period of the model we compare the number of

[o]In the earlier version of the model, all agent heterogeneity was a consequence of local environmental variations.

Table 3. Model timing—household "clocks"

Each household has two internal clocks.

1. One clock tracks the number of years a household is in existence and determines when it fissions and dies. A household fissions when a daughter marries at age 16 to form a new household. Birth spacing is at least 2 years. A household dies once it reaches its death age, a parameter drawn randomly from a uniform distribution according to model parameters.
2. A second clock runs from April to April and reduces the amount of maize in storage by 13.33 kg of maize per month per individual in the household.

Table 4. Base case parameterization of the model

Parameter	Value
Random seed	Varies
Year at model start	A.D. 800
Year at model termination	A.D. 1350
Nutritional need per individual	800 kg
Maximum length of grain storage	2 years
Harvest adjustment	1.00
Annual variance in harvest	0.10
Spatial variance in harvest	0.10
Household fission age	16 years
Household death age	30 years
Fertility (annual probability of fission)	0.125
Grain store given to new household	0.33
Maximum farm to residence distance	1,600 m
Initial corn stocks, minimum	2,000 kg
Initial corn stocks, maximum	2,400 kg
Initial household age, minimum	0 years
Initial household age, maximum	29 years

simulated households at time t, X_t^s, to the historical record, X_t^h. The differences between these two values are cumulated according to an L^p norm, with $p \in \{1, 2, \infty\}$ (23). Optimizing the model with respect to the eight adjustable parameters yields distinct "best" configurations, based on which norm was used in the simulation. The search was conducted for the best realizations as well as the best average set of runs.[p] The optimal parameter settings are summarized in Tables 5 and 6 with typical output shown in Figs. 2 and 3.

Simulated population levels closely follow the historical trajectory (Fig. 2). In the first 200 years the model understates the historical population, whereas the peak population just after A.D. 1100 is somewhat too high in the model. The historical clustering of settlements along the valley zonal boundaries is nicely reproduced in the model (Fig. 3). Although the ability of the model to predict the actual location of settlements varies from year to year, with Fig. 3 being typical, the progressive movement of the population northward over time, clear in the historical data, is also reproduced in the model.

Long House Valley was abandoned after A.D. 1300, as shown in Fig. 2. The agent model suggests that even the degraded environment of the 1270–1450 period could have supported a reduced but substantial population in small settlements dis-

[p]The model incorporates significant stochasticity, as is typical of agent models generally. Both agent initialization and aspects of agent behavior have stochastic components, therefore distinct runs of the model with different seeds to the random number generator yield distinct histories. For multiple runs of a fixed model, varying only the seeds, a "typical" run is constructed by averaging the realized populations in each period. The resulting typical run is likely never to be encountered in practice, and in some circumstances may not even be feasible, but is useful nonetheless as an idealization.

Table 5. Optimized parameter settings based on single "runs" of the model

Parameter/norm	L^1	L^2	L^∞
Minimum death age	26	30	25
Maximum death age	32	39	34
Minimum age, end of fertility	30	28	30
Maximum age, end of fertility	32	30	30
Minimum fission probability	0.125	0.120	0.125
Maximum fission probability	0.129	0.125	0.125
Average harvest	0.60	0.62	0.60
Harvest variance	0.41	0.40	0.40

Table 6. Optimized parameter settings based on the average over 15 runs of the model

Parameter/norm	L^1, L	L^2
Minimum death age	30	25
Maximum death age	36	38
Minimum age, end of fertility	30	30
Maximum age, end of fertility	32	38
Minimum fission probability	0.125	0.125
Maximum fission probability	0.125	0.125
Average harvest	0.6	0.6
Harvest variance	0.4	0.4

persed across suitable farming habitats located primarily in areas of high potential crop production in the northern part of the valley. The fact that in the real world of Long House Valley, the supportable population chose not to stay behind but to participate in the exodus from the valley indicates the magnitude of sociocultural "push" or "pull" factors that induced them to move (20).[q] Thus, comparing the model results with the actual history helps differentiate external (environmental) from internal (social) determinants of cultural dynamics. It also provides a clue—in the form of the population that could have stayed but elected to go—to the relative magnitude of those determinants.

Discussion

As noted, in these initial inquiries our models include only the most basic environmental and demographic specification, permitting calibration with a minimum number of parameters. Introducing more agent and physical heterogeneity, quite accurate results have been obtained. Richer treatments of household characteristics are possible. For example, in calculating mean household values for size, fissioning, and "death," we have envisioned disaggregating the households into individuals of varying ages in the life course.[r] Similarly, the average caloric values used can be adjusted for age of individuals within the household. Nonuniform distributions can be explored. It is, however, interesting that even without implementing these refinements, the output from the current model closely reproduces the record of the archaeological survey.

[q]Dean, J. S., 31st Annual Meeting of the Soc. Am. Archaeol., May 5–7, 1966, Reno, NV.

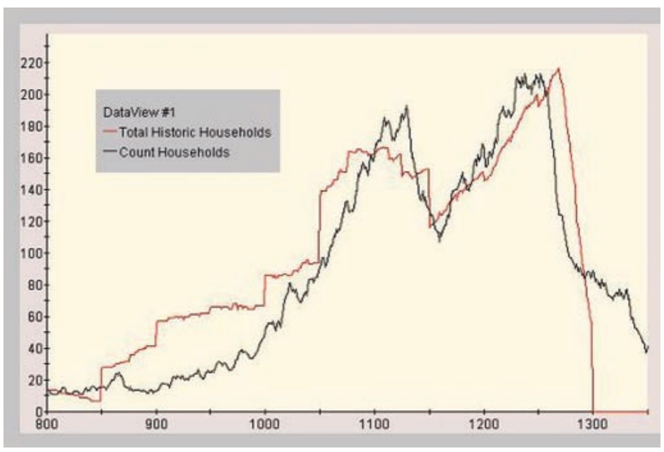

Fig. 2. Best single run of the model according to the L^1 norm. Other best runs based on other norms yield very similar trajectories. The average run, produced by averaging over 15 distinct runs, looks quite similar to this one as well.

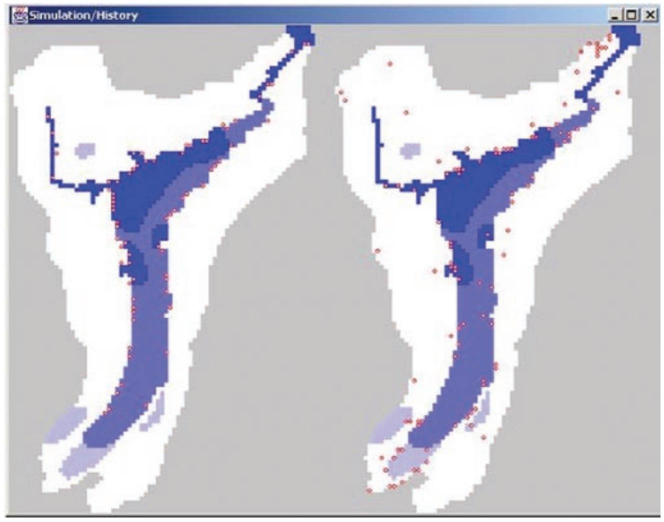

Fig. 3. Simulated and historical settlement patterns, in red, for Long House Valley in A.D. 1125; North is to the top of the page.

Issues remain regarding the interpretation of our findings that some inhabitants of Long House Valley could have remained after the archaeologically determined date of abandonment. The fact that environmental conditions may not have been sufficient to drive out the entire population suggests that additional push or pull factors impelled the complete abandonment of the valley after 1300. Another possibility that can be modeled in future simulations might be a combination of environmental, demographic, and epidemiological factors. That is, synergistic interactions between nutritional stress and precolonial epidemic disease might have decimated the population beyond what our model indicates. In addition, the depressed population may simply have been insufficient to maintain cultural institutions, precipitating a collective decision to leave the valley (26). These are ripe topics for future research.

Conclusions

Our model closely reproduces important spatial and demographic features of the Anasazi in Long House Valley from about A.D. 800 to 1300. To "explain" an observed spatiotemporal history is to specify agents that generate—or grow—this history. By this criterion, our strictly environmental account of the evolution of this society during this period goes a long way toward *explaining* this history.

[r]Using reasonable estimations based on model life tables (24) and fertility schedules (25) for horticultural subsistence populations would create a reasonable set of propensities, or probabilities, that can be used in future simulations.

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