Chapter 2
Modeling Archaeology: Origins of the Artificial Anasazi Project and Beyond

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2.1 Introduction

In 1994 the relatively young Santa Fe Institute (SFI) was moving to its new campus complex at the edge of the city of Santa Fe, New Mexico, USA. Researchers interested in the science of complexity were anxious to participate in this exciting new enterprise. A core resident faculty was being established, while at the same time numerous visiting scholars were invited to present new research and participate, for various lengths of time, in shaping SFI's identity and future trajectory. Within a year's time an important collaboration formed, somewhat by accident, which was to become known as the Artificial Anasazi Project.

Joshua Epstein and Robert Axtell, then of the Brookings Institution in Washington, DC, had come to present their agent-based modeling approach which they called "Sugarscape" (e.g. Epstein and Axtell 1996). In the course of their presentations they mentioned that they were interested in "real-world" applications of the model that could address questions about human behavior. In the audience happened to be George J. Gumerman, a southwestern archaeologist involved with SFI and its emerging program in cultural complexity. Gumerman, along with Jeffrey Dean and colleagues at the University of Arizona, had been collecting detailed

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environmental and archaeological data in the Kayenta Region of northeastern Arizona since the 1970s. They had constructed a huge database of high-quality environmental data as well as extensive information on temporal changes in climate and human habitation of the Long House Valley and other sites in the region. Although maize cultivation spread throughout the American Southwest over several centuries BC, the ancestral Pueblo Indians living in the sites of the Kayenta Region actively adopted agriculture commencing around AD 200. During the period of occupation between approximately AD 800 and AD 1300 the population grew significantly and then collapsed, and the region was abandoned between AD 1275 and AD 1300.

Axtell and Epstein had a powerful agent-based model, ready to be tested. Gumerman, Dean, and colleagues had an extraordinary dataset with a long timeline on which to test it. A research team was formed on the spot, and by 1996 preliminary runs were underway, with limited and often unsatisfying results. Steve McCarroll and Miles Parker were brought on as modeling assistants to Epstein and Axtell, and Alan Swedlund was invited to participate to provide demographic parameters that would be necessary to reflect human population dynamics. The intention was to compare the known settlement and population growth history of the Anasazi with the results generated using Ascape, an extension of the Sugarscape software. In Ascape agents occupy, grow, and populate a representational space designed to address specific research questions of interest. Resources (e.g. food, water, habitation sites, etc.) are distributed in the simulated space and that distribution can change over time if desired. Agents are given decision-making properties that allow them to move, garner resources, and interact with one another. Agents can also grow in numbers over time, necessitating movement as occupied areas become packed and food and other resources become scarce.

The space used in the Artificial Anasazi model is based on detailed paleoenvironmental, climatological, and archaeological data from the Long House Valley in northeastern Arizona.[1] Figure 2.1 shows the time series of several of these types of data. The data were used to design 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 valley (see Fig. 2.2a–c). 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. Historical settlements indicated in the archaeological record are also placed on the model landscape at their known locations within the valley (Fig. 2.2c).

For the initial Artificial Anasazi model it was decided that agents would be households instead of individuals, and households would be capable of clustering in areas where conditions permitted. Households would form much as human families do, averaging 5 individuals including male and female parents, and children of

[1]Although the environmental data are exceptionally fine-grained and detailed, they and the Artificial Anasazi model are not set within a continuous GIS spatial framework.

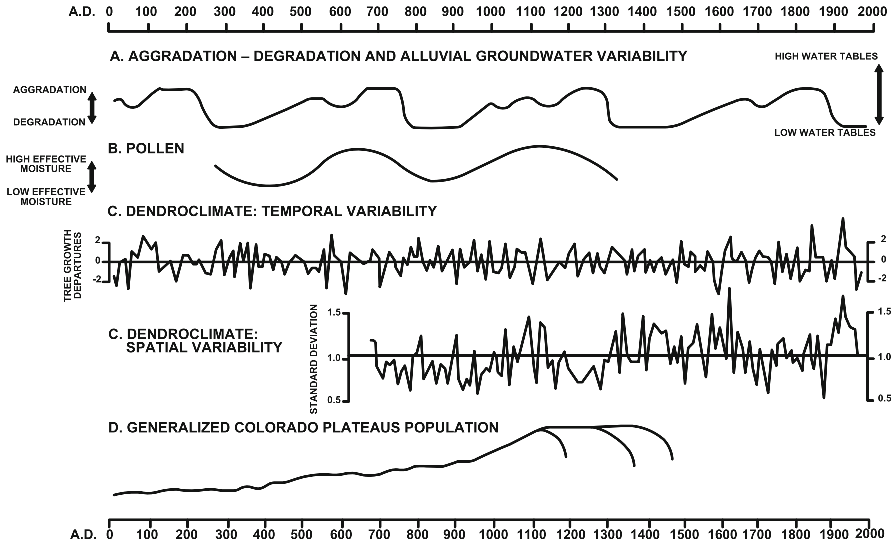

Fig. 2.1 Data used in the Artificial Anasazi model

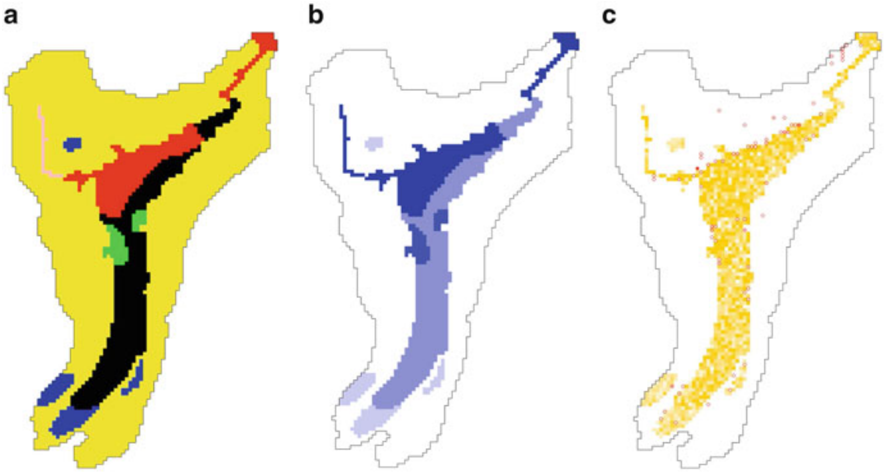

Fig. 2.2 (**a**) Environmental zones. (**b**) Hydrology. (**c**) Plot yields and historic settlements

varying age, although the activities of individual household members were not explicitly modeled. Each agent (household) was endowed with various attributes (e.g., life span, movement capabilities, nutritional requirements, consumption and storage capacities) in order to replicate important features of human households practicing horticulture. The limits, or rules, with which agents interacted with the environment, and with each other, were based on ethnographic reality and anthropological plausibility.

Agent (household) demographic patterns, subsistence, and movement behaviors were carefully built from the "bottom up." That is, deterministic mathematical models of growth or consumption were avoided and mortality, fertility, and consumption needs were based on a two-sex model of individuals of specific age. These were then summarized into households. In the model, the agents go through their life cycles on the empirically based landscape, adapting to changes in their physical environments. The agent-based simulations are then compared to the archaeological estimates generated empirically, and independently, by research archaeologists.

2.2 Structure of the Artificial Anasazi (AA) Model

The original Ascape implementation of the Artificial Anasazi (AA) model contains a number of versions designed for different purposes, in some cases for testing or batch runs and in other cases for experimentation with other types of model structures. We focus our initial discussion on the original AA model as described in Dean et al. (1998, 2000), Axtell et al. (2002), and Janssen (2009). Current efforts, described below, center on a version we call Artificial Long House Valley (ALHV). These two models differ in the basic demographic framework they use. The original AA model focuses on and depends solely on household-level information. "Births" relate to the origination of a new household, "deaths" refer to dissolution of an existing household through either death or abandonment. The ALHV model uses an individual-level framework, with each household's resident individuals considered explicitly.

The general structure of the AA model is shown in Fig. 2.3. The setup of the model is complicated and requires input of the detailed paleoenvironmental and historical data, construction of the valley, and construction and placement of households, settlements, and farm plots at appropriate locations in the valley, as well as determination of the initial harvest amounts available to each household.

Once the setup is complete, the model cycles through a series of steps that occur once a year for each household (Fig. 2.3). The first step is to determine whether each household has enough food available to satisfy its present needs. If there is enough food and the household is below a user-specified death age, then the amount of harvest resources available for the present year are estimated and added to the household's stores (assumed to last for 2 years). If food supplies are insufficient, the household has reached the specified maximum household age, or both, the household is abandoned and removed from the space. Following this series of decisions, households determine whether they have enough food for the coming year. If they do and they are within the user-specified fertility period, they can produce a new household through fissioning.[2] If a household does not have

[2]Note: although within the model this is specified through the naming of variables as reproduction, it is reproduction at the household, not individual level.

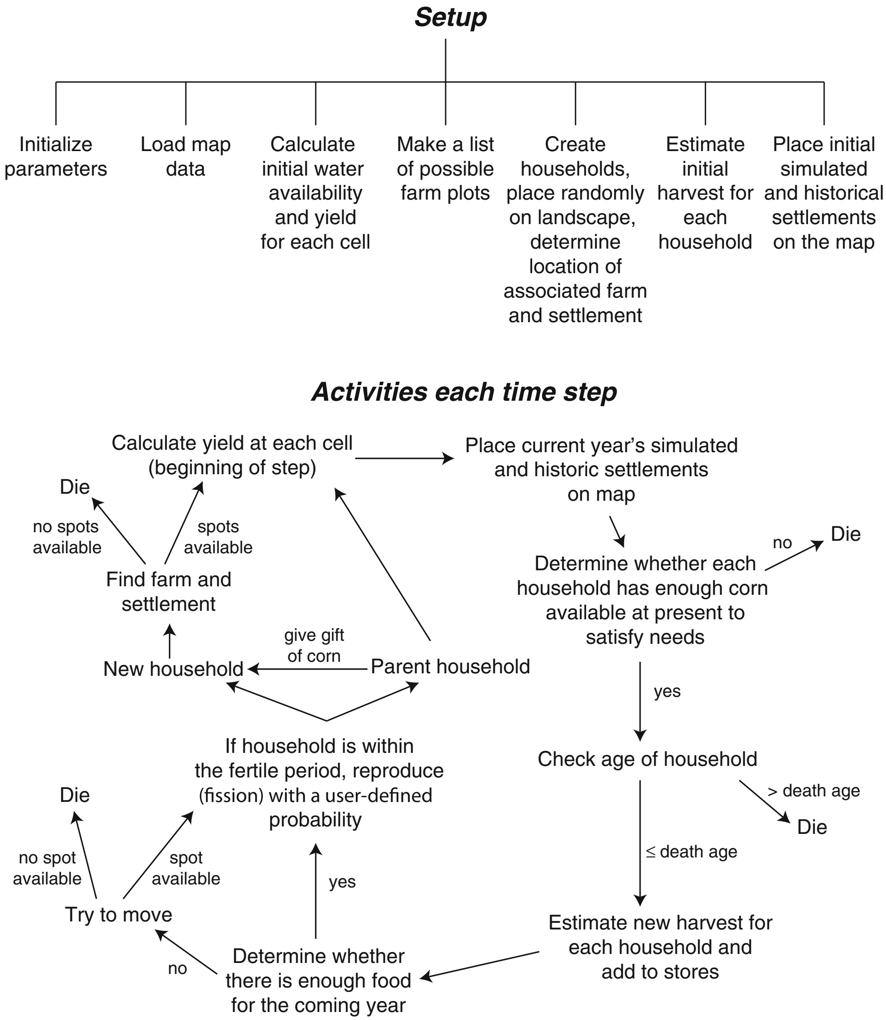

Fig. 2.3 The original Artificial Anasazi (AA) model

enough food in its stores for the coming year, it tries to move to a new location. This process involves a hierarchical series of decisions based on the distance from farm plots and water sources and the suitability of particular locations for the household. If a household is successful in finding a new location, it moves there and assesses whether fission is possible. If a location cannot be found, the household is abandoned and removed from the space. New households that originate after fissioning proceed through a process similar to the movement process of existing households to find suitable locations for their household and farm.

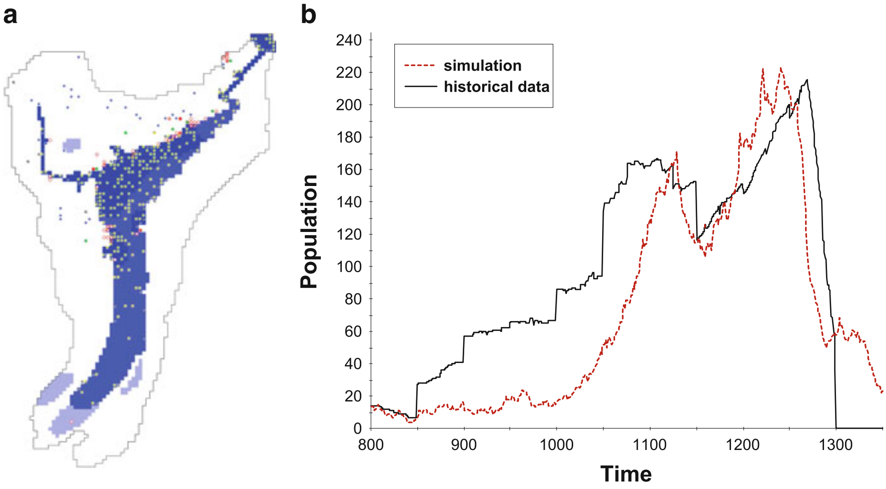

Fig. 2.4 Simulated (**a**) settlement distribution and (**b**) population vs. historical data, AA model

Once all households have completed the entire series of steps, the yield at each step is calculated and the cycle begins again. The simulation begins at AD 800 and runs yearly until AD 1350.

Summaries of outcomes of AA model simulations are given in Dean et al. (2000) and Axtell et al. (2002) (see also Janssen 2009). The earliest runs of the model often had the simulated population overshooting the archaeologically estimated population to a considerable degree, until it reached an apparent carrying capacity (e.g. see Dean et al. 2000, p.190–191; also Janssen 2009). Figure 2.4 provides an example of a simulation run that "fits" the historical data reasonably well. Analyses of the AA model indicate that simulation outcomes are quite variable and are also highly sensitive to the values chosen for the harvest variables (see also Janssen 2009). However, it is not yet clear whether the optimal values reflect more accurate estimates of real harvest potential than is possible using the unadjusted paleoclimatic data input into the model, or whether they are simply a result of adjustments to produce better curve fitting. This assessment requires careful attention to assumptions about how the variables are incorporated into the model as well as more extensive sensitivity analyses of how variation in their values influences model outcomes.

2.3 Selected Socio-Ecological Models Similar to Artificial Anasazi

Prior to the development of Artificial Anasazi, several efforts were aimed at simulating social change in the southwestern United States (Cordell 1972, Dove 1984 for example) but many of these models applied a top-down approach to simulation and hard-coded variables and interaction rules (Gumerman and Kohler 1996). Around the time the Artificial Anasazi research team was coming together, other agent-based models aimed at exploring social and ecological interactions with a bottom-up approach were also in development. Table 2.1 provides a description of several of the major archaeological agent-based models that have been developed. In this section we discuss a selection of those models that most closely relate in purpose and general structure to the Artificial Anasazi model.

The Evolution of Organized Society (EOS) model generated group-level behaviors such as information exchange, group decision-making, and the emergence of hierarchical social structures among foragers in Upper Paleolithic France by modeling the environment and resource-gathering behaviors (Doran et al. 1994). Another model, MAGICAL (Multi-Agent Geographically Informed Computer AnaLysis) (Lake 2000), was developed by combining geographic information systems software with multi-agent simulations to explore possible explanations for the distribution of flint artifacts in the Southern Hebrides. The incorporation of detailed GIS data into this model reinforced a trend in agent-based modeling toward the inclusion of high quality environmental data in models focused on socio-ecological changes.

Just as Artificial Anasazi was influenced by other simulations of social-ecological processes in the Southwest and in other areas, the success of Artificial Anasazi and similar models provided further support for the suitability of agent-based models for exploring changing human-environment interactions in a given geographic space and encouraged the continued development of other models. Most notable among these modeling efforts are the models developed by Kohler and colleagues that comprise the Village Ecodynamics Project (VEP), which commenced development around the same time as Artificial Anasazi and also came out of work being done at the Santa Fe Institute. The goals of this project include exploring the co-evolution of society and environment by accurately recreating the landscape, understanding the factors that contribute to complicated behaviors on this landscape, and developing an understanding of the factors that may have driven village aggregation, growth, and depopulation in southwestern Colorado between AD 600 and AD 1300 (see Kohler et al. 2007, 2012). Much like Artificial Anasazi, the VEP model generates maize production data based on climate, soil quality, and plots farmed, but it also incorporates over-farming as a factor (Kohler et al. 2007). In addition to the maize-related factors that largely drive the Artificial Anasazi simulations, the VEP model also incorporates social and cultural learning, water usage, wood use for fuel, and hunting parameters to explore resource procurement strategies and how such strategies may have contributed to demographic patterns observed in the archaeological record for the area, most notably the depopulation during the late thirteenth century AD (Kohler et al. 2007).

In a model similar to Artificial Anasazi and VEP, Griffin and Stanish (2007) have modeled the Lake Titicaca basin with the goal of exploring the role of environmental and social factors on the development of complex societies in the region. Their model specifically examined factors that led to this political consolidation, such as agriculture, migration, competition, and trade (Griffin and Stanish 2007). Like Artificial Anasazi, their model was situated during a specific

Table 2.1 Survey of similar agent-based models

Start of Project or Earliest Known Publication[a]	Who	Model Name (if available)	Focus
1994	Doran, Palmer, Gilbert, Mellars	Evolution of Organized Society (EOS)	Models Upper Paleolithic social change by focusing on human interactions within a shared environment and explores the factors that contribute to group formation
1996	Dean, Gumerman, Axtell, Epstein, Swedlund	Artificial Anasazi	Explores reasons for why the prehistoric Pueblo (Anasazi) people abandoned Long House Valley in Arizona by modeling how demographic and social constraints interacted with environmental factors in the time leading up to the abandonment of the valley
1999	DiPiazza, Pearthree		Explores theories about the expansion of the Lapita cultural complex across the Southern Pacific Ocean by modeling demography and migration patterns
2000	Lake	MAGICAL	Designed to integrate GIS and agent-based simulations and to form a basis from which other archaeologists could build their own models; the first application explored whether modeling small group foraging patterns could explain artifact distributions in the Southern Hebrides
2002	Kohler, Johnson, Varien, Ortman, Reynolds, and others	Village Ecodynamics Project	Models environmental and social interactions on an accurately recreated landscape to explore factors that drive village aggregation, growth, and depopulation in southwestern Colorado between AD 600 and AD 1300
2003	Brantingham		A neutral model that indicates that raw stone material patterning in the archaeological record matches procurement strategy that does not require adaptive optimization, planning or risk minimization

2007	Griffin, Stanish		Examines the social and ecological dynamics, including agriculture, migration, and trade, that led to patterns of consolidation and emergence of complex society in the Lake Titicaca Basin in South America
2007	Wilkinson, Gibson, Christiansen, Widell, Schloen, and others	Enkimdu	Explores the social and ecological dynamics that led to population change in Bronze Age Mesopotamia especially in times of economic or disease stress
2008	Conolly, Colledge, Shennan		Models the effects of drift and vertical transmission of cultural adaptations to explain the reasons for the reduction in crop variability during the European Neolithic
2008	Kowarik, Wurzer, Reschreiter, Rausch, Totschnig		Simulates the working processes of Bronze Age mines at Hallstatt to gain insight into factors that affect mine output and contribute to mine exhaustion
2009	Graham	Patron World	Models individual-level interactions including grievances and gift giving to explore the emergence of violence and civil unrest in ancient Rome
2010	Premo, Kuhn		Models the effect of local extinctions on diversity, differentiation between groups, and rates of cultural change with regard to stone tool evolution in the Paleolithic
2012	Campillo, Cela, Hernàndez Cardona		Simulates battles, projectile trajectory, site degradation, fieldwork techniques to determine most effective strategies for doing battleground fieldwork

[a]The earliest publications we could find for each of these projects are: Doran et al. (1994), Dean et al. (1998), DiPiazza and Pearthree (1999), Lake (2000), Kohler et al. (2007), Brantingham (2003), Griffin and Stanish (2007), Wilkinson et al. (2007), Conolly et al. (2008), Kowarik et al. (2009), Graham (2009), Premo and Kuhn (2010), Campillo et al. (2012)

time period in a specific region and aimed to increase understanding of social processes occurring in pre-state level agricultural societies. The Titicaca Basin model differed from Artificial Anasazi in that the ecological and agricultural factors shaping the environment were not incorporated with as fine a scale as in Artificial Anasazi and were instead included with the goal of simply creating a reasonable landscape in which the agents could operate. Additionally, this model was validated using multi-dimensional measures in order to fully account for the multiple factors included in the model that contributed to long-term political changes. Griffin and Stanish's Lake Titicaca Basin model continued the trend of modeling with realistic and empirically informed environments and behaviors that began with models like Artificial Anasazi, but also borrowed from a political science model designed to simulate nation-state long-term political change.

Another model, Enkimdu, was developed to look at social and ecological dynamics of population change in Bronze Age Mesopotamia (Wilkinson et al. 2007). Like Artificial Anasazi, this model incorporates natural processes such as weather, crop growth, hydrology, soil quality, and population dynamics, but it also models how social behaviors such as farming and herding practices, kinship-driven behaviors, and trade interact with these natural processes to cause concurrent, dynamic changes in both types of processes (Wilkinson et al. 2007). Relying on modeling concepts from other fields such as the Dynamic Information Architecture System (DIAS) and the Framework for Addressing Cooperative Extended Transactions (FACET), Wilkinson and colleagues explored patterns related to demography, subsistence, kinship, and reciprocal exchange in situations of social stress to test hypotheses related to changing social and ecological dynamics (Wilkinson et al. 2007).

The combination of ecological, agricultural, cultural, and political factors into one model as demonstrated in all these studies illustrates how interdisciplinary work can better inform archaeological agent-based models. These models are also especially valuable because they demonstrate how micro-level behaviors of agents, determined archaeologically and ethnographically, within a specific temporal and geographic space can result in the emergence of macro-level patterns that can also be compared with the archaeological record—an advantage of agent-based models over other forms of modeling (Griffin and Stanish 2007; Schelling 1978; Epstein 1999).

2.4 Current Efforts: The ALHV Model

Recent efforts working with the Artificial Anasazi project center on the ALHV model. This model differs from the AA model in only a few characteristics, but these differences have far-reaching implications for model structure and simulation results. As mentioned above, the primary difference is that individuals within households are now considered to be active agents. Rather than basing fertility and

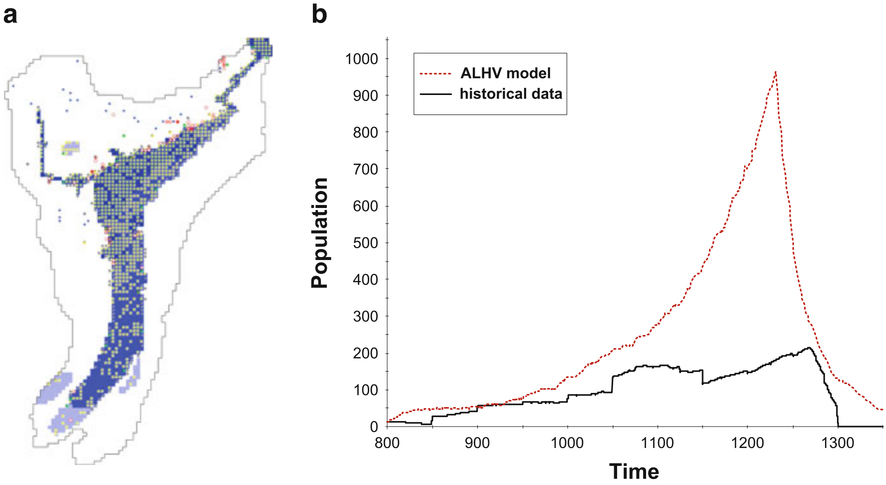

Fig. 2.5 Simulated (**a**) settlement distribution and (**b**) population vs. historical data, ALHV model

mortality levels on aggregate household-level probabilities as in the AA model, in the ALHV model individual agents are endowed with age-specific fertility and mortality schedules that govern their birth and death.

We are still in the process of determining the nature and impact of the specific differences between the two models, but household-level fission and death still do appear to be present. We have determined that they work somewhat differently in the ALHV model, but the particular mechanisms are not yet understood. Eventually the ALHV model, with its disaggregated, individual-level demographic processes, will be used for questions regarding the potential impacts on population growth of morbidity, mortality, and reduced fertility due to disease and food scarcity.

Figure 2.5 demonstrates that results of simulations of the AHLV model are dramatically different from those of the AA model (as shown in Fig. 2.4). The vast majority of runs exhibit a pattern of exponential growth (consistent with the assumption of constant age-specific fertility and mortality rates), followed by a steep decline as the region becomes agriculturally unproductive. Sensitivity analyses using various estimates for fertility, mortality, and harvest variables indicate that, as would be expected, the rate of exponential growth is sensitive to changes in the age-specific fertility and mortality parameters. Interestingly, however, unlike the AA model, the ALHV model outcomes are not influenced by changes in the values of harvest parameters. Clearly, in bringing the individual-level fertility and mortality processes into the model, household-level population control processes related to the environment and harvest potential were decoupled from the model. This decoupling has, however, removed any semblance of a “fit” between the simulations and the archaeological data, with the result that, at present, the ALHV model is not an adequate representation of the population history of the Long House Valley. Reincorporation of the environmental constraints, at a minimum, is required in order for the ALHV model to be a successful model for the rise and abandonment of the Long House Valley.

More importantly, influences such as disease, nutrition, migration, and warfare operate most strongly at the individual level, and these processes have been proposed repeatedly in explanations of the population history of the region. In order for models to pursue questions related to these processes in the Long House Valley and elsewhere, both individual-level demography and household-level environmental constraints are essential components. Thus, present research on the ALHV model is directed at solving the problem of recoupling and integrating individual-level and environmental constraints on population growth.

2.5 Discussion and Conclusions

Artificial Anasazi, its predecessors, and its successors have demonstrated the usefulness of agent-based modeling in archaeological applications. Because agent-based modeling in archaeology allows for hypothesis testing, verifying the accuracy of other methodologies, formalization of theories, exploration, and experimentation that are not always possible with other lines of archaeological inquiry, the continued application of agent-based modeling methodologies to archaeological questions is essential (Kowarik 2011).

In our own work, we envision the following as new directions for Artificial Anasazi and Artificial Long House Valley:

- More extensive and systematic sensitivity analyses
- Incorporation of explicit infectious disease processes, nutritional stresses, violence
- Interactions between the Long House Valley and Black Mesa, a major archaeological region adjacent to the Long House Valley

We also suggest that future applications of ABMs to archaeological questions should consider the following:

- Continued focus on modeling individual-level interactions
- More focus on emergent social patterns that result from local behaviors and socio-ecological dynamics and comparison of these simulated patterns to patterning observed in the archaeological record
- Continued interdisciplinary work

We see the most important goal of our work in the near term, once the ALHV model is up and running well, to be the development of insights into the varying roles of disease, diet, and fertility in the decline and eventual abandonment of the Long House Valley. Once we understand the likely possibilities for the impact of these demographic and nutritional constraints, we may gain clearer understandings of the influence of political and social factors in triggering final abandonment of the region.

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