

SIMULATING PREHISTORIC POPULATION DYNAMICS AND
ADAPTIVE BEHAVIORAL RESPONSES TO THE ENVIRONMENT IN
LONG HOUSE VALLEY AND BLACK MESA, ARIZONA

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SIMULATING PREHISTORIC POPULATION DYNAMICS AND ADAPTIVE
BEHAVIORAL RESPONSES TO THE ENVIRONMENT IN LONG HOUSE
VALLEY AND BLACK MESA, ARIZONA

Presented by Amy L. Warren

A candidate for the degree of

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And hereby certify that, in their opinion, it is worthy of acceptance.

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To my father...

Don't grieve and fret when I am gone, or think that you can be idle and comfort yourselves by being idle and trying to forget. Go on with your work as usual, for work is a blessed solace. Hope and keep busy, and whatever happens, remember that you never can be fatherless. —Louisa May Alcott

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TABLE OF CONTENTS

Acknowledgements.....	ii
List of Figures.....	vii
List of Tables	ix
Abstract.....	x
CHAPTER 1: INTRODUCTION	1
Research Goals	3
Organization.....	6
CHAPTER 2: CULTURE HISTORY, DEMOGRAPHY, AND MIGRATION IN LONG HOUSE VALLEY AND BLACK MESA.....	8
Fundamental Aspects of Prehistoric Pueblo Culture	10
Cultural Change in the Study Areas from AD 800 to AD 1300	17
Demography of the Prehistoric Southwest	21
Demographic Estimates for the Study Areas.....	26
Migration in the Prehistoric Southwest.....	31
Black Mesa and Long House Valley Interactions	36
CHAPTER 3: UNDERSTANDING MOVEMENT BETWEEN BLACK MESA AND LONG HOUSE VALLEY—A PILOT STUDY.....	37
CHAPTER 4: AGENT-BASED MODELING IN ARCHAEOLOGY	46
Agent-Based Modeling Philosophy.....	46
Agent-Based Models in Archaeological Research.....	50
CHAPTER 5: DISAGGREGATING THE MODEL—METHODS AND RESULTS	60
General Model Overview.....	60
Methods for Disaggregating the Model: Households to Individuals.....	64
<i>Adding individuals to the model</i>	65
<i>Person-specific rates in the ALHV-Baseline model</i>	67

Analysis of the ALHV-Baseline Model	76
<i>General results — ALHV-Baseline model</i>	78
<i>Examining fertility in the ALHV-Baseline model</i>	81
<i>Person nutritional need and harvest adjustment</i>	87
 CHAPTER 6: INCORPORATING REALISTIC DEMOGRAPHY—METHODS AND RESULTS	 90
Incorporating Reasonable Ethnographic and Demographic Behaviors.....	90
Incorporating Realistic Fertility and Mortality	93
<i>Age-specific mortality</i>	96
<i>Age-specific fertility</i>	99
ALHV-AgedMort Results	103
<i>Repetition study and sensitivity analyses</i>	103
<i>Demographic outputs</i>	108
 CHAPTER 7: INCORPORATION OF BLACK MESA AND MIGRATION—METHODS AND RESULTS	 116
ALHV-Mesa Results	127
<i>The repetition study</i>	128
<i>Sensitivity analyses</i>	129
<i>Migration patterns</i>	132
 CHAPTER 8: DISCUSSION AND CONCLUSIONS.....	 138
Future Directions	142
Implications.....	144
 REFERENCES	 145
 APPENDIX A: MODEL INPUTS AND PROCESSES.....	 157
Disaggregation: ALHV-Baseline Model	157
Demography: ALHV-AgedMort Model	159
Migration: ALHV-Mesa Model.....	164
 APPENDIX B: FERTILITY AND MORTALITY SCHEDULES FOR SENSITIVITY ANALYSES.....	 170

APPENDIX C: LONG HOUSE VALLEY AND BLACK MESA STARTING POPULATION CHARACTERISTICS	174
Long House Valley Starting Population Characteristics	175
Black Mesa Starting Population Characteristics	177
APPENDIX D: ALHV-MESA MODEL ADDITIONAL SENSITIVITY RESULTS ..	182
Black Mesa Sensitivity Analyses Results	182
Long House Valley Sensitivity Analyses Results	184
APPENDIX E: ALHV MODEL CODE	187
ALHV-Baseline Code	188
ALHV-AgedMort Code	203
ALHV-Mesa Code	227
VITA	258

LIST OF FIGURES

Figure	Page
2.1 A map of the study areas.....	10
2.2 The Long House Valley population curve	28
2.3 Black Mesa population estimates.....	30
3.1 PDSI ranges and Tsegi Canyon PDSI values	38
3.2 Black Mesa environmental stress years--severity.....	41
3.3 Black Mesa environmental stress--duration.....	43
3.4 Black Mesa environmental stress--intervals	43
4.1 Inputs and activities in the Artificial Anasazi model.....	55
4.2 Average runs of the Artificial Anasazi model	56
5.1 Results of ALHV-Baseline repetition—all runs	79
5.2 Results of ALHV-Baseline repetition—extant runs	80
5.3 Comparison of AA and ALHV repetition runs.....	80
5.4 Results of constant vs. age-specific fertility study.....	81
5.5 ALHV-Baseline starting population structures.....	83
5.6 Results of ALHV-Baseline starting population comparisons.....	83
5.7 Final number of households as fertility varies, ALHV-Baseline.....	85
5.8 Peak sizes as fertility varies, ALHV-Baseline	85
5.9 Sum of squared differences as fertility varies, ALHV-Baseline.....	86
5.10 Results of varying PNN and harvest adjustment, ALHV-Baseline	88
5.11 Repetition study results when HA is removed, ALHV-Baseline	89
6.1 Age-specific starvation rates, ALHV-DemogUpdate	94

6.2 Average starvation deaths per year, ALHV-DemogUpdate	95
6.3 ALHV-AgedMort repetition study results, varying fertility.....	104
6.4 Comparing repetition study results, ALHV-Baseline and AgedMort	105
6.5 Select results from ALHV-AgedMort sensitivity analyses	106
6.6 Varying mortality multipliers in ALHV-AgedMort sensitivity analyses	107
6.7 Varying mortality schedules in ALHV-AgedMort sensitivity analyses	108
6.8 Comparison of age-specific mortality rates in ALHV-Aged Mort.....	110
6.9 Comparison of input and simulation combined mortality rates, ALHV-AgedMort..	111
6.10 Comparison of input and simulation starvation rates, ALHV-AgedMort	112
6.11 Comparison of input and simulation general mortality rates, ALHV-AgedMort ...	112
6.12 Comparison of simulation mortality rates, ALHV-AgedMort	113
6.13 Emigration Causes in ALHV-AgedMort simulations.....	115
7.1 Map of the Black Mesa environment.....	118
7.2 LHV and Black Mesa model displays	122
7.3 Results of ALHV-Mesa repetition study	128
7.4 Results of ALHV-Mesa sensitivity analyses	130
7.5 Timing of population trend shifts produced by ALHV-Mesa	133
7.6 Migrations by year due to no suitable land	134
7.7 Migrations by year due to clan reassignment	136

LIST OF TABLES

Table	Page
5.1 Productivity estimates for LHV zones	62
5.2 Comparison of AA and ALHV demographic variables	69
5.3 Parameters used in ALHV-Baseline sensitivity analyses	78
6.1 Fertility schedules considered for ALHV-AgedMort	101
6.2 Comparison of demographic parameters in ALHV-Baseline and AgedMort	102
6.3 Demographic events recorded for ALHV-AgedMort simulations	103
6.4 Parameters used in ALHV-AgedMort sensitivity analyses	105
7.1 Maize productivity estimates for Black Mesa	119
7.2 Criteria for determining settlement locations for LHV and Black Mesa.....	123
7.3 Migration cause codes for the ALHV-Mesa model	125
7.4 Parameters used in ALHV-Mesa sensitivity analyses	127
7.5 Best-fit values for each sensitivity parameter, ALHV-Mesa	131

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ABSTRACT

This project contributes to our understanding of human adaptability to environmental stress and climate change in Long House Valley and Black Mesa, Arizona from AD 800-1350. This was accomplished through the development of a series of agent-based archaeological models. The first stage, Disaggregation, created a model that simulated individual persons within the Long House Valley landscape, a departure from the household-level models common in archaeological modeling. The second stage, Demography, applied empirically derived fertility and mortality rates to these human populations to provide insight into the effects of such rates on population patterns. The final stage expanded the modeled environment to include Black Mesa and allowed for the migration of individuals and households between the two areas in response to varying environmental and demographic pressures throughout the study period.

The results of this project indicate that the introduction of biological and ethnographic realism to a model can produce unexpected results, including those that deviate from the population patterns observed archaeologically. Despite these unexpected interactions, the results support the importance of variations in agricultural productivity in driving human migrations in the region. Future archaeological models should consider further exploration small-scale, local population movements and the effects of dynamically changing fertility and mortality rates.

CHAPTER 1: INTRODUCTION

The factors involved in the late 13th century depopulation of the Colorado Plateau region have been rigorously studied by archaeologists, but the ultimate cause of the abandonment of the area by ancestral Pueblos has not been determined. The archaeological evidence clearly suggests the area was abandoned between approximately AD 1275 and AD 1300 and theories of disease, starvation due to crop failures, and violence have been put forth as explanations, but no single factor alone can be shown to result in the depopulation of the area (Axtell et al. 2002). The project described in this dissertation was developed to gain greater insight into the causal factors leading up to the abandonment of the region by exploring environmental, social, and demographic factors that affected population dynamics from AD 800 to AD 1350 in Long House Valley and Black Mesa, Arizona. Additionally, this project introduces new methods for reconstruction of prehistoric population size and structure, as well as patterns of population growth and decline, which are critical for understanding important questions in Southwest prehistory.

Long House Valley and the northern portion of Black Mesa were chosen as study areas for this project for a number of reasons. First, both areas have been extensively studied archaeologically so sufficient data are available for the proposed project. Second, because of their proximity to each other, there is evidence of long-term interaction between the two populations. At the time just prior to the abandonment of Black Mesa, when their social and economic networks are hypothesized to have been at their smallest extent, archaeological evidence shows continued interaction and exchange with sites as

far as 30 km away, so the occupants of the mesa certainly would have continued interactions with neighboring Long House Valley (Fernstrom 1976). Finally, the abandonment of Black Mesa at approximately AD 1150 likely had tremendous effects on the population of Long House Valley. The archaeological evidence indicates that populations likely moved into agriculturally productive areas during times of environmental stress (Gumerman and Euler 1976). Undoubtedly, some Black Mesa residents looked over the mesa's edge and saw the continuing success of the valley populations despite the harsh climatic circumstances they were experiencing and quickly relocated there.

In addition to the factors that make the study of Black Mesa and Long House Valley compelling study areas, this project is also aided by the existence of an existing agent-based computer model that was developed to simulate the interaction of multiple causal factors thought to contribute to patterns of population growth and decline in the Colorado Plateau region. This model, known as the Artificial Anasazi (AA) model, was developed in the 1990s by a team of researchers associated with the Santa Fe Institute and simulates the dynamically changing environment in Long House Valley, Arizona from AD 800 through AD 1300 and how these environmental changes affected agricultural production and human populations (Axtell et al. 2002). While the AA model generated population counts that were similar to archaeologically determined population estimates, it failed to simulate the complete disappearance of the ancestral Pueblo from the region, indicating that more factors needed to be added to the model to fully simulate the collapse (Axtell et al. 2002). This project uses the same paleoenvironmental data that drive agricultural and population changes in the AA model but focuses its investigations

on the individual instead of the household. By including individuals of varying age and caloric requirements and incorporating individual-level fertility and mortality, the results of simulations using the models developed here provide finer-scale resolution of demographic changes (Swedlund et al. 2014).

In addition to contributing to greater understanding of how environmental change affects population dynamics in the region, efforts also focus on expanding the model outside of Long House Valley. This project contributes to our understanding of human adaptability to environmental stress and climate change in both Long House Valley and Black Mesa by simulating the effects of environmental change on population dynamics in both areas, reconsidering fertility and mortality rates in both areas, especially the way in which these demographic rates are used in the models, and by exploring the nature of migrations, another key demographic factor, between the two groups. This project also demonstrates that agent-based modeling is a useful tool for paleodemographic research that supplements traditional bioarchaeological methods in order to understand questions of long-standing importance in archaeology.

Research Goals

Some of the most important questions about the prehistory of the American Southwest rely on an accurate understanding of population dynamics in the region. Debates about the emergence and intensification of maize agriculture, the expansion of social networks and increased social complexity, and the abandonment of entire regions often include discussions of whether these major cultural changes were caused by changes in population dynamics or if changes in population dynamics observed

archaeologically were the consequence of these cultural changes (Gumerman 1988, Hill et al. 2004, Nelson et al. 1994a). Unfortunately, our understanding of population dynamics in the prehistoric Southwest is rather limited. The overarching aim of the project presented here was to contribute to these ongoing debates by improving understanding of the demography of the region and assessing migration as an important factor in producing observed patterns of population change. This was accomplished through three stages of model development that I have labeled Disaggregation, Demography, and Migration.

The first goal was to gain insight into the effects of both environmental and intrinsic demographic factors, such as fertility and mortality, on the rates of population growth and the structure of the populations in Long House Valley and Black Mesa. In order to address this question, a series of new agent-based models were developed. The first model extends the AA model by introducing heterogeneous individuals, in addition to households (Disaggregation). In this model, individual persons are imbued with varied essential characteristics and, together, represent a realistic human population, a necessary first step for implementing biological rates. The next model developed incorporates empirically derived fertility and mortality rates for the populations under study (Demography). In the AA model and the first disaggregated model, only fertility rates are considered. These were estimated using life tables and fertility schedules derived from a relatively large skeletal collection excavated from Black Mesa and ethnographic data from the greater Southwest and other horticultural groups (Dean et al. 2000, Martin et al. 1991, Swedlund 1994). By exploring additional data sources to develop new fertility rates and adding age-specific mortality rates, this second model better simulates human

demographic processes and the incorporated rates are decoupled from some of the issues known to exist in paleodemographic analyses.

In order to apply these demographic rates to the Black Mesa population, a third model was developed that incorporates the environmental conditions and populations of Black Mesa as they change through the study period. Extensive environmental and archaeological research on the northern portion of Black Mesa has yielded outstanding data for the region (Gumerman and Euler 1976, Powell and Smiley 2002). In the AA model, Black Mesa environmental data were even used as proxies for some Long House Valley environmental data, so developing a simplified environmental base to include in the Black Mesa component was relatively straightforward. The expansion of the existing models to include both Black Mesa and Long House Valley provides a larger geographic extent and more extensive environmental data with which to examine the effects of environmental variation on prehistoric populations.

The second major goal of this project was to gain understanding of how population movements between the study areas may have affected the population structures and dynamics in the two study areas and how these compared to archaeologically derived estimates of these demographic patterns. Development of the third model that incorporates Black Mesa geography, environment, and people allows simulation of patterns of movement between Long House Valley and the northern portion of Black Mesa to explore how migrations at various times and of different magnitudes may have impacted population dynamics (Migration). Population movement is considered to be a major adaptive strategy of ancestral Pueblo populations in response to environmental and social stress. Results of a pilot study (described in Chapter 3) indicate

that episodes of environmental stress on Black Mesa correspond remarkably well with population growth in Long House Valley, where agricultural conditions were more favorable, suggesting that struggling Black Mesa inhabitants moved into Long House Valley to survive during periods when they were unable to successfully grow maize. By incorporating Black Mesa into the existing models, it was possible to simulate the movement of people from one area to the other over time. In addition to large-scale population movements in response to environmental stress, socioeconomic interactions between the areas also suggest smaller-scale, sustained movement between two areas for the purposes of marriage or clan alliance (Gumerman 1988). The expanded models allow for simulation of population movements of varying magnitudes and provide more insight into the effects of migrations on population structure and size, a necessary step for fully understanding the major questions of archaeological interest in the region.

Organization

This dissertation is organized into eight chapters and five appendices. Chapter 2 describes the Long House Valley and Black Mesa study areas and the culture history of the region as it relates to decisions made in developing the models that form the basis of this project. It also discusses prior paleodemographic research in the region, known issues with traditional paleodemographic analyses, and the archaeological and demographic data incorporated into the model. Chapter 2 also summarizes previous research into migrations and population movement in the Southwest. Chapter 3 details the migration pilot study described above. Chapter 4 addresses the justification for the use of the agent-based modeling methods used in this project, introduces the AA model, and examines trends in

archaeological and demographic modeling in anthropology. Chapters 5 through 7 describe the methods used to develop and the results of analyses of the three models implemented in this project. Chapter 8 summarizes the major insights gained through this project, discusses broader implications of these results for archaeology and biological anthropology, and directions for future research. The appendices include figures that summarize critical processes incorporated into the models, fertility and mortality schedules used in various sensitivity analyses, the population input files developed from Pueblo census data and used to initialize Long House Valley and Black Mesa populations, additional results from sensitivity analyses, and complete code for each of the models developed.

CHAPTER 2: CULTURE HISTORY, DEMOGRAPHY, AND MIGRATION IN LONG HOUSE VALLEY AND BLACK MESA

In order to realistically construct the models to study the population dynamics of Long House Valley and Black Mesa from AD 800 to 1350, it is important to have some understanding of these areas, the cultural history of the region, and previous research conducted toward reconstructing these populations. Fortunately, both of these areas are well studied and abundant archaeological, environmental, and demographic data are available.

Black Mesa and Long House Valley lie in the heart of the Kayenta Anasazi region of northeastern Arizona (Figure 2.1). The Black Mesa study area is approximately 200 km², rising to an elevation of 2700 m on its northern rim. The topography is characterized by a system of washes and ephemeral streams, and most archaeological sites on the mesa are near these washes. Water is readily available in these areas during the rainy seasons, late summer and mid-winter, but annual precipitation in the Kayenta region varies widely from 7.59 cm to 23.42 cm, with an average annual rainfall of 14.29 cm (Wright 2010). This variation in available moisture has tremendous effects on the maize productivity of the region as does the length of frost-free days (i.e., the maize growing season) (Gumerman 1988, Wright 2010). Dendroclimatic reconstruction indicates the mesa saw an average of 120 frost-free days per year (Gumerman 1988, Martin et al. 1991). The Black Mesa study area is now part of the Navajo reservation and home to the Peabody Kayenta coal mine. While the mesa landscape is now marred by the presence of infrastructure required for the coal mine, visitors can still stand atop the mesa and look directly into Long House Valley below.

Long House Valley is a geographically discrete, 96 km² valley that lies at an elevation of approximately 1950 m. It is bordered by Black Mesa on the southeast and the Shonto Plateau on the northwest. Annual precipitation is similar to that of Black Mesa and most comes from thunderstorms between July and October and snow or rain showers from November to March. The prehistoric valley was characterized by a perennial stream that served as the main source of potable water for the valley inhabitants (Gumerman 1988). Most of the archaeological sites are situated with easy access to this stream, but under the most favorable conditions, some upland areas also became arable and settlements were established in these areas (Dean 1988). Temperatures in the valley were more amenable to maize agriculture, with a much longer growing period than that experienced on the mesa, approximately 155 frost-free days per year (Dean 1988). Today, Long House Valley is also part of the Navajo reservation and is home to only a few scattered farmsteads. The perennial water source that prehistoric settlements converged upon no longer exists due to damming projects. Instead of a stream, US Highway 160 now bisects the valley. The remains of the prehistoric cultures under study in the project can still be observed when walking through the valley, and remnants of prehistoric structures still exist, especially along the cliffs leading up the neighboring mesas.

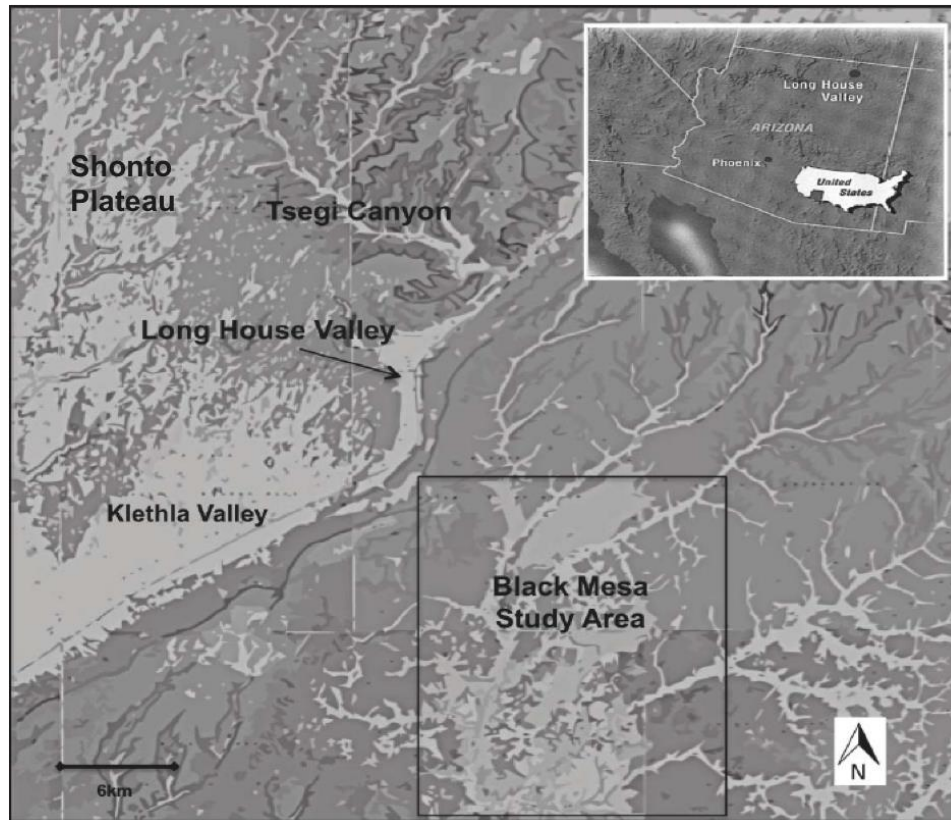


Figure 2.1: A map of the study areas.

Fundamental Aspects of Prehistoric Pueblo Culture

The visible archaeological sites of the American Southwest, whether easily recognized cliff dwellings like those at Mesa Verde or piles of rubble from collapsed pueblos in Long House Valley, have long attracted interest in the region's prehistoric past (Plog 1986). Building on the cultural history defined by archaeologists working during the early and middle of the 20th century, archaeologists in the late 20th century began to focus on understanding prehistoric social dynamics (Longacre 2000). Today, archaeologists use settlement patterns, architecture, ceramic styles and distributions, differences in burials, and physical characteristics of skeletons to infer information about prehistoric social organization (Longacre 2000).

Advances in archaeological technologies have allowed for precise dating of archaeological features in the Southwest and have generated precise environmental reconstructions spanning the period from AD 200 to the present day (Dean et al. 1985, Plog 1986). These advances allow archaeologists to gain significant insights into cultural change because the marginal environments of the Southwest, characterized by high levels of environmental variability and limited water, played a key role in human social adaptations. Social responses, including reorganization or shifts in settlement patterns, were a means, perhaps the primary means, of dealing with environmental stress and unpredictability (Plog 1986).

An excellent ethnographic record for historic and modern Pueblo groups has informed many of the insights archaeologists have gained into prehistoric Pueblo social organization (Ellis 1951, Gumerman et al. 2003, Ware 2014). Pueblo society has often been characterized as one of conservatism and continuity and many of the interpretations regarding prehistoric social organization are made possible by the apparent consistency in the culture through time (Ellis 1951, Ware 2014). One of the most compelling pieces of evidence for continuity is the persistence of the ritual headdress worn by women. Depictions of the Hopi maiden or butterfly headdress have been found in rock art dating back as far as AD 400 and have been recovered in archaeological contexts on pottery dating back to AD 832 (Gumerman, personal communication). Modern Pueblo women still wear the willow wicker headpieces during ceremonies today (Gumerman, personal communication). Although we cannot say that all aspects of prehistoric Pueblo society have persisted and contact with the Spanish likely had tremendous effects, fundamental characteristics such as subsistence strategy (maize horticulture), and inheritance and

residence patterns (matrilocality and matrilineality) appear to extend far into prehistory (Ware 2014).

At the heart of prehistoric Pueblo culture is its reliance on maize horticulture. Coprolite and stable isotope analyses of skeletal remains reveal that corn comprised as much as 75% of the prehistoric diet (Matson 1996). Dry land farming (i.e. depending on rainfall to water crops) seems to have been the predominant form of horticulture, but water control technologies exist in some areas, especially in later periods (Matson 1996). With the intensification of agriculture, shifts toward larger populations and more permanent settlements are seen (Kohler et al. 2008, Swedlund and Sessions 1976). However, whether the intensification of agriculture was the cause of population aggregation or a consequence is widely debated and timing varies based on local and regional contexts (Adler et al. 1996, Blinman 2010, Leonard and Reed 1993, Nelson and Schachner 2002). Because of the importance of maize to the prehistoric Pueblos, it follows that maize production was tightly integrated with the ritual, economic, and social lives of the people (Gumerman et al. 2003).

The archaeological and ethnographic records for this region suggest that, with increasing reliance on maize horticulture beginning at approximately AD 200, a shift toward matrilineal residence patterns and matrilineal descent also occurred (Peregrine 2001). Multiple lines of evidence convince archaeologists this form of social organization prevailed in the region prehistorically. First, modern Pueblos are matrilineal and matrilineal and the importance of this form of organization can be seen in ancient rituals still prevalent today. Additionally, there are a number of social conditions that appear to promote matrilineality cross-culturally. Matrilineal residence is likely to occur when

migration is common, warfare is frequent, and where resources are often stressed (Peregrine 2001). Evidence for all of these patterns can be seen in the prehistoric Southwest. Direct archaeological evidence of matrilocality on Black Mesa was inferred from non-random distributions of stylistic choice on artifacts that would have been produced by women (e.g. ceramics) and random distributions of artifacts produced by men (e.g. tools and baskets) (Clemen 1976). Matrilocality groups also tend to have larger dwellings than patrilocal groups and large residences do emerge in the Southwest during the periods of intense maize production (Peregrine 2001).

Further support for matrifocal social organization can be found by looking at mechanisms in place to unite men who would be coming in from different groups due to exogamous marriage rules. Archaeological evidence indicates multiple prehistoric Pueblo sodalities, including feast groups, religious societies, healing groups, and craft groups that would have allowed men to interact with other men across communities and potentially maintain ties with their natal groups (Gumerman et al. 2003, Peregrine 2001). More recently, others have inferred matrilocality in other Kayenta area communities from village organization and ritual architecture (Stone 2013, 2016) and genetic evidence (Kennett et al. 2017).

Within prehistoric Pueblo culture, the household was the main economic and social unit. The majority of agricultural production was carried out at the household level and stores were also maintained at the household level (Matson 1996). Establishing individual households as the central socioeconomic unit was critical in the marginal environment because it allowed for greater mobility (Benson 1984). Furthermore, when there is evidence for production or storage beyond the level of the household, it appears to be a

relatively short-term, unstable reaction to environmental stress (Benson 1984). When considering prehistoric Pueblo social organization, people often point to the complicated clan systems. It seems likely that the clan system emerged as a means to continue to tie together smaller lineages when there was the need for related households to disperse across the landscape (Chang 1958). So, although clans were important for structuring Pueblo society on larger scales, individual households remained the central socioeconomic unit.

It has long been debated whether the prehistoric Pueblos were egalitarian or hierarchical or some mixture of both. It has been traditionally thought that prehistoric Pueblo societies were egalitarian in the sense that there was no hierarchy beyond differences in age and sex (McGuire and Saitta 1996). Some archaeologists believe that the importance of ritual, seen in the archaeological and ethnographic record, should be interpreted as a means of social integration and cohesion in the absence of formal hierarchy (Potter 1997). Others argue that prehistoric Pueblo society was much more hierarchical than previously assumed (Kennett et al, 2017, Matson 1996, McGuire and Saitta 1996, Price et al. 2017). The arguments for hierarchy assert that there were significant inequalities, mostly stemming from variations in productive capacity of land and control of ritual knowledge, that led to the emergence of elite clans (Kennett et al. 2017, McGuire and Saitta 1996). Archaeological features such as kivas and complex water control systems appear to represent the ability of elites to mobilize labor groups and are often used as evidence of hierarchy (Benson 1984, Price et al. 2017).

Another source of debate is the relative importance of extra-community social networks when compared with intracommunity cooperation and solidarity. Peregrine

(2001) believes that corporate strategies within communities were most important because of the need to rely on the people closest to you during times of environmental stress. He contends that greathouses, shared stylistic features, and the distributed responsibilities for production of ritual goods are all evidence of cultural measures intended to promote corporate or community solidarity by reducing differences between different lineages (Matson 1996, Peregrine 2001).

While there is no doubt that intracommunity cooperation was critical, the marginal environments of the Southwest likely made the social networks *between* groups dispersed throughout the landscape of equal or more critical importance. Social networks allow for the sharing of information, reciprocal exchanges of goods, and communication and cooperation between groups dispersed across the landscape (Braun and Plog 1982). Such networks buffer against environmental risk by distributing the risks across members of the network, opening up spatially expansive lines of communication about environmental conditions in different areas, delineating potential boundaries for fissioning and fusion should that become necessary, and spreading major decision-making responsibilities across many groups (Braun and Plog 1982). Some social networks are established in response to short-term changes and these networks are likely to be between individuals. In response to longer-term periods of risk, networks are established between groups and become deeply imbedded in the social organization of the region and likely maintained ritually and symbolically (Braun and Plog 1982, Mills et al. 2015).

In the Southwest, there are periods in which social networks expanded and contracted due to environmental conditions (Braun and Plog 1982). Here, the changing

scope of social networks is not exactly a function of good or poor environments, but more associated with the levels of environmental unpredictability (Braun and Plog 1982).

Braun and Plog (1982) contend that the levels of regional integration will increase during periods of uncertainty and risk and that the longer such uncertainty persists in a region, the more enduring the effects on social organization will be. In general, because expanded social networks serve to buffer against environmental unpredictability, it is expected that networks will expand during periods of environmental risk and contract during periods of relative certainty, but specific patterns of social network expansion and contraction must be explored at the local level.

Prehistoric Pueblo social organization is further characterized by repeated cycles of population aggregation and dispersal. While aggregation and dispersal are potential strategies for coping with the marginal Southwestern environments, there is major disagreement about the specific reasons for aggregation and dispersal, the role of environment fluctuations in driving these cycles, and their implications for understanding social organization. There is evidence these aggregation and dispersal cycles occurred somewhat independently from environmental perturbations and were instead driven by demographic change and fluctuations in social networks (Hill et al. 2004, Mills et al. 2015). Although the exact mechanisms that led to repeated cycles of aggregation and dispersal may never be fully known, it is clear that these changes in population dynamics must be considered in localized contexts (Leonard and Reed 1993). Attempts to regionalize these dynamics will inevitably fail.

Cultural Change in the Study Areas from AD 800 to AD 1300

In Long House Valley and Black Mesa, population dynamics correspond remarkably well with low frequency (i.e. long-term) changes in environment, especially those related to the amount of available moisture (Dean et al. 1985, Karlstrom et al. 1976). In these areas, population aggregations (as determined by room size and room counts) reliably overlap with productive environmental conditions. Similarly, abrupt changes in styles or other aspects of material culture most commonly occur during periods of drought or otherwise poor environmental conditions (Karlstrom et al. 1976). Clearly, population dynamics are strongly influenced by the interactions of culture and environment in the region.

The study period begins in AD 800, midway through the Pueblo I period. This archaeological era was marked by the pithouse to pueblo transition, the appearance of ceramics in the Colorado Plateaus region, and the widespread reliance on maize horticulture (Cordell 1977, Kohler et al. 2008). In Long House Valley, the population was dispersed on the valley floor and situated in mostly alluvial areas (Lindsey and Dean 1971). On Black Mesa, populations were concentrated in the flood zones near major washes (Gumerman 1988). The period from AD 750 to AD 900 was characterized environmentally by high temporal variation and low spatial variation; water tables were low, erosion levels were high, and effective precipitation was generally low (Dean et al. 1985). As a result of these environmental conditions, the people in the study areas would have faced severe resource uncertainty because they could not predict rainfall during any given year (Dean et al. 1985). Archaeological evidence reveals that population levels were low during this period, suggesting that people dispersed across the landscape in

order to exploit a variety of wild food resources in addition to maize (Dean et al. 1985, Cordell and Gumerman 1989, McGuire and Saita 1996). The environment of Long House Valley would likely have been more naturally productive than that of Black Mesa due to more large game and a wider variety of vegetation (Dean et al. 1985).

In response to the high levels of environmental unpredictability, the prehistoric Pueblos during this period likely established expansive social networks to buffer against this stress (Braun and Plog 1982). The evidence suggests that, during this time of rather low population density, the mating networks spanned the entire Four Corners region, providing further support for this prediction (Plog and Powell 1976). During this period, the Pueblo groups were likely more egalitarian because, despite the high levels of environmental stress, they were probably too dispersed to be stratified.

The next period, Pueblo II (AD 900-1100), began with the relaxation of negative environmental trends. Due to increased water table levels, predictable precipitation was not as important as it had been in the preceding years (Dean et al. 1985). In addition, because of the environmental variability during the prior period, it is likely that people in the region had adapted to uncertain circumstances and developed mechanisms for overcoming resource stress (Dean et al. 1985). During this period, population levels in Black Mesa and Long House Valley increased from the previous period but remained low, suggesting that a dispersal strategy was still being utilized despite the favorable environmental conditions. In Long House Valley, inhabitants are found throughout the valley except in the upland areas and, on Black Mesa, inhabitants still were centered near the major washes, but settlements did extend further out (Lindsey and Dean 1971, Gumerman 1988).

From AD 1000 to approximately AD 1130, the environment in the region was characterized by low temporal variability that included high levels of effective precipitation and high spatial variability (Dean et al. 1985). During this time, there is archaeological evidence for both population growth and interaction between groups (Dean et al. 1985). The evidence clearly indicates that this was a major aggregation episode; population levels rose dramatically on Black Mesa and the number of households in the Long House Valley more than doubled (Dean et al. 1985, Layhe 1981). The classic site settlement configuration emerged during this period and is characterized by room block clusters with jacal wings and central kivas (Clemen 1976, Gumerman 1988).

The final archaeological era during the study period, Pueblo III (AD 1100-1300) was a time of major changes and ultimately ended in the abandonment of first Black Mesa, then Long House Valley. In AD 1130 a major drought began that lasted until approximately AD 1180. On Black Mesa, the beginning of this period saw a shift in site configuration and the establishment of primary and secondary habitation sites thought to be due to the expansion of the population in the previous period followed quickly by degrading environmental conditions (Plog 1986). Just prior to the abandonment of the mesa, settlement locations on the mesa reverted to those seen during Pueblo I; they were concentrated near the major washes that were likely the only remaining productive zones on the mesa at this time (Gumerman 1988). At approximately AD 1150, Black Mesa was abandoned (Dean et al. 1985, Gumerman and Euler 1976).

In Long House Valley, there was a reduction in population size in the period before and during the AD 1130-1180 drought, but the population dramatically increased

following the return of favorable weather patterns at approximately AD 1180 (Dean et al. 1985). The population increase during this period is also at least partially associated with the abandonment of Black Mesa (Gumerman and Euler 1976). Despite rather low levels of effective precipitation, water table levels were up and soil quality was high (Dean et al. 1985). During this period, the residents of Long House Valley expanded settlements to upland areas suggesting environmental conditions were so good that maize horticulture could be supported in areas that were previously considered unproductive (Dean et al. 1985, Lindsey and Dean 1971).

Around AD 1200, a process of re-aggregation began that continued until AD 1250 (Dean et al. 1985). Whether this was a reaction to a failure of the dispersal strategy to provide for the population or was in response to the newly favorable environmental conditions in the valley is unclear. The high levels of stratification that likely emerged in response to stress from the previous period probably carried over and perhaps increased. This period of reorganization and relatively good environmental conditions was immediately followed by environmental calamity. At AD 1275, the “Great Drought” affecting Long House Valley began. The period from AD 1275 to AD 1350 is characterized by this drought and associated low temporal and spatial variability (Dean et al. 1985). The period just before AD 1300 saw valley settlements return to only the better-watered areas and each settlement cluster was linked by clear sight lines (Haas and Creamer 1993). These sight lines and other defensive structures have been interpreted as a response to an increase in the threat or reality of intergroup violence (Haas and Creamer 1993). Furthermore, some argue that the social relationships within the valley in response to the drought immediately preceding the abandonment were strained and that lack of

communication, cooperation, and integration was the ultimate cause for complete abandonment of the valley (Swedlund and Sessions 1976). As a result of such dire environmental conditions and likely deteriorating social conditions, Long House Valley was abandoned at approximately AD 1300 (Dean et al. 1985). It is widely assumed that people moved, as individual households, into areas south of Long House Valley where the drought was not as severe and integrated into other groups (Gumerman and Euler 1976).

Demography of the Prehistoric Southwest

Despite extensive archaeological and biological anthropological research in the prehistoric Southwest, our understanding of the demography in the region is rather limited. Those important questions about whether important cultural changes—the intensification of maize agriculture, the expansion of social networks and complexity, and regional abandonments—were causes or consequences of changing population dynamics remain unsatisfactorily answered (Gumerman 1988, Hill et al. 2004, Nelson et al. 1994a) and resolution requires better understanding of the characteristics of these populations.

Demography is the study of individuals as members of a population and focuses on the analysis of patterns of population growth and decline as a result of varying fertility, mortality, and migration rates. When applied to populations of the past, this study is usually referred to as paleodemography. For living populations, demographers ascertain population structure and population dynamics and demonstrate how these change over time (Preston et al. 2012, Rowland 2003). Making inferences about

prehistoric population structures and dynamics is much more problematic. There is a need for better methods for ascertaining prehistoric population dynamics because existing paleodemographic methods fall short.

Two particular approaches to prehistoric population estimation inform the data input into the models developed as part of this project and also provide data against which model simulations can be compared: examination of human skeletal remains and osteological analyses that generate estimates of fertility and mortality rates, population structure, and population size, and the estimation of prehistoric population size from other archaeological remains.

The goal of demographically-oriented osteological analysis is to develop accurate descriptions of the size and composition of prehistoric populations using data derived from skeletal remains. Over the past 35 years, much of the research in paleodemography has focused on assessing the validity of methods rather than answering the important questions for which good paleodemographic data are required. These methodological issues fall into two distinct, but related categories. The first category pertains to the fundamental issues that are involved in making interpretations about the structure or health of living populations from skeletal populations. The structure of the once living population is distorted in skeletal samples by a number of factors including cultural burial practices that may result in differential burial of individuals, variations in the effects of taphonomic processes, and differential excavation, all of which may lead to a lack of representativeness of the samples studied (Hoppa and Vaupel 2002). Additionally, many of the analytical methods used to infer fertility, mortality, and population structure rely on the assumption that populations are stationary, or at least stable, when real populations

are not (Wood et al. 1992). Methods aimed at overcoming these limitations have been developed, and have resulted in the conclusion that we can most often learn more about the fertility of prehistoric populations from skeletal samples than we can about mortality (Chamberlain 2006, Sattenspiel and Harpending 1983).

The second category is more directly related to the techniques applied to assessing the skeletal samples themselves. Debates beginning in the early 1980s focused on the physical anthropologist's ability to accurately estimate age in adult skeletons and sex from juvenile skeletons, the use of life tables, and issues that arise when analyzing skeletal samples that are clearly not representative of the once living population (Boquet-Appel and Masset 1982, Buikstra and Konigsberg 1985, VanGerven and Armelagos 1983). Methods developed with the goal of overcoming these issues such as the use of hazards models, the application of Bayesian statistics and maximum likelihood estimates for age estimation, and the analysis of the systematic under-enumeration of certain age or sex classes in burial samples have only partially overcome these issues (Hoppa and Vaupel 2002, Konigsberg and Frankenberg 2002, Paine and Harpending 1996).

Paleodemographic methods using skeletal materials usually generate the data needed to estimate the age and sex distribution of a population, but they often do not provide adequate estimates of overall population size. The latter are usually needed to estimate demographic rates, however. To supplement the skeletal analyses, in many regions a variety of types of archaeological data can be used to estimate population size from archaeological remains, although many of the methods and data used are also problematic. The earliest attempts relied on simply counting rooms in structures assumed to be residential, calculating rates of midden refuse accumulation, and relying on

ethnographic accounts of the number of individuals who may have resided in a single household unit (Dohm 1990, Layhe 1981, Nelson et al. 1994a, Turner and Lofgren 1966).

Some argue that many of these archaeological methods of estimation are limited or inherently flawed (Layhe 1981, Nelson et al. 1994a). For example, the estimates are often limited because of incomplete survey and excavation of the study areas (Layhe 1981). Major concerns about their reliability stem from assumptions about the way material remains can inform us about the actual numbers of people that lived in a given area at a given time. These estimates often assume that all sites of a specific type had a similar use, the use of certain types of sites stayed the same through time, periods of occupation can be reliably determined, and all structures of the same type consistently held the same number of people or that people have identical space needs (Nelson et al. 1994a, Powell 1988, Turner and Lofgren 1966). These estimates are further complicated by the fact that assumptions must be made about average family size, the number of families that may have occupied a single structure, and the space required by each individual within a household (Hill et al. 2004, Layhe 1981, Turner and Lofgren 1966).

In order to overcome these assumptions, several new methods for site estimation were proposed and employed by Southwestern archaeologists that did not rely on classifying structures as certain types and instead relied on estimates of total roofed or floor space within a community or village (Dohm 1990, Layhe 1981, Schlanger 1988). Once survey or excavation was completed, the total space was calculated and the number of people supported determined based on floor space needs per person (Layhe 1981). Two methods have been employed to address problems with identifying the length of time structures were occupied or in use. First, much better dates for components of the

structures, such as individual beams, have been used to develop greater chronological control than is possible through ceramic analysis alone (Schlanger and Wilhausen 1993). The second method involves assessing the rate and type of reconstruction and the typical use life of certain construction methods (Schlanger 1988). The final assumption, that the number of people occupying a specific space or structure was consistent through time continues to be debated. Turner and Lofgren (1966) noted a general trend of increasing family size based on the size of serving implements at sites and generated family size estimates that were close to those recorded in early ethnographic records, while Dohm (1990) demonstrated that the amount of space a person required changed based on population density at a site. Others have suggested additional means for population estimation including the measures of artifact accumulation and ceramics breakage. The results of estimates generated through these types of analyses have yielded mixed results (Nelson et al. 1994a).

Both osteological and archaeological methods for paleodemographic reconstruction have been used to explore critically important aspects of Southwest prehistory. However, we still lack a sophisticated understanding of the timing of the emergence of agriculture and the pace of its intensification, the evolution of social complexity, and the nature of population movements and abandonments in the region. Despite decades of research on these topics, they remain “Grand Challenges for Archaeology” (Kintigh et al. 2014), largely because of the lack of good demographic information about the populations under study. The paleodemographic methods described above cannot provide information about population sizes or structures with sufficient detail or the necessary temporal control required for addressing the topics.

Demographic Estimates for the Study Areas

Fortunately, the issues with both traditional paleodemographic analyses of skeletal collections and estimations of population size from archaeological remains outlined above are at least partially ameliorated by the quality of prior research into the demography of our study areas. Previous studies of Long House Valley and Black Mesa have combined the best of the techniques described with attempts to control for the known sources of error in paleodemographic reconstruction.

Despite complete survey of the Long House Valley, no burials were ever identified or excavated from the valley; therefore, all results from osteological analyses are from Black Mesa skeletons (Dean 1988, Lindsay and Dean 1971). Archaeological investigations on Black Mesa continued from 1967 to 1983 through collaborative efforts of Prescott College and Southern Illinois University and, as a result of these efforts, 172 burials were excavated from Black Mesa, along with 100 isolated human bones (Martin et al. 1991). The goals of the paleodemographic research on the Black Mesa skeletal sample were threefold: document patterns of diet, disease, and death through the use of multiple measures of stress, provide measures of adaptive success of the population to marginal environmental conditions, and contribute baseline demographic data against which to compare the results of other prehistoric Southwestern populations (Martin et al. 1991).

The original paleodemographic research team argued that the skeletal samples excavated from Black Mesa are reliably representative of the living population because there is good documentation and provenience of burials excavated and the dates of specific sites are reliable (Martin et al. 1991). Furthermore, the age and sex composition

and distribution of burials across the occupation span also suggest the Black Mesa skeletal population is representative (Martin et al. 1991).

In order to overcome the issues with paleodemographic analyses described above, the research team used multiple methodologies for ascertaining age and sex. Sex determination was not attempted for sub-adults and the team relied on pelvic, cranial, and femoral markers for adult sex determination (Martin et al. 1991). Sub-adult age determination relied on dental development, long bone length, and epiphyseal union while, according to Martin et al. (1991), adult age determination relied on the phase systems developed by Meindl and Lovejoy (1985).

In order to convert the population structures determined through skeletal analyses to life tables, the team relied on the archaeological reconstructions of population size to provide independent calculations of growth rates (Martin et al. 1991). Additionally, the Black Mesa research team made the following assumptions: a) the population represented by the Black Mesa burials is assumed to be closed (i.e., no migration occurred), b) all growth or decline was the result of inherent fertility and mortality, and c) the growth rates remained the same through time (Martin et al. 1991). As a result of these assumptions and the skeletal analyses, the team constructed stationary life tables for the entire skeletal population and for both early and late Pueblo samples (Martin et al. 1991).

For both Long House Valley and Black Mesa, detailed estimates of population sizes as they changed through time are available. Long House Valley was 100% surveyed and the data used to reconstruct population size were taken directly from the Southwestern Anthropological Research Group database master file (Dean et al. 2000). In this database, locations and sizes of archaeological sites were recorded and those that

were determined to be habitation sites were used to calculate the number of *households* within the valley in any year within the study period (Axtell et al. 2002, Dean et al. 2000). No attempts were made by earlier research teams to estimate the number of individuals within the valley through time. The population sizes estimated for Long House Valley through the study period are depicted in Figure 2.2.

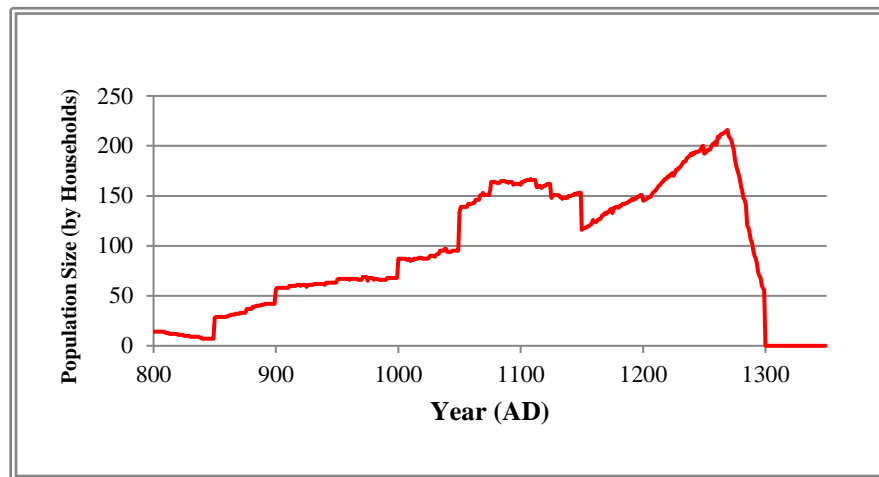


Figure 2.2: Long House Valley population curve developed by the Southwestern Archaeological Research Group (SARG), who completed survey of the valley.

Estimates of population size on Black Mesa are slightly more well-developed than those for Long House Valley and several methods have been applied in order to provide estimates of the number of individuals inhabiting the mesa at any given time throughout the study period. Swedlund and Sessions (1976) created a developmental model of population growth for northern Black Mesa based on estimates of room counts at specific times during the study period. From these room counts, they assumed an average of 5.5 persons per household and calculated the total number of persons represented in the study area during key periods. Later, Layhe tackled the problem of estimating population size

from archaeological remains as a main goal of his 1981 doctoral dissertation. Building on the work of Swedlund and Sessions (1976) and other population size estimates attempted for prehistoric Southwestern sites, he calculated the Black Mesa study area population size using four different methods (Layhe, 1981).

Before applying each of the four methods, Layhe (1981) first calculated an individual site population index using multiple regression analyses of site area and artifact densities. His first method calculates the total population of the study area through time by summing the individual site population indices within each 25-year span for sites that were greater than 100m²; sites less than 100m² were likely limited activity sites, not habitation sites (Layhe, 1981). Layhe's second method considers seasonal use of sites in its estimates and uses the same individual site population index values and 100m² criteria, but considers only 50% of the individual site population index values for sites dated prior to AD 1000 (Layhe 1981). Layhe argues that site density post-AD 1000 would preclude seasonal use of the area (Layhe 1981). The third method incorporates the criteria of the first two, but excludes sites without redware artifacts (Layhe 1981). These sites are assumed not to have been habitation structures because they were unlikely to have the necessary subsurface structures (Layhe 1981). The fourth method is an average of the population estimates derived using the first three methods (Layhe 1981). A comparison of smoothed versions of Swedlund and Sessions (1976) and Layhe's (1981) population size estimates are shown in Figure 2.3. I have chosen to use the fourth estimate as our baseline because each method Layhe considered above has strong archaeological justifications and averaging estimates derived using multiple methods of estimation may smooth out potential sources of error in each individual method.

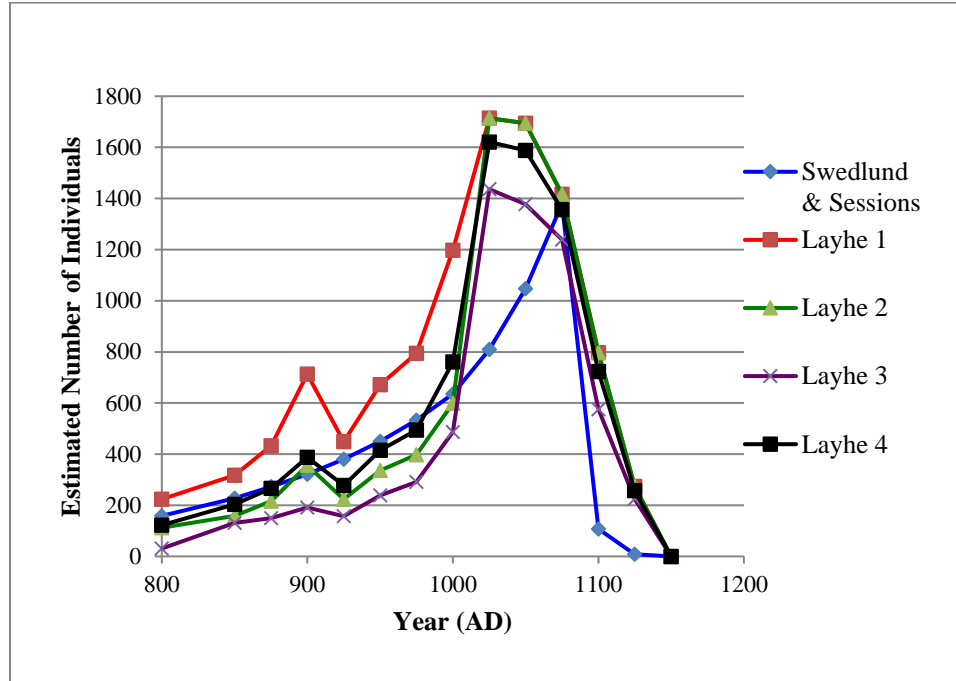


Figure 2.3: Black Mesa individual population counts developed through the various methods described above.

The cultural history of Long House Valley and Black Mesa informs the construction of the models developed as part of this project. This basic understanding of ancestral Pueblos subsistence strategy, residence and inheritance rules, and economic organization allow accurate recreations of the interactions between members of the simulated populations that are vital for creating models that can be used as tools for fine-scale paleodemographic research. The paleodemographic data available for the study areas provide us with invaluable data against which to compare model results. None of this information, however, can provide specific information on the timing and magnitude of migrations, despite the critical role population movements would have played in the prehistoric Southwest.

Migration in the Prehistoric Southwest

The prehistory of the American Southwest is characterized by population movements that occurred at least partially in response to changing environmental conditions in marginal environments for maize agriculture (Braun and Plog 1982, Hill et al. 2004, Matson et al. 1988, Nelson and Schachner 2002, Ware 2014). Despite abundant archaeological evidence for migrations, understanding the effect of migrations on prehistoric demographic patterns has been limited by the low temporal resolution of the archaeological data. However, the available high-resolution paleoenvironmental data available for the study areas in this project have the potential to shed light on both the timing and nature of prehistoric migrations in ways that other efforts have lacked. While environmental and climatic perturbations may not be the sole reason an individual, family, or population chooses to relocate, the environmental data available for Long House Valley and Black Mesa can be analyzed to identify periods of environmental stress, both small- and large-scale and short- and long-term, that may have potentially motivated such movements.

Population movement was a major adaptive strategy to buffer against various types of environmental stress and is considered a normal part of settlement history in the prehistoric Southwest (Cameron 1993, Ezzo and Price 2002). The earliest migration research in archaeology focused on identifying likely migrations from the archaeological record (Rouse 1958, Rouse 1986). Archaeologists have looked for evidence of migrations by examining cultural discontinuity among artifacts, changes in architectural styles, changes in foodways as evidenced by floral and faunal remains, and differences in burial

practices, as well as the skeletal morphology or isotopic composition of those burials (Adams et al. 1978, Boyer et al. 2010, Cameron 1993, Ezzo and Price 2002).

Although numerous methods exist for identifying migrations from the archaeological evidence, many of these efforts have fallen short for a number of reasons (Cameron 1993, Lightfoot 1993, Rouse 1958, Rouse 1986, Tomka and Stevenson 1993, Woodson 1999). First, small-scale (individual or family) or short-distance migrations do not typically leave traces in the archaeological record like community-wide or larger migrations do (Adams et al. 1978). Additionally, it is often difficult to determine if observed patterns are the result of trade or diffusion rather than migration because the movement of objects does not necessarily indicate the permanent movement of people (Anthony 1990). Finally, a lack of knowledge of the population dynamics in the donor and recipient regions prevents identification of these migrations by means of demographic changes (Ahlstrom et al. 1995, Hill et al. 2004).

Later migration research in the Southwest has placed an emphasis on examining likely causes for migration (Dean 2010, Wright 2010). Migrations are often framed as responses to negative “push” factors in the home region with concurrent positive “pull” factors from the neighboring regions (Ahlstrom et al. 1995, Anthony 1990, Cameron 1993). Push factors may include environmental conditions and related resource stress, health and nutrition, disease, immigrant pressure, conflict, or ideological differences (Nelson and Schachner 2002). Pull factors are less straightforward, but better environmental conditions in the recipient region, the need to strengthen social ties with neighboring groups, and trade have been considered (Nelson and Schachner 2002).

A number of studies have taken a more holistic view of migrations and examine not only the archaeological signatures of the proposed migrations but also the demographic or social contexts in which these movements occurred. Hill et al. (2004) examined the role of intrinsic demographic change on aggregation and migration in the San Pedro Valley. Their findings suggest that gradual population decline, due to disease and nutritional stress, may have led to a need for immigrants just to maintain their populations and that complex demographic processes, in addition to social and environmental factors, finally led to the abandonment of the area by the few that remained in the region (Hill et al. 2004).

Others have looked at migrations from less of a push/pull perspective and have instead assessed the relationship between migrations and social connections that predate the upheaval that characterizes the period from AD 1200 to AD 1450. Some have argued these larger-scale migrations should be considered natural outcomes of existing relationships and are better characterized as expanded versions of serial migrations or the normally occurring circulation of individuals between populations (Bernardini 2005, Schachner 2010). Still others have used analyses of ceramic and obsidian distributions to provide insight into the changing social networks throughout the Southwest and to characterize the relationships between migrant communities and local populations (Ferguson et al. 2016, Mills et al. 2015). These approaches both identify types of social connections that can be elucidated through archaeological investigation but also consider their role in shaping the nature of population movements in the prehistoric Southwest.

Despite the diversity of these investigations into migrations in the Southwest, many explanations continue to rely on mostly environmental explanations while acknowledging

that other factors may also have contributed to movement decisions (Ahlstrom et al. 1995, Anthony 1990, Cameron 1993, Kohler et al. 2012). Research into both local and regional abandonments in the Southwest has established that environmental variation within regions or climate differences across regions provide likely explanations for both smaller-scale population movements and large-scale abandonments (Ahlstrom et al, 1995, Anthony 1990, Dean 2010, Schlanger 1988, Schlanger and Wilhausen 1993, Woodson 1999, Varien 1999). Dean et al. (1985) proposed one theoretical model for expected behavioral responses to environmental change that is especially useful for this project. They suggested that low-frequency environmental processes are those that occur over spans of approximately 25 years and these low frequency changes have a dramatic impact on human populations if they are severe enough to reduce the carrying capacity to a level that cannot support the existing human populations (Dean et al. 1985). Typically the responses to changes in low frequency processes involve major behavioral modifications over longer periods of time, including strategies such as large-scale population movement (Ahlstrom et al. 1995, Dean et al. 1985, Schlanger 1988). High frequency variations, on the other hand, occur in shorter cycles, typically five to eight years (Dean et al. 1985, Schlanger 1988). These high frequency processes include seasonal and annual variations in climate, changes in crop yield, and changes in natural resource productivity, and are especially important when populations are at or near carrying capacity (Dean et al. 1985). Populations respond to high-frequency environmental changes with buffering adaptations including small-scale emigrations, relocation of fields, diversification of arable environments, water control measures, and

increased reliance on wild food resources (Ahlstrom et al. 1995, Dean et al. 1985, Schlanger 1988).

Following this theoretical model, Schlanger (1988) put forward three hypotheses regarding the nature of population movements and the expected population response. Short-term environmental fluctuations (< 2 years) that lead to crop shortfall may result in temporary, short-distance movements that either are not observable archaeologically or appear as periods of population maintenance in the donor area. Moderate-length (5-8 years) shortfalls will result in longer-term, longer-distance migrations including the abandonment of habitations but not entire sites. These will appear, if observable archaeologically, as short-term population declines in the donor area. Finally, long-term environmental fluctuations (>25 years) that result in shortfalls will result in permanent, large-scale abandonment of sites with concurrent population decline (Schlanger 1988).

Despite abundant environmental time series data available for many areas of the Southwest dating back as far as AD 200, these theoretical models rely on more qualitative descriptions of the nature of the environmental change when attempting to explain the reasons for prehistoric population movements. Attempts to test these hypotheses have involved the use of room counts to identify population size changes as they correlate with environmental conditions (Schlanger 1988, Hill et al. 2004). Both Schlanger and Hill et al.'s studies failed to adequately characterize the nature of the migration or better explain the causes, nor have any of these earlier studies examined only local population movements. The Black Mesa and Long House Valley areas are ideal locations to further evaluate these models because the abundant environmental and demographic data available permit the investigation of the effects of even the most minor

environmental perturbations on local population movements and resulting demographic patterns.

Black Mesa and Long House Valley Interactions

Because of the proximity of Black Mesa and Long House Valley, it is reasonable to assume long-term, regular interactions between the populations of the two areas. It is also likely that episodes of environmental stress on Black Mesa had tremendous effects on the population structure of Long House Valley and *vice versa*, but these effects have not been previously investigated.

Archaeological evidence from the time of the abandonment of Black Mesa reveals that its residents took everything they owned, including heavy metates, when they left the mesa, suggesting that they knew where they were going and that their destination was only a short distance away (Gumerman and Euler 1976). Throughout the region, it appears that displaced populations moved into the few areas that remained agriculturally productive. In the case of the Black Mesa population, it is most likely that during times of environmental stress they moved off the northern edge of the mesa into the Tsegi Canyon drainage area, which includes Long House Valley (Gumerman and Euler 1976). As a result of these interactions and environmental differences between the two areas, migration from Black Mesa into Long House Valley should be expected during periods of environmental stress on Black Mesa and observed as periods of marked population growth in Long House Valley. The next chapter presents the results of a pilot study that explored this hypothesis.

CHAPTER 3: UNDERSTANDING MOVEMENT BETWEEN BLACK MESA AND LONG HOUSE VALLEY—A PILOT STUDY

Given the expected interactions between the Black Mesa and Long House Valley populations, I set out to evaluate whether episodes of environmental stress on Black Mesa might affect population patterns observed in Long House Valley. The archaeological reconstructions of population counts for Long House Valley indicate periods where the population size increased faster than would be expected through internal growth (Dean et al. 2000). This observation, coupled with the likelihood of regular interactions between the two populations, suggests that population movement into the valley from the mesa may have been an essential component of valley demography.

In order to evaluate the relationships between these populations, environmental variation, and resulting population movements, I conducted a pilot study to test the effects of mesa-top environmental variation on the valley population. In this study, I hoped to analyze the fine-scale environmental data using a variety of quantitative methods and, in conjunction with the theoretical models described above, predict periods in which migrations, both short- and long-term, might have occurred. The methods employed in this pilot study can potentially be applied to data sets throughout the Southwest to explore interactions between groups in various areas within the region based on spatial environmental variability.

Data necessary for this migration study include Palmer Drought Severity Indices (PDSI) and population estimates for the study region. PDSI are measures of the effects of drought on potential crop production for a given area during a given time period (Palmer 1965). The PDSI data for the Tsegi region, which includes both Black Mesa and Long

House Valley, were generated by the University of Arizona Tree-Ring Laboratory's Southwest Paleoclimate Project (Dean and Robinson 1977). These data give yearly estimates of drought severity throughout the study period. Drought range designations and the actual PDSI data are shown in Figure 3.1.

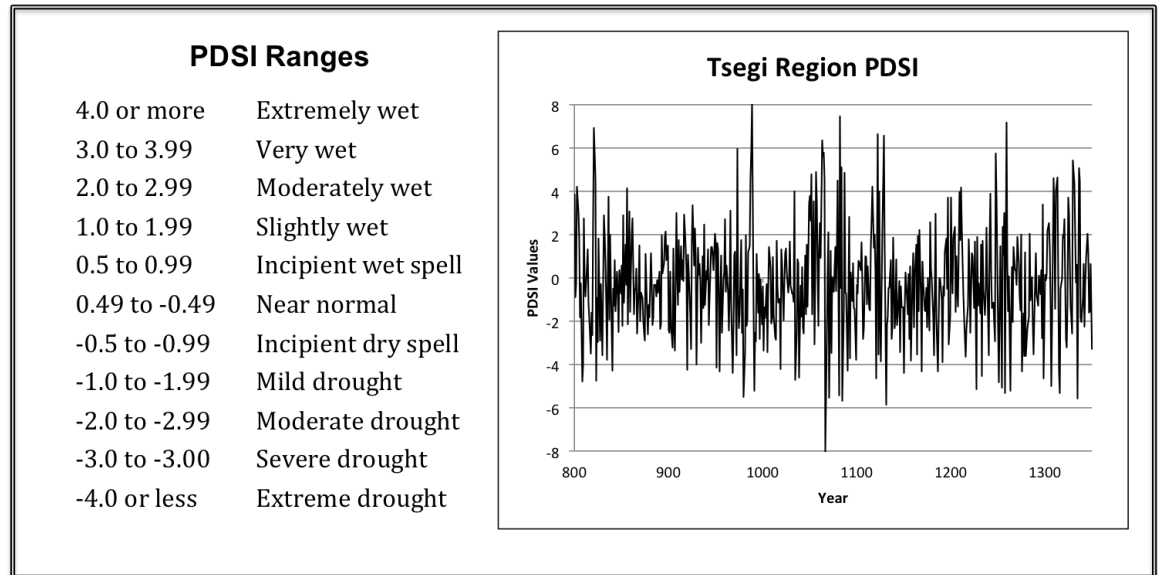


Figure 3.1 PDSI Ranges and Tsegi Canyon PDSI values for the study period

The population estimates used in this pilot study were developed by archaeologists involved in the Long House Valley project, a component of the Southwestern Anthropological Research Group, using the techniques described in Chapter 2. They produced estimates of household counts for each year for the entire valley throughout the study period (see Figure 2.2) (Euler and Gumerman 1978). Data analyses in this pilot study were conducted using the NumPy (van der Walt 2011) and Pandas (McKinney 2010) libraries for data analysis in iPython Notebook (Perez and Granger 2007) and Microsoft Excel.

Data were analyzed using the tools above to explore the specific effects of Black Mesa environmental change on the Long House Valley population patterns. First, I used a variety of methods designed to identify periods of environmental stress of different magnitudes and durations that might be perceived by the human populations living on Black Mesa. Then, these stress periods were mapped onto the Long House Valley population curves to determine if there were relationships between mesa stress episodes and rapid population growth in the valley. Following the hypothesis proposed by Dean et al. (1985) and Schlanger (1988) I developed three separate methods.

Method I assumed that the people who are making migratory decisions have perfect environmental knowledge and memory. The script first identified “stress years” or years in which the PDSI value is below -1 . After each stress year was identified, and following Schlanger’s (1988) classifications of length of environment stress episodes, the average of the PDSI values for the previous 2, 8 and 25 years were calculated. If the calculated average PDSI value for each period was below -1 , the originally defined “stress year” was classified as mild (average of 2 years previous is less than -1), moderate (average of previous 8 years is less than -1), or severe (average of previous 25 years is less than -1). The classified years were then plotted on top of the Long House Valley population curve.

Method II used moving averages to determine stress years. Its aim was to simulate migratory decision-making based on perception of medium- and long-term environmental trends in a certain number of years prior to the year being evaluated. To do this, moving averages of PDSI values were calculated for each year in the study period (8- and 25-year moving averages for the years AD 807-1350 and AD 824-1350, respectively). If the value of the 8-year moving average for the year was less than -1 , the year was classified

as one with moderate environmental stress. Similarly, if the value of the 25-year moving average was less than -1 , the year was classified as one with severe environmental stress. These moderate and severe episodes of environmental stress on Black Mesa were then plotted on the Long House Valley population curve.

Method III was also developed to simulate decision-making based on medium and long-term environmental trends, but instead of calculating moving averages, this method first divided the data for the study period into 8- and 25-year intervals and then averaged the PDSI values for all years in those intervals. Transforming the data in such a way does not permit the use of the $PDSI < -1$ threshold used in the first two methods. Instead, following a study by Schlanger and Wilshusen (1993), the mean PDSI value for the entire study period was calculated and episodes of environmental stress were identified as those 8- or 25- year intervals in which the average PDSI value was one or more standard deviations below the mean. The values for each year within the interval were used to determine whether the environment was improving or degrading. If the trend was negative and the interval met the PDSI criteria, they were identified as moderate (8-year) or severe (25-year) periods of environmental stress on Black Mesa and plotted on the Long House Valley population curve.

Results of the pilot study revealed that periods of environmental stress on Black Mesa corresponded extremely well with periods of marked population growth in Long House Valley. Although the results obtained using each of these methods are similar, each method reveals interesting information about the nature of potential population movements between Black Mesa and Long House Valley.

Figure 3.2 illustrates the results of Method I, which identified stress years and then calculated PDSI values for previous years. Three periods of severe environmental stress are identified (at AD 892, AD 1014-1020, and AD 1156-1165) that precede episodes of population growth in Long House Valley. The archaeologically determined date for the abandonment of Black Mesa by ancestral Pueblo people is approximately AD 1150 (Gumerman and Euler 1976), which is slightly earlier than the environmental data would suggest. However, because of the limited resolution of archaeological ceramic dating methods that were used to estimate the time of abandonment, it seems likely that the abandonment occurred during the final stress period identified by this analysis. Numerous periods of moderate environmental stress on Black Mesa correspond well with less dramatic population increases as well. Finally, short-term periods of environmental stress on Black Mesa are found in periods before slight periods of population growth on Long House Valley, but because responses to such short-term stress are difficult to observe archaeologically, this relationship might not be meaningful.

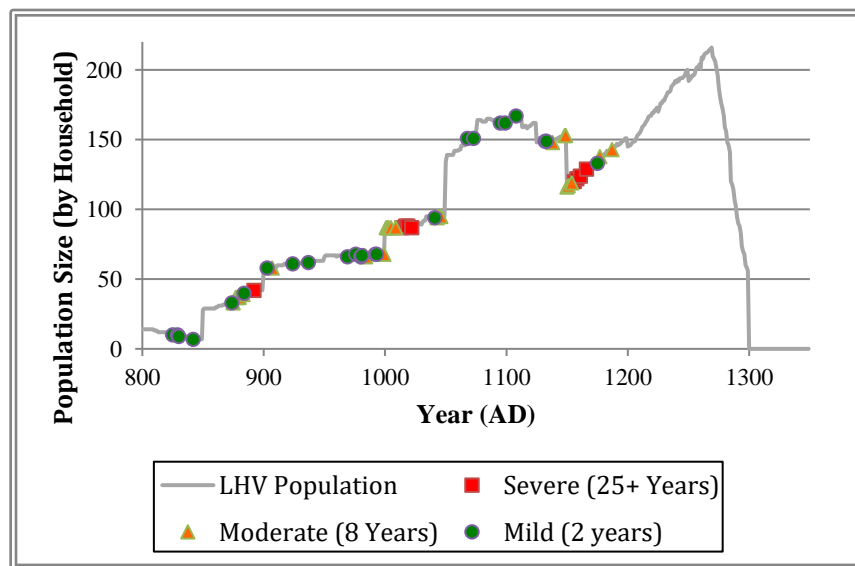


Figure 3.2: Episodes of Black Mesa environmental stress of differing severity plotted on the Long House Valley population curve.

The results of Method II, using moving averages to determine unfavorable environmental trends, are shown in Figures 3.3a and 3.3b. The results shown in Figure 3.3a are quite similar to those periods of severe environmental stress identified using the first method, while the results in Figure 3.3b are generally similar to those periods identified as moderate stress using the first method. An interesting difference between the results of the two methods is the identification of additional environmental stress episodes after the abandonment of Black Mesa. Continued periods of environmental stress on Black Mesa following the major abandonment event provide a reasonable explanation for why an area that had been continuously inhabited for several hundred years was not reestablished during the later years of the study period. Undoubtedly, similar periods of post-AD 1150 environmental stress would have been identified using the first method, but because of the decision to end the analysis at AD 1200, these episodes were not identified. Further investigation of post-AD 1150 environmental data in the models should reinforce these findings.

Another difference between Methods I and II is the identification of several periods of moderate stress during the early (AD 1100) peak in the Long House Valley population curve. Several periods of short-term environmental stress were identified using the first method but the classification of these episodes as those of moderate duration using the second method may better explain the slight population increases seen on the Long House Valley curve during this first peak.

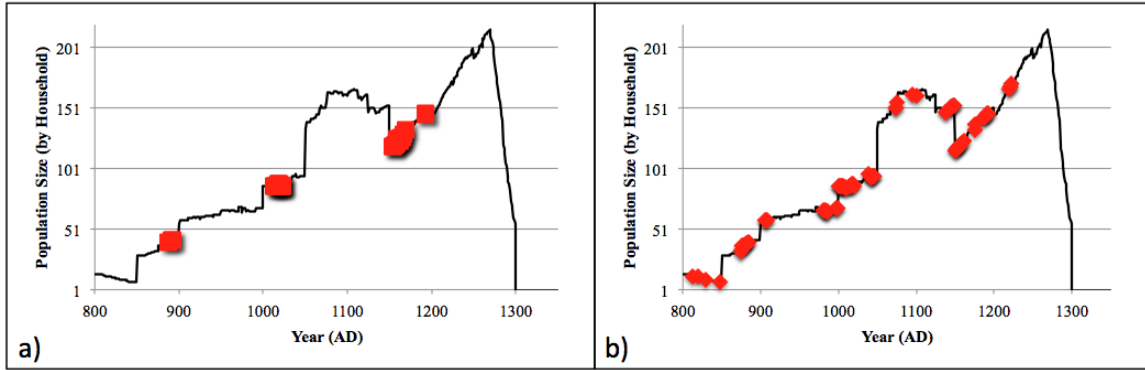


Figure 3.3: Episodes of Black Mesa environmental stress plotted on Long House Valley population estimates: a) 25-year duration b) 8-year duration.

When the PDSI data are converted into 8- and 25-year intervals and trends within these intervals are considered, as in Method III, fewer periods of environmental stress on Black Mesa are identified and they do not align as well with periods of population growth in Long House Valley (Figures 3.4a and 3.4b). Intervals of moderate and severe stress are identified for periods just before the approximately AD 1150 abandonment of Black Mesa, however, demonstrating that there was prolonged environmental stress leading to the abandonment of the valley. A late, moderate episode at approximately AD 1200 also points to continued environmental stress on Black Mesa post-abandonment.

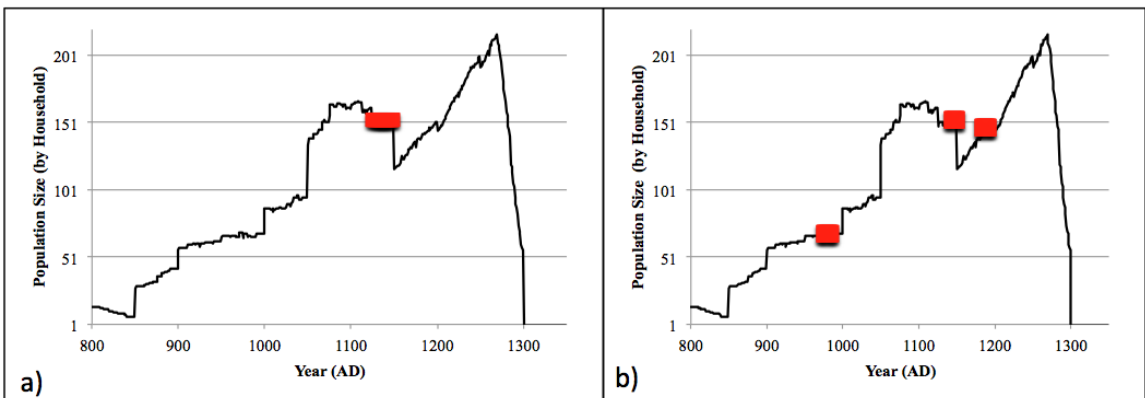


Figure 3.4: Periods of PDSI one standard deviation from mean with negative overall trends when data is divided into intervals and plotted on Long House Valley curve: a) 8-year intervals and b) 25-year intervals.

The results of this study reveal a clear relationship between episodes of environmental stress on Black Mesa and dramatic population increases in Long House Valley. These results appear to confirm that long-term interactions between the people of Black Mesa and Long House Valley allowed for population movements from Black Mesa into Long House Valley as an adaptive strategy for overcoming periods of resource stress of different durations. Combining fine-grained environmental data with archaeological population estimates for two relatively small areas allows for the characterization of potential local population movements that are traditionally unobserved archaeologically. Because of the correlation between environmental stress episodes of varying lengths and magnitudes and population pattern changes in Long House Valley, the results of this study suggest that any consideration of demographic trends in Long House Valley must necessarily consider the role of population movement in driving the trends.

The approach used in this pilot study permits a greater understanding of the interaction processes that lead to population movements within specific areas and that may be of such small magnitudes that they may not be recognized archaeologically. Additionally, these methods give explicit consideration to both the donor and recipient regions. By incorporating the data used in this project, as well as more complex social and demographic processes, into the agent-based models that underlie this project, I hope to generate a clearer picture of the processes that drove the archaeologically-observed population patterns in Long House Valley and Black Mesa. This localized approach can potentially be applied to other areas in the Southwest to form a more nuanced picture of the nature of small migrations and, eventually, be expanded to permit more precise

explanations for the archaeologically observed patterns of migrations between larger regions.

CHAPTER 4: AGENT-BASED MODELING IN ARCHAEOLOGY

Through the years, archaeology has applied many methodological approaches, incorporating increasingly sophisticated analytical and interpretive techniques as technology improves. Agent-based models (ABMs) like the ones used in this project have become a standard methodological tool in many of the sciences because they require precise design and parameters that produce objective and repeatable results and because they allow “bottom-up” empirical research (i.e., patterns emerge from simple rules coded into the model, thus generating new data that can be analyzed and interpreted) (Axelrod 1997, Epstein 1999, Doran and Gilbert 1994, Gilbert and Troitzsch 1999, Lake 2014, Wilkinson 2005). ABMs have been used as investigative tools in a wide variety of anthropological research, from reconstructing kinship and social structures (Gilbert and Hammel 1966) to describing the spread of epidemics (Carpenter and Sattenspiel 2009, O’Neil and Sattenspiel 2010, Sattenspiel et al. 2016). ABMs are also an acceptable methodological tool in population projection and reconstruction among demographers studying modern populations (Billiari and Prskawetz 2003, Silverman et al. 2013). ABMs have become commonly used as tools for archaeological investigation and, although the majority of the earliest models focused on modeling socio-ecological interactions, more recent efforts have started incorporating demographic parameters and behaviors similar those used in the models developed for this project.

Agent-Based Modeling Philosophy

Since the 1980s, agent-based models and simulations have been used in many social sciences because they provide a new way to do empirical research (Epstein 1999,

Gilbert and Troitzsch 1999). These models gained acceptance and popularity because they represent a natural way to describe social systems by replicating the actions of individuals within a society, allowing us to explore our assumptions and experiment with different inputs that could have affected social change (Gilbert and Troitzsch 1999, Wilkinson et al. 2007). Major benefits of agent-based modeling include the precision with which models must be built and parameters set, and the objective and repeatable results that are produced by the models (Doran and Gilbert 1994, Kowarik 2011). ABMs are a powerful means by which to do empirical research that is neither wholly inductive nor deductive, but instead is better characterized as generative (Epstein 1999). The classic ABM places agents in a specific spatial environment, assigns them specific rules for interaction and, from these simple rules, group-level patterns emerge that might not be obvious just from looking at the local rules (Axelrod 1997, Epstein 1999, Gilbert and Troitzsch 1999, Wilkinson 2005). As a result of these models, new patterns and data are generated that can then be analyzed and interpreted (Epstein 1999, Wilkinson 2005).

ABMs can be distinguished from other types of modeling because they do not require assumptions of homogeneity, equilibrium, normality, or linearity and instead can successfully address nonlinear, dynamic questions in heterogeneous populations (Epstein 1999, Henrickson and McKelvey 2002, Wilkinson 2005). Dynamic systems that include heterogeneous agents that change and adapt over time while also being the drivers of that change are difficult to model using equations, but are exactly the sort of systems ABMs are best equipped to handle (Epstein 1999, Wilkinson 2005).

Agent-based modeling and simulation can be used for a variety of purposes: prediction, performance, training, entertainment, education, theory formalization, and

discovery but, in social science research, the emphasis is largely on prediction, performance, formalization, and discovery (Axelrod 1997, Gilbert and Troitzsch 1999). Additionally, the ability to do the sort of experimentation allowed with ABMs is very rare in social science research but is critical for establishing causal relationships in the past (Gilbert and Troitzsch 1999). By using ABMs, theories and hypotheses about the situations being studied can be formalized by incorporating them into model construction and determining whether the model outputs provide evidence in support of such theories (Gilbert and Troitzsch 1999).

ABMs are ideal for examining the dynamic and complex processes that have led to cultural change. They allow us to explore how the seemingly minor decisions made by a small number of individual actors interact to establish the characteristics of larger social groups (Epstein 1999, Gilbert and Doran 1994, Gilbert and Troitzsch 1999).

Agent-based modeling has emerged as an attractive alternative to traditional mathematical models for a variety of reasons. Mathematical models are often praised for their generalizability, parsimony, and reducibility (Bonabeau 2002, Doran et al. 1994), are appropriate for modeling all sorts of social and natural processes, and continue to form the basis of most formalized models (Gilbert and Hammel 1966, Doran and Gilbert 1994). However, many have criticized the use of mathematical models for simulating societies for a number of reasons. Differential equations models lack the ability to easily connect micro- to macro- relationships and do not adequately model behaviors (Bonabeau 2002, Epstein 1999). That interactions between the micro-level or small-scale behaviors or decisions of small groups yield emergent macro-level or large-scale rules is a fundamental aspect of understanding human society, but differential equations are not

suited for explicit exploration of these interactions or relationships (Parunak et al. 1998, Schelling 1978). Similarly, equation-based models are only able to evaluate the outcomes of the behaviors; they cannot emulate the behaviors themselves (Parunak et al. 1998). The formalized mathematics of differential equations models also removes nuance from the phenomena they are studying and prohibits qualitative observation of processes as they emerge (Epstein 1999).

Despite these limitations, the choice to use either an ABM or a mathematical model is conditioned on the questions asked and the nature of the systems or processes under study. While a large set of mathematical equations may approach recreating an ABM, there is a point when creating such equations becomes intractable, especially where there are multiple interacting agents (Bonabeau 2002, Epstein 1999). ABMs, with their requirement of bounded rationality (i.e., agents are only able make decisions based on the information and reasoning capacities coded into the model), are also better to simulate situations where the behavior of the agent is not optimal or purely rational (Dyke 1981). In addition, ABMs are preferable when there is a need to model stochastic processes—noise can be added to equation-based models but randomness cannot be targeted on specific individuals or events at specific times as it can be in ABMs (Bonabeau 2002).

On a more practical level, ABMs have advantages over mathematical models because they are most often computer programs. Doran et al. (1994) argue that programming languages are more descriptive than mathematics and they are better equipped to handle parallel processes and processes in which the order of occurrences is not specified. Furthermore, the programming and results of computational models can be

understood without an advanced knowledge of math (Epstein 1999). Mathematical models, however, are praised for their ease of communication between researchers because of the codified language of mathematics. Sharing the specifics of ABMs through publications is more difficult than sharing mathematical models because of the need for explaining every component of these complex models before sharing the results (Grimm and Railsback 2005).

Agent-Based Models in Archaeological Research

ABMs are especially well suited for addressing archaeological questions because the types of data typically generated by the archaeological record provide ideal information from which to start model construction (Kohler and van der Leeuw 2007). The vertical distributions of artifacts provide abundant time series data against which to calibrate and validate models, while the horizontal distribution of artifacts, features, and settlements provide key data about spatial patterning (Axtell et al. 2002, Kohler and van der Leeuw 2007). These are precisely the types of data that permit exploration of questions about how human behaviors have changed through time and across space and they form the foundation of many archaeological ABMs (Kohler and van der Leeuw 2007, Mithen 1994).

Archaeologists are faced with the challenge of interpreting dynamic changes over time and space from the static archaeological record. ABMs can not only fill in some gaps in these data, given sufficient data gathered from field or lab work or from background research to set model parameters, but they can also aid in understanding the relationships between rules and interactions and how these actions manifest in the

patterns observed in the archaeological record (Doran and Gilbert 1994). As a result, ABMs have been applied to multiple archaeological questions and have generated both answers to important questions and new hypotheses for consideration.

Despite the obvious benefits of the application of ABMs to archaeological research, there are critics that point to problems associated with such an approach. These issues fall into two separate categories: issues related to model construction, analysis, and dissemination of results, and problems related to differences in theoretical approaches. One of the most daunting problems is obtaining sufficient evidence to support model assumptions or to set model parameters (Doran and Gilbert 1994, Kowarik 2011). Although there is hope that continued use of ABM methodologies will help inform our understanding about how fundamental human attributes such as cooperation, altruism, or social organization evolved, it is not clear how these attributes manifest themselves in the archaeological record and, therefore, the data required to construct models of these processes is unavailable. Beyond the issues of not knowing which data to use, in some parts of the world and some time spans, the archaeological data required to build even a relatively simple socio-ecological model simply do not exist (Kohler 2007, Kowarik 2011).

Even when there are sufficient data to build an appropriate model, the time and effort required to construct a model is overwhelming to many archaeologists who have little experience with the mathematics, cognitive science, and computer science foundations required to build models (Aldenderfer 1998). When models are actually built, there are issues with both the replication of the results and the dissemination of results to others; for example, the failure to complete sufficient runs to thoroughly

validate the data and the inability to completely describe the model in the short space allotted by many journals (Axelrod 1997).

Theory-related issues with ABMs and archaeology involve the view by many post-processualist archaeologists that such models are too objective, artificial, and imposed and that they fail to truly model social change (Aldenderfer 1998). Whole society models were embraced by those who espoused the systems approach associated with processual archaeology, but the movement toward methodological individualism and subsequent rise in popularity of approaches focused on individuals led to criticism of these types of models (Aldenderfer 1998). Indeed, in many early applications of ABMs in archaeology, the primary goal was to create models that produced the best fit to the archaeological record. Missing from these models were attempts to actually understand the processes of human interactions, how they manifest in the archaeological record, and how they lead to the formation of modern societies. Fortunately, ABMs are especially suitable for addressing these issues because individual agents can be modeled as the drivers of model behaviors.

Despite the evidence that indicates ABMs are a useful theoretical and methodological tool for exploring ideas about the past, the relatively few archaeological ABMs developed demonstrates that the potential of these models is not being fully realized (Cegielski and Rogers 2016, Doran and Gilbert 1994, Kowarik 2011). By constructing new models and expanding existing models, focusing on analysis and validation of model outputs, and increasing communication between modelers, field archaeologists, and others, ABMs have the potential to address novel research questions and make significant contributions to archaeological knowledge.

The earliest applications of agent-based modeling in archaeology were designed to answer questions related to socio-ecological dynamics, spatial processes, adaptation, long-term culture change, and social interactions, and several have dealt with field applications such as cultural resource management strategies, the prediction of site location, and testing of archaeological field methodologies (Kohler 2007, Kowarik 2011). Recently, Cegielski and Rogers (2016) examined a selection of archaeological ABMs and identified common themes among them. Historical models that attempt to match or confirm the archaeological record are the most common, followed by models that examine processes that lead to the formation of social complexity, then models that explore human ecology and its role in changing the environment over long spans of time, and finally those that model evolutionary processes (Cegielski and Rogers 2016). Descriptions of a variety of archaeological ABMs are provided in Swedlund et al. (2014) and Cegielski and Rogers (2016) but, of particular interest here, are those that model socio-ecological interactions and the relationship between human ecology and the environment.

The model that forms the basis of this project, Artificial Anasazi (AA), is among the earliest of these socio-ecological archaeological ABMs and was designed to explore reasons for why the prehistoric Pueblo people abandoned Long House Valley sometime around A.D. 1300 (Axtell et al. 2002). While archaeologists knew that drought, disease, and warfare likely played important roles in the abandonment of the valley, the AA researchers were interested in how demographic and social constraints interacted with these other factors in the time leading up to the abandonment of the valley (Axtell et al. 2002). ABMs require environments on which agents act according to some specific set of

rules, and Long House Valley was chosen because it provided a bounded space for which earlier research had generated an abundance of detailed environmental data.

The dynamic environment of Long House Valley was reconstructed from paleoenvironmental data including Palmer Drought Severity Index values, hydrological cycles, and soil aggradation curves. Agents in the AA model are households that are endowed with various attributes (e.g., life span, fissioning, nutritional requirements, corn consumption and storage capabilities) determined archaeologically and ethnographically in order to replicate important features of human households practicing horticulture.

At each time step, the households consider the productivity of their current farm plot, any stored corn, and potential yields for the upcoming year (calculated using the fine-scale environmental data) and make decisions based on these factors. Figure 4.1 details the inputs and activities that are carried out during each run of the AA model. While the results of runs are somewhat variable, in general the population data generated by the model are a good fit for the population data generated by extensive archaeological survey and excavation (Axtell et al. 2002). Figure 4.2 shows average AA model behavior.

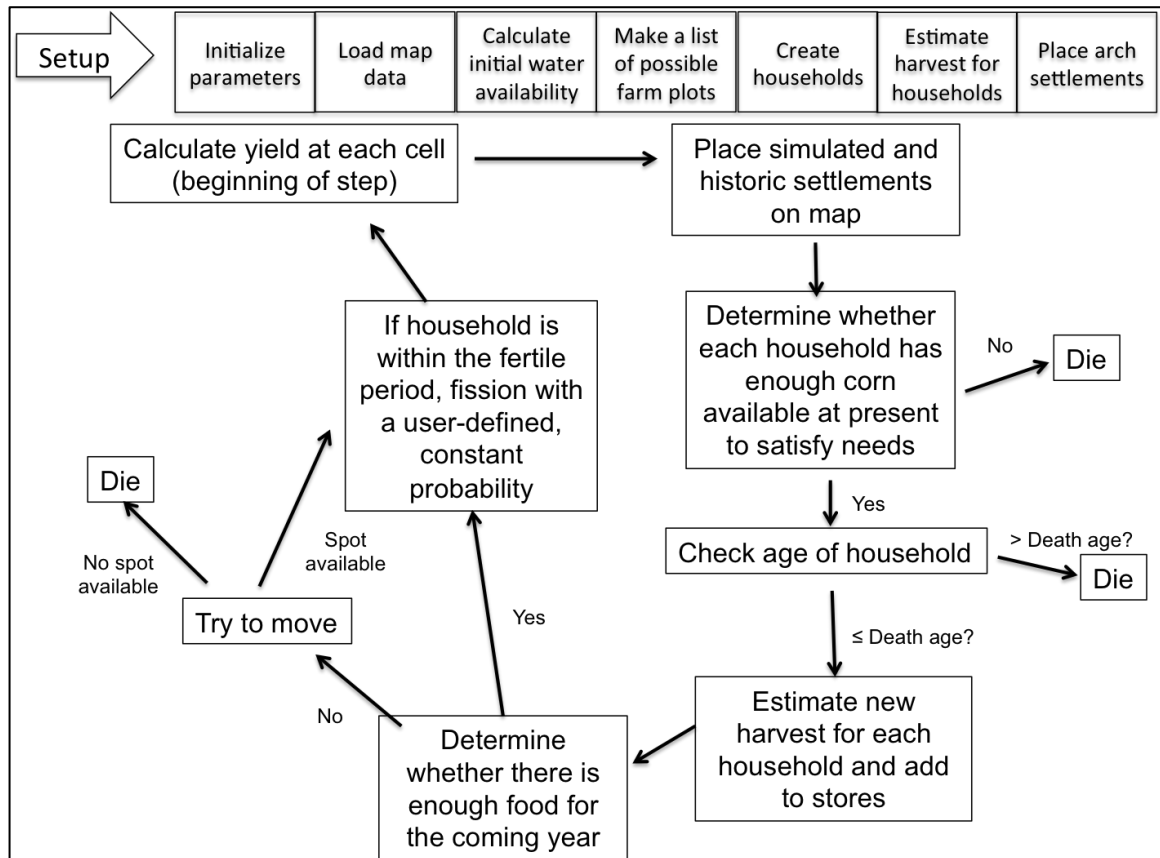


Figure 4.1: Artificial Anasazi model setup and activities carried out in each time step of the model.

The success of Artificial Anasazi motivated the development of additional ABMs that investigate social and ecological dynamics in other time periods in different areas of the world. The models developed as part of the Village Ecodynamics Project explored human-environment interaction in the Mesa Verde region and attempted to find underlying reasons for prehistoric aggregation, growth, and depopulation observed in the region (Kohler 2007, Kohler et al. 2012). These models utilize many of the same data types as the AA model but also incorporate additional data such as the availability of wild food resources and wood, as well as the potential effects of over-farming (Kohler et al. 2012).

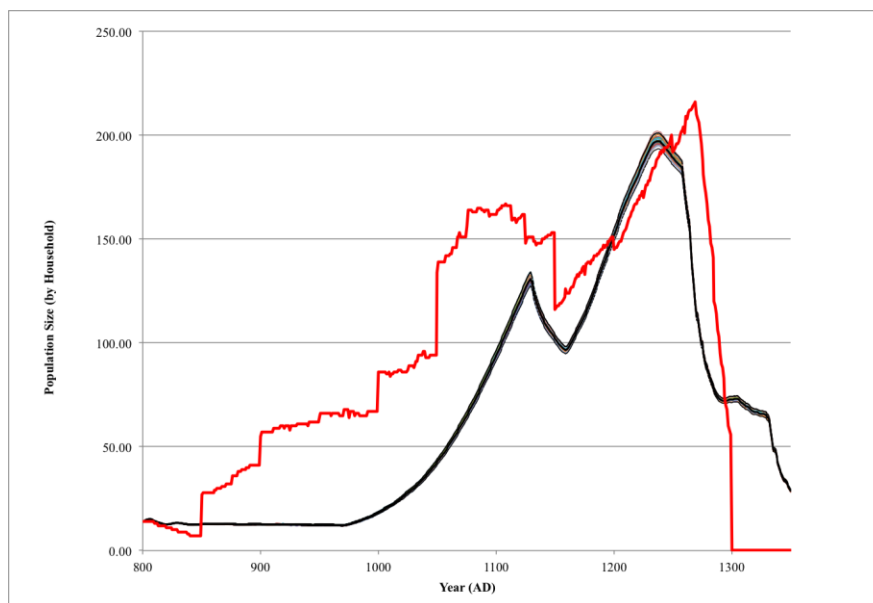


Figure 4.2: Average behavior of 20,000 runs of the AA model. Model behavior shown in black.

Another socio-ecological model, developed by Griffin and Stanish (2007), focuses on the development of complex societies in the Lake Titicaca basin. Like the others discussed above, this model considers the role of both social and environmental factors that may have led to political consolidation in the basin. The Lake Titicaca Basin model differs from both the Artificial Anasazi and the Village Ecodynamics models in that the environmental input data lack the temporal and spatial resolution of the others; the environment is only considered as a realistic landscape on which these processes and agents can operate (Griffin and Stanish 2007).

Each of the models described above focus on how the interaction between agents, both with each other and their environments, led to the development of social phenomena that are observed archaeologically. In each of these models, however, the agents are aggregate units like households, communities, or villages that are typically not assumed to have reasoning or decision-making abilities independent of those individuals that

comprise them. Recent archaeological modeling efforts have begun to incorporate realistic demographic processes and are specifically focusing on population dynamics, although most still resolve to the level of the household or community, instead of the individual (Cegielski and Rogers 2016, Lake 2014, Wurzer et al. 2014). The three archaeological ABMs described above all include demographic components. However, it is the way in which the demographic processes operate on the agents that differentiate the efforts of the Artificial Long House Valley extensions of the AA model (the focus of this dissertation) from these others.

Some of the models that comprise the Village Ecodynamics Project consider individual people within households (Kohler et al. 2012). Individuals reproduce (up to a maximum number of eight children) and die according to a rate tied to the food available to their household (Kohler et al. 2012). This modeling decision allows the population growth rate to fluctuate with resource availability and the model captures archaeologically observed population trends, but it does not permit exploration of the effects of different age-specific demographic rates on population dynamics. The Titicaca Basin model includes an enormous starting population (38,000 people who comprise numerous aggregated settlements), so modeling individual behavior was not feasible at the time the model was developed (Griffin and Stanish 2007). However, a certain percentage of the population does migrate to other settlements in each time step and the population is imbued with constant birth rates that fluctuate depending on regional conditions (Griffin and Stanish 2007). Again, while this model incorporates demographic processes that act on individuals, they are considered only as a means of capturing behaviors of the aggregate population.

The AA model included demographic processes similar to those in the Village Ecodynamics and Titicaca Basin models, but these acted on households. Individuals were not explicitly considered in published versions of the model (Axtell et al. 2002). The demographic parameterization and processes included in the AA model is described in depth in Chapter 5 as the process of disaggregating the model to the individual level is described. The goals of the Artificial Long House Valley project presented in this dissertation include not only providing insight into the prehistory of the study areas, but explicitly assessing the effects of various demographic processes that act specifically upon individuals on the population dynamics in the region.

Several recent models attempt to specifically address the role of variable demographic rates or processes on model behaviors, but do not realistically model demographic phenomena, such as biological reproduction or human mortality. For example, many models include a fertility parameter, but individuals reproduce at a constant rate (Alden Smith and Choi 2007, Barcelo et al. 2015, Premo 2006) or a rate that varies based on external conditions such as available energy (Barton 2014, Crema 2014). Others include fertility age ranges and or a target total fertility rate for their individuals (Christensen and Altaweel 2005, Kohler et al. 2012).

Archaeological ABMs that model individual mortality also differ in their approaches. As with fertility, the most common approach to modeling mortality in these models relies on the use of either constant death rates or a maximum age (Alden Smith and Choi 2007, Balbo et al. 2014, Kohler et al. 2012, Premo 2006). Others include increased mortality risks for the very young and very old or those especially susceptible to mortality from outside causes (Barton 2014, Crema 2014, del Castillo et al. 2014).

White's (2013, 2014) FamilyNet2 model is explicitly used to showcase the use of ABMs as tools for paleodemography and his demographic parameterization most closely approaches the level of demographic realism incorporated into the models developed for this project. This model incorporates a biologically appropriate fertility range (ages 16 to 35) and interbirth interval, but reproduction is modeled using a target total fertility rate (White 2013, 2014). Mortality is modeled as a constant rate from birth to reproductive age and is then reduced for adults up to a maximum age of 70. The results of analyses of White's (2013, 2014) model do match ethnographic fertility and mortality rates and illustrate one way that ABMs can be used as a valid alternative to mathematical modeling approaches typically used in paleodemography. However, the use of constant fertility and mortality rates instead of age-specific rates and other unrealistic demographic parameters or processes can result in unexpected consequences, as will be discussed in Chapter 6.

The models developed as part of this project represent the natural progression that has occurred with regard to the use of ABMs as appropriate methodological tools for archaeological and paleodemographic research. By disaggregating the populations to the level of individuals, incorporating realistic demographic parameters and processes, and allowing migration between two areas, the model can be used to test hypotheses about the population dynamics in the study area generated through other lines of archaeological and paleodemographic inquiry.

CHAPTER 5: DISAGGREGATING THE MODEL—METHODS AND RESULTS

In order to address the research questions described in the previous chapters, I, with assistance from Lisa Sattenspiel and Alan Swedlund, developed a series of models that extended the original Artificial Anasazi model. The model developed in the first stage of this project (Disaggregation) retained the same general structure of the original model, but was disaggregated in such a way that individuals, not households, were the primary agents (this chapter). The second stage (Demography) required endowing these individual agents with realistic demographic characteristics, such as age-specific mortality and fertility rates (Chapter 6). The final stage of the project (Migration) added the Black Mesa study area and allowed for migration between the two simulated regions (Chapter 7).

General Model Overview

The project described in this dissertation derives from the Artificial Anasazi (AA) model introduced in Chapter 4, and began with two different versions of the Artificial Anasazi model—one created by the original development team (Axtell et. al. 2002) using Ascape, a Java-based agent-based modeling framework and another developed by Janssen (1999) in NetLogo (Wilensky 1999), another agent-based modeling software. Because the fundamental structure of the modeling languages used to develop these two versions is so different, the first steps were to carefully examine both versions of the AA model, identify differences, and decide which modeling software to use as the models were extended. After thorough review, we determined that the essential processes, parameters, and outputs of the two models were equivalent. We chose to move forward

using the Jannsen (1999) model as our base model because NetLogo includes an inherent structure that makes the development and visualization of agent-based models somewhat simpler and because it is easier to analyze model outputs using built-in NetLogo features like BehaviorSpace, which allows for straightforward sensitivity analyses.

All model versions that include the Long House Valley landscape rely on the original environmental data sources developed using data collected during the Southwestern Archaeological Research Group's (SARG) survey of Long House Valley (Lindsey and Dean 1971) and organized into a number of separate data files that are input into the model during setup. The map file loads spatially explicit data for the different environmental zones within the Long House Valley landscape. These zones are: general valley, north valley, north valley dunes, mid-valley, mid-valley dunes, natural, uplands, Kin Biko, and empty. Once loaded, each of these environmental zones is given a maize zone designation that is used to determine its agricultural productivity potential. The water file includes the geographic coordinates of the various water sources, the type of water source, and the duration of the water source's availability within the study period. The adjustedPDSI file includes an adjusted Palmer Drought Severity Index (PDSI) value for each environmental zone during each year of the study period. The original AA development team derived the values by combining PDSI, hydrology, and soil aggradation data (Dean et al. 2000). These data are used to calculate the agricultural yield in each environmental zone during each year of the study period. Finally, the environment file includes the raw PDSI values, hydrology, and soil aggradation data for each zone during each year of the study period. Once these data are read in, the model determines the annual productive yield of each zone based on the adjusted PDSI values

and the crop production estimates developed by VanWest (1994). Table 5.1 shows these productivity estimates for each zone given a particular adjusted PDSI range.

Table 5.1: Productivity estimates for LHV productive zones developed by VanWest (1994) and original AA development team (Dean et al. 2000)

Adjusted PDSI Range	Yield 1 (North and Mid-valley floors, Kin Biko)	Yield 2 (General valley floor)	Yield 3 (Uplands)	Yield 4 (Sand dunes)
<= -3.0	1153	961	769	1201
-3 to -1	988	824	659	1030
-1 to 1	821	684	547	855
1 to 3	719	599	479	749
>= 3	617	514	411	642

Like the environmental data, the archaeological settlement data were derived from SARG surveys of the Long House Valley and were included in the settlement file. This file contains data about the various settlements, including the geographic coordinates of each settlement site, the duration of that site, the type and description of settlement, the size of the settlement, the number of rooms within the site, and the elevation of the site. These data are used to place archaeological settlements on the map, and to compare the number of simulated sites, as well as their location and size, to the archaeological record of the valley. They are also used to calculate the number of households on the landscape at any given time during the study period and provide the data needed to estimate the archaeological population sizes in all models that include the Long House Valley landscape.

All models that simulate the environment of Long House Valley also use the same general agricultural cycle described in Chapter 4 (see Figure 4.1) unless specifically noted. Once the environmental and settlement data are read in and the productivity of each zone is determined, an additional amount of heterogeneity is added through the use

of a quality calculation, which adjusts the yield of individual cells. This calculation uses two variables, harvest adjustment and harvest variance, to increase or decrease the annual productive potential for each plot. The resulting estimate of quality is used as a means of accounting for crop loss or other differences between actual and projected harvest amounts (Dean et al. 2000).

At initialization, households are created, placed randomly on the landscape, and they then locate nearby settlement locations and farms that meet the household's nutritional needs. Areas with the highest productivity are preferred as farm sites while settlement areas are selected because of their distance from the farm site or nearby water sources and their relative lack of productive potential. After each farm's yield is determined for each year, the amount of that year's harvest and the amount of a household's stored corn (drawn randomly from a range between 2000kg to 2400kg) are calculated. Based on these maize amounts, the model determines whether the maize supply is adequate for the household's needs. If it is not sufficient, the model calculates the difference between the available maize and the nutritional requirements of a household and that amount is set as the household's nutritional shortfall. The household then goes through the process of either finding a new farm and settlement to support itself or abandons the valley. If there is any surplus maize after needs are met, that amount is added to the stored maize amount and can be used for up to two years. This process is repeated for each year during a household's lifespan.

While the environmental data and agricultural processes remain similar between the AA model and subsequent versions, the process of disaggregating the model from a household-only model to one that includes individuals required significant rethinking of

the individual responses to changes in agricultural productivity. The major strategies used to complete this task are the focus of the next section.

Methods for Disaggregating the Model: Households to Individuals

The original Artificial Anasazi model compared population growth and decline to the archaeological estimates of *household* counts for each year of the AD 800 to 1350 study period. This decision was a logical one made by the original model developers because the archaeological data resolves only to the level of the household (i.e., only individual households could be recognized during the archaeological survey of the valley) (Axtell et al. 2002, Dean et al. 2000). However, it is clear that members of the original development team realized the need to disaggregate the model to the level of the individual in order to address more nuanced questions about population dynamics in Long House Valley. In the Ascape version of the AA model, developers had included a model extension, LHVDisaggregate that was designed to model behaviors of individual persons, as well as those of households. Unfortunately, it appears the original development team encountered a major challenge of model disaggregation: linking individuals to their respective households in such a way that both are subject to the underlying processes that drive the model. The LHVDisaggregate extension did not work because it was decoupled from the underlying environmental variables that help drive the population dynamics in the model. However, this attempt at extension did serve as a guide for us in our disaggregation efforts.

We named the first disaggregated version of the model Artificial Long House Valley-Baseline (ALHV-Baseline). In all model versions developed subsequent to this

baseline model, the ALHV designation is used to indicate model versions that include individual persons. The goal in developing the ALHV-Baseline version was to make it as similar as possible to the original AA model. Therefore, the majority of the differences in the two models reflect the need for person-specific variables and methods. As this version is the baseline for all other models developed as part of this project, the descriptions of model structure below are quite detailed.

Adding individuals to the model

In order to create an individual-level model, the first step was to create new populations of both household and person agents. In the AA model, as well as the ALHV-Baseline model, household characteristics were not read in from an external data file. Instead, fourteen households (i.e., the number of households present in the valley at AD 800, based on archaeological data) were created, given randomly defined amounts of stored corn and placed on the landscape in accordance with a specific method (*find-farm-and-settlement*) designed by the original modeling team to govern the task of selecting appropriate locations for farms and households when needed. In the AA model, household age was initialized at 16 to represent the minimum age of fertility of a hypothetical daughter within the household and household nutritional need was initialized at 800 kg (which assumes five persons per household, following the calculations of Sanders et al. (1979)). In the ALHV-Baseline model, the initialization of households was nearly identical to that in the original model, but household age, nutritional need, and an additional variable, household size, were initialized at zero and then *calculated* from the

characteristics of the individuals who were assigned to the household. These individuals and their characteristics were read in from a newly created persons data file.

The ALHV-Baseline model uses an initial population of individuals randomly selected from the 1885 Pueblo census available online (National Archives, 2014). From these census records, I collected sex, age, and relationships (e.g., mother, father, daughter, son) for members of 500 nuclear families. Using a random number generator, five sets of 14 families (households) were selected from those recorded. From those, I chose the set that had the characteristics most similar to the hypothetical households used in the original AA model (14 fertile females with the majority in the most fertile age classes). Each individual was assigned a personal identification number, a household identification number, a natal community (all individuals being read in are assumed to be native to the valley), a residence identification number (the location where they currently live, all live in the valley in this version of the model), and a random clan identification number (for a total of seven clans within the valley).

While age, sex, and relationships were recorded directly from the census records, the rest of the necessary individual characteristics either had to be calculated or inferred from known information. The mother was assigned the designation of head of household, due to the matrilineal social organization among the Pueblos, classified as married, and her mateID was designated to be the assigned ID for the father of that household. Fathers were also designated as married and assigned the mate ID of their spouse. Children within the household were assumed to be unmarried. The eldest child designation was assigned to the eldest child listed within that household in the census records and was

used to calculate the parents' fertility age (parents' age minus the age of the eldest child minus one). The fertility age of children within the household was set to zero.

Each of the person characteristics described above was read in to the model directly from the data file; these data are listed in Appendix C. When the persons file is read in, the fertility age of the children of the household is set to a random number within the min-and max fertility age range, and the fertility ends age for all individuals is set to a random number within the min- and max fertility ends age range. The age-specific fertility rates for each person were also set according to the age-specific fertility schedule specific to the particular model run and an individual's nutritional need was calculated according to methods discussed in detail below. In addition, the person's individual nutritional shortfall was set at zero for this first step in the simulation. Death age was randomly drawn from a range of minimum and maximum death ages.

After persons have been initialized, the model calculates household-level characteristics from the characteristics of the individuals who comprise the households. The household's nutritional need is set to be the sum of the individual nutritional needs of each member of the household, the household size is the count of individuals within the household, and the household age is set to be the age of the eldest child plus one to account for conception and pregnancy.

Person-specific rates in the ALHV-Baseline model

The fertility, mortality, and nutritional need characteristics that were now attributed to persons had been assigned to households at setup in the AA model.

Translating these household-level fertility and mortality values to the individual level was

a major undertaking in disaggregation of the model. In the AA model, households had minimum and maximum fertility ages drawn from within a range, a constant chance of reproduction as long as they remained within the fertile age range, and a death age also drawn from within a specific range. These values are included in Table 5.2 below and compared to those assigned to persons in the ALHV-Baseline model. Because the goal was to create a model as similar as possible to the original AA model, the same variable designations were used.

Minimum and maximum fertility age variables were used to determine the age at which an agent is first fertile. The baseline values for the parameters were both set at age 16 to remain consistent with the values used in the AA model to represent the age at which the eldest daughter would be able to establish her own household (fissioning from her parent household). The age at which a person's fertility ends was also randomly chosen from within a range. The AA model used these parameters to represent the age at which a household could no longer fission, but our parameter represents the age at which females were no longer able to reproduce (i.e., menopause). A female was assumed to be able to form her own household upon reaching sexual maturity (age 16) and to maximize consistency with the AA model, these baseline values of the individual end of fertility were assumed to be equal to the values in the AA model plus 16 years. This model does not explicitly incorporate male fertility, but does prohibit fertility outside of marriage. Therefore, a male could continue to reproduce only as long as he was married to a woman within her reproductive period.

The fertility rate for each female was determined using an age-specific fertility schedule developed by Alan Swedlund and included in the LHV-Disaggregate version of

the AA model. Swedlund developed this schedule specifically for the Long House Valley and Black Mesa populations using a combination of Black Mesa skeletal data, historic Pueblo ethnographic data, and fertility data for naturally reproducing, small scale horticulturalist populations (Swedlund, personal communication). This schedule (shown in Table 5.2) produced total fertility and gross reproductive rates identical to those obtained through fissioning at a constant rate of 0.125 used in the AA model. At each time step, the model checks the age of the woman and assigns the appropriate fertility rate value.

Table 5.2: Comparison of demographic variables used in the AA and ALHV-Baseline Models

	Artificial Anasazi Model (Households)	ALHV Model (Individuals)
Minimum fertility age	16	16
Maximum fertility age	16	16
Minimum fertility ends age	30	46
Maximum fertility ends age	32	48
Fertility	0.125	16-19: 0.047 20-29: 0.128 30-32: 0.104 35-39: 0.072 40-44: 0.03
Minimum death age	30	46
Maximum death age	36	52
Nutritional need	800kg/household	180kg/adult persons

In the original AA model, households died under two conditions: when they reached their death age or when the productivity of their farm could not support their nutritional need and they could not locate a new farm location. In the ALHV-Baseline model, the death age was randomly drawn within a range of 46 and 52 years, which corresponds to the household death ages used in the model plus 16 years. This adjustment

was necessary because, in the AA model, households did not begin aging until they fissioned from the parent household (at age 16) while our individual agents begin aging at birth. The annual amount of nutrition required for an entire household in the AA model was 800 kg per year. That value was divided by the average household size of five to derive a nutritional need of 160 kg per adult person in the ALHV-Baseline model. Children's nutritional need was proportionally smaller than that of an adult and was calculated as a function of age. Infants (up to 1 year) were assumed to have 35% of the adult nutritional need (United Nations, 2001) and that need increased linearly with age until adulthood.

Once the attributes assigned to households and people were defined, the processes required for disaggregation were developed. A disaggregated model required that persons be grouped into unique households and that they recognize the household to which they belong. Similarly, households needed to be able to recognize which persons are their members. In order to accomplish this, each house was assigned a unique household identification number and each person was assigned both a unique person identification number and a person-household identification number that matched their assigned household. Whenever a household's location changed, all persons whose person-household identification numbers matched that household identification number also moved to the new location.

In the ALHV-Baseline model, households and individuals were both subject to two key demographic processes, reproduction and death. The household-level reproductive processes are best thought of as fissioning. Households fissioned when a female child living in the household reached adulthood, married, and formed her own

household. This was accomplished through a series of methods in the ALHV-Baseline model. When a young woman reached fertility age, she called the *find-mate* method and identified potential mates. Potential mates were mature, unmarried males whose ages were no more than ten years younger or twenty years older than the calling female's age, and whose clan identification and household identification numbers were different from the calling females. If potential mates were identified, the female called the *build-house* method (described in detail below) and, if she successfully found a new farm and settlement site, she married one of the potential mates by setting both of their statuses to married, their mate identification number to the other's person identification number, and setting the female's head of household status to be true. Some basic housekeeping, such as calculating the size of the new household and using the *move-persons-with-household* method to ensure the new couple was in the same geographic space as their new settlement site, completed the marriage process.

As should be clear from the description above, there are two ways in which a woman could fail to find a mate: 1) there were no suitable mates found or 2) there were no suitable farm or settlement locations available for the new household. If there were no suitable locations found, the woman simply did not get married, remained in her parent household, and repeated the process in the next time step. If no suitable mates were found, the *marry-outsider* method was called. This method exists because, in the AA model, there were no constraints on the ability of a household to fission other than age, the fertility rate, and land availability. Because there were no individuals, there were no marriages and households would fission without the need to become married. As a result, a method was designed that alleviates any constraints on a fertile female's ability

to successfully find a mate. Furthermore, the matrilineal residence pattern of the ancestral Pueblos and research into the extent of marriage networks in the region (Plog 1986) suggest that it is reasonable to assume that marriageable men would have come into the valley from outside areas. The *marry-outsider* method was created with these issues in mind.

In this method, the calling female essentially created a new person with the attributes of a suitable mate. The newly created male was given a unique person identification number but was assigned to the same household as the calling female. In this model natal community was set to 5 (outside community) for data collection purposes. The new male's clan was assigned to be different from that of the calling female's, his age was randomly calculated to fall within the suitable age range for her husbands, marital status was set as unmarried, fertility age was set to be the male's calculated age. Fertility ends and death ages were randomly drawn from the established ranges and age-specific fertility rate and person's nutritional need were calculated based on age. All attributes of the new male that were not explicitly set in this method are identical to those same attributes of the calling female.

Once the outside mate had been created, the calling female ensured that the new male satisfied her marriage criteria, which are identical to the potential mates' criteria in the *find-mate* method with the exception of needing to have a different household identification number. In this method, the new mate was assigned the same household ID as the calling female to ensure that the calling female married the man she created and not one created by another female in the valley who was also unable to find a mate in the same time step. Once it had been determined that the new male met the criteria, the

marry-outsider method was identical to the *find-mate* method. The only way this marriage was not successful was if the new couple could not find a suitable farm or settlement in which to live.

Both the *find-mate* and *marry-outsider* methods called the *build-house* method as soon as a potential new mate was identified. However, marriages were not guaranteed to occur unless the female was successful in finding suitable farm and settlement locations to inhabit with their new spouse. In this method, a new household was created, assigned a new household identification number, and placed randomly on the landscape. This new household's age was set to 0, its nutritional need to 320 (the individual need of two adult persons), its size to 0, and its last harvest to 0. *Find-farm-and settlement* was called and, if a suitable farm and/or settlement location was not found, the household was removed from the landscape. It is important to note that the calling female and the potential spouse were not assigned to this household prior to calling *find-farm-and-settlement* and were, therefore, not removed from the landscape with the household.

If suitable farm and settlement locations were found, the calling female's household identification number was set to be the new household, the household identification number counter was incremented, and the `houseNeeded` variable was set to false. The path of the model then returned to either the *find-mate* or *marry-outsider* method (depending on which one the *build-house* method was called from) and the marriage actions described above were continued. If no suitable locations were found, the calling female attempted again to find a spouse in the next time step.

After the new household had successfully found both farm and settlement locations on the landscape, another method, *give-maize-gift*, was called to provide the

new household with some initial stores of corn to see the newly married couple through their first year of marriage. This method took one-third of corn stores from the marrying female's parent household and added it to the corn stocks of the new household. The female was also removed from her natal household's size count in this method.

After marriage, a woman had the potential to reproduce immediately and for as long as she remained married and within the fertile span. The probability that a woman reproduced during any given year in which she met these criteria varied according to the age-specific fertility schedule described above. If a randomly chosen number was lower than the age-specific fertility rate, a new person was created (i.e., a baby was born). Upon birth, babies were given a unique person identification number and assigned an age of zero. The sex of the new child was determined randomly (with 50/50 probability). Fertility and mortality attributes were calculated from within the initialized ranges and nutritional need was calculated using the function described above. The new child was then added to their mother's household and their nutritional need was added to the total need of the household.

The other fundamental demographic process incorporated into the ALHV-Baseline model was death, both of households and of individuals. Household-level death is better thought of as abandonment in the ALHV-Baseline model. Households died (or abandoned the valley/left the simulation) when they were unable to meet their nutritional needs and no suitable farm or settlement locations were available. In this case, the individuals within these abandoning households were also removed from the landscape. Households were also abandoned when all persons living within them died via the methods described below.

Individuals were able to die through either starvation or old age. The first of these methods, individual death by starvation, was initiated when a household had a nutritional shortfall that year. If there was a shortfall, the method removed individual members of the household in age order from the youngest to the oldest until the shortfall equaled zero. Ethnographic sources indicate that, during more recent periods of drought affecting the Pueblo people, young children were either left to their own resources (e.g., scavenging for any available food, including maize remnants found in human excrement) or killed by their parents (Beaglehole and Beaglehole, 1937). If a married person was among those who were killed in this step, the model allowed for that person's mate to remarry in subsequent years by simply setting their marital status to single. Household size was reduced by the number of individuals within it who died and, if the household was empty, the household died and was removed from the landscape. The final means of death in the ALHV-Baseline model was death by old age. If a person was over their assigned death age, they were removed from the simulation, their spouse was allowed to remarry, and their household size decremented.

A summary of the model inputs and activities that were undertaken during each time step are included in Appendix A. Other than these fundamental changes required for disaggregating the model from the household to the individual level, the model remained as similar as possible to the AA model. The only other significant sources of difference relate to data collection variables that were introduced to assist in model analysis. In the ALHV-Baseline model a single output file was created that reported the values used for person-related variables, harvest adjustment, harvest variance, the number of archaeological households, and the number of both simulated households and persons.

Data from this output file were used to conduct a series of tests to determine whether the model was behaving as expected, that the results were reasonable when compared to the results obtained through analyses of the AA model, and to better understand effects of changes in parameter values on model behaviors.

Analysis of the ALHV-Baseline Model

The repeatability and reliability of the model's behavior was examined through a repetition study. In this study, I ran twenty sets of 1000 simulation runs. For each of these sets of runs, I calculated the mean number of households and persons produced by the model across each of the simulation runs for each year of the study period. I then assessed the variation in the 20 resulting mean curves by year and compared each to the grand mean of these 20 curves. Because of the stochasticity built into the model through the random drawing of parameter values from a range for some of the demographic variables and the heterogeneity added to the production landscape through the use of the harvest adjustment and variance variables, some randomness in model outputs is expected. However, when means from all 20 sets of repetition study runs were compared, the model behavior was fairly consistent and all averages were within two standard deviations of the grand mean.

A guideline for the minimum number of runs required for sensitivity analyses was determined by examining the model behavior when fewer than 1000 runs were averaged. These results indicated that 500 simulation runs would be sufficient because the model behaved consistently with this number of runs; the level of variability in the mean curves was deemed higher than desired for sets including fewer than 500 runs. The results of the

repetition study also allowed comparison of model outputs to those of the AA model. These results are discussed later in this chapter.

In order to determine the relative importance of minor changes in parameter values, a series of sensitivity analyses were undertaken. The parameters and value ranges used are listed in Table 5.3. In these analyses, one parameter value was varied across a broad range while keeping all other parameter values constant. The justifications for the default values are outlined above and, in most cases, the ranges were determined by looking at the ranges used in similar analyses of earlier models. The value range for the fertility onset age, however, was chosen because it captures biologically reasonable ages for menarche. For fertility rates, new age-specific fertility schedules had to be developed that produced the desired range of total fertility rates (TFR). These are included in Appendix B. For dual variable analyses, the values of two parameters were varied concurrently within ranges identified through the single variable analyses.

For each set of parameters, I analyzed the final number of households, extinction time, the peak number of households from AD 800-1149 and the year in which that peak occurred, the peak number of households from AD 1150-1350 and the year in which that peak occurred, and the proportion of households that went extinct over the entire run as well during the spans listed above. I also performed a number of basic statistical tests to assess goodness of fit. Selected results from these sensitivity analyses are discussed below.

Table 5.3: Parameters and associated values used in ALHV-Baseline sensitivity analyses

Parameter	Constant values	Range of analyzed values
<i>Single Variable Analyses</i>		
Harvest adjustment	0.56	0.5 to 0.62, in steps of 0.02
Harvest variance	0.4	0.0 to 0.7, in steps of 0.1
Fertility onset age*	Minimum: 16 Maximum: 16	13 to 19, in steps of 1
Fertility ends age*	Minimum: 33 Maximum: 35	29 to 39, in steps of 2
Death age*	Minimum: 51 Maximum: 57	47 to 61, in steps of 2
Person nutritional need	160	160 to 320, in steps of 40
Fertility rate	TFR ~4.0	TFR 3.0 to 6.0, in steps of ~0.5
<i>Dual Variable Analyses</i>		
Person nutritional need (160-320) + harvest adjustment (0.6-1.0) Person nutritional need (160-320) + harvest variance (0.2-0.6) Fertility rate (3.0-6.0) + fertility ends age (32-36) Fertility ends age (32-36) + death age (49-53) Fertility rate (3.0-6.0) + death age (48-53)		

* These parameters require a minimum and maximum value in the model, but to allow for sensitivity analyses with consistent values, these values were set to be the same.

General results — ALHV-Baseline model

As described above, the 20,000 run repetition study allowed better understanding of the behavior of the model. For this version of the model, the primary interests were; 1) how well the model reproduced the archaeological population counts, and 2) how well the model reproduced results from similar repetition studies of the Artificial Anasazi model, as our goal was to create a disaggregated model as similar to the original model as possible. Three types of data sets were considered in the repetition study: the set of all runs (Figure 5.1), runs that survived beyond AD 1149 (Figure 5.2), and runs that survived beyond AD 1299 (results not shown).

These results showed that, although the ALHV-Baseline model generally captured some of the major trends present in the archaeological population counts, the model deviated from these in two main ways. Perhaps most obvious is that for all time periods

except the earliest, the model failed to capture the estimated population size at any time when all runs were analyzed. However, when only runs that have survived through the first peak (through AD 1149) were considered, the model did reproduce the estimated population size observed at the time of the second peak. Second, the model did not adequately capture the magnitude of the first peak that occurred from approximately AD 1050 to 1150, although there was a clear increase in the growth rate within that general time period.

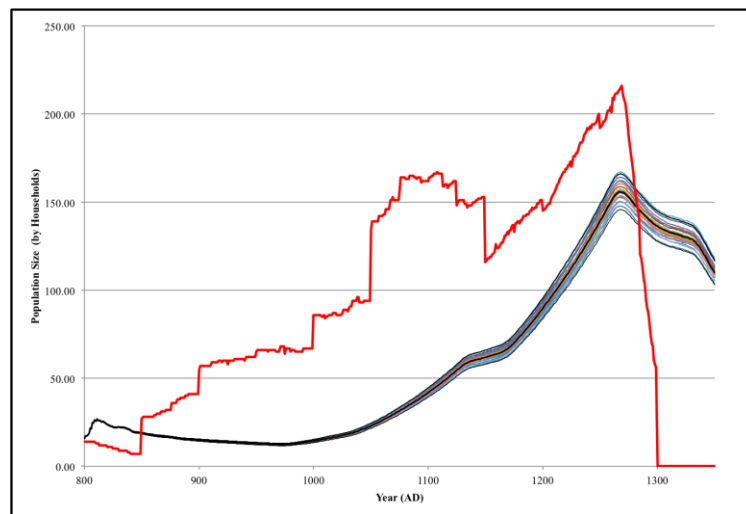


Figure 5.1: Results of ALHV-Baseline repetition study; means of 20 sets of 1000 runs plotted against the Long House Valley archaeological curve (red). The heavy line in the middle of the 20 curves is the grand average of all 20 sets.

These results differed from the repetition studies completed on the Artificial Anasazi model, confirming that disaggregation did have some effects on model behavior despite our efforts to make them as equivalent as possible (see Figure 5.3). The AA model more accurately captured the timing and size of the first peak, but the ALHV-Baseline Extant 1149 runs best captured the timing and magnitude of the second peak. The likely cause of these differences between the model versions was the incorporation of an age-specific fertility rate, versus the constant fertility rate used in the AA model.

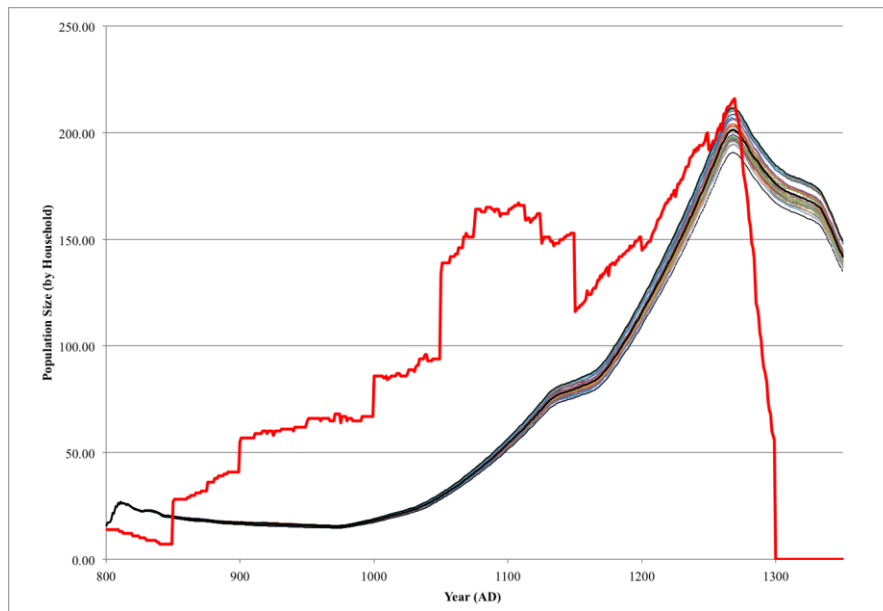


Figure 5.2: Results of ALHV-Baseline repetition study; means of 20 sets of 1000 runs, including only those runs that survived beyond AD 1149 plotted against the Long House Valley archaeological curve (red).

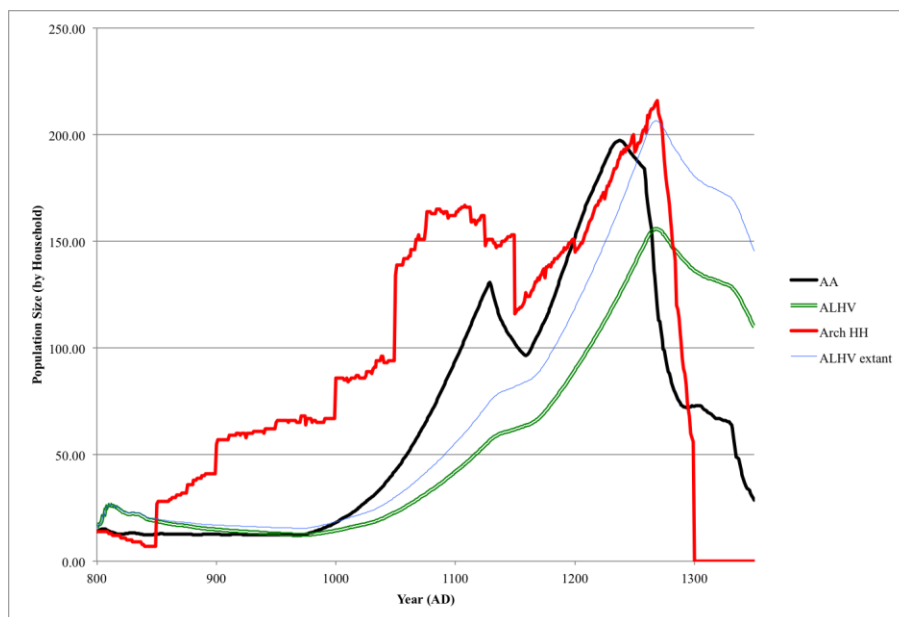


Figure 5.3: Comparison of repetition study results for Artificial Anasazi, ALHV-Baseline (all runs), ALHV-Baseline (Extant 1149), and the archaeological population estimates.

Examining fertility in the ALHV-Baseline model

In order to assess the effects of using a constant fertility rate versus an age-specific fertility rate, I carried out a study that specifically explored this issue using simplified versions of the model. This study was conducted in collaboration with another graduate research fellow, Uttam Bhat of Boston University, at the Santa Fe Institute during the Summer of 2014. In these test scenarios we considered the AA households' fission rate of 0.125 per time step for women within the fertile age span (16-32) and the age-specific schedule developed by Alan Swedlund (see Table 5.2 above for that schedule) for women ages 16 through 44. This yielded an equivalent gross reproductive rate of 2.5 for each of the fertility schemes. Next, we implemented these two fertility schemes in a simplified growth model. This model included a starting population of five individuals at age 16 and ran for 100 years. The average results of 1,000 runs of this model are shown in Figure 5.4 below.

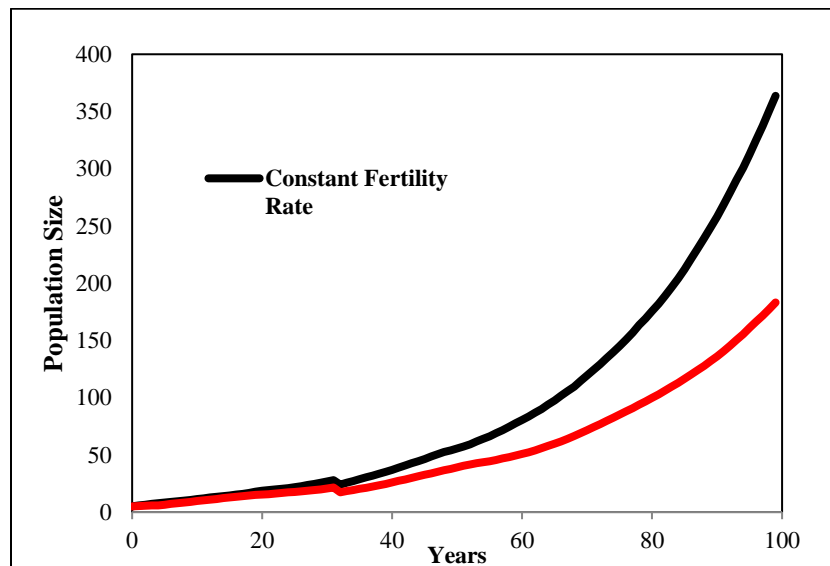


Figure 5.4: Results of a simplified model examining the effect of constant vs. age-specific fertility rates.

Clearly, using a constant versus age-specific fertility scheme had a tremendous effect on the growth rate and realized size of the population. Higher fertility in the youngest age class (16-19 years, constant rate: 0.125, age-specific rate: 0.047) resulted in the increasing disparities in both growth rates and population sizes generated through time. To clarify, in the constant fertility scheme, a population of 20 women within the youngest age class would produce on average 2.5 children per year while, in the age-specific scheme, the same population would produce only 0.94 children between them. These differences in generation one population size compound with each generation resulting in the disparities seen above.

The results of this fertility study revealed that different fertility schemes, even if they have equivalent gross reproductive or TFRs, do not produce equivalent growth rates or population sizes. These findings aided in understanding differences between the outputs of the AA and ALHV-Baseline, but also should inform the archaeological modeling and bioarchaeological communities as a whole. Although using these constant demographic rates may be more tractable when describing population trends for large areas or over long spans of time, these results highlight the sensitivity of population estimates to assumptions about fertility schedules and underlying age distributions.

Related to the findings above, I became curious about the effects of the structure of the starting populations. In developing the ALHV-Baseline model, I had generated five different starting populations from the 1885 Pueblo census records (National Archives, 2014). The population pyramids for these potential starting populations are pictured in Figure 5.5. Three of these five populations had the desired 14 females within the fertile range (Populations 3,4 and 5), while the other two had 11 and 12 (Populations 1 and 2,

respectively). To test the effects of the composition of the starting population, I created data files for each of the potential populations, read them into the ALHV-Baseline model, and compared the average of 100 runs. The results are shown in Figure 5.6.

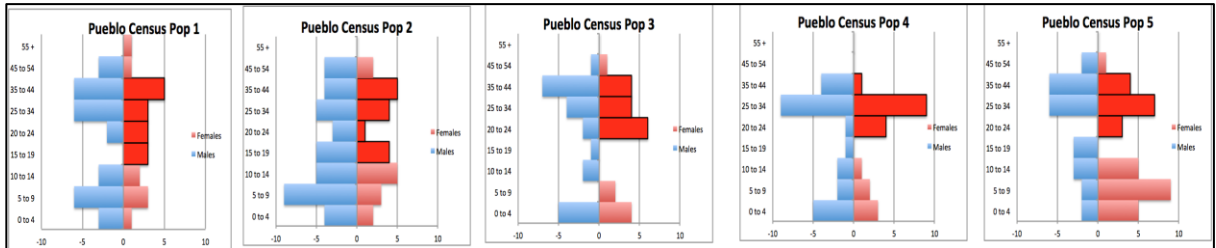


Figure 5.5: Structure of the 5 potential starting populations used in the ALHV-Baseline model, drawn randomly from the 1885 Pueblo Census (National Archives, 2014).

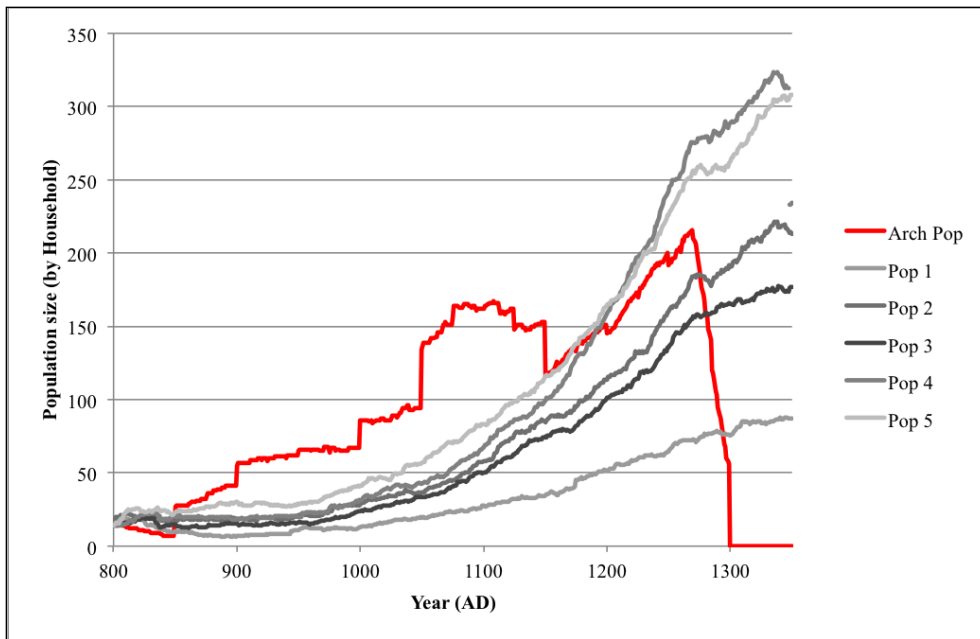


Figure 5.6: Results of ALHV-Baseline starting population comparisons; note variation between runs.

As expected, Population 1, with the fewest number of fertile women, generated the smallest population size when added to the model. However, Population 2, with only 12 fertile women, did not generate the second smallest population size; Population 3 did. Population 3 lacks any women in the youngest age class (ages 16-19), while Population 2

has an abundance, which likely contributes to the results seen here. Populations 4 and 5 generated the largest population curves, likely because they have the greatest number of women in the most fertile age class (20-29, fertility rate: 0.128). The results of this starting population analyses confirmed that the structure of the starting population may have significant effects on the model outcomes and should be considered very carefully when building a demographic model.

The final considerations regarding the implementation of age-specific fertility rates in the model were the results of fertility sensitivity analyses. I suspected that the default fertility rate used was too low to capture the archaeological curves, but examined the exact role of varying fertility through these analyses. To do this, I created six additional age-specific fertility schedules that produced average TFRs of approximately 3.0 to 6.0 by scaling up or down from the baseline fertility schedule (Appendix B).

The first analysis focused on the effects of varying fertility on number of households existing on the landscape at the end of model runs, when considering all runs and only those that survived to the end. Figure 5.7 summarizes these results. As expected, increasing the total fertility rate did increase the final number of households up to a TFR of approximately 5.0, but then the number of households began to decline rapidly. This was most likely due to the fact that these highest rates result in 1) too many households for the landscape or 2) households so large there was no available plot of land that would provide for their nutritional needs. In either case, these households leave the simulation (migrate), resulting in the declines seen in this result.

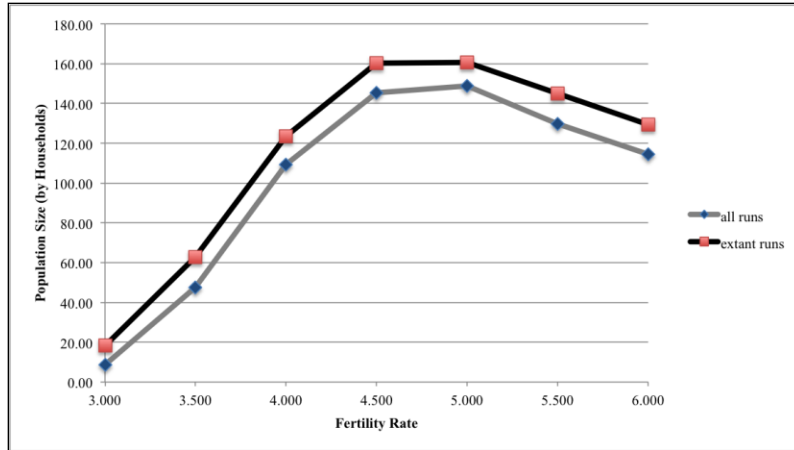


Figure 5.7: Final number of households produced when fertility is varied in the ALHV-Baseline model.

Sensitivity analyses also examined how well the models with varied parameter values capture the peaks seen in the archaeological record. To do so, both the size of the peak and the timing were considered. Figure 5.8 shows results for peak sizes. For the AD 800-1149 peak, the peak size was not captured by the default total fertility rate of 4, nor was the timing of the peak. For the AD 1150-1350 peak, the default fertility rate did capture both peak size and timing. Overall, the default fertility rate best captured the archaeological population curve when compared to the other implemented fertility rates (Figure 5.9).

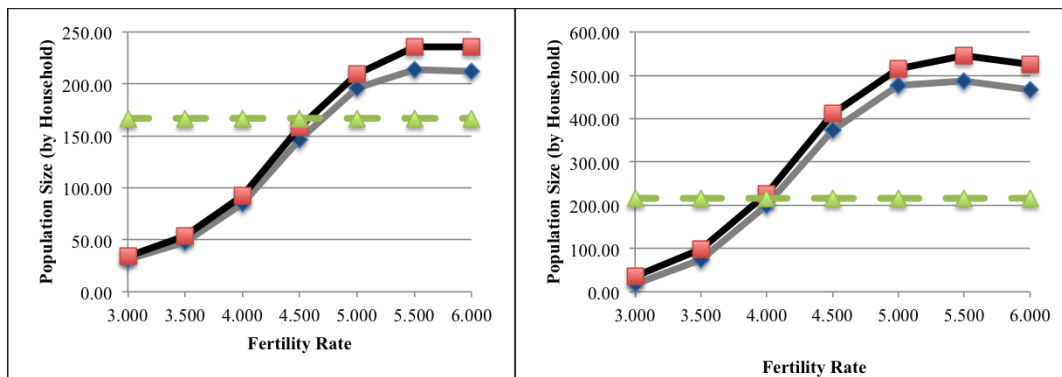


Figure 5.8. ALHV-Baseline peak sizes when fertility is varied. The gray lines represent all runs, the black lines represent extant runs, and the dashed lines the archaeological peak: a) AD 800-1149 peak, b) AD 1150-1350 peak.

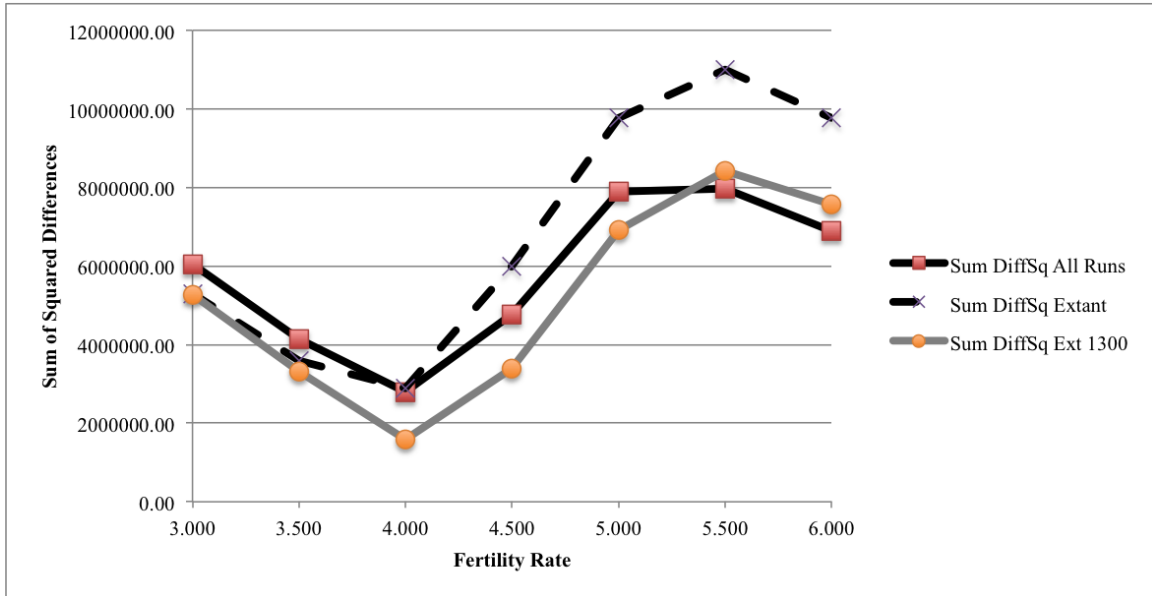


Figure 5.9: Sum of differences squared between the ALHV-Baseline model and the archaeological population curve when varying fertility.

The results of the various fertility analyses described above provided insight into the effects of changing from a constant-fertility scheme to an age-specific fertility schedule. It should be noted again, however, that the ALHV-Baseline model does not include realistic death rates or post-death processes. Sensitivity analyses of the effects of varying death rates were completed and analyses indicated that the only effect of death on model behavior occurred when the death age fell below the maximum fertility ends age. Therefore, the only effect of death in this model version was its potential ability to reduce the length of the fertile span, which did not happen under default model conditions. The failure of the current fertility rate to adequately capture the archaeological population curve in this version of the model was expected to be exacerbated when realistic mortality was incorporated. Results presented in the next chapter confirm that this is, in fact, the case.

Person nutritional need and harvest adjustment

One benefit of sensitivity analyses is the ability to use results from prior model analyses when developing subsequent versions. From the beginning of the work on the Artificial Anasazi model, we had noted that model behavior was extremely sensitive to changes in harvest adjustment values. This parameter was used in the quality calculation that determines maize productivity and is described by Dean et al. (2000) and Axtell et al. (2002) as a means to simulate reduced yields due to crop loss. However, the VanWest (1994) reconstructions already took crop loss due to a variety of factors into account.

Similarly, it was also evident that the nutritional needs incorporated into the original model, 800 kg per household or 160 kg per person per year, were a little low. The original AA development team determined this value following Sanders et al. (1979). However, review of this article showed that this estimate was too low for the model, because Sanders et al. (1979) assumed only 80% reliance on maize. Since we assumed that maize is a proxy for all food sources in all ALHV versions, it seemed reasonable to increase the maize need for individuals. Thinking in terms of persons and their average caloric need, not in terms of household need, further supported the need to increase the nutritional need. Kowalewski (1982) estimated that the average adult maize need in pre-Hispanic North America was actually between 160 and 290 kg of maize per year (1,534 to 2,781 calories per day). Given the extremely harsh environment modeled, and the difficulties cultivating corn in the Colorado Plateau region, it seemed reasonable to assume that the actual individual nutritional need was on the higher, rather than lower, end of that estimate.

Harvest adjustment and a person’s nutritional need are clearly linked model parameters. A series of dual-variable sensitivity analyses were completed to further explore this relationship and it was noted that, when the harvest adjustment parameter was 1.0 (i.e., it had no effect on productivity estimates), model results better matched the archaeological record when more reasonable values for person nutritional need were used (Figure 5.10). A repetition study also confirmed that this decision would not affect the model behavior (Figure 5.11). This repetition study showed virtually no effect due to these changes. Based on these results, the decision was made to remove the effects of harvest adjustment from all future model versions and to set the baseline person nutritional need value at 285 kg/year, which aligns with nutritional estimates made by Kowalewski (1982) for 100% maize reliant populations.

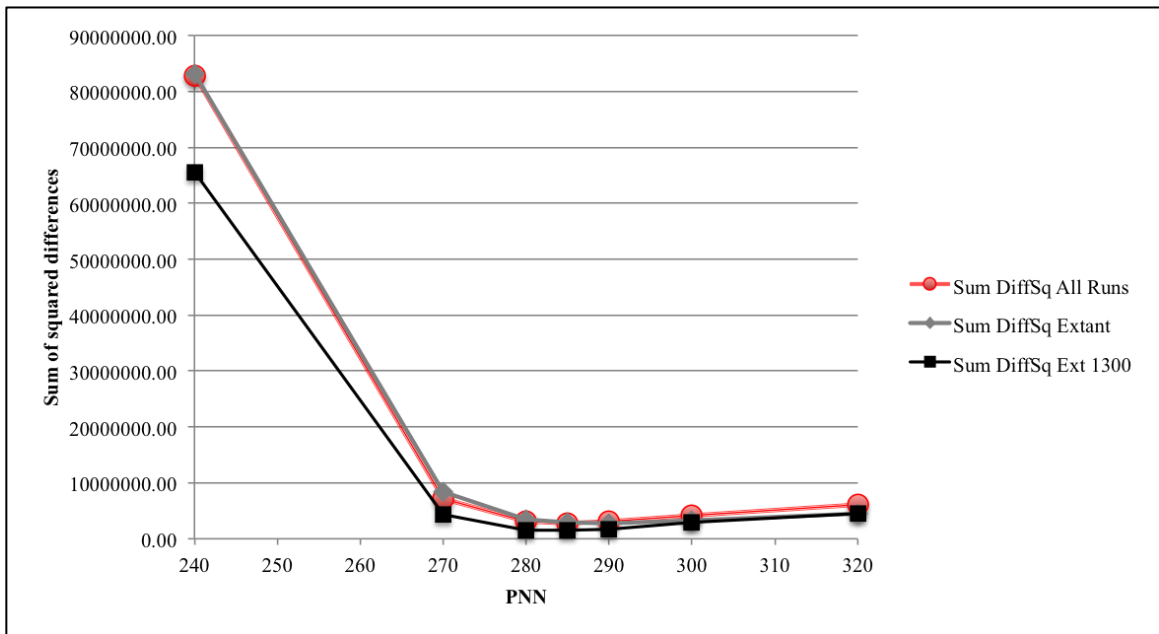


Figure 5.10: Results of sensitivity analyses considering nutritional need when harvest adjustment is 1.0.

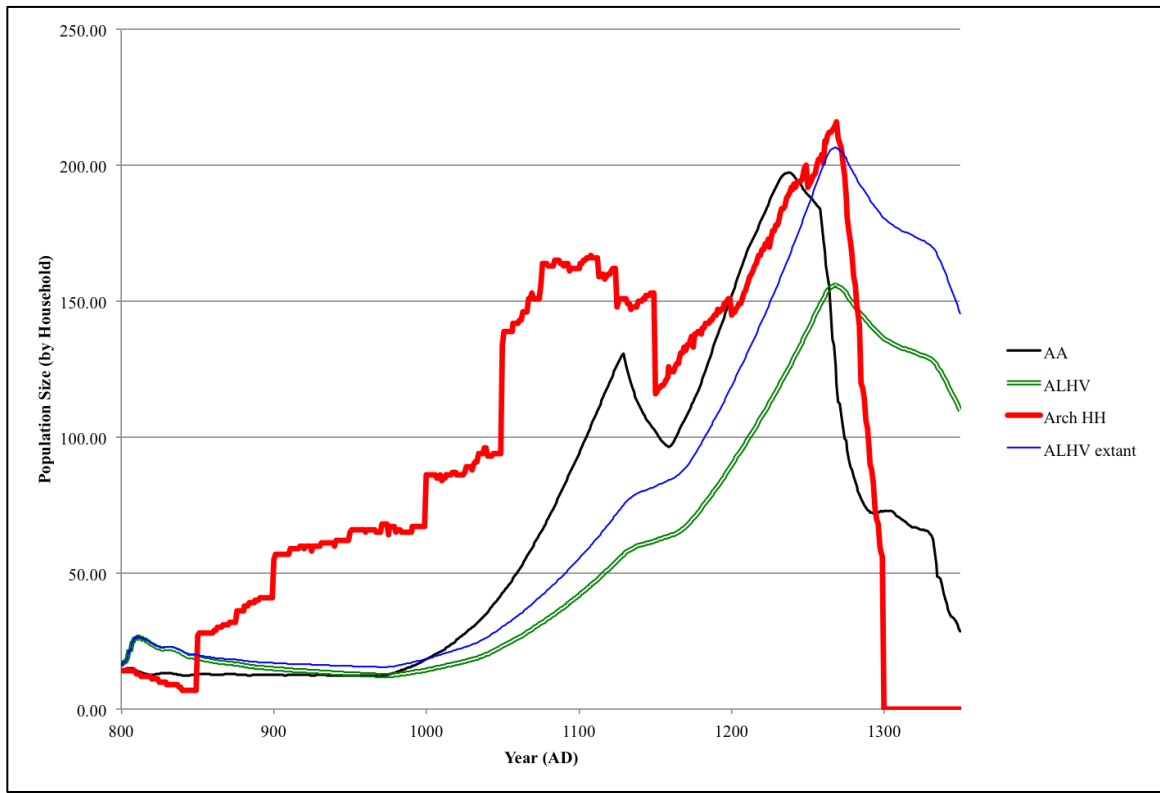


Figure 5.11: Comparison of repetition study results for Artificial Anasazi, ALHV-Baseline (all runs), ALHV-Baseline (Extant 1149), and the archaeological population estimates when harvest adjustment is removed and person nutritional need is increased to 285 kg/year.

Although numerous additional analyses were completed, the results presented in this chapter focus specifically on those analyses that either evaluated major changes in the model structure made when disaggregating the original AA model, like the addition of age-specific fertility, or informed modeling decisions that would be incorporated into subsequent model versions. The next iterations of the model build upon the results explored here and add realistic demographic behaviors and mortality rates.

CHAPTER 6: INCORPORATING REALISTIC DEMOGRAPHY—METHODS AND RESULTS

The next stage in model development, Demography, required the creation of two models that incorporated more ethnographic and demographic realism than the previous ALHV-Baseline mode: ALHV-DemogUpdate and ALHV-AgedMort. Simulated persons in the ALHV-DemogUpdate model were assumed to be governed by the demographic processes and rates included in the ALHV-Baseline model, but additional behaviors that would have occurred among the ancestral Pueblo in the aftermath of deaths were added to the model. The ALHV-AgedMort model built upon the ALHV-DemogUpdate model but included a revised age-specific fertility schedule and added age-specific mortality.

Incorporating Reasonable Ethnographic and Demographic Behaviors

To start development of the next model version processes were identified in the ALHV-Baseline model that did not reflect demographic or ethnographic realities. The baseline version did not deal with any issues related to household composition following deaths within a household, except to disallow households of one; those households were simply forced to leave the simulation. Four death aftermath scenarios were identified that required additional consideration: newly widowed persons without children, newly widowed persons with children, children and older women who were left in households without parents, and unmarried adult children who remained in parent households after the death of their parents. We resolved these issues by creating a *death-aftermath* method that assessed the composition of households in which a member had died during the time

step and then directed individuals within the household to carry out particular behaviors. Appendix A includes figures that summarize death aftermath and its associated methods.

Widows and widowers have to be considered differently. Because of the assumed matrilineal structure of the ancestral Pueblo populations, widowed males needed to identify a new wife and join her household. A widowed female needed to identify a new husband and bring him into her household. A widowed male with children or post-menopausal women in his household could not bring them with him to a new wife's household, so any such family members needed to join a different household that included a married, female head of household of their mother's clan before the widower was able to remarry. This process was ethnographically reasonable and served to place children in households belonging to their mother's matriline.

In the new model, widowed males with children first called a new *reassign-to-clan* method. This method asked one remaining member of the widower's household to create a "reassigned" group (which did not include the widower) and then that person searched the valley for an appropriate household to join. Once identified, the reassigned group joined the new household. If no appropriate household existed, the group left the simulation, presumably to find members of their mother's clan elsewhere. Once the widowed male's family members were reassigned, he called the *find-next-wife* method. In this method, the newly widowed male created a list of potential wives. These potential wives had to be within the fertile span, unmarried or widowed, and of a clan different from his own. There were no constraints regarding the age of the potential wife. After creating a list of potential wives, the newly widowed male went through the potential wife candidates one by one. If the potential wife already had her own farm and household

location (i.e., recently widowed herself), they went through the marriage process and he joined her household. If the potential wife did not already have a farm and household location, then she called the *build-house* method. If the new couple was able to successfully identify a new farm and/or settlement location, they married and moved to the new location together. If there were no potential wives or no available farm and settlement locations, the male left the simulation. Widowed males without children simply went through the *find-next-wife* method as described above.

Widowed females remained with the children and older women who resided in their household at the time of her husband's death. We created a new method, *find-next-husband*, that allowed her to search the valley for a new husband. Suitable husbands were unmarried (never married or widowed) men, within the fertile span, who were no more than ten years younger than the widow, and who did not belong to her clan. Since the widow already had an established household, she simply identified a suitable husband and they completed the marriage process, with him moving into her household. If there were no suitable men in the valley, she created an outside husband according to the *marry-outsider* method described in the previous chapter and he joined her household.

The final death aftermath scenarios addressed in the ALHV-DemogUpdate version of the model were situations where children or older women remained in households without any surviving parents. In any case where a group remained in a household without a female head-of-household, clan reassignment would occur (i.e., the survivors would move to the household of a clan relative). In addressing this issue, we also realized that adult male children could possibly remain in their parents' household until they found a suitable wife even if their parents were living. This is not

ethnographically reasonable, so we decided to remove males from the simulation if they remained unmarried beyond age 20. In cases where both of an adult male child's parents died, he would be part of an orphan group and would be reassigned to a household within his mother's matriline as described above. As in the ALHV-Baseline model households of one were not permitted and sole residents of such households either remarried or were reassigned according to the rules above.

Incorporating Realistic Fertility and Mortality

Once the updates to the death aftermath and its related processes were completed, the next steps focused on incorporating more realistic age-specific fertility and mortality rates into the model. Prior to the implementation of these rates, the effect that starvation was having on individual mortality needed to be assessed. Presumably, deaths by starvation would be included in any general mortality schedule that was implemented, so failure to discount these mortality rates without understanding the role of starvation would essentially expose individuals to twice the risk of death by starvation. We decided that the current ALHV-DemogUpdate model would be a good model from which to generate starvation rates because procedures for death by starvation and old age were the only causes of death implemented. In order to complete the starvation study, two new types of data, starvation and population counts by age class, were collected and recorded every 50 years. The model was run 500 times and the number of deaths by starvation and population counts across all 500 runs at each 50-year time point (i.e., at year AD 850, 900, ..., 1350) were averaged. For each of these years, the average number of deaths by starvation in each age class was divided by the average population count for each age

class. This determined the age-specific starvation rate for each of the years (Figure 6.1). Finally, the starvation rates for all age classes at each date were averaged to develop the age-specific starvation rates to be used in the next iteration of the model (Figure 6.2).

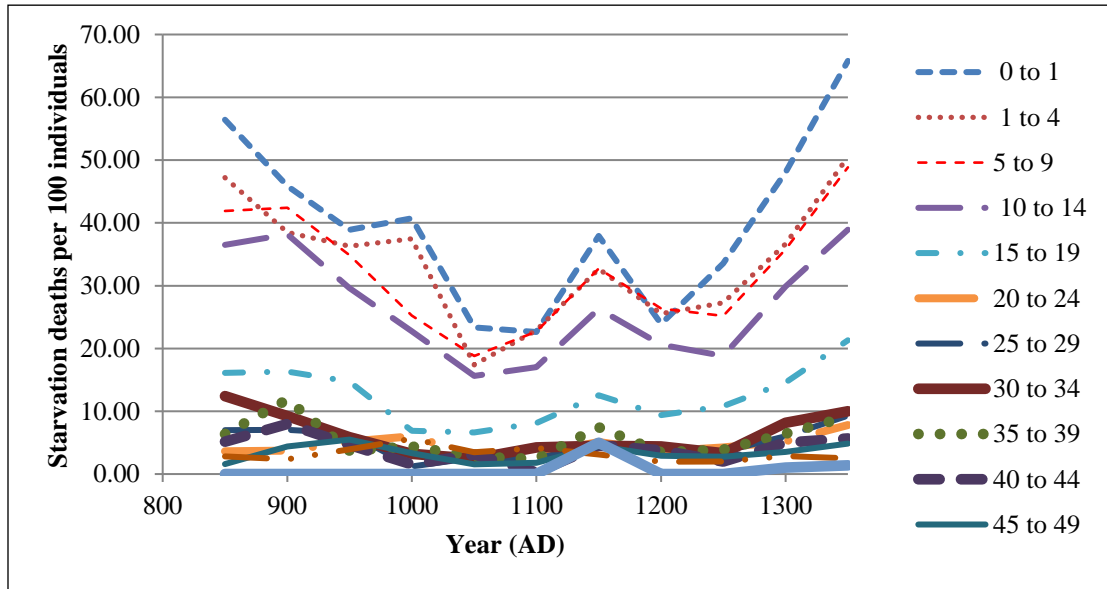


Figure 6.1: Age-specific starvation by year generated through analyses of the ALHV-DemogUpdate model; note the variation in patterns between age groups.

In addition to being able to use these rates when incorporating more realistic mortality into the model (as described below), these results illustrate how critical the effects of the environmental conditions simulated in the model are on the number of starvations. Figure 6.2 compares the starvation rate with the population curve in Long House Valley and clearly indicates that these starvation rates tracked the population trends in the region, which correspond to shifting environmental conditions. Although these results are not surprising, they provide substantial insight into how heavily the LHV populations might have been influenced by poor environmental conditions.

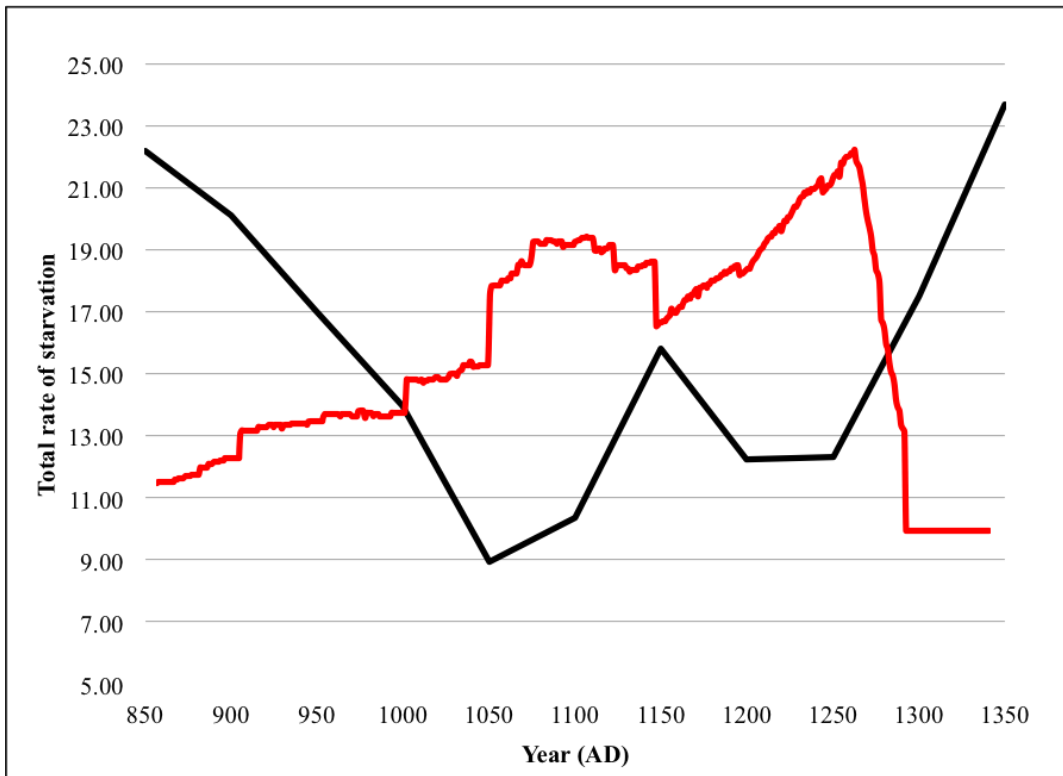


Figure 6.2: Average starvation deaths per year across all age classes, plotted on the Long House Valley population curve.

After implementation of reasonable death aftermath processes and completion of the starvation study, the age-specific mortality and fertility schedules needed to be incorporated into the model. As discussed in the previous chapter, we already knew that the fertility rate was slightly too low to capture the population curve generated by archaeological estimates and that non-starvation-related death (death age) had no effect on model behavior except in extreme scenarios where the death rate examined constrained the fertile span. We suspected that the inclusion of age-specific mortality would further exacerbate the fertility rate issues and, therefore, decided to implement the age-specific mortality schedule as the first step in developing a new model version, ALHV-AgedMort.

Age-specific mortality

When selecting the mortality schedule for implementation, several critical components of the schedule itself, as well as numerous data sources, aided the decision-making process. The best sources of anthropologically appropriate mortality schedules are the model life tables developed by Weiss and Wobst (1973). These life tables include data related to juvenile mortality, the proportion of the population over the age of 50, and the proportion of the population over the age of 70 in addition to traditional life table calculations. To determine target proportions for each of these measures three different data sources were consulted: the 1790 and 1823 Pueblo census data discussed below, ethnographically-derived mortality schedules developed by Gurven and Kaplan (2007), and mortality schedules that were developed using skeletal samples from throughout the Southwest (Nelson et al. 1994b).

In October 2015, I spent five days at the National Archives in Washington, D.C. digitizing the Spanish and Mexican Colonial Censuses of New Mexico for the years 1790 and 1823. These census records enumerated persons residing in various pueblos in the New Mexico territories. The Catholic missionary priests who conducted the censuses recorded the name of the pueblo and numbered each household within the pueblo. They recorded first and last names of adults in the households, first names of children, gender and age of all household members, and occupation of the male adults. While at the National Archives, I recorded data for all individuals enumerated in the 1790 census and most of those in the 1823 census, a total of 6,572 individuals.

Analyses of the Pueblo census data revealed that only 11% of the population ($n = 684$) were aged 50 or over and less than 2% ($n = 98$) were over age 70. I realized there is

a high degree of uncertainty in these data because of the census-taking practices of the Catholic missionary priests charged with the responsibility, although I was unable to locate any specific information about these census practices. It is possible that some individuals, especially older individuals, might not have converted to Catholicism as readily as younger people and, therefore, may not have been enumerated. Weiss and Wobst's model life table MT: 27.5-55.0 aligns best with these data with 12.3% of the population over age 50 and 1.8% over age 70. We assumed the 45% childhood mortality included in this life table was also appropriate, but this cannot be confirmed with census data. Interestingly, the census-based schedule aligns with a mortality schedule developed by Alan Swedlund for the AA model that was never implemented (Swedlund, personal communication).

The second data sources examined were the ethnographically derived mortality conditions for forager-horticulturalist populations in Gurven and Kaplan (2007). They estimate a childhood mortality rate of 36%, 34% of the population over age 50, and 18% over age 70 (Gurven and Kaplan 2007). Weiss and Wobst's model life table MT 35.0-65.0 best matches these conditions with 35% childhood mortality, 32.5% over the age of 50, and 15.6% over age 70.

The final data sources were the model life tables developed by Nelson et al. (1994b) from Southwestern skeletal samples. They averaged numerous samples to develop an average childhood mortality of 41% and estimated that only 6.8% of the population was over age 50 (Nelson et al. 1994b). They did not estimate the proportion of the population over age 70. When looking for the corresponding Weiss and Wobst (1973) model life table, it was decided to look for tables that had 45% childhood mortality to

account for the issues of underenumeration of infants known to be associated with archaeological samples (Hoppa and Vaupel 2002). The best match model life table was MT 20.0-55.0 with 45% childhood mortality, 6.1% of the population over age 50, and 0.4% over age 70.

The ethnography-based schedule of MT 35.0-65.0 was chosen for initial implementations into the model because of potential issues with the other data sources. To implement the schedule in the model it was first necessary to reduce the mortality rates by the age-specific starvation rates generated through analysis of the ALHV-DemogUpdate model. This reduction was needed to account for the fact that starvation would have been included in the mortality conditions that motivated the choice of the age-specific mortality schedule and would have been considered in the construction of the model life table from which it was drawn. We did have concerns about using simulation output (i.e., starvation study results) to derive the starvation mortality rates; however, we believe this is justified because 1) the baseline age-specific mortality schedule was derived from outside sources and 2) starvation in the current version of the model was generated from realistic processes built into the model—death by starvation was not imposed in ALHV-DemogUpdate. The process of starvation incorporated into the model is both ethnographically and biologically realistic and the rates derived are also reasonable when compared to the limited available empirical data for starvation during famines (UNICEF, 2017).

To implement the new mortality regime that includes both the rates drawn from the model life table and starvation study, a *find-age-specific mortality* method was created that used the age-specific mortality rates from the MT: 35.0-65.0 model life table,

subtracted the age-specific starvation rate and then divided that rate by the number of years in each age class. In each time step, individuals call this method to reset their mortality rate for their current age. Next, an *age-specific-dying* method was created that replaced the death-by-old-age method in previous model versions. This method functions in exactly the same way except, instead of comparing an individual's current age to their randomly drawn death age, the individual randomly chooses a number between 0 and 1. If that number is below the individual's age-specific mortality rate in that time step, the individual sets off death aftermath procedures and dies.

Age-specific fertility

Initial tests of the model after the incorporation of a realistic age-specific mortality schedule resulted in almost immediate extinctions in every model run. As discussed in Chapter 5, previous versions of the model used an age-specific fertility schedule that resulted in a TFR of approximately 4. This fertility rate produced acceptable results in model versions that did not include causes of mortality other than starvation or old age, but clearly was not sufficiently high to overcome the addition of realistic mortality. Additionally, because a long-term goal of the project is to be able to compare the model output to life tables generated from analyses of the Black Mesa skeletal collection, it was necessary to develop a new fertility schedule that did not use the fertility rates developed by Alan Swedlund, since his schedule was based on the analyses of the Black Mesa skeletal data. Several sources of data were considered when determining the age-specific fertility schedule to incorporate into the ALHV-DemogUpdate model.

The first of these data sources were Spanish and Mexican Colonial Censuses of New Mexico for the years 1790 and 1823 described above. From these census data, I was able to calculate age-specific fertility rates by picking a specific age, identifying all recorded individuals of that age, subtracting that age from the age of the female adult in their households to create a list of mothers, and then counting the number of mothers in each age class. I repeated this process again and then averaged the results to develop the age-specific mortality schedule in Table 6.1. This resulted in a TFR of 5.35 for the census population.

In examining the age structure of the census populations, we discovered that children appeared to be underenumerated compared to typical distributions. We believe this underenumeration of children could potentially be the result of the failure of the priests to include children in the census prior to their baptism into the Catholic church, but again we were unable to find any record of the specific methods employed by the Spanish or Mexican priests to confirm our suspicions. This underenumeration, however, would result in underestimations of the actual fertility levels of the population.

Table 6.1: Fertility rates considered for including in the ALHV-AgedMort model, plus Coale-Trussell (1978, scaled) rate chosen

Age-Class	Swedlund Fertility Rate	Census Fertility Rate	Scaled Coale-Trussell Fertility Rate
≤15	0.000	0.031	0.000
16-19	0.047	0.146	0.263
20-24	0.128	0.210	0.294
25-29	0.128	0.192	0.276
30-34	0.104	0.197	0.253
35-39	0.072	0.136	0.206
40-44	0.030	0.075	0.107
45-49	0.000	0.047	0.015
50+	0.000	0.049	0.000
TFR	3.96	5.35	7.07

Several tests of the model revealed that this 5.35 total fertility rate derived from the census records was still too low when more realistic mortality rates were incorporated. Since there was reason to believe that the census-derived estimate for fertility was too low, the demography literature was searched to find a reasonable rate for comparable, naturally reproducing populations. A study of 70 naturally reproducing populations revealed an average total fertility rate of 6.1, with a range of 4.5 to 8.5 (Wood 1994). Based on these data, a decision was made to use the Coale-Trussell (1978) standard fertility schedule scaled up to more reasonable fertility rates for the study population. The standard total fertility rate is only 2.21, so multipliers of 3.0 and 3.2 were used to generate schedules producing total fertility rates of 6.63 and 7.07 and these were tested within the model. The results of model runs with these two fertility regimes will be

discussed below. Table 6.2 summarizes the differences between the demographic rates included in the ALHV-Baseline and ALHV-AgedMort models.

Table 6.2: Comparison of the differences in demographic parameters included in the ALHV-Baseline and ALHV-AgedMort models

Parameter	ALHV-Baseline	ALHV-AgedMort
Total fertility rate	3.976	7.07
Age at menarche	16	15
Age at menopause	33-35; value drawn from range	48-50, value drawn from range
Annual nutritional need	160 kg per person	285 kg per person
Starvation mortality	Death youngest to oldest when maize supply inadequate	Death youngest to oldest when maize supply inadequate
Other mortality	Old age; maximum lifespan 51-57; drawn from range	Age-specific mortality (MT: 35.0-65.0 minus effects of starvation)

The final changes to the ALHV-AgedMort model involved adding additional code to record births, death, and migrations as they occur in the model. Table 6.3 details the events recorded. For each of these demographic events, the year, the personID, sex, and age of the individual reporting the event, the household and clan they belong to and, if applicable, their mate's identification number were also recorded. These data, once thoroughly analyzed, can provide information about ages at first birth, completed family size, realized total fertility rates, deaths by age, year, and cause, as well as data about migration timing and cause. Although migration between areas was not included in the ALHV-AgedMort model, cases were recorded where individuals entered or left the simulation. Tracking these 'migrations' was helpful in developing the next iteration of the model.

ALHV-AgedMort Results

Repetition study and sensitivity analyses

The first task to be accomplished in analyses of the ALHV-AgedMort model was to determine the most appropriate fertility schedule to use as the baseline. Results of preliminary testing showed that using schedules that generated TFRs of 6.63 and 7.07 yielded reasonable results (i.e., surviving populations that generally reflected the trends seen in the archaeological curve), but we needed to evaluate which produced the best results. To do this, a full 20,000 run repetition study was completed to compare the results of the two schedules (Figure 6.3). While neither of the fertility schedules produced model results that capture the archaeological population curves, the TFR 7.07 age-specific fertility schedule yielded more consistent results and so it was used as the baseline for all subsequent analyses.

Table 6.3: Events recorded in ALHV-AgedMort demographic analysis output file

Demographic Events Recorded in ALHV-AgedMort		
Event	Cause	Code
Emigration	Males who cannot find a spouse by age 20	43
Immigration	Outside male created	30
Emigration	Individual cannot move because no suitable land is available	41
Emigration	Male count not marry due to lack of wives available	42
Emigration	Reassigned group could not find suitable clan household	44
Birth	Child is born (both mother and father report event)	10
Death	Starvation	21
Death	Age-specific death (all causes except starvation)	20

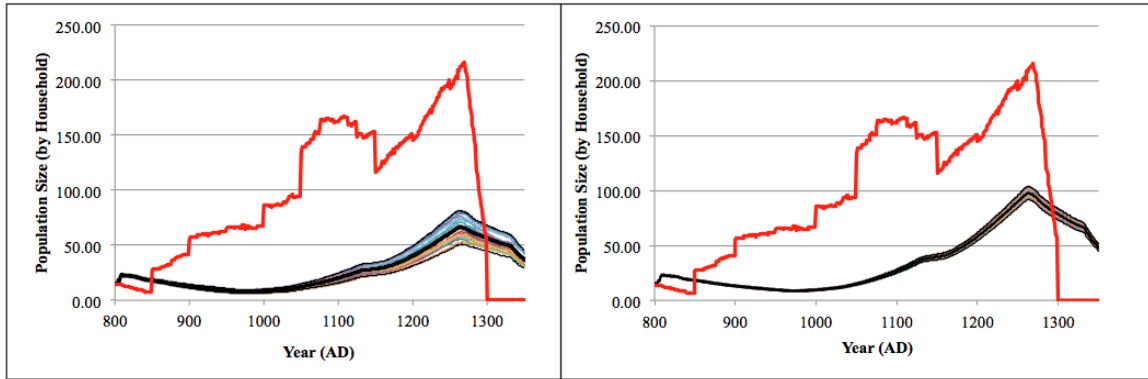


Figure 6.3: Results of repetition studies of ALHV-AgedMort with TFRs of 6.63 (left) and 7.07 (right).

Comparison of the results of ALHV-AgedMort to those seen in repetition studies of the ALHV-Baseline version (Figure 6.4), indicated clearly that the additional demographic processes added to the model produced population sizes far below that of the ALHV-Baseline version and continued to miss the timing and magnitude of both peaks seen in the archaeological population curve. The interplay between fertility and mortality produced these results; population sizes are likely smaller due to higher rates of juvenile mortality even though there was a large increase in fertility rates. Despite these results, we believe that the demographic rates we have implemented in the ALHV-AgedMort model are empirically sound and we are therefore reluctant to make any additional changes to fertility or mortality rates in this version of the model.

A number of sensitivity analyses were conducted to better ascertain the effects of varying parameter values on model behaviors. For the ALHV-AgedMort, the methods described for analyses of the ALHV-Baseline model were followed, although there were modifications to the specific parameters that were varied and the ranges across which they were varied (Table 6.4).

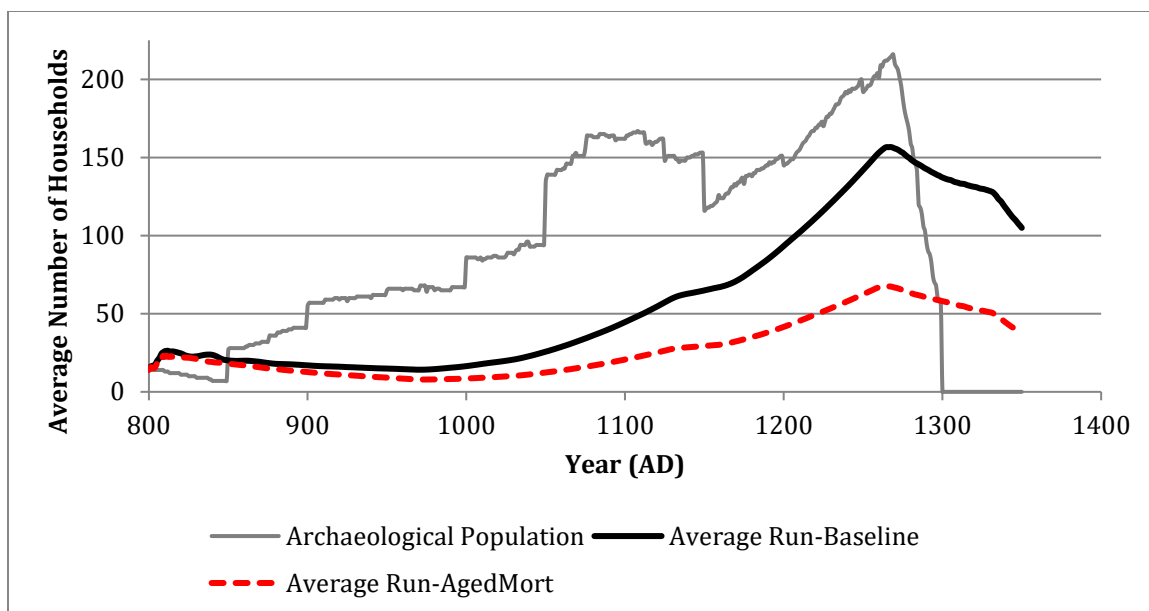


Figure 6.4: Comparisons of average model behavior over 20k runs of the ALHV-Baseline and ALHV-AgedMort models.

Table 6.4: Parameters and associated values used in ALHV-AgedMort sensitivity analyses

Parameter	Constant values	Range of analyzed values
<i>Single Variable Analyses</i>		
Harvest variance	0.4	0.3 to 0.7, in steps of 0.1
Fertility onset age*	Minimum: 15 Maximum: 15	12 to 18, in steps of 1
Fertility ends age*	Minimum: 48 Maximum: 50	45 to 55, in steps of 2
Fertility rate	TFR = 7.07	TFR 6.63 to 8.84, using multiplier 3 to 4, in steps of 0.2 [^]
Person nutritional need	285	270 to 300, in steps of 5
Mortality rate	MT: 35.0-65.0 (from Weiss and Wobst 1973)	Multipliers 1 to 2.4, steps of 0.23 Varying life tables MT: XX.X-65.0 [^]

* These parameters require a minimum and maximum value in the model, but to allow for sensitivity analyses with consistent values, these values were set to be the same.

[^] Complete fertility and mortality schedules used in sensitivity analyses available in Appendix B.

Sensitivity analyses (Figure 6.5) did show that, as fertility rates increased, the model captured the archaeological population curves somewhat better, but it was still far from accurate. As expected, the final number of households increased as the fertility rate

increased. The model failed to capture the size or the timing of the AD 800-1149 peak no matter which fertility value was used, however. Higher levels of fertility were able to capture the magnitude of the second peak, but all fertility levels captured the timing. Finally, sum of differences squared calculations showed that higher levels of fertility more closely matched the archaeological population curve.

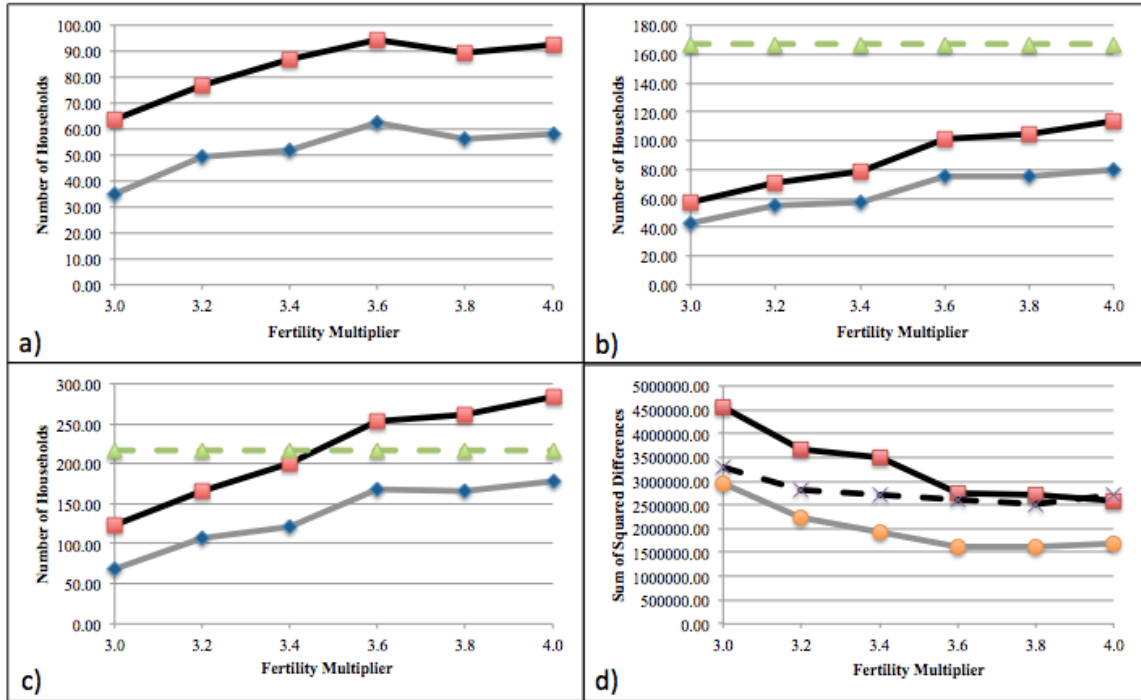


Figure 6.5: Select results from sensitivity analyses of ALHV-AgedMort, varying fertility rates. The charts represent results from: a) final number of households, b) AD 800-1149 peak size, c) AD 1150-1350 peak size, and d) the sum of differences squared. A-C show all runs (gray), extant runs (black). B-C show these plus archaeological counts (dashed).

To ascertain the effects of mortality, two different sensitivity analyses were completed; the schedules used are detailed in Appendix B. First, multipliers were applied to the selected mortality schedule (MT:35.0-65.0 from Weiss and Wobst 1973) to increase the mortality rate. As mortality rates increased, it was expected that the population sizes generated by the model would further deviate from the archaeological

population sizes, as more individuals were removed from the population during each time step. Analyses support this expectation. Figure 6.6 shows the goodness of fit measures from these analyses and the default mortality schedule produces the best fit. The same trend is observed in all other analyses varying mortality by multipliers.

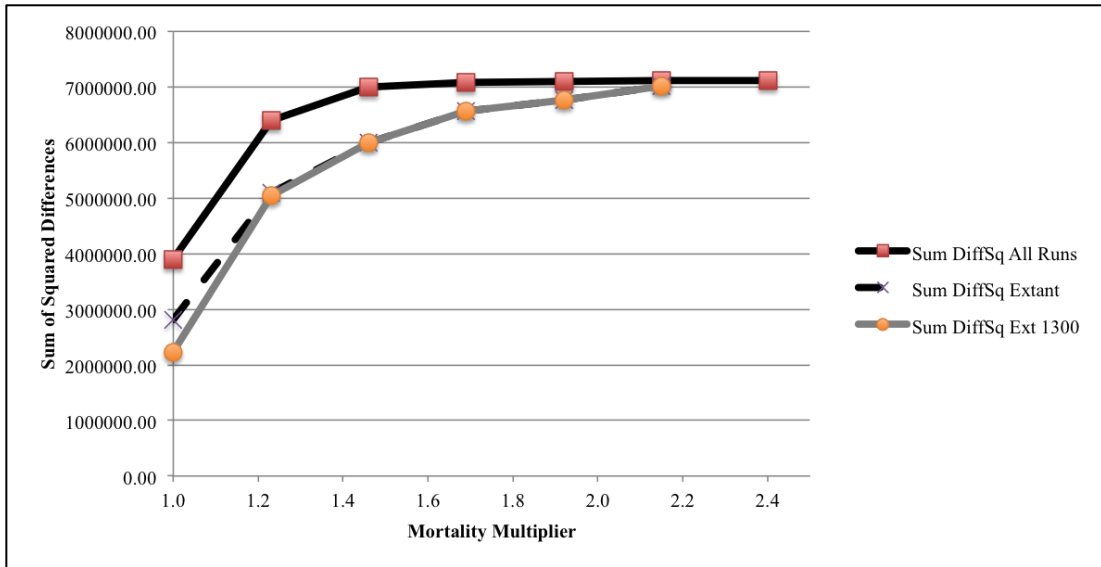


Figure 6.6: Results of varying mortality by multipliers in the ALHV-AgedMort model. The default schedule (multiplier 1.0) is clearly the best fit.

Next, the mortality schedules were varied by using all of the Weiss and Wobst (1973) model life tables from MT: 20.0-65.0 to 35.0-65.0. In these model life tables, the first number represents the expectation of life at age 15 (i.e., the number of additional years a 15 year old is expected to survive). The second number is childhood survivorship to age 15. Choosing the MT: XX -65.0 series of life tables maintains a consistent childhood mortality rate of 35%, while varying expected survivorship beyond age 15. Since the default schedule included the maximum life expectancy values, this analysis also increased overall mortality (i.e., reduces survivorship) as in the multiplier study. Again, the default mortality schedule produced the best quantitative fit to the

archaeological record (Figure 6.7) and best captured the other sensitivity elements examined (timing and magnitude of peaks, final number of households, etc.) better than the other mortality schedules considered. The results seem to suggest that the effects of lower mortality rates (higher survivorship) should also be explored, but the model behavior already produced such small population sizes that a decision was made not to do these analyses at this time.

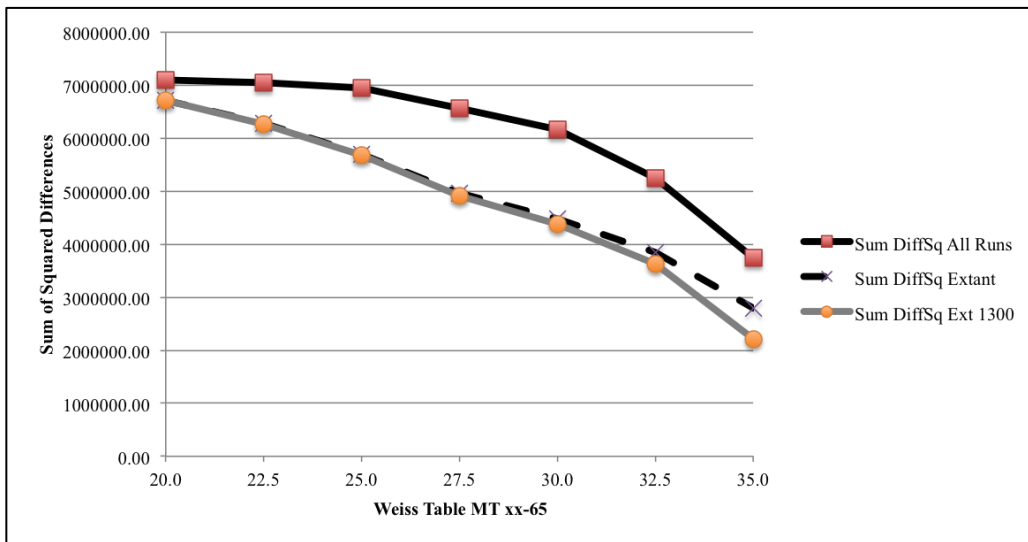


Figure 6.7: Results of varying mortality using schedules from different model life tables in the ALHV-AgedMort model. The default schedule (MT: 35.0-65.0) is clearly the best fit.

Demographic outputs

Prior to the development of the next iteration of the model, we also wanted to use some of the demographic data recorded by the model to determine the realized fertility and mortality rates in the model, as well as estimate of the amount of migration occurring in the current model. The analyses of some of the demographic output allowed us to look at how the stochastic processes in the model may have affected the input demographic

rates and provided an example of the types of demographic analyses that are possible with the new model format and data collection methods.

To assess the fertility rates output by the model, I determined the total number of births and the total number of persons in each age class for each of the 10 sets of demographic data that have been generated so far. In these data sets, population counts cannot be separated by gender, so I divided the total number of births (including births reported by males) by the population count to generate the age-specific fertility rate for each set. Finally, I averaged the rates across all 10 sets to generate an average simulation age-specific fertility schedule.

A comparison of these results to the age-specific fertility rate used in the model is shown in Figure 6.8. Although the shape of the curves generated by plotting the rate by age class are clearly different, the overall schedules are not significantly different when compared using a Student's *t*-test ($p = 0.49$). Fertility is reduced in the youngest age classes and increased in the highest age classes.

There are two potential explanations of these results. First, because total birth and population counts were used in these analyses it is possible that, because of the wide age range of suitable husbands, women were regularly marrying older men (who were also reporting births) thus driving down the age-specific fertility rate for the earliest age classes and driving up those rates in the oldest. Another possible explanation relates to the death by starvation method. Although women within their fertile years had relatively low age-specific mortality rates, they could often be the youngest person in a household of two (the woman and her husband) and more subject to starvation mortality. Since

deaths occurred in the model's annual steps before births, it is definitely possible this contributed to the observed differences between the input and output fertility schedules.

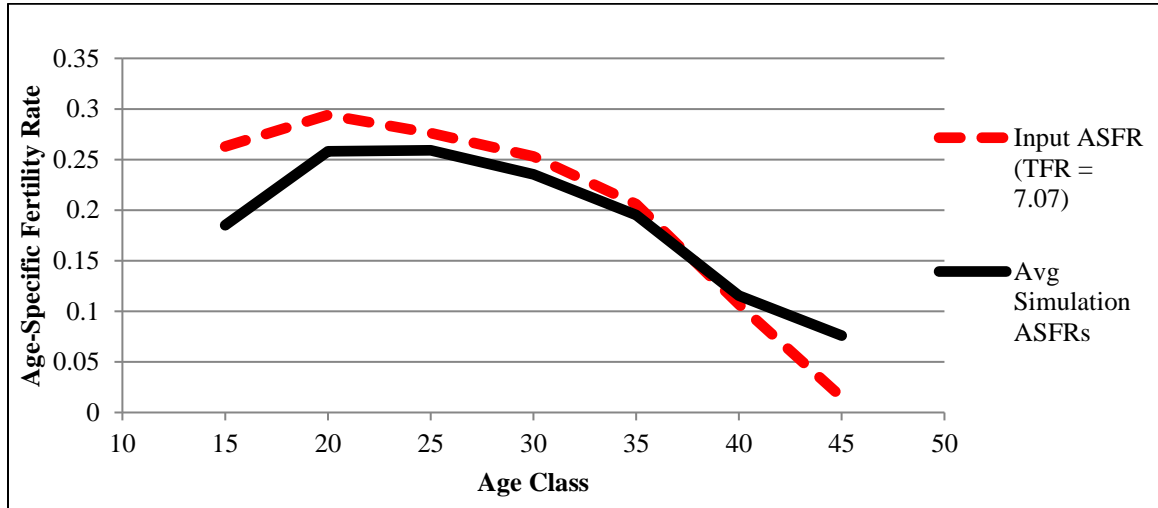


Figure 6.8: Comparison of age-specific mortality rates. The red line indicates the input rate (Coale-Trussell 1978 standard x 3.2), the black line represents the output rate.

An analysis of mortality output by the simulation also produced interesting results. Because of the way the model was coded, agents reported a death and the specific cause. The ALHV-AgedMort version included only starvation and deaths according to the general age-specific mortality schedule. To do these analyses, I counted the number of deaths in each age class for category 2 (all deaths) and causes 20 and 21 (other causes and starvation, respectively) for each set of demographic data. I then divided these counts by the number of individuals in each age class to produce the age-specific mortality rates. Figure 6.9 compares the input mortality rates to those generated by the simulations. These mortality schedules are significantly different ($p = 0.0002$). Most notably, the simulation mortality rate is much lower overall for all age classes except infants. The

input age-specific mortality schedule also produced a gentler curve when compared the output mortality, especially for the 50+ age classes.

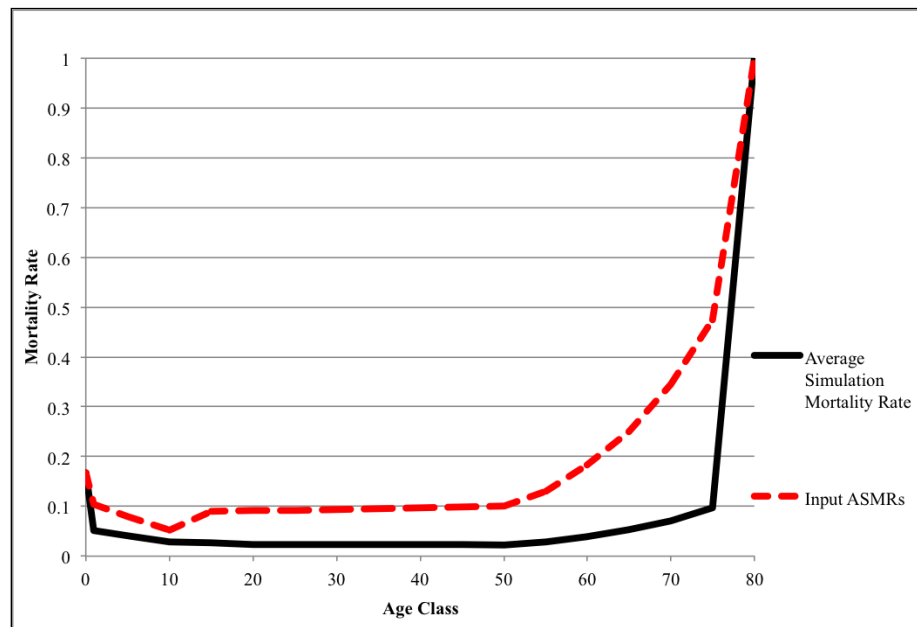


Figure 6.9: Comparison of input and simulation age-specific mortality rates for all causes of death combined.

A comparison of starvation mortality rates indicates the schedules are not significantly different ($p = 0.167$). Although there were some minor differences in the starvation rates, the overall trends were similar (Figure 6.10). Finally, a comparison of deaths caused by all other causes except starvation (Figure 6.11) revealed a pattern that at first glance seems nearly identical to the one seen in Figure 6.9 for all deaths and differs significantly ($p = 0.00002$). Figure 6.12, however, reveals an important difference that may explain the disparities between the input age-specific mortality schedules and those generated by the model.

By plotting the three age-specific mortality schedules considered above together, the effects of starvation mortality on the overall mortality rate are clear. Starvation mortality had a much greater effect on the youngest age classes (ages 0-15). In fact, it

appears that the effect of starvation mortality was so great it reduced the relative effects of a general age-specific mortality, even though those rates were also quite high, especially for infants. Once the effects of starvation wane (beyond age 20), the other causes and overall mortality better aligned with each other.

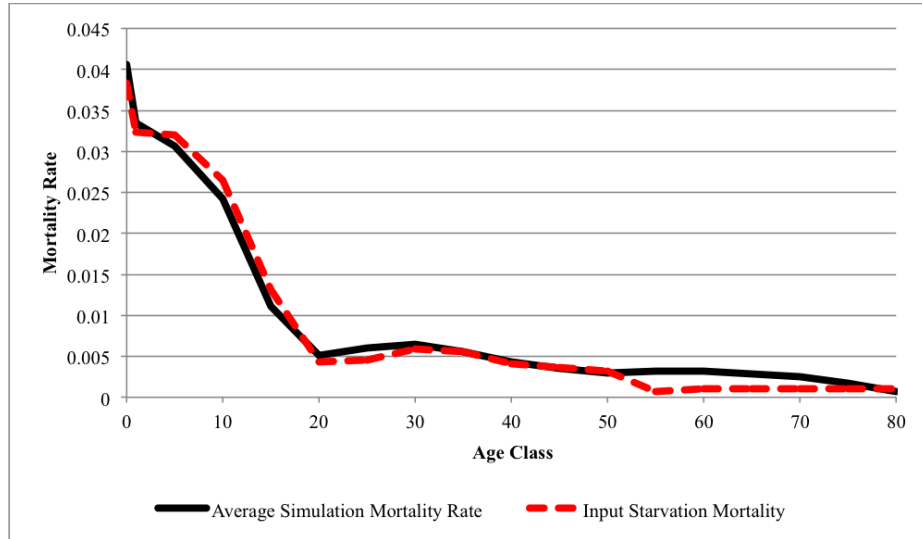


Figure 6.10: Comparison of input and simulation starvation mortality rates.

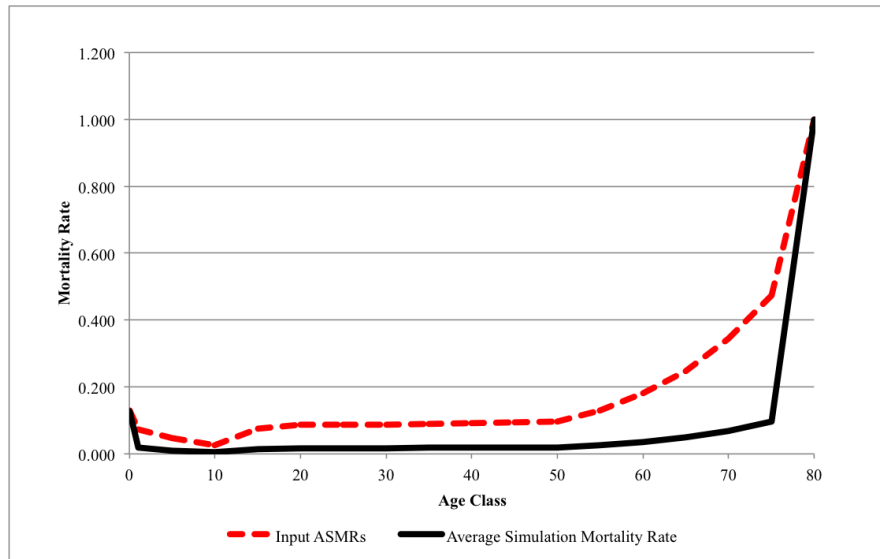


Figure 6.11: Comparison of input and simulation age-specific mortality rates for all other causes of death.

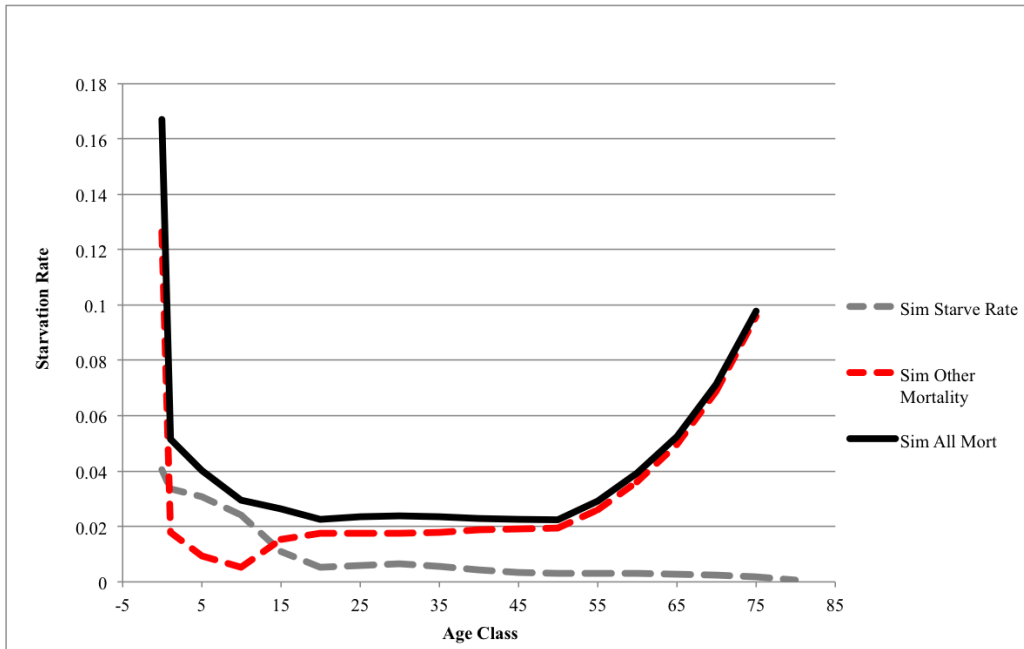


Figure 6.12: Comparison of simulation mortality rates.

Figures 6.9-6.12 explain the relationship between the simulation mortality rates, but they do not adequately explain why the general and other mortality simulation rates vary significantly from those input into the model. There are two potential explanations for this, both of which likely play some role in producing these results. The first relates to the way data are collected in the model. The population distributions are calculated at the beginning of each time step, while deaths and fertility occur later in the time step. Mortality rates are usually calculated from the population from which they were drawn. In our modeling scenario, that population would actually be the one enumerated at the beginning of the next step, after deaths and reproduction have occurred. While this phenomenon requires more investigation using the demographic and population output data, it may contribute to the disparities between the general and other cause mortality rates output and those that were input. Even more significantly, this explanation

introduces the need to consider the timing of data collection *within a single year*, an issue known to modern demographers but likely never considered by paleodemographers because data at this scale are typically unavailable. The types of data output by the model create new analytical possibilities for the understanding of prehistoric population dynamics.

The second explanation for the disparity between the input and output mortality rates is related to migration. Because of the structure of this model version, not every person who leaves the simulation reports a death; some report an emigration instead. In order to better understand the potential role of migration in the observed mortality results, I simply counted the number of emigrants reported for each cause (see Table 6.2 above) and divided that by the total population size for each of the ten demographic data sets and then averaged the results. The relative contribution of each emigration cause to overall emigration rates is shown in Figure 6.13. Overall, 1.8% of the population were leaving the simulation through migration. The unavailability of land and wives were the leading drivers of migration (0.38% and 0.39%, respectively). These results suggest the young, unmarried males were probably the most common migrants but, because entire families migrate due to the lack of suitable land, we suspect the demographic breakdown of the total migrant group is fairly diverse. We have the ability to examine the migrant demographic profile with the data available to us, but that is outside the scope of this dissertation.

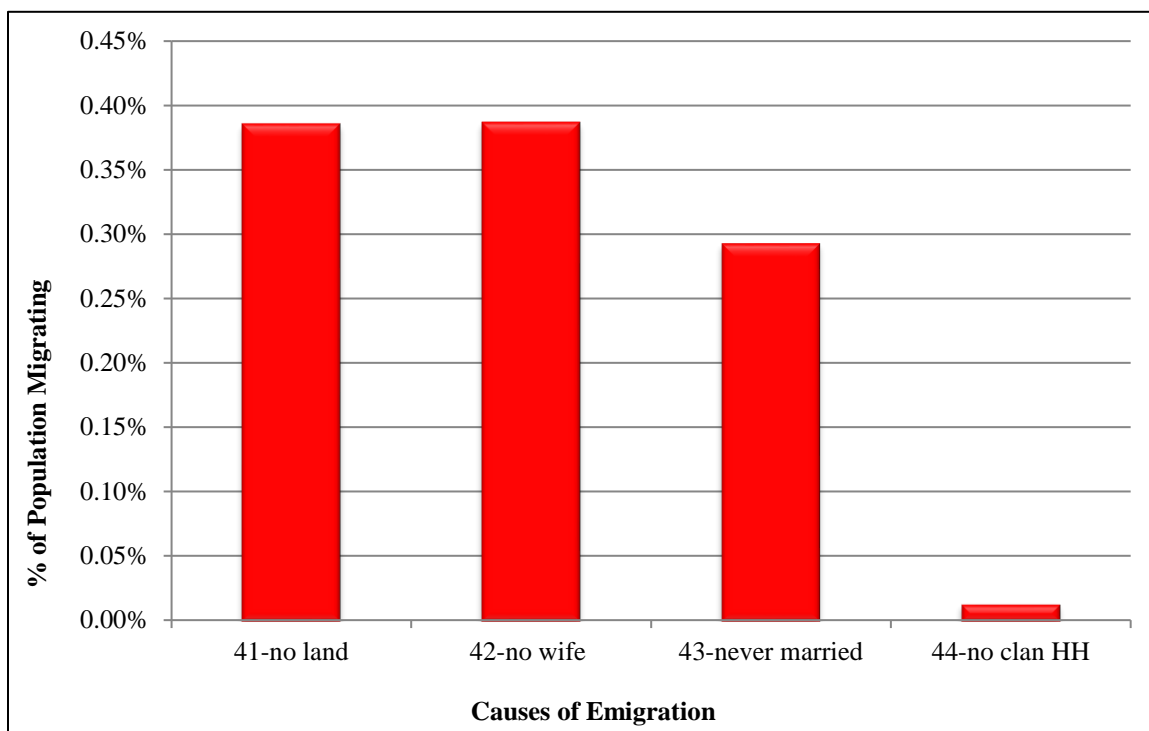


Figure 6.13: Comparison of emigration causes in ALHV-AgedMort simulations.

In the next stage, Migration, the ALHV-AgedMort model is extended to include Black Mesa geography, environment, and population and allow for real movement of individuals between the two areas. Integrating actual migration due to multiple ethnographically realistic reasons, permits greater understanding of the demographic effects of the movement of individuals from one area to another.

CHAPTER 7: INCORPORATION OF BLACK MESA AND MIGRATION— METHODS AND RESULTS

Following the development of the ALHV-AgedMort model, the next step in the project was to add the Black Mesa environment and populations to permit migration between the two study areas. In order to accomplish this Migration stage, it was necessary to determine the best way to recreate the Black Mesa landscape, simulate environmental change through the study period, and establish the structure of the initial population.

Establishing the starting population of Black Mesa was relatively straightforward, as it involved a similar method to that described above for determining the initial Long House Valley population. Instead of the 1895 census I used previously, I randomly drew families from the 1790 and 1823 Pueblo census files created from my research at the National Archives. The Layhe (1981) reconstruction chosen as a comparative archaeological population estimated that 121 individuals would have inhabited the mesa at the beginning of the study period, AD 800. It was desirable to reconstruct families as realistically as possible, so I randomly drew households from the census population until I reached the target number of individuals. Due to the random drawing of households, I ended up with a starting population of 122 individuals (to avoid breaking up the real households that form the basis of our starting population) and 26 households. Attributes such as age, sex, and relationships within families were derived directly from the census data. Other person characteristics were determined using the same methods described in

Chapter 5 for the creation of the Long House Valley starting population. These population data are also included in Appendix C.

Developing a model representation for the Black Mesa landscape presented a novel challenge and I chose to closely follow the methods used by the original AA development team as they recreated the Long House Valley landscape (Dean et al. 2000). In the AA model, Long House Valley is represented on an 80 x 120 grid that corresponds to 96 km² (9,600 hectares). Within this grid, each individual cell (1 x 1 unit) was assigned a number that designated it as one hectare within a specific environmental zone. Within the model, these data are read in and the map is created by assigning each cell its appropriate color and maize yield zone. The geographic perfection of the original AA model was not required for this project, so I devised a similar, yet simpler, strategy to determine the environmental zone and maize yield of each cell. The Black Mesa study area is 256 km² (25,600 hectares) so I first created a 160 x 160 grid and then mapped the areas surrounding the three main washes—Coal Mine, Moenkopi, and Dinnebito—and the washes themselves onto this grid. The washes were designated as intermittent water sources, the areas surrounding them were designated as fertile zones, and the remainder of cells were designated as empty or non-productive. These designations are read into the model and create the map pictured in Figure 7.1.

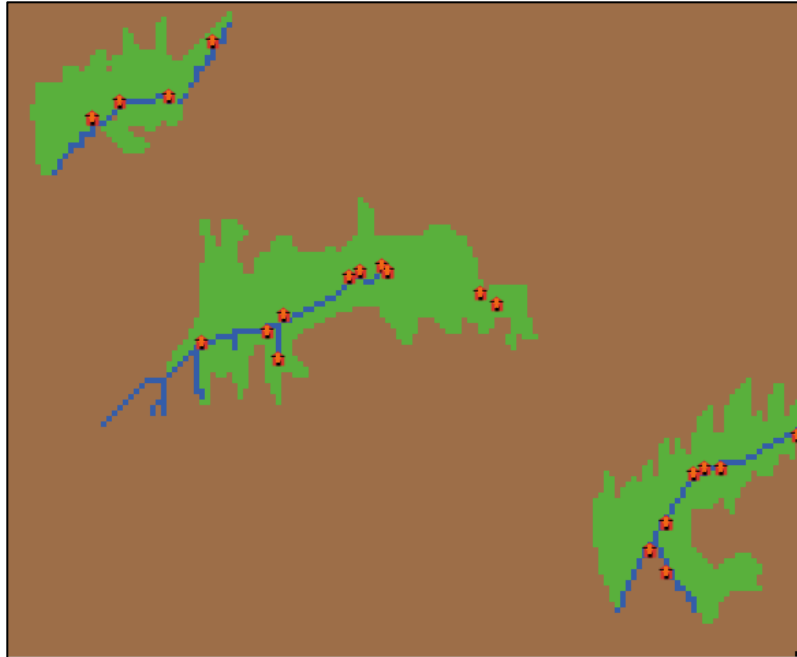


Figure 7.1: The map of the Black Mesa environment. Green indicates fertile areas around the three washes, blue the courses of the washes themselves, and brown unproductive areas. Red squares represent households placed on the map during setup.

In addition to simplifying the map representation of Black Mesa, both the productive landscape and the environmental inputs were simplified. Instead of the multiple maize yield zones in the AA model, there is only a single productive zone designation for Black Mesa. The calculation of productive potential for this zone was straightforward because, in developing the productive estimates for the Long House Valley area, the AA modeling team had identified the soil type found in each maize yield zone, found analogs for these in soils analyzed from Black Mesa, and then used the Black Mesa analogs to determine which of VanWest's (1994) crop yield estimates were most appropriate. The Ustollic Haplargrid x/y alluvial soils prevalent on Black Mesa were used by the original AA team as the analog for the LHVgensoil and for productive estimates for the General Valley Floor yield zone in the original model (Dean et al. 2000). For this

soil type, VanWest (1994) had determined the productive potentials as they vary by availability of moisture (PDSI), as shown in Table 7.1.

Table 7.1: Maize productivity estimates for Black Mesa area for each PDSI range

Annual Palmer Drought Severity Index Range	Maize Yield Estimate
≥ 3.0	961
1.0 to 3.0	824
-1.0 to 1.0	684
-1.0 to -3.0	599
$\leq - 3.0$	514

The final step in reconstructing the productive landscape of Black Mesa was determining the Palmer Drought Severity Index values for each year. In the AA model extensions developed as part of this project, the adjusted PDSI values calculated by the original team for Long House Valley productivity estimates were used. These adjusted PDSI values were arbitrarily assigned based on a combination of PDSI, hydrology, and aggradation with the justification that good hydrology could overcome moisture deficits, while bad aggradation values may not be sufficient to overcome even periods of abundant moisture (Dean et al. 2000). Unfortunately, all but the most generalized hydrological and aggradation data are lacking for the Black Mesa study area, so only the most recent raw PDSI values for the region (Cook et al. 2008) were used as the environmental data to be read into the model.

At this point, a stand-alone prototype Black Mesa model was constructed and used to insure the data were being read in correctly and that model behavior was reasonable. This Black Mesa-Test model retained the structure of the ALHV-AgedMort model but was modified slightly to account for differences in environmental data available. It quickly became apparent from the test runs that some way to improve the

environmental quality of the mesa was needed, because all populations were almost immediately going extinct. In examining the maize productivity estimates provided in Table 7.1, we realized that even under the best conditions ($PDSI \geq 3$) the annual productivity could have only supported households of three individuals. To overcome this issue, an additional parameter was added to the Black Mesa-Test model that allowed increases in the productivity of the mesa using a multiplier—mesa adjustment. Dean (2010) and Kohler (2012) both refer to the higher productive potential atop mesas, so we felt justified in making this decision. Results from a small set of sensitivity analyses suggested that the ideal value for the mesa adjustment parameter was 1.3. This parameter was used in calculating all mesa maize productivity estimates and the effects of changing its value in the combined model will be discussed below.

Runs of the Black Mesa-Test model were also used to generate the final data required for the addition of Black Mesa to the existing ALHV model: an archaeologically supported count of households for each year during the study period, which are used in analyses for comparison purposes. As discussed in Chapter 2, a number of population estimates based on archaeological data were available; the estimates generated using Layhe's fourth method were chosen. However, Layhe's population estimates could not be incorporated wholesale into the model for two reasons: they estimated the counts of individuals and they only included counts for every 25 years during the study period. In the ALHV models, simulation data were compared to archaeologically generated estimates for both households and individuals for each year during the study period. In order to create an equivalent Black Mesa population data set, the growth rate between each of Layhe's estimates was calculated and then those growth rates were used to

estimate person counts for each intervening year. Estimates of the number of households per year were derived from these individual person estimates by calculating the average household size generated during the Black Mesa-Test repetition study and dividing the number of persons by the average household size.

Once the necessary data files were created, the process of incorporating Black Mesa into the ALHV-AgedMort model began, and led to the creation of the final model, ALHV-Mesa. This combined model adds Black Mesa environmental conditions and populations to the ALHV-AgedMort model described in Chapter 6 and allows individuals and households to migrate between the two areas under specific conditions. Creating the combined ALHV-Mesa model required three main tasks: adding the Black Mesa map and underlying environmental conditions, adding members of the Black Mesa population, and modifying existing agricultural and demographic methods to allow for movement between the two areas.

Adding the Black Mesa map and environment to the existing model was relatively straightforward. First, the program had to be written in such a way that, despite being displayed on the same map, the two areas were treated as separate entities. This was accomplished by designating part of the display as Patch Region 1 (Long House Valley) and the other half as Patch Region 2 (Black Mesa) and then reading in the map data for each area separately. All map and environmental setup methods used these Patch Region designations to differentiate between the areas. This results in the display shown in Figure 7.2. Next, calculation of the yields for each hectare of land in each model was required. This was accomplished by creating two methods that calculate yields in each of

the areas separately, dependent on the environmental data and the maize productivity estimates for the specific soil types within each region.

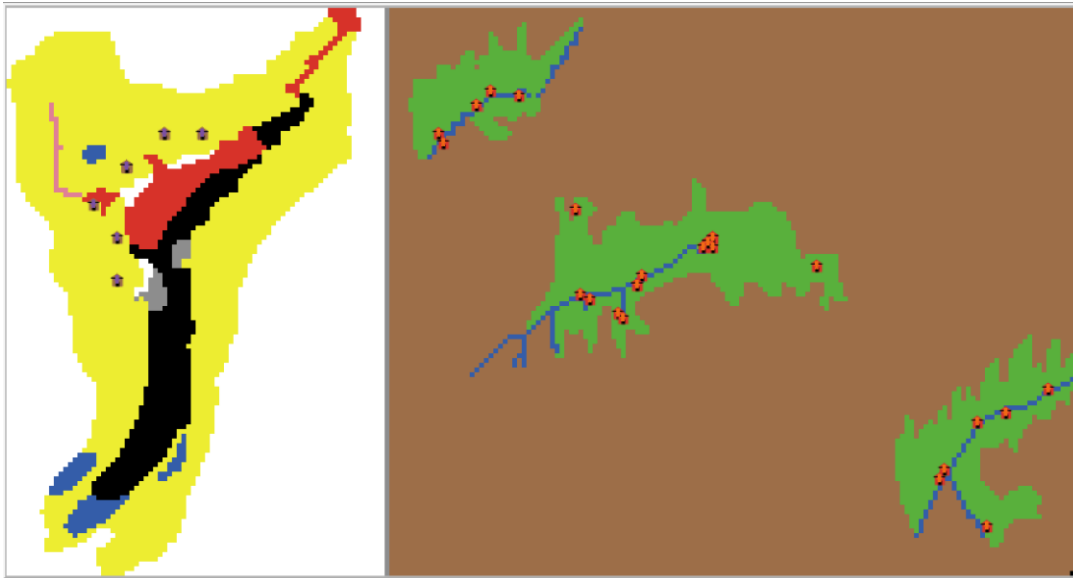


Figure 7.2: Combined model display. Long House Valley is pictured on the left, Black Mesa on the right.

The next step was to create households and their associated individuals for each of the areas. Again, the most reasonable modeling decision was to do this separately. The *initialize-household* and *initialize-persons* methods were retained from the ALHV-AgedMort model to establish the initial Long House Valley population and then new methods for initializing Black Mesa households and persons were added. A fundamental part of the *initialize-households* method was establishing initial farms and settlements in suitable areas, which required the *find-farm-and-settlement method*. Because this method was a major driver of the model activities and would be key to household migrations due to maize shortages, we had to think very carefully about how best to modify this method. When the household initialization method was called for either region, the household randomly selected a farm and household site within their home region. Then a list of

potential, suitable farms was generated for each area and *find-farm-and-settlement* was called. *Find-farm-and-settlement* called either the *search-valley* or *search-mesa* method, which placed the household's farm site on the nearest location that met their nutritional needs within their home region and then systematically chose the most appropriate, nearby settlement site using the criteria outlined in Table 7.2. For initial households and other newly formed households, the search area was constrained to only the home region. If no suitable farm and settlement location was identified in the home region (a theoretical possibility, but one that does not actually occur), the households would leave the simulation. Once suitable farm and settlement locations were occupied by the initial households in both the valley and the mesa, the individual populations were initialized by reading in person characteristics from the appropriate data file.

Table 7.2 Criteria used to determine settlement locations in *search-valley* and *search-mesa* methods

SEARCH VALLEY CRITERIA	SEARCH MESA CRITERIA*
Identify best farm location and occupy	
CRITERION 2	
Search for nearby empty sites with low yield and poor hydrology within user-defined distance from water source. Occupy if one is available. Move to criterion 2 if not.	Search for nearby empty sites with low yield within user-defined distance from water source that is not a water source itself. Occupy if one is available. Move to criterion 2 if not.
CRITERION 2	
Search for nearby empty sites with poor hydrology within user-defined distance from water source. Occupy if one is available. Move to criterion 3 if not.	Search for nearby empty sites within a user-defined distance from water source. Occupy if one is available. Move to criterion 3 if not.
CRITERION 3	
Search for nearby empty sites with poor hydrology. Occupy if one is available. Leave home region if not.	Search for any nearby empty sites. Occupy if one is available. Leave home region if not.

* These criteria are different for the two regions because of differences in the available environmental data.

Once the setup steps were completed, the annual cycle began. The yield of each cell was calculated according to the conditions in each region and individuals consumed the harvest according to their nutritional need, noting any shortfalls.

Next, the death methods were called. These methods—starvation and death according to age-specific mortality rates—were identical to those in the ALHV-AgedMort model and acted on both populations in the same way. The death aftermath processes, however, were modified to allow for migration of individuals when there was widow remarriage and reassignment to new clan households. As in the ALHV-AgedMort model, if the widowed person was a male, any children and older women remaining in his household would try to find another clan household to join. The ALHV-Mesa model deviated from the ALHV-AgedMort method in the way in which these household members were reassigned. Instead of only searching in the home region to find a suitable new household, the reassigned group first searched for a suitable new household in their home region and, if unsuccessful, searched in the neighboring region. Those who found a suitable home in the neighboring region reported their migration as appropriate to the migration cause codes defined in Table 7.3. If they were still unsuccessful in finding a new household, they left the simulation and reported that they had migrated out of the simulation areas. Orphaned children and women whose age exceeded fertility age who were left alone in households following deaths were also reassigned in this way.

Once a widowed male's household members had been reassigned, the widowed father then called the *find-next-wife* method. This method allowed him to search first his home region and then the neighboring region for a suitable wife according to the same criteria defined for widower remarriage in the ALHV-AgedMort model. If he found a

wife outside of his home region, he reported his migration status. If he could not find a wife in either region, he reported his migration cause accordingly and left the simulation. If the widowed person was a female within her reproductive span, she called the *find-next-husband* method. She first searched her home region and then searched the neighboring region. Because we assume the ancestral Pueblo were a matrilineal society, any husband found in the neighboring region moved into her region and reported that migration. If no suitable husbands were found in either region, she created an outside husband as in the earlier models and he reported his immigration into the model population.

Table 7.3: Migration cause codes for the ALHV-Mesa model

Migration Cause	Migration Cause Code
Orphan group is reassigned to a clan household outside of their home region	44V for persons who originated in the valley 44M for persons who originated in the mesa
Orphan group is unable to find a suitable clan household in either region	44X for all persons
Widowed male finds wife in neighboring region	42V for persons who originated in the valley 42M for persons who originated in the mesa
Widowed male cannot find a wife in either region due to shortage of women	42X for all persons
Widowed male cannot find wife due to shortage of land on which to establish new household	41X for all persons
Widowed female finds husband in the neighboring region.	30V for new husbands from the valley 30M for new husbands from the mesa
Female creates outside husband	30X for all newly created husbands
Household identifies new farm or settlement location in neighboring region.	41V for members of valley households 41M for members of mesa households
Household fails to identify new farm or settlement location in either model region.	41X for all household members
Female finds first husband in the neighboring region.	31V for new husbands from the valley 31M for new husbands from the mesa
Unmarried male over leaves the simulation to marry elsewhere	43X for all persons

Once the death aftermath process had been completed, households updated their size and nutritional need and then began to look forward to the next year. As in earlier models, if the estimated harvest and their maize stores would not sufficiently provide for them in the next year, households attempted to move according to the rules in *find-farm-and-settlement* and the search valley and mesa methods. Unlike new households discussed above, however, existing households had the option of first exploring their home region for suitable farm and settlement locations, and then, if unsuccessful, exploring the neighboring region. Individuals within households who found new locations in the neighboring region reported their migration according to the codes in Table 7.3. If households were unable to find suitable locations in either area, they left the simulation and reported the migration.

Following the movement of households facing shortages, households and individuals updated their information. During this process, young men who had yet to find wives by age 20 migrated out of the simulation. Since potential wives were searching both regions for husbands in the ALHV-Mesa model, this method did not change from previous versions. Next, young never-married women who were within their fertility span first tried to build a house (in their home region only) and then looked for their first husbands. As with widowed women described above, the new wife would first search her home area for a suitable husband and then looked to the neighboring area. Husbands chosen from other regions moved into their new wife's region and reported their migration. If no suitable husbands were identified in either region, she created a new husband who reported his immigration into the model population. Finally, married women within their fertile span reproduced following the same methods described in the

ALHV-AgedMort model. All vital events, such as births and deaths, were recorded as in earlier models and output in the demographic data file.

The model changes described above allowed for movement of individuals and households between the Long House Valley and Black Mesa areas under very specific circumstances. The migratory decisions incorporated into this ALHV-Mesa model aligned with the ethnographic and demographic behaviors of the ancestral Pueblo people. Model outputs provide data on both the numbers of individuals migrating and the reasons for their migration. Below we discuss the analyses of these fine-scale data regarding prehistoric population movements of a type previously unavailable to researchers.

ALHV-Mesa Results

In order to test this model in the time available, I conducted a 2,000 run repetition study to understand typical model behavior. Selected sensitivity analyses were also performed to understand the interaction between various parameters. Both of these analyses were completed as described in previous chapters. The variables and ranges considered in the sensitivity analyses are listed in Table 7.4.

Table 7.4: Parameters and associated values used in ALHV-Mesa sensitivity analyses

Parameter	Constant Values	Range of Analyzed Values
Harvest variance	0.4	0.0 to 0.8 in steps of 0.2
Fertility rate	TFR = 7.07	TFR 5.30 to 7.96, using multipliers 2.4 to 3.6, in steps of 0.2 plus 2.9 and 3.1 [^]
Mortality rate	MT: 35.0-65.0 (from Weiss and Wobst 1973)	Multipliers 1 to 2.4, steps of 0.46, plus limited analyses of 0.54 and 0.77
Person nutritional need	285	275 to 296, in steps of 5
Mesa adjustment	1.3	1.0 to 1.5, in steps of 0.1

[^] Full mortality and fertility schedules used in these analyses included in Appendix B.

To best assess the specific effects on Long House Valley and Black Mesa separately, I compared the count of simulation households in each year during the study period to the independent archaeological estimates for each area. I also compared a combined count of simulation and archaeologically estimated household counts. This practice revealed interesting trends in the simulation results that perhaps would not have been otherwise obvious.

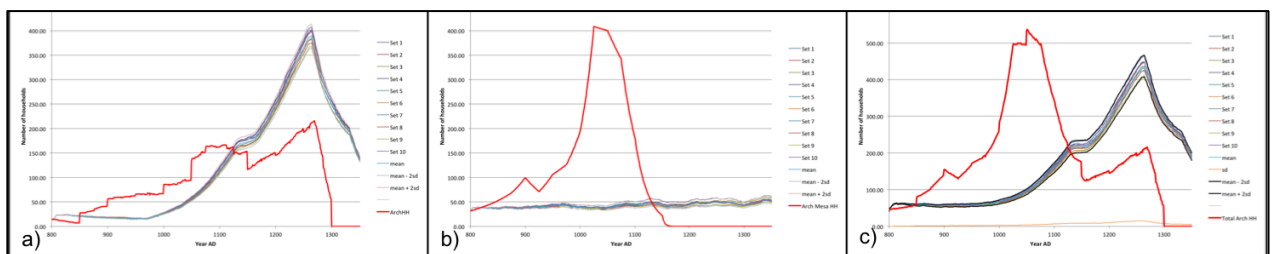


Figure 7.3: Results of a 2,000 run repetition study of the ALHV-Mesa model a) results for Long House Valley, b) results for Black Mesa, c) results for total population

The repetition study

The most notable trend observed in the repetition study was the consistent underestimation of the mesa population size and overestimation of the valley population size when the default parameters are used. Figure 7.3 shows the results from the 2,000 run repetition study. These results were somewhat unexpected because, in analyses of the ALHV-AgedMort model, the population sizes of the valley were consistently below the estimated archaeological population curve. Although no demographic rates were changed from the previous model version, it appears that the addition of migration had dramatic effects. Even though the mesa population is far below the archaeological estimates, there

were clearly enough mesa individuals moving into the valley to increase growth rates and population sizes in the valley.

The simulated Black Mesa population levels remained consistently low. One likely reason for this is the environmental inputs used in the model. The simulated populations felt the effects of each fluctuation of available moisture and there were several years with low PDSI values in the first 15 years of the study period. Perhaps because of this, many individuals migrated into to the valley early in the study period and never returned to their home region. Only a small, persistent population remained on the most productive mesa plots. The migration analysis in the following section explores this further. Another reason simulated population counts remained low is that they never recovered from the extremely poor environmental conditions just after AD 1000. The archaeological evidence, however, suggests that the period following this environmental hardship was the largest period of population growth for the mesa. Again, this could be due to the environmental inputs or fertility rates that were too low for a population trying to reestablish itself after a period of environmental hardship. This could also result from the fact that, although we allow migration between Long House Valley and Black Mesa, the model still represents a closed system. Migrants from neighboring areas to Black Mesa could have also contributed to the population patterns observed archaeologically. Regardless, it is clear from the repetition study results that more work needs to be done to better model the Black Mesa environmental conditions.

Sensitivity analyses

In order to assess other potential reasons for the poor overall fit of the populations generated by the ALHV-Mesa model to the archaeological estimates, I conducted

sensitivity analyses using the parameters and ranges outlined in Table 7.4. Because of the repetition study results, I decided to focus on best fit to both archaeological curves and then to the combined curve. Figure 7.4 shows the results of the sum of differences squared test for all of the parameters varied except harvest variance for the total population and Table 7.5 lists the best fit value for all parameters to all curves. The sum of differences squared charts for the valley and mesa are included in Appendix D.

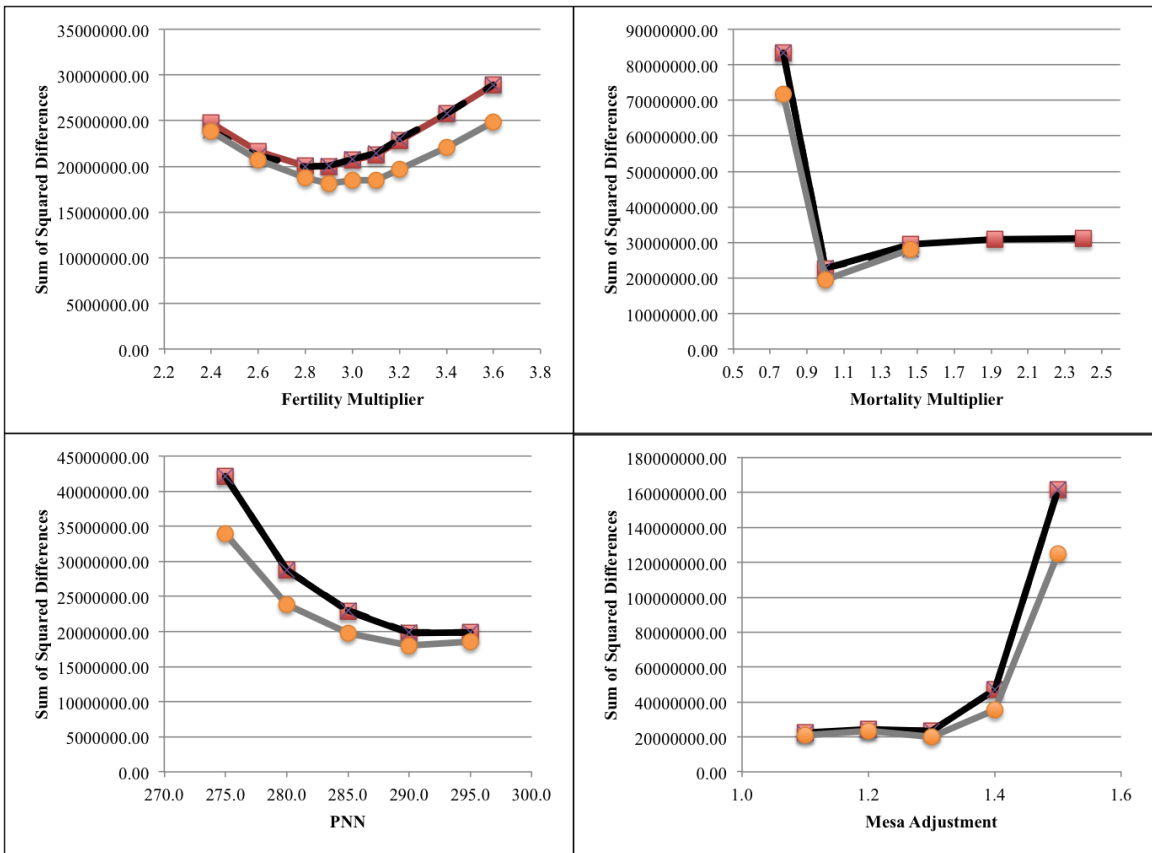


Figure 7.4: Results of sensitivity analyses of the ALHV-Mesa model. Each block shows the sum of differences squared curve for the parameters varied.

These results highlight the differences in model behavior when simulating valley versus mesa populations. As would be expected from the repetition study results, the parameter values that best fit the LHV population curve are those that constrain population growth more than the default parameters. The best-fit fertility rate, a main

driver of model behavior (as shown in previous chapters), is lowered from the default TFR of 7.07 to 6.41, while the nutritional need is raised from the default value of 285 to 295. Mesa adjustment, the multiplier that increases the productivity of mesa plots, is lowered to 1.1 instead of the 1.3 default value. As is expected, given the results of the repetition study, the best-fit mesa parameters move in the opposite direction: a higher fertility rate (TFR 7.96) and lower person nutritional need (275). Despite the consideration of both Long House Valley and Black Mesa archaeological population curve estimates being included in the total population counts, the best-fit parameters when compared to this curve more closely align with those for the valley alone. This likely relates to the relatively small size of the mesa population at all times during the simulation.

Table 7.5: Best-fit values for each sensitivity analysis parameter in the LHV, Black Mesa, and total populations

Parameter Varied	LHV best value	Black Mesa best value	Total curve best value
Fertility	TFR 6.41 (2.9 multiplier)	TFR 7.96 (3.6 multiplier)	TFR 6.63 (3.0 multiplier)
Mortality	MT 35.0-65.0 (default)	MT 35.0-65.0 (default)	MT 35.0-65.0 (default)
Nutritional Need	295	275	290
Mesa Adjustment	1.1	1.3 (default)	1.1
Harvest Variance	0.4 (default)	0.4 (default)	0.4 (default)

The issues of population over- and underestimation in the ALHV-Mesa model are too much to overcome within the scope of this project, but these models are still informative about the relative role of Black Mesa population movement on the Long House Valley population dynamics. The archaeological evidence supports the idea that, when Black Mesa populations needed to move due to poor environmental conditions, they simply packed up and moved into more productive areas nearby, including Long

House Valley (Gumerman 1988). The largest of these movements was the abandonment of the mesa, which occurred at approximately AD 1150.

Analyses of the ALHV-Mesa model can show the timing of declines in mesa growth and subsequent valley growth, but this shift does not occur when it should (Figure 7.5). As the fertility rate declined in our sensitivity analyses, the timing of the shift became somewhat better. The timing is best with a TFR of 5.30 and the shift, which occurs at approximately AD 1075, is clearer than with other fertility schedules. As the fertility rate increases, the timing of the shift moves further away from the archaeologically supported dates. This again supports the idea that, in our simulations, the Black Mesa is not able to overcome an earlier period of environmental stress to eventually experience the growth rates between AD 1050 and AD 1150 seen archaeologically.

Migration patterns

A major addition to the ALHV-Mesa version of the model is the ability for individuals and households to migrate due to a variety of circumstances (see Table 7.3 for descriptions) and to report the timing and cause of this movement. My final analyses focused on the migration patterns observed to see whether this would provide any additional insight into model behavior. In order to assess the magnitude and timing of migrations, the model was set up with the best-fit parameters for the total population curve, 5 sets of 50 runs were run, and relevant data were recorded each time an individual reported a migration and its cause.

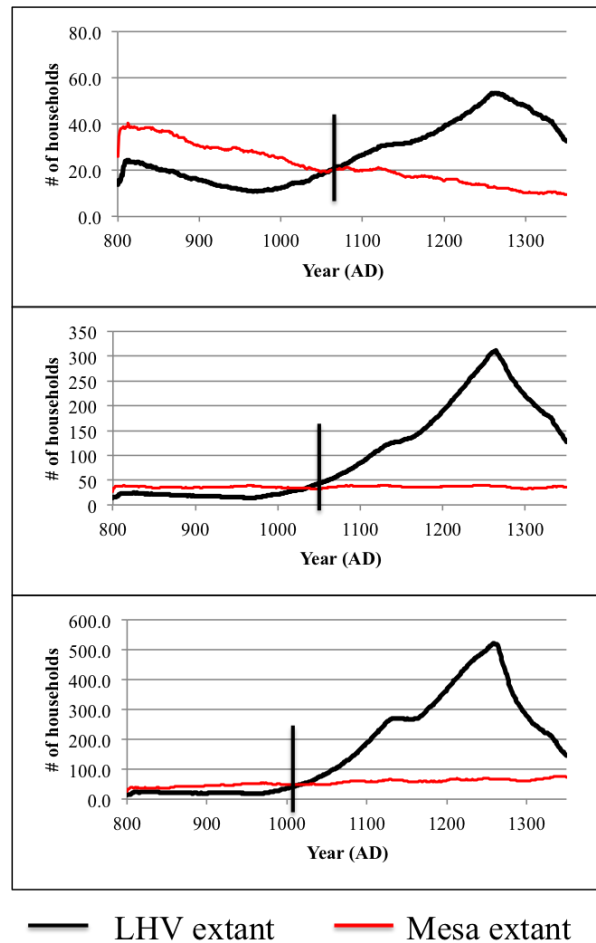


Figure 7.5: The timing of population trend shifts between Black Mesa and Long House valley. LHV growth rates begin to increase as the mesa rates decline: a) TFR = 5.30 b) TFR = 6.63, c) TFR = 7.96.

The most common reason for migrations (35% of all migrations) in the current version of the ALHV-Mesa model, as expected, was the need to move to find a suitable farm or settlement location. As shown in Figure 7.6, most of the migrations were out of the study regions entirely, but in the earliest periods (AD 800 to 850) a large number of Black Mesa households were migrating into Long House Valley. This trend declined continuously until approximately AD 1050 when very few of these migrations occurred. These results support the assumption, made above, that mesa conditions were so harsh at the beginning of the simulations that households left the mesa for the valley or other

regions to survive and did not return to the mesa later when environmental conditions improved, primarily because at that time the conditions were also adequate in their new location, so there was no need to migrate again. Interestingly, a large number of households were moving from Long House Valley onto Black Mesa late in the study period (post-AD 1200). Because the mesa was mostly empty at this point, the terrible environmental conditions throughout the region were forcing households to find any available spot. Constraints on settlement locations were relaxed on the mesa (refer to Table 7.2). These less rigorous constraints, plus lack of available space within the valley, likely contributed to these results.

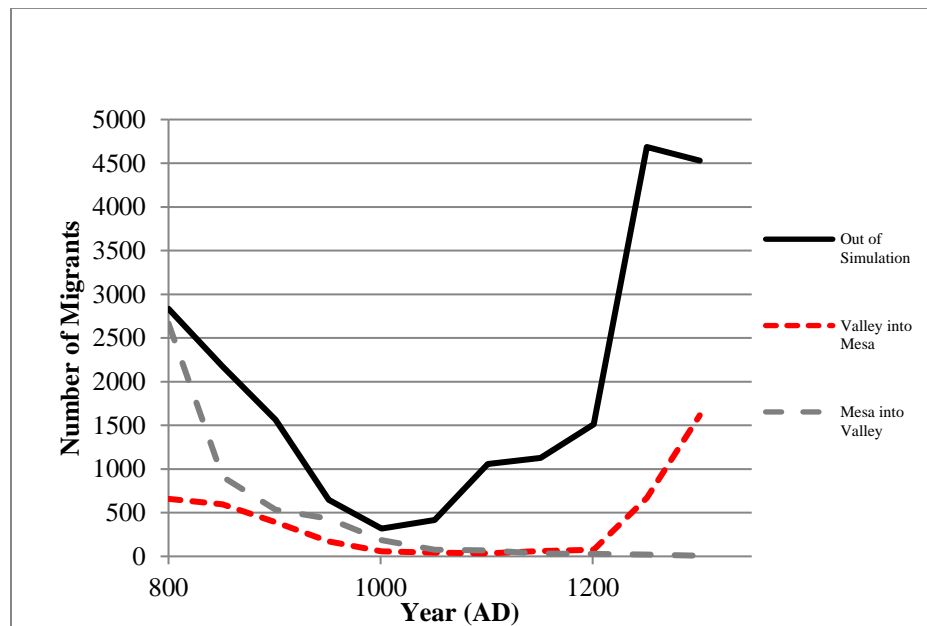


Figure 7.6: Migrations that result from not being able to find farm or settlement locations that meet minimum criteria in current region.

After the inability to find suitable space for farms or settlements, the next major migratory causes are males who are relocating to either marry widows (28%) or find new

wives after being widowed (23%). These migrations were functions of land availability as well. Widowed men were easily able to marry widows as widows already had established farm and settlement sites and they could simply move into their households. If there were no widows available, widowers had to find a new bride who could establish new farm and settlement sites in her home region. If none were available, widowers were either moving to a different region or out of the simulation to marry because of a lack of available land in either their home region or the neighboring region (i.e., new brides could not find suitable farms and settlements in these regions). In this model version, the vast majority of males were emigrating out of the study area to find wives and outside males were being created by widows and immigrating into the simulation. This is due to the structure of the current model and will be revisited in future model versions. Despite the large number of males both being created by widows and leaving the simulation, the overall behavior of the model is likely not affected much because female fertility is not being constrained.

The final three migration scenarios incorporated into the ALHV-Mesa model were the movement of males who remain unmarried by age 20 who had to leave the study region entirely (10%), first husbands who moved into a new region in order to marry newly available wives (3%), and clan reassignment (1%). Although the clan reassignment migrations were the least common, the results were especially interesting as they indicate that the need for new households within their mother's matriline for both Long House Valley and Black Mesa populations was at its peak during the early years of the study period (AD 800-1100) (Figure 7.7). This suggests that the initial populations were not large enough to allow easy identification of suitable clan households within regions at

first, but the need to migrate was alleviated as populations in both areas became more established.

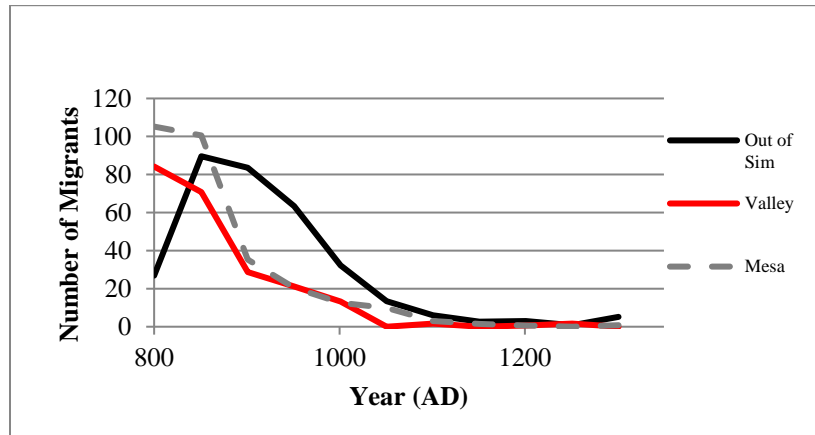


Figure 7.7: The number of individuals migrating to find households belonging to their matriline outside of their home region.

Although the outputs of the ALHV-Mesa version of the model did not reproduce population patterns similar to those developed using archaeological methods, the results above did provide some insight into patterns of prehistoric population movement. While recognizing the shortcomings of the current model version, we contend that the results of ALHV-Mesa model analyses serve as strong support for the contention that small-scale migrations and the later abandonment of Black Mesa contributed to population surges in Long House Valley. Despite the use of the archaeological curves in our comparative analyses, our intentions are not to produce models that provide the best fit to these curves; rather, the goal is to devise models that are based on sound assumptions about human demographic and agricultural behavior and incorporate parameter estimates that are grounded in actual data derived from existing archaeological, ethnographic, and environmental studies. The archaeologically observed population pattern occurred exactly once in prehistory and, although analyses of averages of several thousand runs are

not consistent with the archaeological record, a single individual run may capture the prehistoric trends perfectly. However, consistency in model outputs that align with the observed population trends in Long House Valley and Black Mesa is a primary goal moving forward. The next chapter revisits the important results from this project and identifies directions for additional research.

CHAPTER 8: DISCUSSION AND CONCLUSIONS

The project presented here contributes to issues of importance in both archaeology and physical anthropology by providing additional insight into prehistoric population dynamics. It demonstrates the ways these dynamics can be reconstructed from the available environmental, archaeological, and demographic data using sophisticated modeling and simulation techniques. Migration, as a critical adaptive strategy for buffering against environmental variation and its effects on prehistoric Southwestern populations, is also a critical component needed to understand the demography of any population. This project serves to improve our understanding of prehistoric population dynamics and to demonstrate how agent-based modeling can be used as a tool in paleodemographic research that surmounts some of the limitations associated with current methods of paleodemographic analyses.

The development and analyses of the models described in previous chapters has provided several important insights into the ancestral Pueblo populations under study. A key finding is that the models, as demographic realism and ethnographic complexity were added, yielded unexpected results with regard to the population sizes generated. None of the new models capture the Long House Valley population curve as accurately as the original AA model. The ALHV-Baseline and ALHV-AgedMort models underestimate Long House Valley population sizes when compared to the archaeological estimates, while the ALHV-Mesa model overestimates them. At the same time, the ALHV-Mesa model also greatly underestimates the mesa population size. Although I have been able to tease apart some of the reasons for these outcomes in the discussions in previous chapters, the results suggest that we need to consider future versions of the model that

account for fluctuations in fertility rates based on social or environmental conditions as they change throughout the study period. For example, evidence suggests that populations may increase their birth rates in the wake of natural disasters (Cohan and Cole 2002, Williams and Parkes 1975), which could, in concert with the improved environmental conditions of the years following, help explain the population surge in Black Mesa following the AD 1025 drought period.

Despite the failure of the newly developed models to capture the observed archaeological trends for the study areas, this project has provided additional information about the likeliest baseline fertility and mortality rates for the ancestral Pueblo populations. Our best-fit fertility schedule for the ALHV-Mesa model produces a total fertility rate of 6.63, which aligns with estimates for other naturally reproducing populations and estimates derived from a much later census of Pueblo populations (Wood 1994). Other researchers have also recently found evidence that birth rates in the region were higher than previously considered for the Colorado Plateau region from AD 500 to AD 1300 (Kohler and Reese 2014). The models developed for this project provide additional support for these high birth rates in prehistoric Pueblo populations.

In addition to the fertility trends observed, model results also provide insight into typical population structures for the ancestral Pueblo people. In both the ALHV-AgedMort and ALHV-Mesa models, the Weiss and Wobst (1973) model life table MT: 35.0-65.0 produces the best results. Although this life table was used to determine the mortality schedule in the model, it also provides information about the living population. According to this schedule, 35% of children in our study populations did not make it past the age of 5-years-old but, if they managed to survive to age 15, they could reasonably

expect to live to age 50. Indeed, this life table estimates that 34% of the population would have been over the age of 50 and 15.6% over the age of 70. The relatively high representation of older adults in the population is also supported by osteological analyses on the Black Mesa skeletons, which revealed such a high number of skeletons in the oldest age classes that researchers decided to redistribute them into other age classes when constructing life tables from the skeletal remains (Martin et al. 1991). The high rates of childhood mortality and indicators of biological stress in the Black Mesa skeletons (Nelson et al. 1994b) suggest that new model versions that more fully explore the role of other causes of mortality would be a significant addition to the literature in the future.

A major contribution of this project is the ability to enumerate the number of migrants across the study period and the ethnographic, demographic, and environmental conditions that led to these migrations. While the analyses of the migration data produced by these models are only preliminary, the results of these analyses clearly reinforce the results of the pilot study presented in Chapter 3: the lack of land with maize productivity sufficient for supporting the populations during periods of environmental stress in both Black Mesa and Long House Valley was a main motivator for population movement. Further analyses of these migration results will allow reconstruction of the profiles of migrant groups to better understand how environmental stress may have differentially affected people of various demographics. This project is unique in its ability to produce such fine-scale data about the magnitude and timing of prehistoric migrations in the region.

In addition to characterizing migrations, the models built for this project are able to generate additional demographic data that are necessary to derive standard demographic quantities that are not possible with other paleodemographic methods. The demographic and population data collected can be used to calculate realized fertility and mortality rates, determine completed family sizes, and provide specific information on the age structure of the population at any given time. Furthermore, we can break down these collected data even further to examine what particular demographic characteristics of a population allow them the best chance at surviving environmental or demographic challenges they may have encountered during the study period.

This project has also provided crucial insights applicable to archaeological and demographic modeling in general. Perhaps the most important implication that emerges from the model is the need to consider age-specific fertility rates when attempting to reconstruct population growth patterns in archaeological or demographic models. The results of the fertility study clearly indicate that the use of constant fertility rates dramatically affects model performance. Although constant fertility rates or target total fertility rates may be more tenable when considering prehistoric populations about which there is little specific information on fertility schedules, the results of this project indicate it is worth the effort to devise an age-specific fertility schedule to more realistically model this human biological process.

Results that pertain to the link between environmental conditions, productive capacity of the land, and nutritional need are also informative. Our effort to imbue the models with demographic and ethnographic reality only partially alleviates the models' tendency toward environmental determinism. Modifying parameters related to maize

productivity or consumption change model behavior in major ways. A rethinking of how real individuals would have perceived production deficits due to environmental and climatic conditions is warranted not only in future extensions of the models that form the basis for this project, but also in any models that examine population patterns as they vary on a landscape that links agricultural productivity and human population dynamics.

In addition to considering human perception of environmental fluctuations, models such as these should also consider interactions between multiple causes of mortality beyond general mortality and starvation. The interplay between starvation and general mortality in the ALHV-AgedMort model identified one way in which these interactions can produce unexpected results. The roles of disease, both infectious and chronic, interpersonal violence, and warfare, among others, should also be explicitly considered when trying to capture realistic mortality in prehistoric environments.

Finally, our results reinforce the need for extensive analyses of any model outputs. Many model-based studies publish the results of only a few runs or unique individual runs that best capture the intended model behaviors, but we have seen how unexpected model behaviors emerge with careful analyses. As more archaeological and biological anthropology research turns to modeling as a methodological tool, the community needs to develop standards for what are considered sufficient analyses.

Future Directions

The results of analyses of the models presented here as well as the consideration of the implications of these results point clearly to future directions for research. Perhaps most importantly, a standalone Black Mesa model should be created, not as a test model,

but with the goal of capturing the population trends developed through archaeological research at least as well as the ALHV-Baseline and ALHV-AgedMort models capture general trends for Long House Valley populations. We have elucidated a number of reasons why the current ALHV-Mesa model does not come close to reproducing mesa population trends above, but the major issues are most likely due to the simplification of the Black Mesa landscape and underlying environmental reconstructions. Any future extensions will greatly benefit from the addition of paleoenvironmental experts to the modeling team to provide more nuanced and accurate environmental estimates to reconstruct the Black Mesa productive landscape.

As detailed above, extensions of the models described in this dissertation need to include both condition-specific fertility (i.e., fertility rates that change with social or environmental conditions) and additional causes of mortality that would have been especially relevant to prehistoric populations. Our models, with the addition of age-specific fertility and mortality provide us with greater insight into the processes that led to prehistoric population patterns but, in real populations, these rates are changing almost constantly due to reactions to both internal and external stimuli. Future versions will explicitly consider these fluctuations.

Once we are satisfied that models of Long House Valley and Black Mesa are sufficiently capturing the major demographic processes as well as is feasible, the next major step will be the addition of more study areas. As discussed in Chapter 7, the lack of migrants from other neighboring areas may also contribute to the small mesa populations seen in the current version of the ALHV-Mesa model. By incorporating an ever-expanding network of neighboring regions to the models, we will gain even greater

insight into the timing, magnitude, or motivations for population movement. Through the analyses of multiple local migrations, better explanations for large-scale, regional migrations may emerge.

Implications

The goals of the project strongly align with the “great challenges” of archaeology recently identified by Kintigh et al. (2014). These challenges include the need for 1) increased understanding of human-environment interactions, which requires better methods for reconstructing prehistoric populations, and 2) the need for greater insight into the nature and cause of population movement, specifically as it relates to environmental and resource variability, population dynamics, and social structures. The project described in this dissertation, which incorporated environmental change and critical demographic factors into a series of agent-based models, permits the future study of the relative effects of additional adaptive behavioral strategies for buffering against environmental and climatic variability, conflict and violence, disease, and sociopolitical complexity on the population dynamics in the prehistoric Southwest.

The study also illustrates that agent-based modeling has the potential to overcome some of the limitations of traditional paleodemographic analyses. It has long been lamented that current paleodemographic methods are unable to accurately reconstruct living populations from deceased populations. By using the models developed in this dissertation to simulate demographic processes and output detailed population data, this research frees paleodemographic reconstruction from these limitations and produces perhaps the most detailed, testable reconstructions of prehistoric population structures and dynamics currently available.

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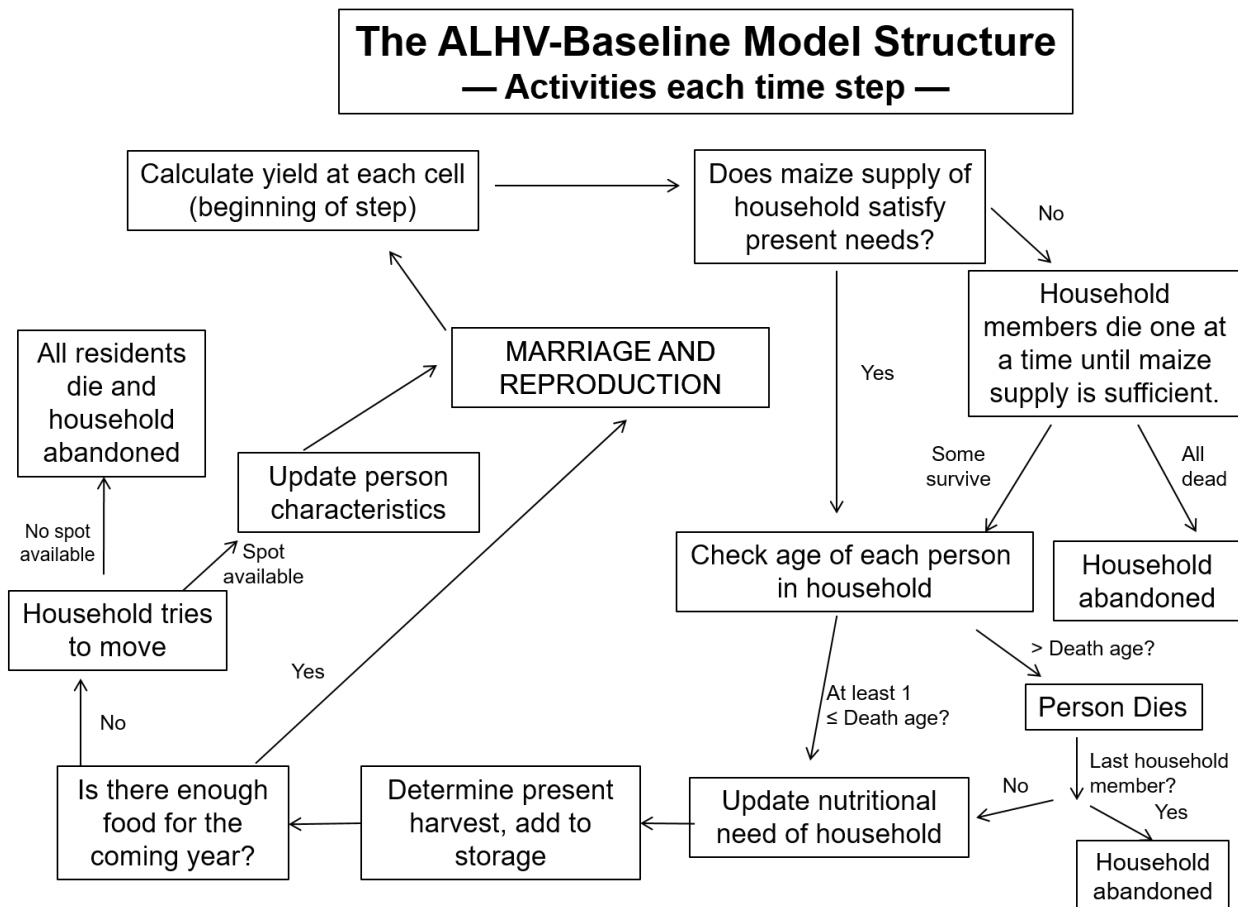
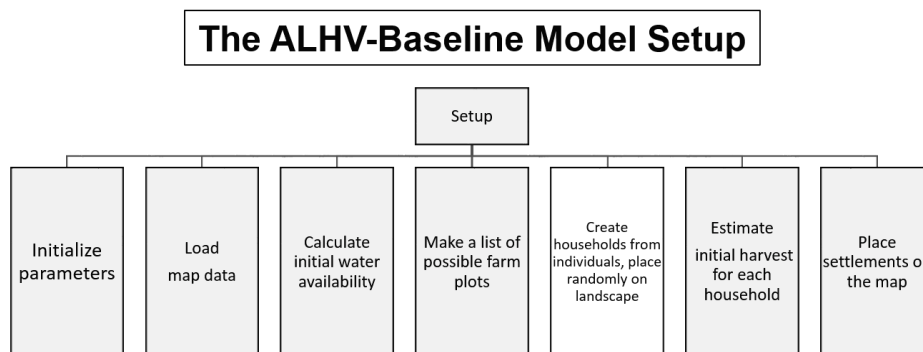
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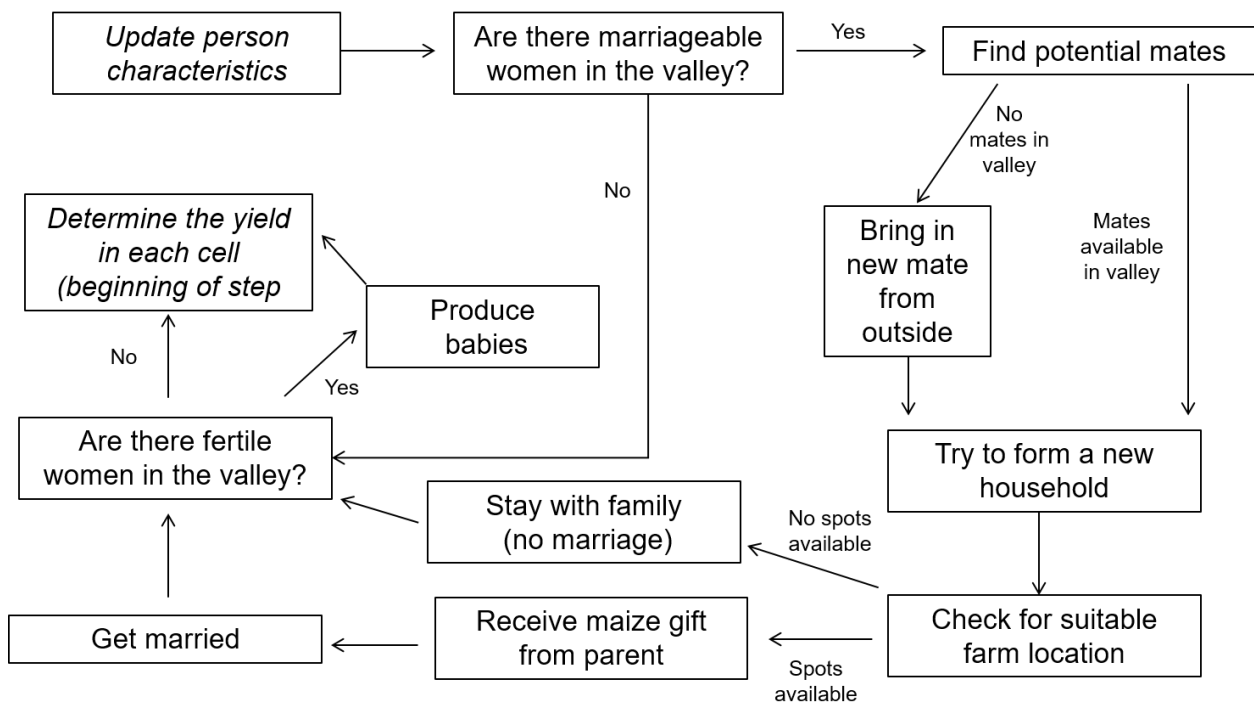
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APPENDIX A: MODEL INPUTS AND PROCESSES

Disaggregation: ALHV-Baseline Model

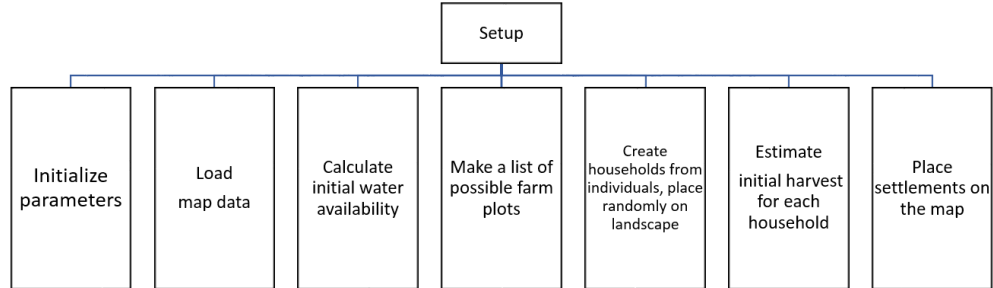


ALHV-Baseline Marriage and Reproduction

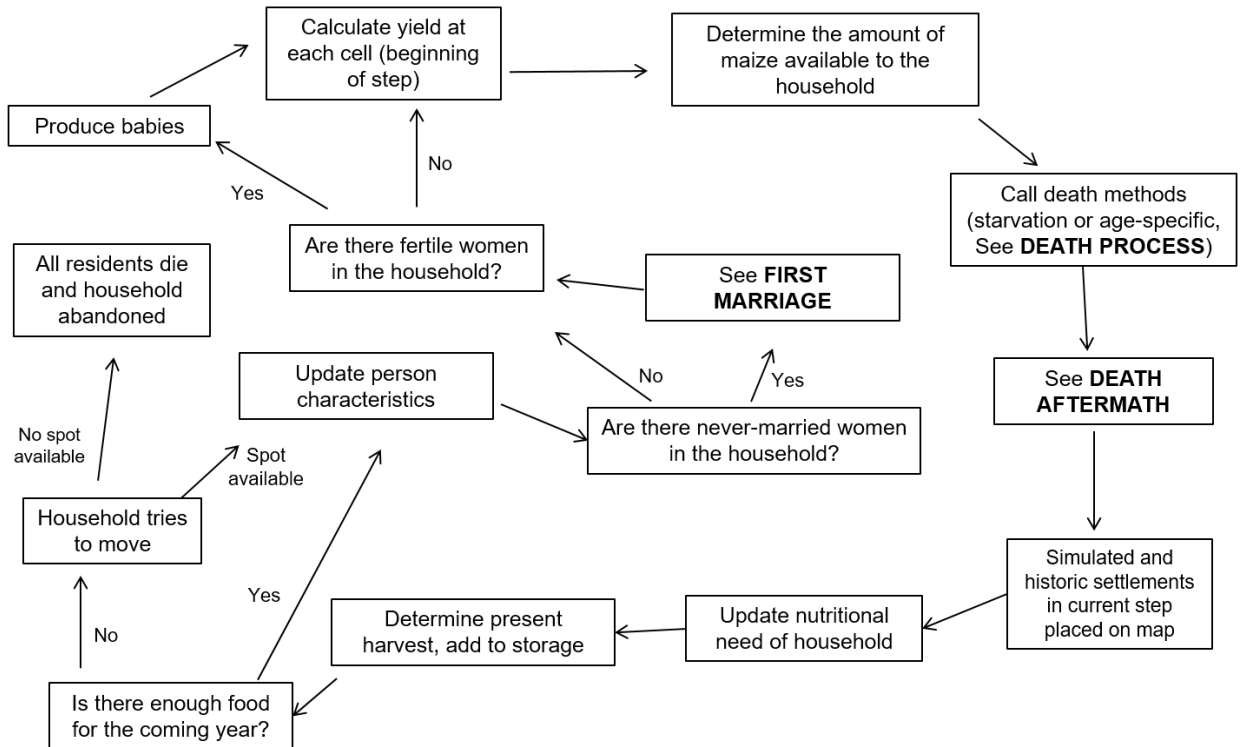


Demography: ALHV-AgedMort Model

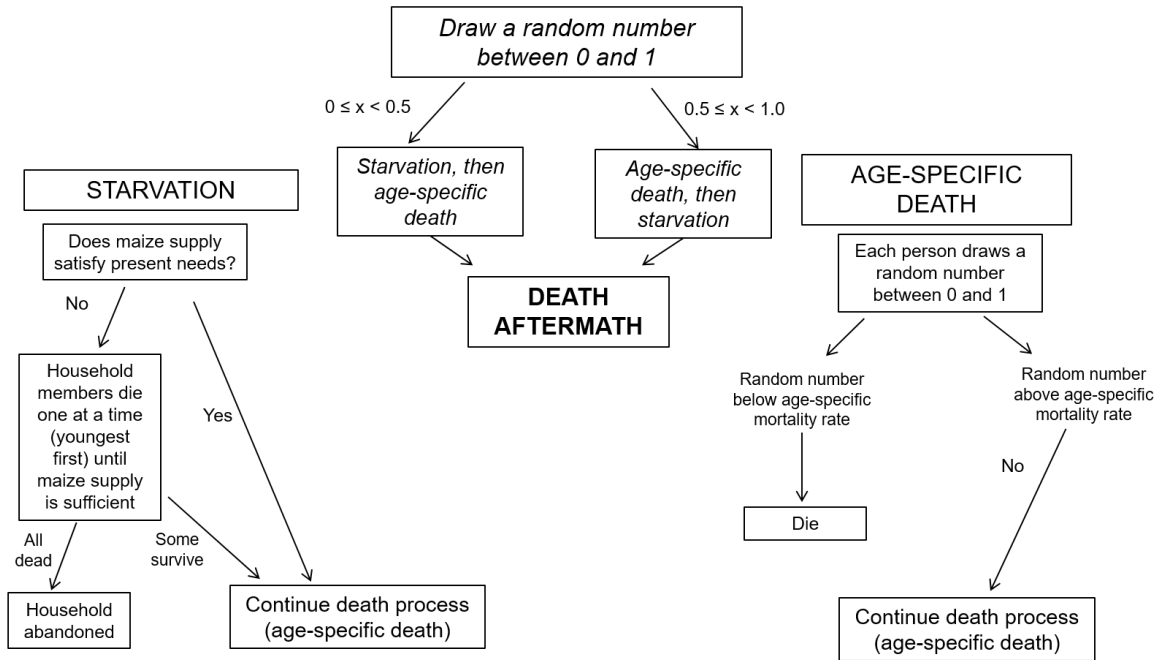
The ALHV-AgedMort Model Setup



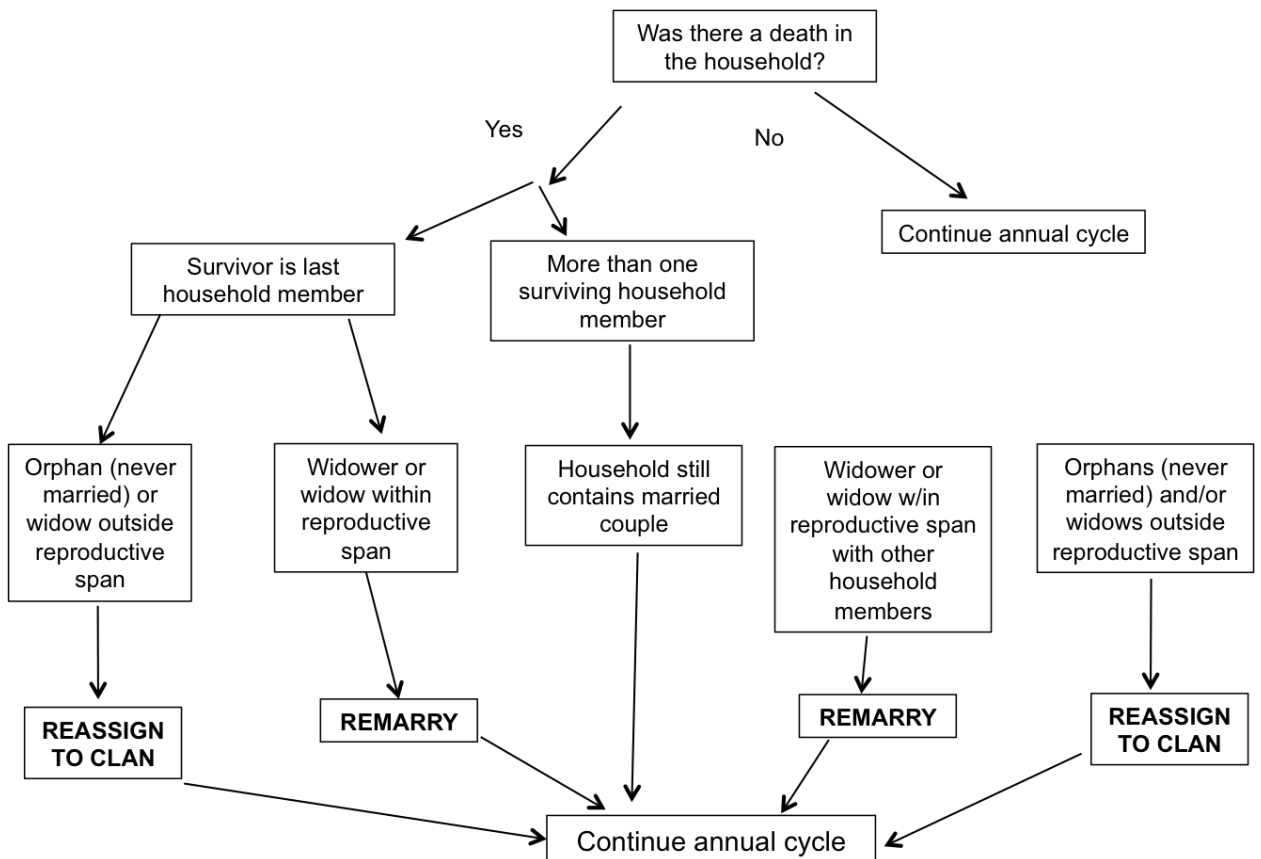
The ALHV-AgedMort Model Structure — Activities each time step —



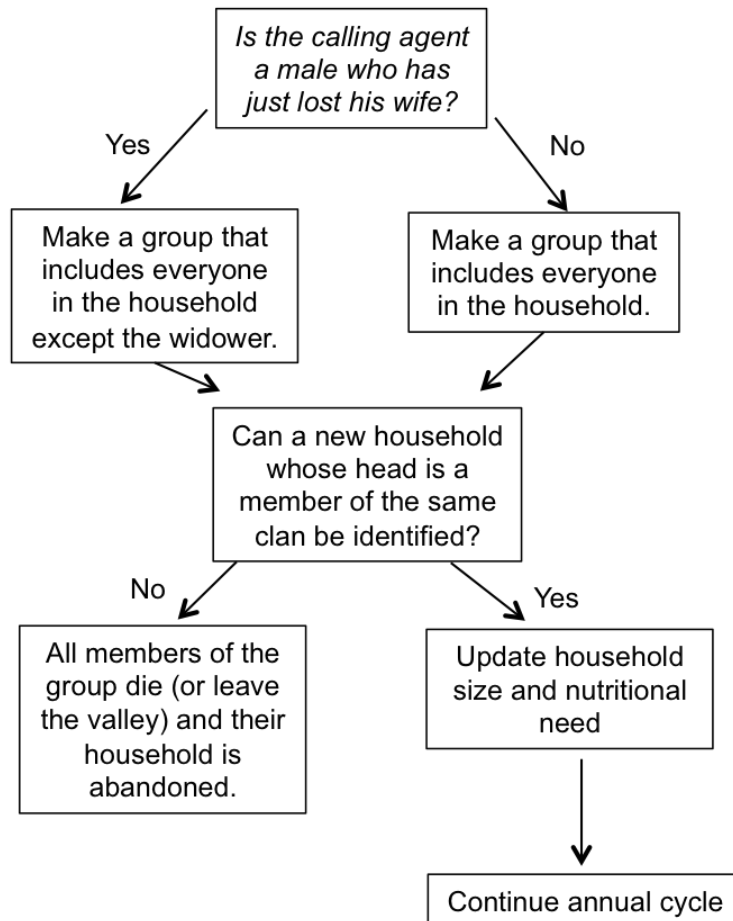
ALHV-AgedMort Death Processes



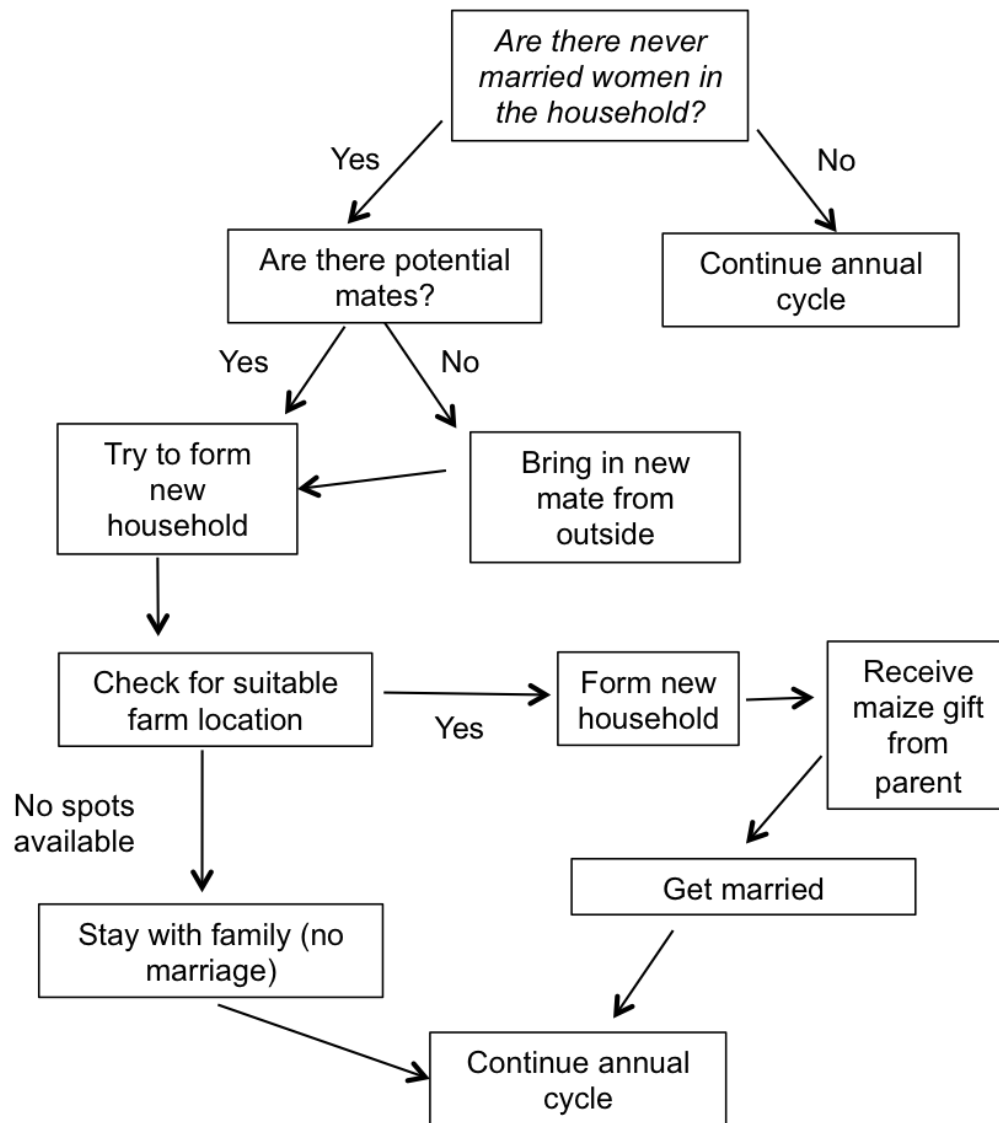
ALHV-Aged Mort Death Aftermath



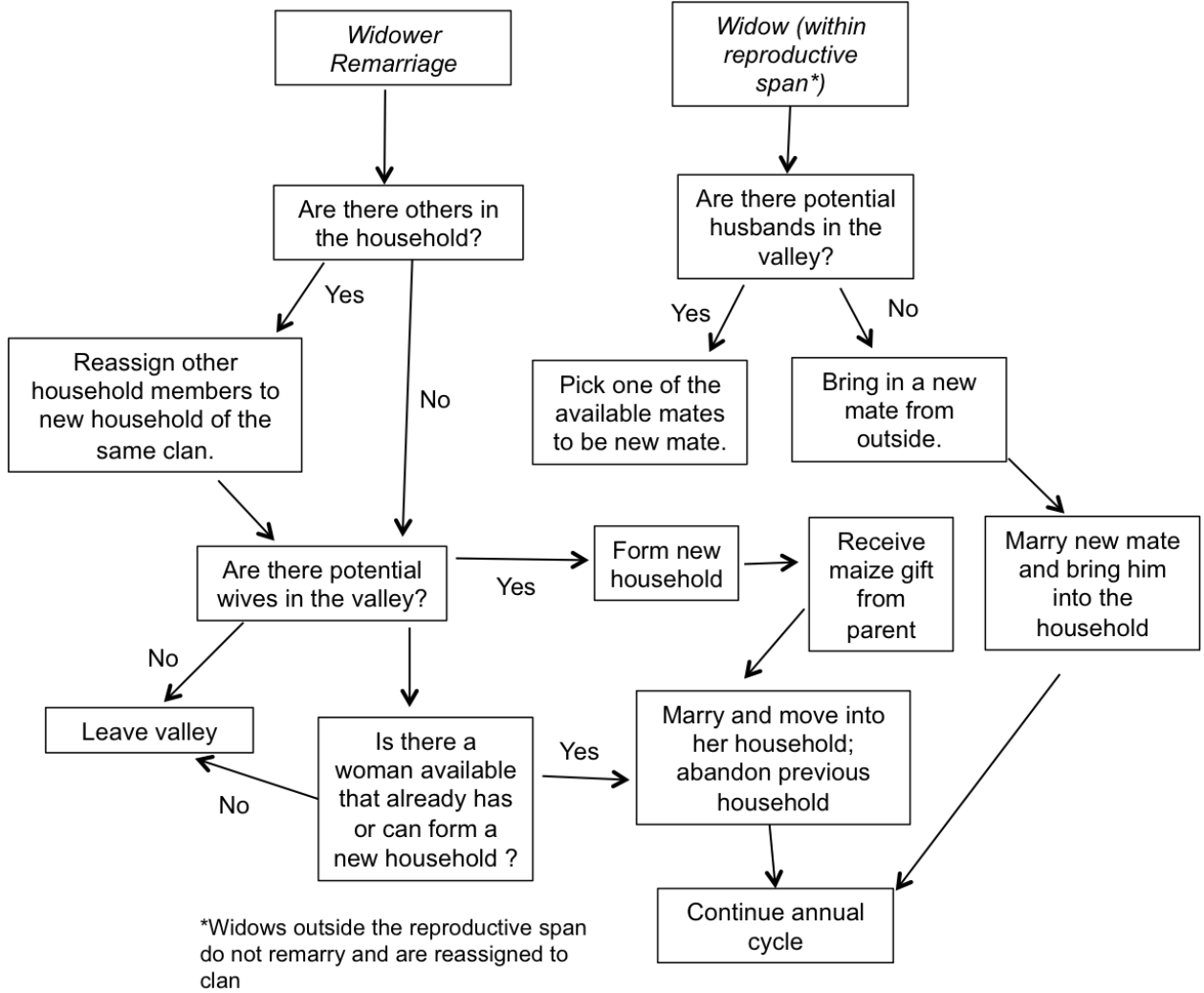
ALHV-AgedMort Reassign to Clan



ALHV-AgedMort First Marriage

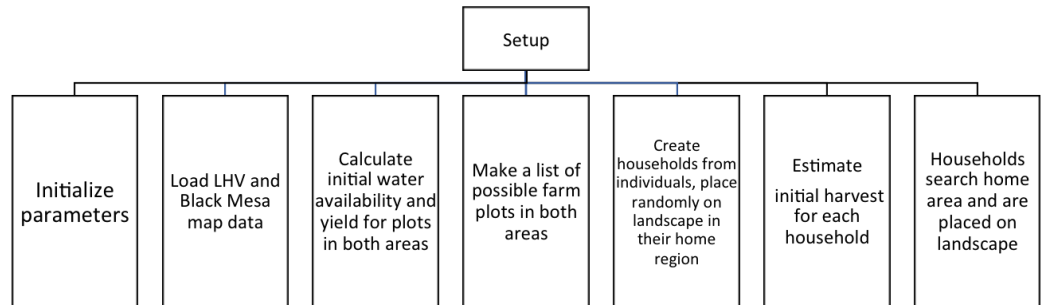


ALHV-AgedMort Remarriage

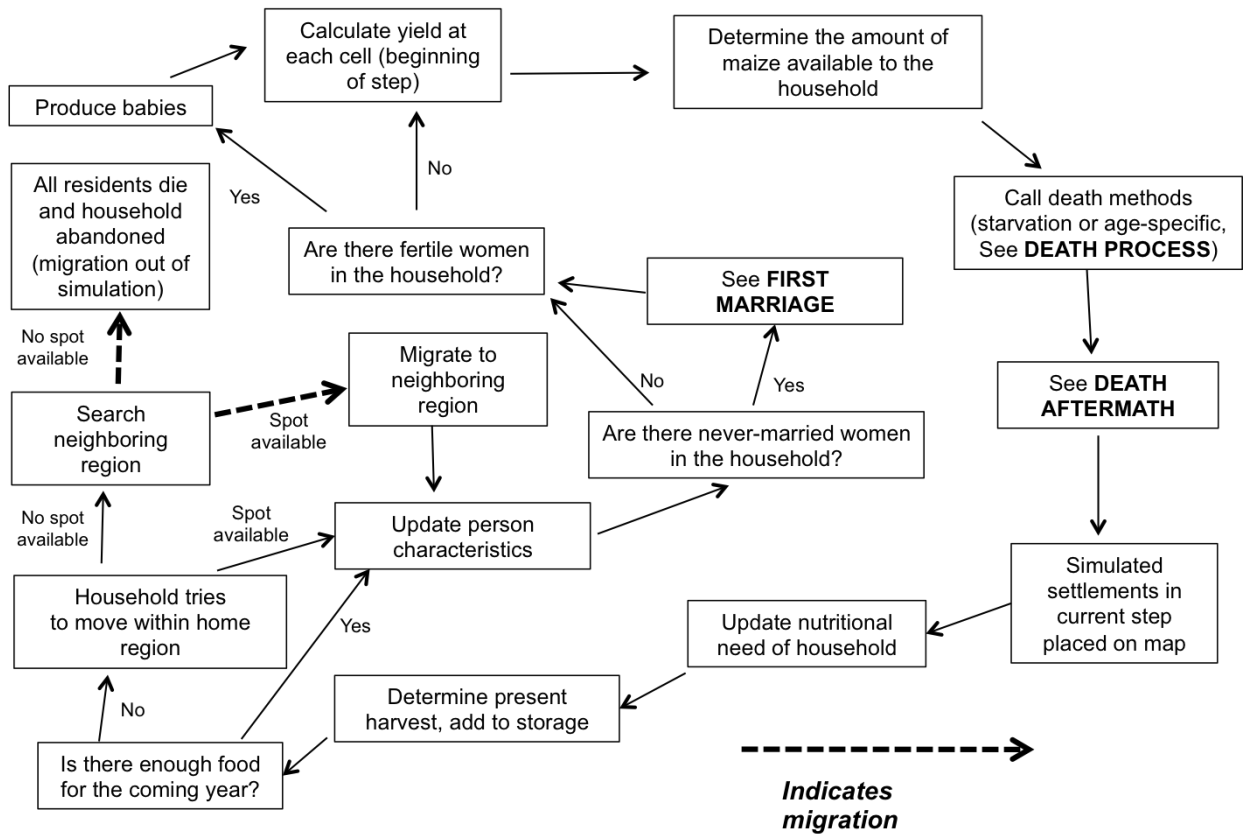


Migration: ALHV-Mesa Model

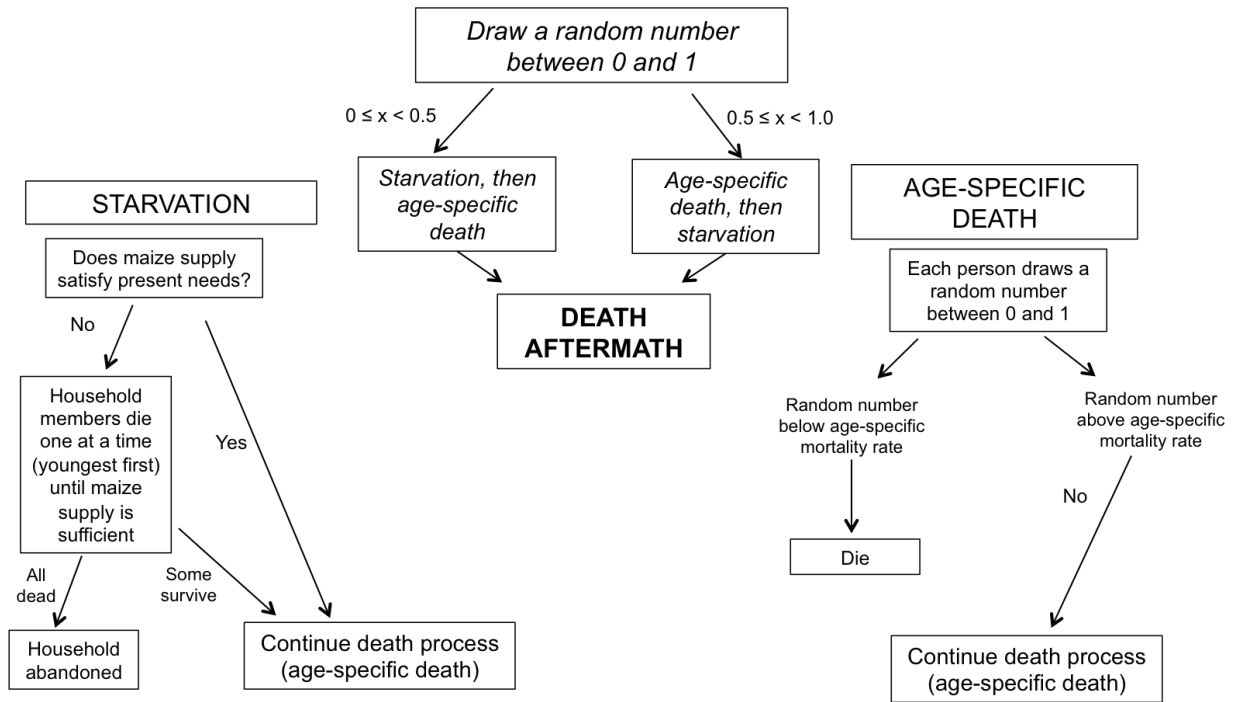
The ALHV-Mesa Model Setup



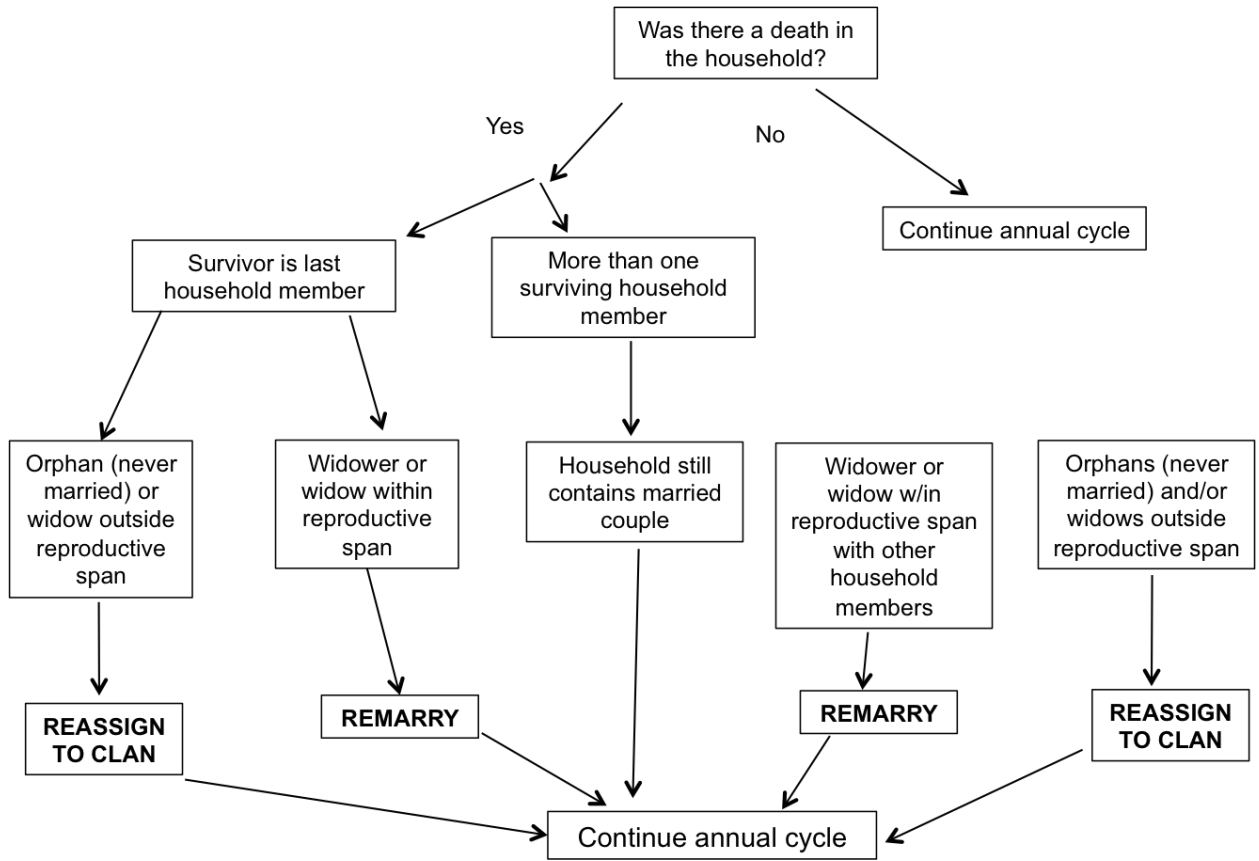
The ALHV-Mesa Model Structure — Activities each time step —



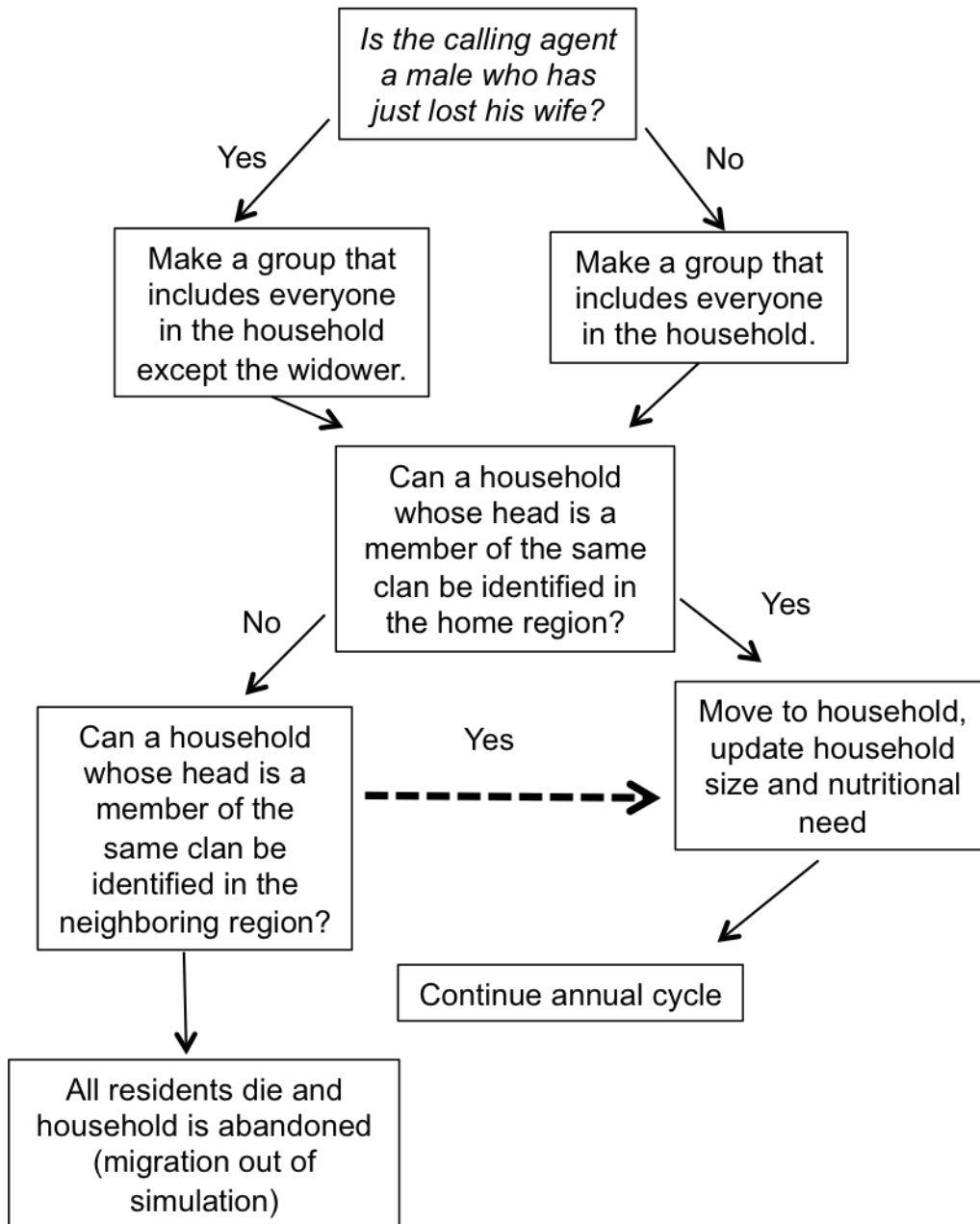
ALHV-Mesa Death Processes



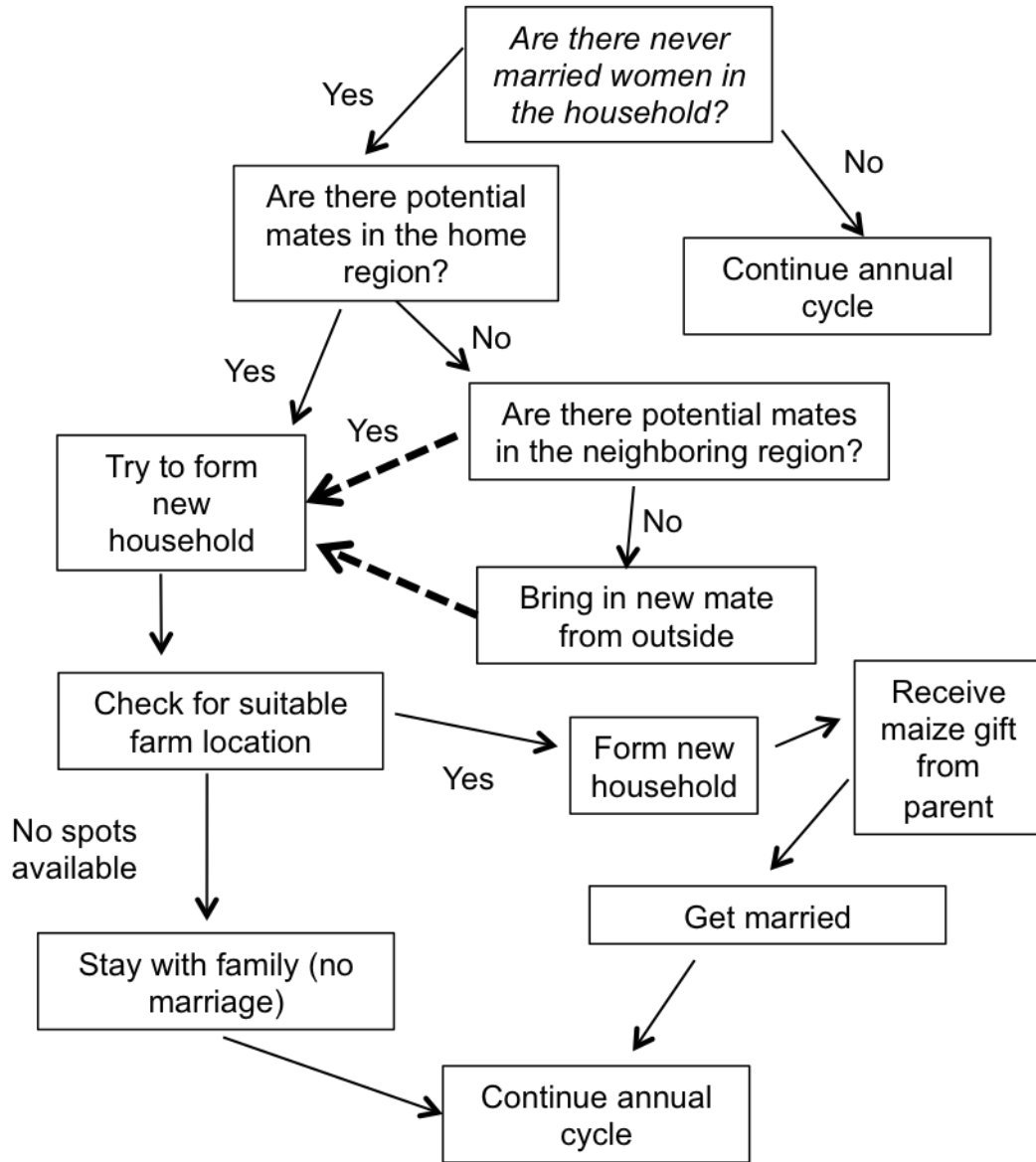
ALHV-Mesa Death Aftermath



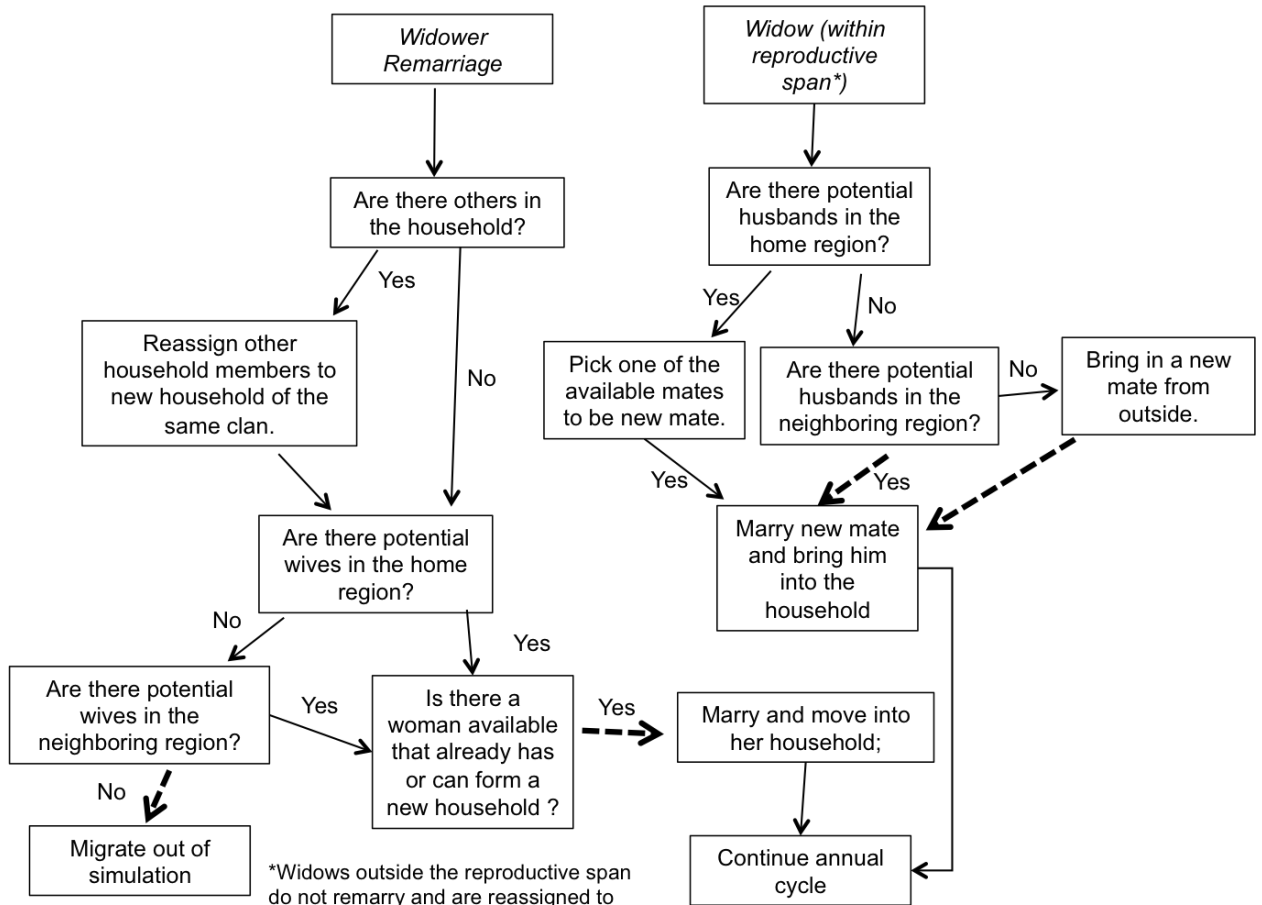
ALHV-Mesa Reassign to Clan



ALHV-Mesa First Marriage



ALHV-Mesa Remarriage



APPENDIX B: FERTILITY AND MORTALITY SCHEDULES FOR SENSITIVITY ANALYSES

Sensitivity analyses of the models developed in this project required the development of several additional fertility and mortality schedules. Fertility schedules were developed in two ways. For the ALHV-Baseline analyses, we calculated schedules by selecting a number of constant fertility rate equivalents (i.e., the age-specific schedules produced the same total fertility rate as a constant fertility rate).

Table B.1. Fertility schedules used in ALHV-Baseline sensitivity analyses

Constant fertility equivalents							
Age	0.19	0.22	0.25*	0.28	0.31	0.34	0.37
16-19	0.071	0.083	<i>0.094</i>	0.105	0.117	0.128	0.139
20-24	0.195	0.225	<i>0.256</i>	0.287	0.317	0.348	0.379
25-29	0.195	0.225	<i>0.256</i>	0.287	0.317	0.348	0.379
30-34	0.158	0.183	<i>0.208</i>	0.233	0.258	0.283	0.308
TFR	3.022	3.498	3.976	4.453	4.930	5.407	5.884
* <i>The 0.250 equivalent is the default fertility rate used in this model version.</i>							

For the ALHV-AgedMort and ALHV-Mesa sensitivity analyses, multipliers were used to increase and decrease the fertility rates around a baseline value. The Coale-Trussel (1978) standard fertility schedule was used with the 3.0 and 3.2 multipliers based on the estimated total fertility rate of our study populations. Analyses discussed in Chapter 6 showed that the 3.2 multiplier (TFR = 7.07) produced the best results in the ALHV-AgedMort model while the 3.0 multiplier (TFR = 6.63) produced the best overall results in the ALHV-Mesa model.

Table B.2. Fertility schedules used in the ALHV-AgedMort and ALHV-Mesa sensitivity analyses

Age	x 2.4	x 2.6	x 2.8	x 2.9	x 3.0	x 3.1	x 3.2	x 3.4	x 3.6	x 3.8	x 4.0
15-19	0.197	0.214	0.230	0.238	0.247	0.255	0.263	0.279	0.296	0.312	0.329
20-24	0.221	0.239	0.258	0.267	0.276	0.285	0.294	0.313	0.331	0.350	0.368
25-29	0.207	0.224	0.241	0.250	0.259	0.267	0.276	0.293	0.310	0.328	0.345
30-34	0.190	0.205	0.221	0.229	0.237	0.245	0.253	0.269	0.284	0.300	0.316
35-39	0.155	0.167	0.180	0.187	0.193	0.200	0.206	0.219	0.232	0.245	0.258
40-44	0.080	0.087	0.094	0.097	0.100	0.104	0.107	0.114	0.120	0.127	0.134
45-49	0.012	0.012	0.013	0.014	0.014	0.015	0.015	0.016	0.017	0.018	0.019
TFR	5.300	5.750	6.120	6.410	6.630	6.850	7.070	7.510	7.960	8.400	8.840

In order to assess the effects of changes in age-specific mortality rates, alternate schedules were also developed for sensitivity analyses. In analyses of the ALHV-AgedMort model, two strategies were used to develop new schedules: using multiplier and using addition model life tables from Weiss and Wobst (1973). Analyses of the ALHV-Mesa model only used the multiplier-based schedules.

Table B.3. Mortality schedules developed using the multiplier method in ALHV-AgedMort and ALHV-Mesa analyses

Age	MT 35.0-65.0*	X 1.23	x 1.46	x 1.69	x 1.92	x 2.15	x 2.4
0-1	0.1670	0.205	0.244	0.282	0.321	0.359	0.4008
1-4	0.1050	0.129	0.153	0.177	0.202	0.226	0.2520
5-9	0.0800	0.098	0.117	0.135	0.154	0.172	0.1920
10-15	0.0523	0.064	0.076	0.088	0.100	0.112	0.1255
15-19	0.0897	0.110	0.131	0.152	0.172	0.193	0.2153
20-24	0.0912	0.112	0.133	0.154	0.175	0.196	0.2189
25-29	0.0927	0.114	0.135	0.157	0.178	0.199	0.2225
30-34	0.0942	0.116	0.138	0.159	0.181	0.203	0.2261
35-39	0.0957	0.118	0.140	0.162	0.184	0.206	0.2297
40-44	0.0972	0.120	0.142	0.164	0.187	0.209	0.2333
45-49	0.0988	0.122	0.144	0.167	0.190	0.212	0.2371
50-54	0.1004	0.123	0.147	0.170	0.193	0.216	0.2410
55-59	0.1311	0.161	0.191	0.222	0.252	0.282	0.3146
60-64	0.1824	0.224	0.266	0.308	0.350	0.392	0.4378
65-69	0.2493	0.307	0.364	0.421	0.479	0.536	0.5983
70-74	0.3450	0.424	0.504	0.583	0.662	0.742	0.8280
75-79	0.4746	0.584	0.693	0.802	0.911	1.000	1.0000
80+	1.0000	1.000	1.000	1.000	1.000	1.000	1.0000
* from Weiss and Wobst 1973							

Table B.4. Age-Specific mortality schedules drawn from model life tables of Weiss and Wobst (1973) used in ALHV-AgedMort and ALHV-Mesa sensitivity analyses

Age	MT 20.0-65.0	MT 22.5-65.0	MT 25.0-65.0	MT 27.5-65.0	MT 30.0-65.0	MT 32.5-65.0	MT 35.0-65.0
0	0.1670	0.1670	0.1670	0.1670	0.1670	0.1670	0.1670
1-4	0.1050	0.1050	0.1050	0.1050	0.1050	0.1050	0.1050
5-9	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800
10-15	0.0523	0.0523	0.0523	0.0523	0.0523	0.0523	0.0523
15-19	0.1905	0.1672	0.1476	0.1305	0.1154	0.1019	0.0897
20-24	0.1970	0.1722	0.1516	0.1336	0.1178	0.1038	0.0912
25-29	0.2038	0.1774	0.1556	0.1367	0.1203	0.1057	0.0927
30-34	0.2108	0.1828	0.1598	0.1400	0.1228	0.1077	0.0942
35-39	0.2180	0.1882	0.1640	0.1432	0.1254	0.1096	0.0957
40-44	0.2254	0.1939	0.1684	0.1466	0.1280	0.1116	0.0972
45-49	0.2330	0.1996	0.1728	0.1500	0.1306	0.1137	0.0988
50-54	0.2409	0.2055	0.1774	0.1536	0.1334	0.1158	0.1004
55-59	0.2812	0.2434	0.2134	0.1879	0.1663	0.1475	0.1311
60-64	0.3646	0.3187	0.2823	0.2513	0.2251	0.2023	0.1824
65-69	0.4546	0.4030	0.3619	0.3270	0.2974	0.2717	0.2493
70-74	0.5738	0.5162	0.4704	0.4315	0.3986	0.3700	0.3450
75-79	1.0000	1.0000	0.6125	0.5698	0.5336	0.5021	0.4746
80+	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000

APPENDIX C: LONG HOUSE VALLEY AND BLACK MESA STARTING POPULATION CHARACTERISTICS

Starting populations for Long House Valley and Black Mesa were randomly selected from either online Pueblo census records or those that I digitized from paper format at the National Archives. Long House Valley populations are drawn from the 1885 Pueblo census (National Archives, 2014), while the Black Mesa populations were drawn from the 1790 and 1823 Spanish and Mexican Colonial Censuses of New Mexico. These sources were chosen because they represent realistic family composition of historic Pueblo groups, the closest proxy for our prehistoric Pueblo populations under study. The census records included name, age, sex, and family relationships. Other characteristics were assigned as described in Chapters 5 and 6.

Table C.1. Long House Valley starting population characteristics

Person	Community	Residence	Household	Clan ID	Sex	Age	HH Head?	Eldest Child?	Married?	Fertility Age	Mate ID	# of Children
1	1	1	1	2	Male	38	No	No	Married	27	2	4
2	1	1	1	1	Female	35	Yes	No	Married	24	1	4
3	1	1	1	1	Female	10	No	Yes	Unmarried	0	0	0
4	1	1	1	1	Female	8	No	No	Unmarried	0	0	0
5	1	1	1	1	Male	2	No	No	Unmarried	0	0	0
6	1	1	1	1	Female	1	No	No	Unmarried	0	0	0
7	1	1	2	5	Male	40	No	No	Married	28	8	1
8	1	1	2	2	Female	28	Yes	No	Married	16	7	1
9	1	1	2	2	Female	11	No	Yes	Unmarried	0	0	0
10	1	1	3	4	Male	45	No	No	Married	45	11	0
11	1	1	3	3	Female	40	Yes	No	Married	40	10	0
12	1	1	4	2	Male	30	No	No	Married	21	13	2
13	1	1	4	4	Female	31	Yes	No	Married	22	12	2
14	1	1	4	4	Female	8	No	Yes	Unmarried	0	0	0
15	1	1	4	4	Male	5	No	Yes	Unmarried	0	0	0
16	1	1	5	6	Male	26	No	No	Married	19	17	1
17	1	1	5	5	Female	24	Yes	No	Married	17	16	1
18	1	1	5	5	Female	6	No	Yes	Unmarried	0	0	0
19	1	1	6	7	Male	26	No	No	Married	26	20	0
20	1	1	6	6	Female	24	Yes	No	Married	24	19	0
21	1	1	7	6	Male	43	No	No	Married	27	22	3
22	1	1	7	7	Female	36	Yes	No	Married	20	21	3
23	1	1	7	7	Male	15	No	Yes	Unmarried	0	0	0
24	1	1	7	7	Female	10	No	No	Unmarried	0	0	0

25	1	1	1	7	7	Female	8	No	No	Unmarried	0	0	0	0
26	1	1	1	8	7	Male	43	No	No	Married	27	27	3	3
27	1	1	1	8	1	Female	36	Yes	No	Married	20	26	3	3
28	1	1	1	8	1	Male	15	No	Yes	Unmarried	0	0	0	0
29	1	1	1	8	1	Female	10	No	No	Unmarried	0	0	0	0
30	1	1	1	8	1	Female	8	No	No	Unmarried	0	0	0	0
31	1	1	1	9	4	Male	40	No	No	Married	19	32	2	2
32	1	1	1	9	2	Female	45	Yes	No	Married	24	31	2	2
33	1	1	1	9	2	Female	20	No	Yes	Unmarried	20	0	0	0
34	1	1	1	9	2	Male	10	No	No	Unmarried	0	0	0	0
35	1	1	1	10	5	Male	32	No	No	Married	25	36	2	2
36	1	1	1	10	3	Female	31	Yes	No	Married	24	35	2	2
37	1	1	1	10	3	Female	6	No	Yes	Unmarried	0	0	0	0
38	1	1	1	10	3	Female	4	No	No	Unmarried	0	0	0	0
39	1	1	1	11	4	Male	50	No	No	Married	35	40	4	4
40	1	1	1	11	5	Female	30	Yes	No	Married	15	39	4	4
41	1	1	1	11	5	Female	14	No	Yes	Unmarried	0	0	0	0
42	1	1	1	11	5	Female	7	No	No	Unmarried	0	0	0	0
43	1	1	1	11	5	Female	4	No	No	Unmarried	0	0	0	0
44	1	1	1	11	5	Male	0	No	No	Unmarried	0	0	0	0
45	1	1	1	12	5	Male	40	No	No	Married	29	46	3	3
46	1	1	1	12	4	Female	34	Yes	No	Married	23	45	3	3
47	1	1	1	12	4	Male	10	No	Yes	Unmarried	0	0	0	0
48	1	1	1	12	4	Female	6	No	No	Unmarried	0	0	0	0
49	1	1	1	12	4	Female	2	No	No	Unmarried	0	0	0	0
50	1	1	1	13	7	Male	30	No	No	Married	13	51	3	3
51	1	1	1	13	6	Female	30	Yes	No	Married	13	50	3	3

52	1	1	1	13	6	Male	16	No	Yes	Unmarried	16	0	0
53	1	1	1	13	6	Female	8	No	No	Unmarried	0	0	0
54	1	1	1	13	6	Female	1	No	No	Unmarried	0	0	0
55	1	1	1	14	5	Male	27	No	No	Married	12	56	2
56	1	1	1	14	7	Female	29	Yes	No	Married	14	55	2
57	1	1	1	14	7	Male	14	No	Yes	Unmarried	0	0	0
58	1	1	1	14	7	Male	9	No	No	Unmarried	0	0	0

Table C.2. Black Mesa starting population characteristics

Person	Community	Residence	Household	Clan ID	Sex	Age	HH Head?	Eldest Child?	Married?	Fertility Age	Mate ID	# of Children
1	2	2	1	5	M	40	No	No	Married	29	2	2
2	2	2	1	1	F	30	Yes	No	Married	19	1	2
3	2	2	1	1	M	10	No	Yes	Unmarried	0	0	0
4	2	2	1	1	F	3	No	No	Unmarried	0	0	0
5	2	2	2	6	M	60	No	No	Married	37	6	3
6	2	2	2	2	F	50	Yes	No	Married	27	5	3
7	2	2	2	2	F	18	No	Yes	Unmarried	15	0	0
8	2	2	2	2	F	17	No	No	Unmarried	15	0	0
9	2	2	2	2	F	2	No	No	Unmarried	0	0	0
10	2	2	3	2	M	26	No	No	Married	20	11	3
11	2	2	3	3	F	24	Yes	No	Married	18	10	3
12	2	2	3	3	F	5	No	Yes	Unmarried	0	0	0
13	2	2	3	3	F	3	No	No	Unmarried	0	0	0
14	2	2	3	3	F	1	No	No	Unmarried	0	0	0
15	2	2	4	5	M	33	No	No	Married	28	16	1

16	2	2	4	4	F	20	Yes	No	Married	15	15	1
17	2	2	4	4	F	4	No	Yes	Unmarried	0	0	0
18	2	2	5	2	M	28	No	No	Married	15	19	2
19	2	2	5	5	F	29	Yes	No	Married	16	18	2
20	2	2	5	5	F	56	No	No	Unmarried	15	0	1
21	2	2	5	5	F	12	No	Yes	Unmarried	0	0	0
22	2	2	5	5	F	10	No	No	Unmarried	0	0	0
23	2	2	6	3	M	32	No	No	Married	19	24	3
24	2	2	6	6	F	31	Yes	No	Married	18	23	3
25	2	2	6	6	M	9	No	No	Unmarried	0	0	0
26	2	2	6	6	M	4	No	No	Unmarried	0	0	0
27	2	2	6	6	F	12	No	Yes	Unmarried	0	0	0
28	2	2	7	5	M	60	No	No	Married	30	29	7
29	2	2	7	7	F	48	Yes	No	Married	18	28	7
30	2	2	7	7	F	29	No	Yes	Unmarried	15	0	0
31	2	2	7	7	F	28	No	No	Unmarried	15	0	0
32	2	2	7	7	M	18	No	No	Unmarried	15	0	0
33	2	2	7	7	M	17	No	No	Unmarried	15	0	0
34	2	2	7	7	M	14	No	No	Unmarried	0	0	0
35	2	2	7	7	F	12	No	No	Unmarried	0	0	0
36	2	2	7	7	F	8	No	No	Unmarried	0	0	0
37	2	2	8	2	M	66	No	No	Married	54	38	1
38	2	2	8	1	F	40	Yes	No	Married	28	37	1
39	2	2	8	1	M	11	No	Yes	Unmarried	0	0	0
40	2	2	9	7	M	38	No	No	Married	29	41	2
41	2	2	9	2	F	32	Yes	No	Married	23	40	2
42	2	2	9	2	M	8	No	Yes	Unmarried	0	0	0

43	2	2	2	9	2	F	2	No	No	Unmarried	0	0	0	0
44	2	2	2	10	2	M	40	No	No	Married	36	45	2	2
45	2	2	2	10	3	F	20	Yes	No	Married	16	44	2	2
46	2	2	2	10	3	M	3	No	Yes	Unmarried	0	0	0	0
47	2	2	2	10	3	F	2	No	No	Unmarried	0	0	0	0
48	2	2	2	11	5	M	50	No	No	Married	42	49	2	2
49	2	2	2	11	4	F	30	Yes	No	Married	22	48	2	2
50	2	2	2	11	4	M	7	No	Yes	Unmarried	0	0	0	0
51	2	2	2	11	4	F	5	No	No	Unmarried	0	0	0	0
52	2	2	2	12	2	M	48	No	No	Married	33	53	2	2
53	2	2	2	12	5	F	35	Yes	No	Married	20	52	2	2
54	2	2	2	12	5	M	14	No	Yes	Unmarried	0	0	0	0
55	2	2	2	12	5	F	13	No	No	Unmarried	0	0	0	0
56	2	2	2	13	1	M	40	No	No	Married	28	57	5	5
57	2	2	2	13	6	F	29	Yes	No	Married	17	56	5	5
58	2	2	2	13	6	F	11	No	Yes	Unmarried	0	0	0	0
59	2	2	2	13	6	M	9	No	No	Unmarried	0	0	0	0
60	2	2	2	13	6	F	6	No	No	Unmarried	0	0	0	0
61	2	2	2	13	6	F	4	No	No	Unmarried	0	0	0	0
62	2	2	2	13	6	M	2	No	No	Unmarried	0	0	0	0
63	2	2	2	14	4	M	46	No	No	Married	27	64	4	4
64	2	2	2	14	7	F	42	Yes	No	Married	23	63	4	4
65	2	2	2	14	7	M	18	No	Yes	Unmarried	15	0	0	0
66	2	2	2	14	7	F	15	No	No	Unmarried	15	0	0	0
67	2	2	2	14	7	M	3	No	No	Unmarried	0	0	0	0
68	2	2	2	14	7	F	14	No	No	Unmarried	0	0	0	0
69	2	2	2	15	6	M	51	No	No	Married	40	70	2	2

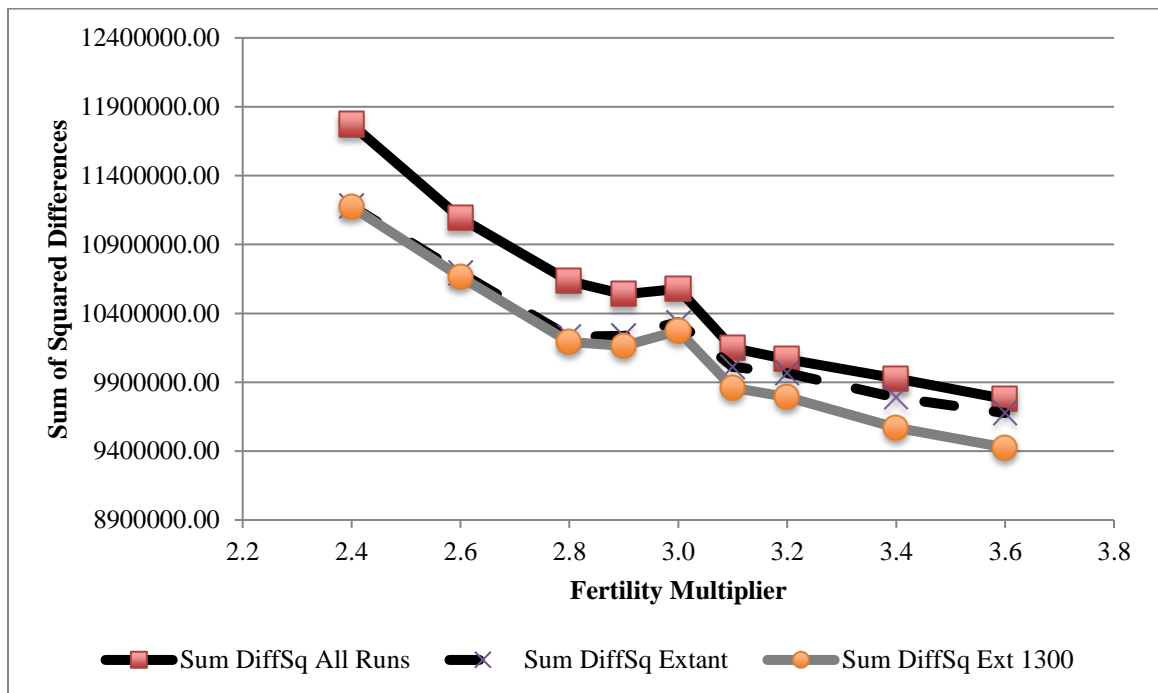
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72	2	2	2	2	15	1	F	5	No	No	Unmarried	0	0	0
73	2	2	2	2	16	3	M	28	No	No	Married	18	74	2
74	2	2	2	2	16	2	F	28	Yes	No	Married	18	73	2
75	2	2	2	2	16	2	F	9	No	Yes	Unmarried	0	0	0
76	2	2	2	2	16	2	M	7	No	No	Unmarried	0	0	0
77	2	2	2	2	17	6	M	59	No	No	Married	53	78	2
78	2	2	2	2	17	3	F	21	Yes	No	Married	15	77	2
79	2	2	2	2	17	3	M	5	No	Yes	Unmarried	0	0	0
80	2	2	2	2	17	3	M	3	No	No	Unmarried	0	0	0
81	2	2	2	2	18	2	M	30	No	No	Married	15	82	0
82	2	2	2	2	18	4	F	25	Yes	No	Married	15	81	0
83	2	2	2	2	19	6	M	50	No	No	Married	31	84	1
84	2	2	2	2	19	5	F	40	Yes	No	Married	21	83	1
85	2	2	2	2	19	5	M	18	No	Yes	Unmarried	15	0	0
86	2	2	2	2	20	3	M	46	No	No	Married	33	87	6
87	2	2	2	2	20	6	F	30	Yes	No	Married	17	86	6
88	2	2	2	2	20	6	M	12	No	Yes	Unmarried	0	0	0
89	2	2	2	2	20	6	M	10	No	No	Unmarried	0	0	0
90	2	2	2	2	20	6	M	7	No	No	Unmarried	0	0	0
91	2	2	2	2	20	6	F	8	No	No	Unmarried	0	0	0
92	2	2	2	2	20	6	F	6	No	No	Unmarried	0	0	0
93	2	2	2	2	20	6	F	1	No	No	Unmarried	0	0	0
94	2	2	2	2	21	6	M	50	No	No	Married	33	95	4
95	2	2	2	2	21	7	F	40	Yes	No	Married	23	94	4
96	2	2	2	2	21	7	F	16	No	Yes	Unmarried	15	0	0

97	2	2	21	7	M	13	No	No	Unmarried	0	0	0	0
98	2	2	21	7	M	8	No	No	Unmarried	0	0	0	0
99	2	2	21	7	M	3	No	No	Unmarried	0	0	0	0
100	2	2	22	4	M	51	No	No	Married	39	101	2	2
101	2	2	22	1	F	45	Yes	No	Married	33	100	2	2
102	2	2	22	1	F	11	No	Yes	Unmarried	0	0	0	0
103	2	2	22	1	F	6	No	No	Unmarried	0	0	0	0
104	2	2	23	3	M	62	No	No	Married	41	105	6	6
105	2	2	23	2	F	25	Yes	No	Married	16	104	2	2
106	2	2	23	2	M	18	No	Yes	Unmarried	15	0	0	0
107	2	2	23	2	F	16	No	No	Unmarried	15	0	0	0
108	2	2	23	2	F	14	No	No	Unmarried	0	0	0	0
109	2	2	23	2	M	12	No	No	Unmarried	0	0	0	0
110	2	2	23	2	M	8	No	No	Unmarried	0	0	0	0
111	2	2	23	2	F	2	No	No	Unmarried	0	0	0	0
112	2	2	24	2	M	40	No	No	Married	24	113	4	4
113	2	2	24	3	F	33	Yes	No	Married	17	112	4	4
114	2	2	24	3	M	15	No	Yes	Unmarried	15	0	0	0
115	2	2	24	3	M	11	No	No	Unmarried	0	0	0	0
116	2	2	24	3	M	10	No	No	Unmarried	0	0	0	0
117	2	2	24	3	M	7	No	No	Unmarried	0	0	0	0
118	2	2	25	7	M	30	No	No	Married	28	119	1	1
119	2	2	25	4	F	22	Yes	No	Married	20	118	1	1
120	2	2	25	4	M	1	No	Yes	Unmarried	0	0	0	0
121	2	2	26	2	M	22	No	No	Married	15	122	0	0
122	2	2	26	5	F	22	Yes	No	Married	15	121	0	0

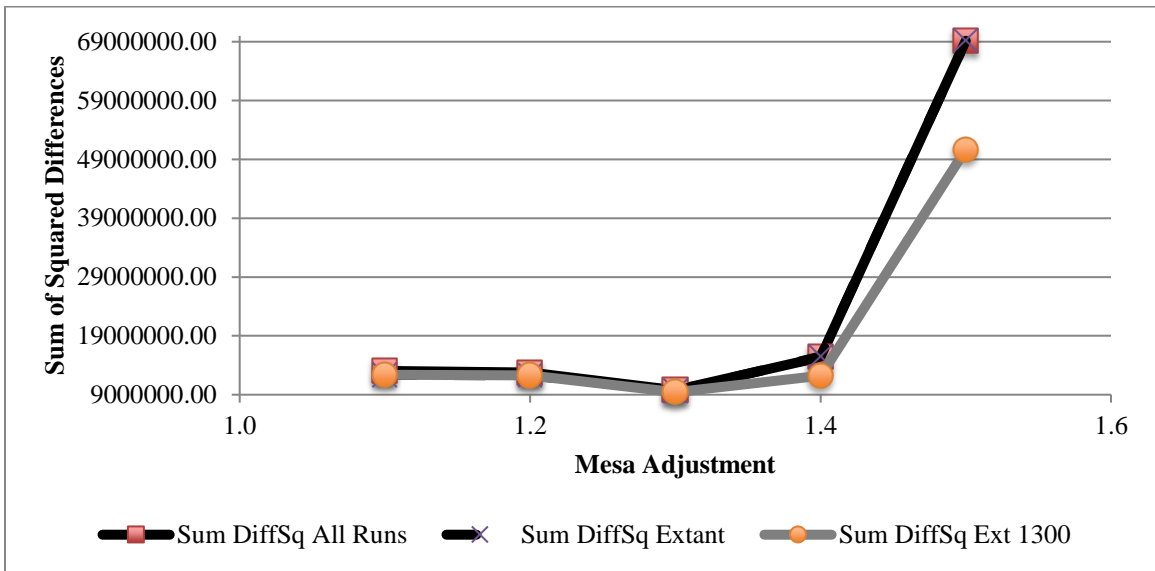
APPENDIX D: ALHV-MESA MODEL ADDITIONAL SENSITIVITY RESULTS

In Chapter 7, selected results of sensitivity analyses of the ALHV-Mesa model were shared and discussed. One complication in understanding the behavior of this model is the fact that Long House Valley and Black Mesa needed to be considered as both independent areas while, at the same, assessing the behavior of the integrated model. This appendix includes the results of sensitivity analyses that considered each study area independently. These results demonstrate that the population trajectories of the two areas are very different despite the same parameterization.

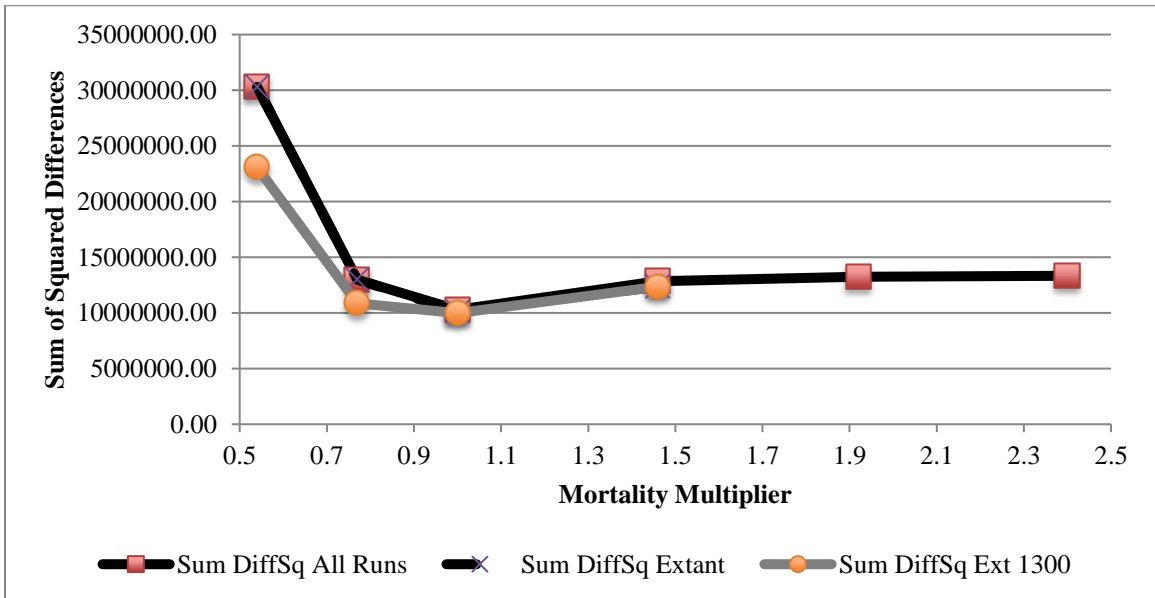
Black Mesa Sensitivity Analyses Results



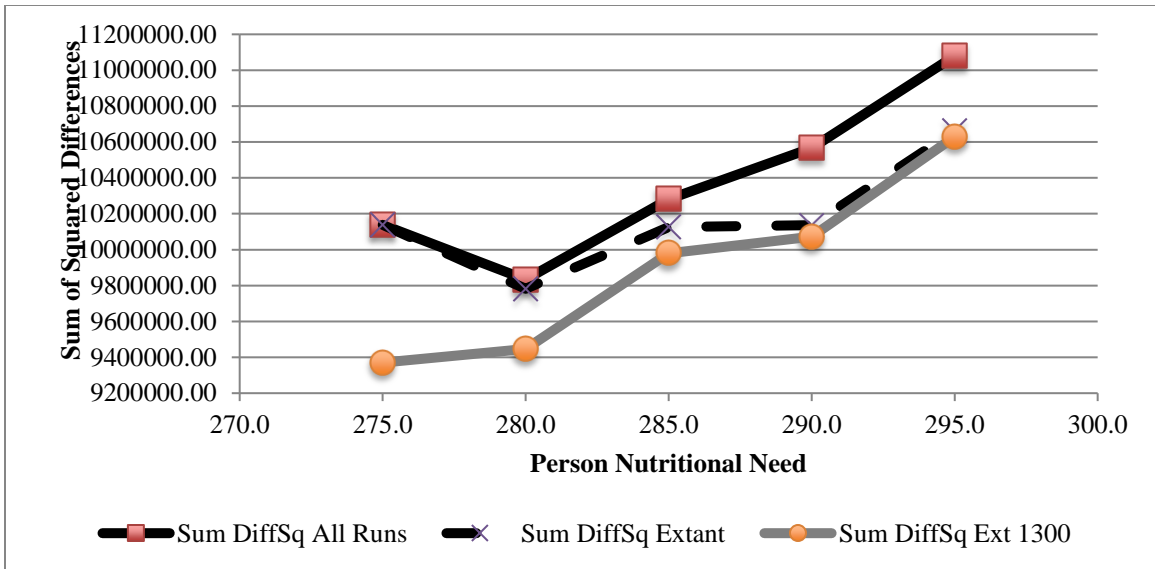
D.1. Sum of differences squared analyses of the ALHV-Mesa model when fertility is varied.



D.2. Sum of differences squared analyses of the ALHV-Mesa model when mesa adjustment is varied.

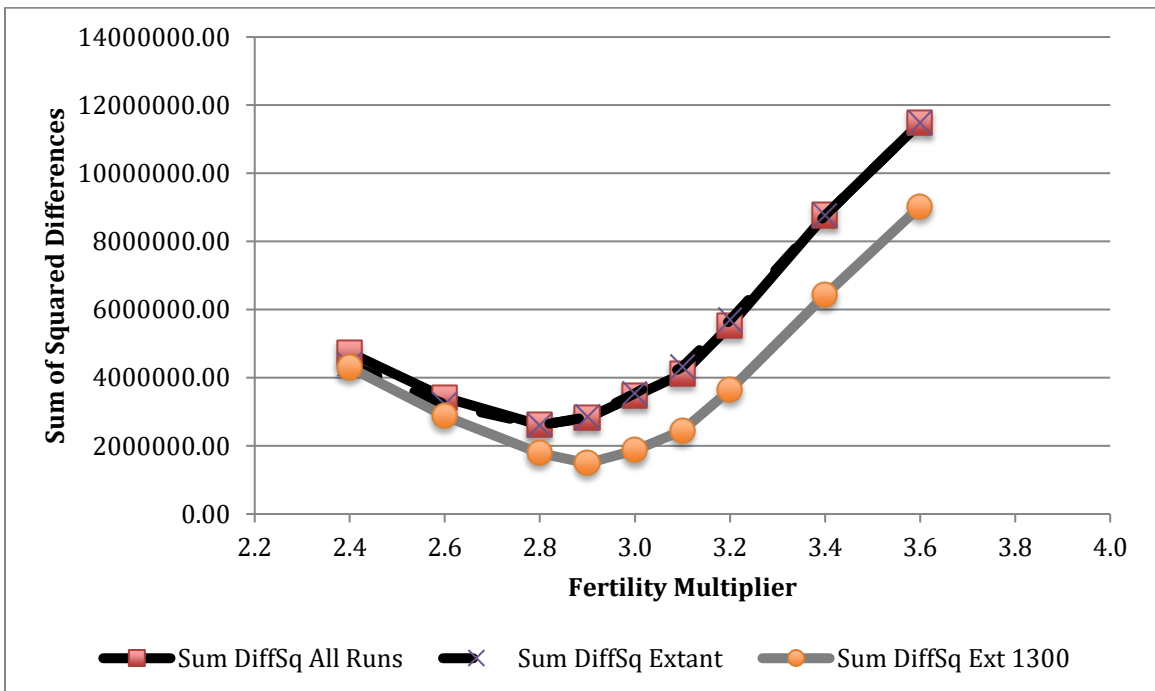


D.3. Sum of differences squared analyses of the ALHV-Mesa model when mortality is varied.

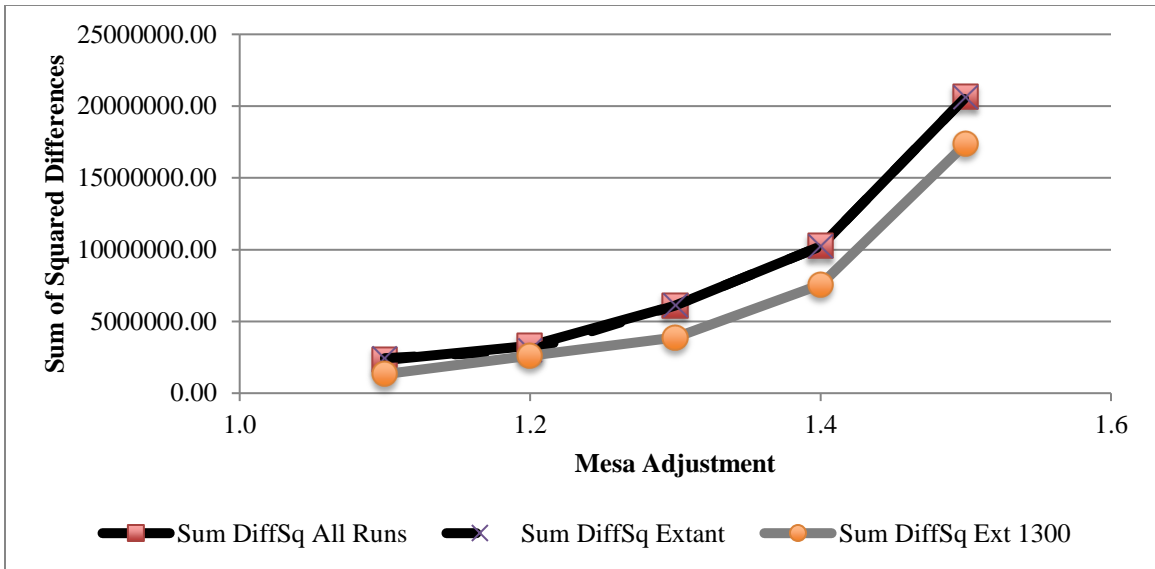


D.4. Sum of differences squared analyses of the ALHV-Mesa model when person nutritional need is varied.

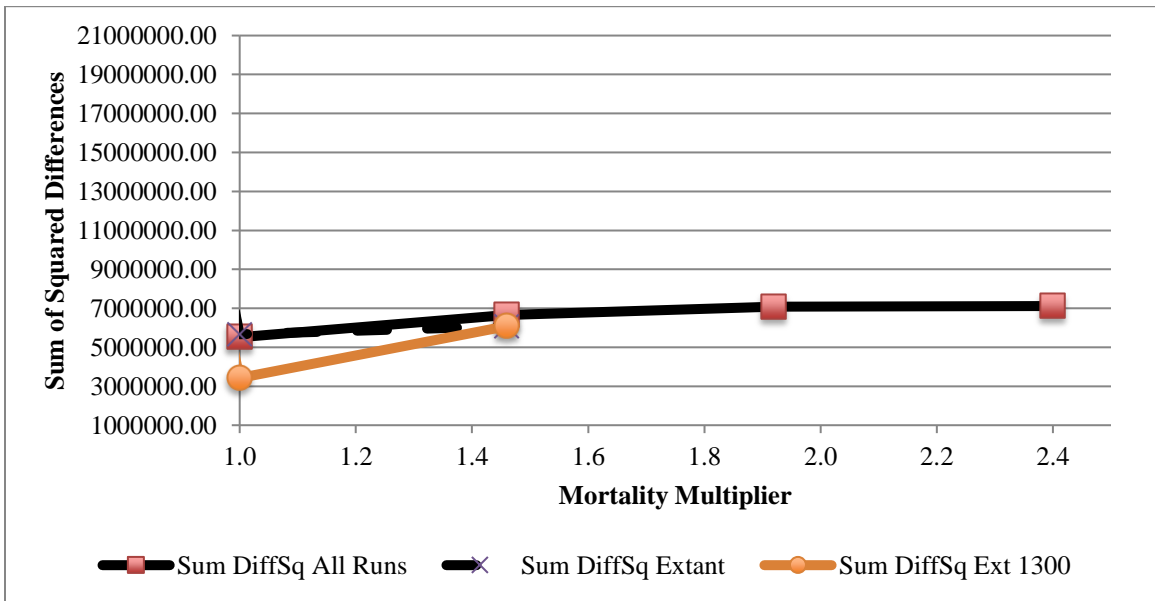
Long House Valley Sensitivity Analyses Results



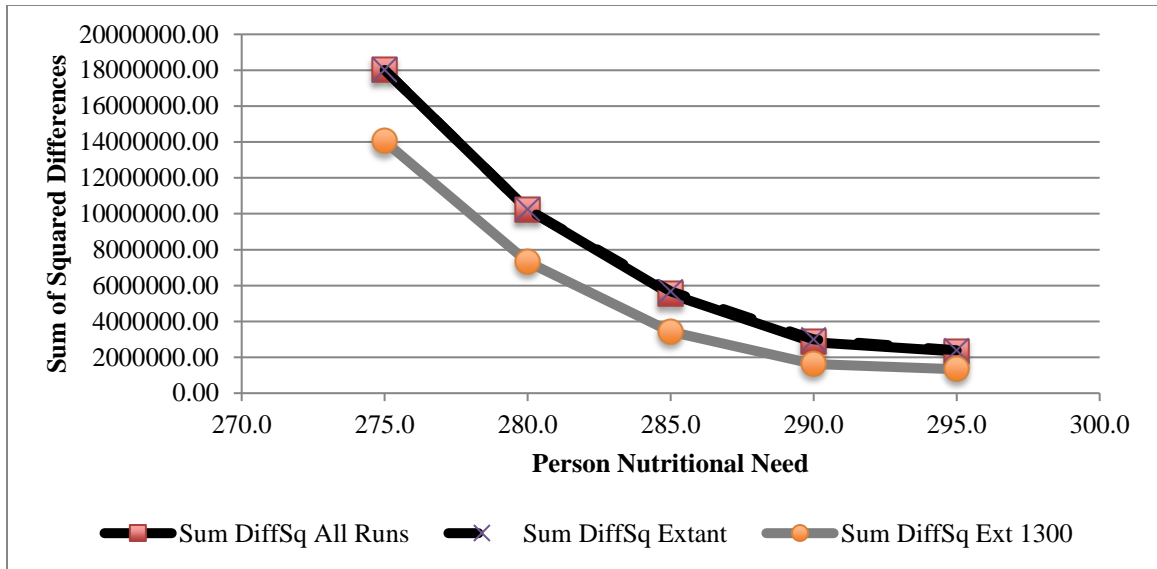
D.5. Sum of differences squared analyses of the ALHV-Mesa model when fertility is varied.



D.6. Sum of differences squared analyses of the ALHV-Mesa model when mesa adjustment is varied.



D.7. Sum of differences squared analyses of the ALHV-Mesa model when mortality adjustment is varied.



D.8. Sum of differences squared analyses of the ALHV-Mesa model when person nutritional need is varied.

APPENDIX E: MODEL CODE

This appendix will include the code for the three main models described in this dissertation: ALHV-Baseline, ALHV-AgedMort, and ALHV-Mesa. The code included in this appendix was generated by converting the NetLogo code to PDF.

```

;; ALHV-BASELINE MODEL CODE

patches-own [value waterSource? zone apdsi hydro quality maizeZone yield baseYield ofcfarm ocfarm ocfarm household nrh]
breed [households household ]
; breed [settlements settlement] ; occupation of simulated households ;; Not used in present version.
breed [archsettlements archsettlement] ; archaeological occupation
breed [waterpoints waterpoint]
breed [persons person]

; settlements-own [settlementX settlementY nrhouseholds] ;; Not used in present version.

archsettlements-own [archsettlementX archsettlementY SARG meterNorth meterEast startdate enddate mediandate typeset sizeset description roomcount e

waterpoints-own [waterpointX waterpointY sarg meternorth metereast typewater startdate enddate]

households-own [

householdID ; ID of a household; assigned at the time a household is formed
householdX householdY ; location of the household on the space
householdSize ; the number of persons assigned to a household
householdAge ; self-explanatory, initialized at age 0
householdNutriNeed ; combined nutritional needs of all agents within a household
householdNutriShortfall ; difference between the estimated nutrients available and the household nutrition need
farmX farmY ; location of the household's associated farm on the space
farmplot ; a household's farmplot; assigned after finding the best farm in findFarmAndSettlement methc
lastHarvest ; base yield of the most recent harvest
availableCorn ; estimate of the maize that will be available the following year; combines existing stock ar
agedCornStocks ; stores of maize from harvests of the previous two years; each year retains its identity
houseIsNew? ; a boolean that describes whether the house is a newly created house or an old one trying to
]

persons-own [

;; GENERAL CHARACTERISTICS
personID ; ID of a person; assigned at initialization or birth
personX personY ; location of a person on the space
natalCommunity ; site at which the person was born; 1 = Long House Valley, 5 = outside male
residence ; site at which the person is living; 1 = Long House Valley
personHouseholdID ; the household to which a person is assigned
clanID ; ID of a person's clan; assigned at initialization or birth, newborns are assigned their mot
sex age ; age and sex of persons formed at initialization reflect a realistic age-sex distribution, 1
headOfHousehold? ; boolean that indicates whether a person is head of her household
eldestChild? ; boolean that indicates whether a person is the eldest child (male or female); used to deter
married? ; boolean that indicates whether a person is married
mateID ; the personID of a person's mate
newMother? ; boolean that indicates whether a woman is a new mother; used to determine whether a child i
houseNeeded?
personNutriNeed ; the nutritional requirements of a person, based on age and sex
personNutriShortfall ; the amount of personal nutritional need that is not being met by the available maize

; DEMOGRAPHIC VARIABLES
fertility ; age-specific probability that a female gives birth in any particular year
fertilityAge ; set at initialization for adults; for younger agents, chosen at initialization or birth
; from range determined by min- and maxFertilityAge
fertilityEndsAge ; chosen at initialization or birth from range determined by min- and maxFertilityEndsAge
deathAge ; chosen at initialization and hatching (outside males and newborns)
]

globals [

;; INTERFACE VARIABLES
; harvestAdjustment ; a variable in the original AA model that reflects actual vs. maximum possible
; harvestVariance ; a variable in the original AA model that reflects spatial variation in yields
; mapview ; a chooser that allows the user to view different types of data on the map
; archaeologyview ; a switch that allows the user to control whether archaeological sites are see
; personBaseNutriNeed ; the amount of food needed per adult, initialized at 160 kg
; minFertilityAge maxFertilityAge ; boundaries of age range within which a female can reproduce
; minFertilityEndsAge maxFertilityEndsAge ; boundaries of age range for end of female reproductive period
; minDeathAge maxDeathAge ; boundaries of age range during which agents die

;; HOUSEHOLD VARIABLES
householdIDindex ; a variable to keep track of numbering for new households
minHouseholdNutriNeed ; the minimum value for a household's nutritional need; required for the determ
; because households need this when they are first made; changed each step tc
householdMinInitialCorn householdMaxInitialCorn ; boundaries of the range of maize stocks available at initialization of a hous
totHouseholds ; simulated number of households
archTotHouseholds ; the number of archaeological households at a given time; based on archaeologi
weddingMaizeGift ; the proportion of stored maize given by a parent household to new, daughter h

;; PERSON VARIABLES
personIDindex ; a variable to keep track of the numbering for new persons
totPopSize ; total number of persons at any time
totFertRate ; gives the value of the total fertility rate. Used to keep simulation results

;; FIND FARM AND HOUSEHOLD LOCATION VARIABLES
potfarms ; list of potential farm sites
bestfarm ; the best farm site available
streamsExist? alluviumExist? ; self-explanatory booleans
; farmSitesAvailable ; number of farm sites available
waterSourceDistance ; the maximum distance in number of cells an agent likes to live away from wate
yearsOfStock ; number of years maize can be stored = 2 years

```



```

;; MISCELLANEOUS VARIABLES
year                                ; year of the simulation
environment-data                    ; empirical data read into the program
apdsi-data                          ; empirical data read into the program
map-data                            ; empirical data read into the program
settlements-data                    ; empirical data read into the program
water-data                          ; empirical data read into the program
]

; The following variable names have been changed from Janssen's version: estimate to availableCorn, age to householdAge, nutritionNeed to household
; nutritionNeedRemaining to householdNutriShortfall, maizeGiftToChild to weddingMaizeGift

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;; SETUP AND GO METHODS          ;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to setup ; initialize the parameters and variables of the model and download the datafiles
clear-all
; set-default-shape settlements "tile log" ;; Simulation settlements not used in present version.
set-default-shape archsettlements "tile stones"
set-default-shape households "house"
set-default-shape persons "person"
load-map-data
set streamsExist? false
set alluviumExist? false
set year 800 ; initial year
ask patches
[
  set waterSource? false
  set quality ((random-normal 0 1) * harvestVariance) + 1.0 ; quality assigns a measure to a patch that is used below to introduce spatial hetero
  if (quality < 0) [set quality 0]
]
set waterSourceDistance 16.0 ; maximum distance between a household and water source
; set harvestAdjustment 0.56 ; (slider) 0.56 is Janssen's default value
; set harvestVariance 0.40 ; (slider) 0.4 is the default value in both the Ascape and Janssen version
; set personBaseNutriNeed 160 ; (slider) an adult needs 160 kg of food (maize) each year; children's need will be determined by their age at init
; set minFertilityAge 16 ; (slider) minimum age when persons reach maturity and can marry, form new households, and reproduce.
; set maxFertilityAge 16 ; (slider) maximum age when persons reach maturity and can marry, form new households, and reproduce. The present settir
; set minFertilityEndsAge 49 ; (slider) minimum age at menopause (= 16 years + minFertilityEndsAge in Janssen)
; set maxFertilityEndsAge 51 ; (slider) maximum age at menopause (= 16 years + maxFertilityEndsAge in Janssen)
; set minDeathAge 51 ; (slider) minimum age at death (= 16 years + minDeathAge in Janssen)
; set maxDeathAge 57 ; (slider) maximum age at death (= 16 years + maxDeathAge in Janssen)
set householdIDindex 1 ; needed to assign IDs to new households
set personIDindex 1 ; needed to assign IDs to new persons
set weddingMaizeGift 0.33 ; the proportion of parent's maize given to new household by parent household at marriage of a daughter
set yearsOfStock 2 ; number of years maize can be stored
set minHouseholdNutriNeed 800 ; initialization value of a household's nutrition need; calculated subsequently from the individual nutritional nee
set householdMinInitialCorn 2000 ; lower bound of possible maize stock at initialization of a household
set householdMaxInitialCorn 2400 ; upper bound of possible maize stock at initialization of a household

;; If sensitivity analyses are being run, paired variables that are being studied need to be set at the same values. The appropriate line below,
; set maxFertilityAge minFertilityAge
; set maxFertilityEndsAge minFertilityEndsAge
; set maxDeathAge minDeathAge

ask archsettlements [set hidden? true] ; if true, don't show archaeological sites
water ; calculate water availability for initial time step
calculate-yield
ask patches [set baseYield yield * quality * harvestAdjustment] ; NOTE: "yield" is the natural output of a plot; "baseYield" is the output adjust
; which introduces spatial heterogeneity among patches within the same productive
; harvest adjustment which reflects crop loss

determine-potfarms ; makes a list of the possible farm sites given the land quality and space available
set archTotHouseholds 14 ; initialization of the same number of simulation households as there are archaeological households in the data
create-households archTotHouseholds [init-households] ; creates the same number of simulation households as archaeological, imbues them with appr
set householdIDindex archTotHouseholds + 1 ; sets the householdIDindex so that the first household created after setup will be the next consecuti
init-persons
update-household-size
set totHouseholds count households
set totPopSize count persons
set totFertRate 4.0
estimate-harvest
map-settlements
create-files
write-to-annual-file
reset-ticks
end

;-----

to go ; core procedure of the model, which defines the cycle of activities each year
set archTotHouseholds 0
set totHouseholds 0
set year year + 1
ask households [set houseIsNew? false]
calculate-yield
if archaeologyview [archaeological-population] ; this statement govern how the archaeological data is shown on the map. The decision whether they
harvest-consumption
ALHV-death
update-household-size
; The following code causes the simulation to end early if all agents have died.
; ifelse count households < 1
; [
; ; type "It's year " type year print ". All agents have died."
; map-settlements
; stop

```

```

; ]
; [

map-settlements
ask households [update-ALHV-householdNutriNeed]
estimate-harvest
set minHouseholdNutriNeed personBaseNutriNeed * 2 ; minHouseholdNutriNeed is assumed to be the need of a household with two adults in it
ask households
[
  if (availableCorn < householdNutriNeed)
  [
    determine-potfarms
    ask patch farmX farmY [set ocfarm 0] ; this statement codes for abandonment of the present farm plot. In the next statement, a new plot is sc
    find-farm-and-settlement
  ]
]
ask persons
[
  set age age + 1
  find-age-specific-fertility
  update-ALHV-personNutriNeed
  move-persons-with-household ; the positioning of this method call here ensures that all persons in households that need to move because of inad
  ; Movement because of demographic events is completed at the time of those events. Placing the method call here see
  ; find-farm-and-settlement because that method is an observer method, not a person method, and so we would have to
  ; household changed locations. The placement here moves all agents that have changed households at the same time.
]

determine-potfarms

; The following block sets conditions on marriage and childbirth.
ask persons [
  if ((married? = false) and (sex = 1) and (age >= fertilityAge) and (headOfHousehold? = false)) [find-mate]
  if ((sex = 1) and (married? = true) and (age >= fertilityAge) and (age <= fertilityEndsAge) and (random-float 1.0 < fertility)) [produce-babies]
]

update-household-size
set totHouseholds count households
set totPopSize count persons
water ; here we reassess the availability of water in each cell of the map
map-settlements
; type "Ocfarms1 in year " type year type ": " print count patches with [ocfarm = 1]
; type "Households in year " type year type ": " print count households
update-annual-output
if year = 1350 [stop]
tick
; ]; This bracket is associated with the ifelse code that stops the simulation when all agents are dead. Not needed when end of simulation is se
end

;-----
to load-map-data
; load spatially explicit data to populate the landscape with a map of different types of land cover
ifelse ( file-exists? "Map.txt" )
[
  set map-data []
  file-open "Map.txt"
  while [ not file-at-end? ]
  [
    set map-data sentence map-data (list (list file-read))
  ]
  file-close
]
[ user-message "There is no Map.txt file in current directory!" ]

clear-patches
clear-turtles
let yy 119
let xx 0
; The numbers after each "? =" are values given to each patch during the process of converting actual map data to a rasterized form that can be r
; the available NetLogo GIS extension.
foreach map-data [
  ask patch xx yy [set value first ?]
  if first ? = 0 [ask patch xx yy [set pcolor black set zone "General" set maizeZone "Yield_2"]] ; General Valley
  if first ? = 10 [ask patch xx yy [set pcolor red set zone "North" set maizeZone "Yield_1"]] ; North Valley
  if first ? = 15 [ask patch xx yy [set pcolor white set zone "North Dunes" set maizeZone "Sand_dune"]] ; North Valley ; Dunes
  if first ? = 20 [ask patch xx yy [set pcolor gray set zone "Mid" ifelse (xx <= 74) [set maizeZone "Yield_1"][set maizeZone "Yield_2"]]] ; Mid Val
  if first ? = 25 [ask patch xx yy [set pcolor white set zone "Mid Dunes" set maizeZone "Sand_dune"]] ; Mid Valley ; Dunes
  if first ? = 30 [ask patch xx yy [set pcolor yellow set zone "Natural" set maizeZone "No_Yield"]] ; Natural
  if first ? = 40 [ask patch xx yy [set pcolor blue set zone "Uplands" set maizeZone "Yield_3"]] ; Uplands Arable
  if first ? = 50 [ask patch xx yy [set pcolor pink set zone "Kinbiko" set maizeZone "Yield_1"]] ; Kinbiko Canyon
  if first ? = 60 [ask patch xx yy [set pcolor white set zone "Empty" set maizeZone "Empty"]] ; Empty
  ifelse yy > 0 [set yy yy - 1][set xx xx + 1 set yy 119] ]

; SARG (Southwestern Archaeological Research Group) number, meters north, meters east, start date, end date, median date (1950 - x), type, size,
ifelse ( file-exists? "settlements.txt" )
[
  set settlements-data []
  file-open "settlements.txt"
  while [ not file-at-end? ]
  [
    set settlements-data sentence settlements-data (list (list file-read file-read file-read file-read file-read file-read file-read file-read fi
  ]
  file-close
]
[ user-message "There is no settlements.txt file in current directory!" ]

```

```

foreach settlements-data [
  create-archsettlements 1 [
    set SARG first ?
    set meterNorth item 1 ?
    set meterEast item 2 ?
    set startdate item 3 ?
    set enddate item 4 ?
    set mediandate (1950 - item 5 ?)
    set typeset item 6 ?
    set sizeset item 7 ?
    set description item 8 ?
    set roomcount item 9 ?
    set elevation item 10 ?
    set baselinehouseholds last ? ]]

; number, meters north, meters east, type, start date, end date
ifelse ( file-exists? "water.txt" )
[
  set water-data []
  file-open "water.txt"
  while [ not file-at-end? ]
  [
    set water-data sentence water-data (list (list file-read file-read file-read file-read file-read file-read))
  ]
  file-close
]
[ user-message "There is no water.txt file in current directory!" ]

foreach water-data [
  create-waterpoints 1 [
    set sarg first ?
    set meterNorth item 1 ?
    set meterEast item 2 ?
    set typewater item 3 ?
    set startdate item 4 ?
    set enddate item 5 ?]]
; The following code converts the input coordinates for each waterpoint to the simulation map coordinates so that they will appear on the map in
ask waterpoints [
  set xcor 24.5 + int ((meterEast - 2392) / 93.5)
  set ycor 45 + int (37.6 + ((meterNorth - 7954) / 93.5))
  set hidden? true
]

ifelse ( file-exists? "adjustedPDSI.txt" )
[
  set apdsi-data []
  file-open "adjustedPDSI.txt"
  while [ not file-at-end? ]
  [
    set apdsi-data sentence apdsi-data (list file-read)
  ]
  file-close
]
[ user-message "There is no adjustedPDSI.txt file in current directory!" ]

; The 15 file-read statements below refer to the structure of the data, which consists of three values for each of the five environment zones for
; Only the hydrology data (the second of the three values per environment zone) are used in the program.
ifelse (file-exists? "environment.txt")
[
  set environment-data []
  file-open "environment.txt"
  while [not file-at-end?]
  [
    set environment-data sentence environment-data (list (list file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read))
  ]
  file-close
]
[ user-message "There is no environment.txt file in current directory!" ]

ask patches [set ocfarm 0 set ochousehold 0] ; all patches are initialized as vacant (i.e., with no farms or households on them)
end

;-----
to calculate-yield
; calculate the yield (unadjusted) and whether water is available for each patch based on the adjusted PDSI and the presence of a suitable water
; table level (indicated by the hydrologic data).

; The following 6 lines indicate where in the apdsi-data file to find the specific values for each environment for a particular year.
; In the apdsi-data file, all values are placed linearly in a single line. The apdsi values for north and kinbiko are identical to each other, as
; are the values for natural and upland. This is consistent with what is published in the article in the Kohler and Gumerman volume (Dean et al.
let generalapdsi item (year - 200) apdsi-data
let northapdsi item (1100 + year) apdsi-data
let midapdsi item (2400 + year) apdsi-data
let naturalapdsi item (3700 + year) apdsi-data
let uplandapdsi item (3700 + year) apdsi-data
let kinbikoapdsi item (1100 + year) apdsi-data

; the following 6 lines indicate the location of the hydrology data for each environment in a given year. Note: item 1 is actually the second ite
; in a row of the environment data. Natural and upland have identical hydrology values, although at specific times the values are overridden in t
; program to reflect the rare times when the two differ.
let generalhydro item 1 (item (year - 382) environment-data)
let northhydro item 4 (item (year - 382) environment-data)
let midhydro item 7 (item (year - 382) environment-data)
let naturalhydro item 10 (item (year - 382) environment-data)

```

```

let uplandhydro item 10 (item (year - 382) environment-data)
let kinbikohydro item 13 (item (year - 382) environment-data)

; See Dean et al. (2000, in Kohler and Gumerman volume) for explanation of zone identification and yield calculations.
ask patches [
  if zone = "General" [set apdsi generalapdsi]
  if zone = "North" [set apdsi northapdsi]
  if zone = "Mid" [set apdsi midapdsi]
  if zone = "Natural" [set apdsi naturalapdsi]
  if zone = "Upland" [set apdsi uplandapdsi]
  if zone = "Kinbiko" [set apdsi kinbikoapdsi]

  if zone = "General" [set hydro generalhydro]
  if zone = "North" [set hydro northhydro]
  if zone = "Mid" [set hydro midhydro]
  if zone = "Natural" [set hydro naturalhydro]
  if zone = "Upland" [set hydro uplandhydro]
  if zone = "Kinbiko" [set hydro kinbikohydro]

  if (maizeZone = "No_Yield" or maizeZone = "Empty") [set yield 0]
  if (maizeZone = "Yield_1") [
    if (apdsi >= 3.0) [set yield 1153]
    if (apdsi >= 1.0 and apdsi < 3.0) [set yield 988]
    if (apdsi > -1.0 and apdsi < 1.0) [set yield 821]
    if (apdsi > -3.0 and apdsi <= -1.0) [set yield 719]
    if (apdsi <= -3.0) [set yield 617]]

  if (maizeZone = "Yield_2") [
    if (apdsi >= 3.0) [set yield 961]
    if (apdsi >= 1.0 and apdsi < 3.0) [set yield 824]
    if (apdsi > -1.0 and apdsi < 1.0) [set yield 684]
    if (apdsi > -3.0 and apdsi <= -1.0) [set yield 599]
    if (apdsi <= -3.0) [set yield 514]]

  if (maizeZone = "Yield_3") [
    if (apdsi >= 3.0) [set yield 769]
    if (apdsi >= 1.0 and apdsi < 3.0) [set yield 659]
    if (apdsi > -1.0 and apdsi < 1.0) [set yield 547]
    if (apdsi > -3.0 and apdsi <= -1.0) [set yield 479]
    if (apdsi <= -3.0) [set yield 411]]

  if (maizeZone = "Sand_dune") [
    if (apdsi >= 3.0) [set yield 1201]
    if (apdsi >= 1.0 and apdsi < 3.0) [set yield 1030]
    if (apdsi > -1.0 and apdsi < 1.0) [set yield 855]
    if (apdsi > -3.0 and apdsi <= -1.0) [set yield 749]
    if (apdsi <= -3.0) [set yield 642]]

  if mapview = "yield" [set pcolor (40 + baseYield / 140)]
]
end

;-----

to init-households

; This method is for initialization of the founding households only; new households are initialized in the build-house method. Besides creating th
; initial households, this method finds a spot for each household's farming plot and settlement

set size 3
set color brown
set householdID householdIDindex
set farmX random 80 set farmY random 120
set householdX random 80 set householdY random 120
set bestfarm self
set agedCornStocks []
set agedCornStocks fput (householdMinInitialCorn + random-float (householdMaxInitialCorn - householdMinInitialCorn)) agedCornStocks
set agedCornStocks fput (householdMinInitialCorn + random-float (householdMaxInitialCorn - householdMinInitialCorn)) agedCornStocks
set agedCornStocks fput (householdMinInitialCorn + random-float (householdMaxInitialCorn - householdMinInitialCorn)) agedCornStocks
set farmplot self
set householdAge 0
set householdNutriNeed 0
set householdSize 0
set houseIsNew? false
set lastHarvest 0
determine-potfarms
find-farm-and-settlement ; we need to denote that this is a method call

set xcor householdX
set ycor householdY
set householdIDindex householdIDindex + 1

end

;-----

to init-persons ; this method is for initialization of the founding population only; new persons are initialized in the produce-babies method
  ifelse ( file-exists? "CensusPop5-6c.txt" )
  [
    file-open "CensusPop5-6c.txt"
    ; The following code reads in all the data in the file. Each line of data contains the values for 12 attributes per agent in the order listed b
    while [not file-at-end?]
    [
      let items read-from-string (word "[" file-read-line "]")
      ; Items is a temporary list of variables read in as string but converted to the appropriate variable type. "Word" concatenates

```

```

; the brackets to the line being read in, because list arguments need to be in brackets (see Netlogo user manual).
create-persons 1 [
  set personIDindex personIDindex + 1
  set size 2
  set color green
  set personID item 0 items
  set natalCommunity item 1 items
  set residence item 2 items
  set personHouseholdID item 3 items
  set clanID item 4 items
  set sex item 5 items
  set age item 6 items
  set headOfHousehold? item 7 items
  set eldestChild? item 8 items
  set married? item 9 items
  set fertilityAge item 10 items
  set mateID item 11 items

  ask persons [
    ifelse any? households with [householdID = [personHouseholdID] of myself]
      [move-persons-with-household]
      [die]
  ]

  ifelse headOfHousehold? = 0 [set headOfHousehold? false][set headOfHousehold? true]
  ifelse eldestChild? = 0 [set eldestChild? false][set eldestChild? true]
  ifelse married? = 0 [set married? false][set married? true]
  set houseNeeded? false
  set newMother? false
  if fertilityAge = 0 [set fertilityAge minFertilityAge + random (maxFertilityAge - minFertilityAge)]
  set fertilityEndsAge minFertilityEndsAge + random (maxFertilityEndsAge - minFertilityEndsAge)
  set deathAge minDeathAge + random (maxDeathAge - minDeathAge)
  find-age-specific-fertility
  update-ALHV-personNutriNeed
  set personNutriShortfall 0
  ; The following block of code calculates the household nutrition need by adding up the personal need of each assigned agent, calculates the
  ; from the age of the eldest child.
  ask households with [householdID = [personHouseholdID] of myself]
  [
    set householdNutriNeed householdNutriNeed + [personNutriNeed] of myself
    if [eldestChild? of myself = true] [set householdAge [age] of myself + 1]
    ; The household age is assumed to be the age of the eldest child + 1 because of the length of gestation time (i.e., the
    ; eldest child was most likely born more than a year after the formation of the household)
  ]
]
]
file-close
]
[ user-message "The person file called is not in the current directory!" ]
end

```

```

-----
to create-files
  if (not file-exists? "ALHVbaselineJ-PNN-285-HA-1.0-Repetition.csv") [
    file-open "ALHVbaselineJ-PNN-285-HA-1.0-Repetition.csv"
    file-type "Run number,"
    file-type "Year,"
    file-type "TFR,"
    file-type "minFertilityAge,"
    file-type "maxFertilityAge,"
    file-type "minFertilityEndsAge,"
    file-type "maxFertilityEndsAge,"
    file-type "minDeathAge,"
    file-type "maxDeathAge,"
    file-type "personBaseNutriNeed,"
    file-type "harvestAdjustment,"
    file-type "harvestVariance,"
    file-type "Arch Households,"
    file-type "Sim Households,"
    file-print "Sim People,"
    file-close
  ]
end

```

```

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;; DEMOGRAPHIC METHODS ;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

```

```

to find-mate

```

```

; This method determines who the mate of an eligible unmarried woman will be. In order to marry, she must be able to build a new house. In the bl
; set several personal variables, including her value of newMother?, which is always set to true. This is ok for women entering their first marri
; Right now, the model only uses the newMother variable to set the value of a woman's eldestChild variable, but the latter is only used during ir
; read in with other characteristics of a child. Both of these variables are included to keep the characteristics of newly created agents consist
; data on age at first birth or redistribute children following the death of the mother, etc. When those kinds of behaviors are incorporated, we
; of how many children she has.

```

```

set houseNeeded? true
let potential-mates persons with [(sex = 0) and (age >= minFertilityAge) and ((age >= [age] of myself - 5) and (age <= [age] of myself + 20))
  and (headOfHousehold? = false) and (married? = false) and (clanID != [clanID] of myself) and (personHouseholdID != [personHouseholdID] of myself)

```

```

; This method first looks for a mate from within the community. If a suitable mate cannot be found, the marry-outsider method is called.
ifelse any? potential-mates

```

```

[
  build-house ; A female looking for a mate has to have a house available in order to marry. If she cannot build a house (e.g., if there is no space
    ; she remains unmarried and will look for a husband in the next time period. If a house can be built, the variable houseNeeded? is
  ifelse houseNeeded? = false
  [
    set married? true
    set headOfHousehold? true
    set newMother? true
    let possible-mate one-of potential-mates
    ask possible-mate
    [
      set mateID [personID] of myself
      set personHouseholdID [personHouseholdID] of myself
      set married? true
    ]
  ]
  set mateID [personID] of persons with [mateID = [personID] of myself]
  ask persons with [personHouseholdID = [personHouseholdID] of myself]
  [
    move-persons-with-household
  ]
]
[set houseNeeded? false ; houseNeeded? is set to false because, in this situation, a female cannot marry stay's in her parent's (existing) house
]
]
[marry-outsider]
end

```

```

to marry-outsider
; This method creates a potential mate for a woman when no others are available in the community. It is done to guarantee
; that a woman who comes of age or who loses her husband by death can make a new household. This is needed to keep this model
; equivalent to the original model, which had no constraints on fissioning other than finding suitable farm land.
; Eventually this method may involve finding a mate from another community rather than just creating one (when more than one
; community is incorporated into the model).

hatch-persons 1 [
;   print "A husband is being found in another community!"
  set personID personIDindex
  set personHouseholdID [personHouseholdID] of myself ; this is a failsafe to make sure that the calling agent does in fact marry the agent it
    ; since it is a clone of the calling agent.
  set natalCommunity 5 ; 5 is an arbitrary ID to designate an unspecified outside community

  ; The following four statements ensure that the designated spouse does not come from the same clan.
  let tempClan random 6
  while [(tempClan = 0) or (tempClan = [clanID] of myself)]
    [set tempClan random 6]
  set clanID tempClan

  set sex 0
  ifelse [age] of myself < 21
  [set age 16 + random 6]
  [set age [age] of myself + (-5 + random 11)]

  set color blue
  set size 2
  set headOfHousehold? false
  set married? false ; the actual act of marriage occurs further below in this method
  set mateID 0
  set newMother? false
  set fertilityAge age
  set fertilityEndsAge minFertilityEndsAge + random (maxFertilityEndsAge - minFertilityEndsAge)
  set deathAge minDeathAge + random (maxDeathAge - minDeathAge)
  find-age-specific-fertility
  set personNutriNeed personBaseNutriNeed
  set personNutriShortfall 0
]

set personIDindex personIDindex + 1 ;this increments the personIDindex so that the next agent created has a unique ID number

; Because of the way outside mates are created, their personHouseholdID must be the same as the calling agent and their natalCommunity must be different
; the created mate in this time step. All other constraints are the same as in the find-mate method.
let outside-mates persons with [(sex = 0) and (age >= fertilityAge) and ((age >= [age] of myself - 5) and (age <= [age] of myself + 20))
and (headOfHousehold? = false) and (married? = false) and (clanID != [clanID] of myself) and (personHouseholdID = [personHouseholdID] of myself)
and (natalCommunity != [natalCommunity] of myself)]

; The following process is the same as that for the find-mate method, including the issue regarding the newMother variable discussed in that method
ifelse any? outside-mates
[
  build-house
  ifelse houseNeeded? = false
  [
    set married? true
    set headOfHousehold? true
    set newMother? true

    ask one-of outside-mates
    [
      set mateID [personID] of myself
      set personHouseholdID [personHouseholdID] of myself
      set married? true
    ]
  ]
  set mateID [personID] of persons with [mateID = [personID] of myself]
  ask persons with [personHouseholdID = [personHouseholdID] of myself]

```

```

    [
      move-persons-with-household
    ]
  ]
  [
    set houseNeeded? false
  ]
]
[print "I made a new man. I should have a husband, but something went wrong! Please help!"]
end

;-----
to build-house
; This method is our ALHV fission method. It is called when a woman tries to marry and there is an eligible bachelor available. It creates a new h
; maize stocks with a gift from the parent household, and finds a spot for the household's farming plot and settlement

ask households with [householdID = [personHouseholdID] of myself]
[
  hatch 1
  [
    set size 3
    set color red
    set householdID householdIDindex
    set householdAge 0
    set householdNutriNeed personBaseNutriNeed * 2 ; this initialized the householdNutriNeed; the actual value will be calculated as persons move
    set householdSize 0
    set lastHarvest 0
    set houseIsNew? true
  ]
]
ask households with [householdID = householdIDindex]
[
  determine-potfarms ; this needs to be called to ensure the potfarms list is up to date whenever a new house is build; change added 1/28/16
  find-farm-and-settlement
]

; If the house is created above cannot find a suitable farming plot and settlement in the find-farm-and-settlement method, it dies and there will b
; If that is the case, nothing further happens which means that the calling agent continues to be part of her original household (i.e., her personF
; that household is given the maize gift from the parents before her personHouseholdID is changed, so that the parent household can still be identi

let newHouse households with [householdID = householdIDindex]
ifelse any? newHouse
[
  give-maize-gift (newHouse)
  set houseNeeded? false
  set personHouseholdID householdIDindex
  set householdIDindex householdIDindex + 1
]
[ ; ; No suitable location was found for new house. Do nothing! ]
]

end

;-----
to give-maize-gift [newHousehold]
;This methods takes a user-designated proportion of the corn stocks from a parent household and gives it to the new household.
ask households with [householdID = [personHouseholdID] of myself]
[
  let ysParent yearsOfStock
  while [ysParent > -1]
  [
    set agedCornStocks replace-item ysParent agedCornStocks ((1 - weddingMaizeGift) * (item ysParent agedCornStocks))
    set ysParent ysParent - 1]
]

ask newHousehold
[ let ysNew yearsOfStock
  while [ysNew > -1]
  [
    set agedCornStocks replace-item ysNew agedCornStocks ((weddingMaizeGift / (1 - weddingMaizeGift)) * (item ysNew agedCornStocks))
    set ysNew ysNew - 1
  ]
]

end

;-----
to produce-babies

hatch-persons 1 [
  set personID personIDindex
  set age 0
  let sex-prob random-float 1.0
  ifelse sex-prob < 0.5
  [set sex 0]
  [set sex 1]
  set headOfHousehold? false
  set married? false
  set mateID 0
  set newMother? false ; this is the newMother value of the baby
  ifelse [newMother?] of myself = true [set eldestChild? true][set eldestChild? false]

  set fertilityAge minFertilityAge + random (maxFertilityAge - minFertilityAge)
  set fertilityEndsAge minFertilityEndsAge + random (maxFertilityEndsAge - minFertilityEndsAge)
]

```

```

set deathAge minDeathAge + random (maxDeathAge - minDeathAge)
find-age-specific-fertility
update-ALHV-personNutriNeed
set personNutriShortfall 0
ask households with [householdID = [personHouseholdID] of myself]
  [
    set householdNutriNeed householdNutriNeed + [personNutriNeed] of myself
  ]
]
set newMother? false ; this is the newMother value of the mother
set personIDindex personIDindex + 1 ; this increments the personIDindex so that the next agent created has a unique ID number
end

;-----

to find-age-specific-fertility
  ifelse ((age >= 0 and age < fertilityAge) or age > fertilityEndsAge) [set fertility 0.00]; 0.00
  [
    if (age >= fertilityAge and age < 20) [set fertility 0.094] ; 0.148; these values were used in the original ALHV disaggregate model; developed
    if (age >= 20 and age < 25) [set fertility 0.256] ;0.206
    if (age >= 25 and age < 30) [set fertility 0.256] ;0.228
    if (age >= 30 and age < 35) [set fertility 0.208] ;0.203
    if (age >= 35 and age < 40) [set fertility 0.144] ;0.228
    if (age >= 40 and age < 44) [set fertility 0.06] ;0.117
    if (age >= 44 and age <= fertilityEndsAge) [set fertility 0.012] ;0.045
  ]
;; The current fertility values were derived Alan Swedlund's age-specific fertility schedule for small-scull horticultural populations.
end

;-----

to ALHV-death
;; This method is called near the beginning of the go method and governs individual agent death by starvation or old age. At the present time, in
;; situation where their household is not able to find a suitable location if forced to move. This is consistent with assumptions made in the ori
;; Eventually, other causes of individual agent death will be included in this or additional methods.
;; NOTE: This method is our closest approximation to the AA-death methods, but it is impossible to make it identical to the household level methc

;; BLOCK 1-- Starvation

;; The underlying assumption about death by starvation is that the youngest will die first. In the starvation block, we first determine if there
;; to oldest) until the nutritional need of the household is low enough that all needs can be met with existing maize stocks (i.e., householdNutri
;; the marital status of the surviving spouse.

if any? households
  [
    ask households
    [
      if (householdNutriShortfall > 0)
      [
        let household-members persons with [personHouseholdID = [householdID] of myself]
        if any? household-members [
          while [householdNutriShortfall > 0]
          [
            let youngest min-one-of household-members [age]
            set householdNutriShortfall householdNutriShortfall - [personNutriNeed] of min-one-of household-members [age]
            if [married?] of youngest ;; if the youngest person is married
            [
              ask persons with [mateID = [personID] of youngest]
              [
                set married? false
                set headOfHousehold? false
                set mateID 0
              ]
            ]
          ]
          ask youngest
          [
            die
          ]
        ]
        type " A death has occurred in household ID: " type householdID type "Household Size: " print householdSize
        if count household-members = 0 [set householdNutriShortfall 0] ;; Kill the households if no household-members
      ]
    ]
  ]

;; BLOCK 2-- Old Age

;; Death by old age is assume to occur within the same user defined age range for all agents, assuming they don't die before reaching their desig
;; the marital status of the surviving spouse.

ask persons
  [
    if age >= deathAge
    [
      if married?
      [
        ask persons with [mateID = [personID] of myself]
        [
          set married? false
          set headOfHousehold? false
          set mateID 0
        ]
      ]
    ]
  ]

```



```

]
die
]
]

;; BLOCK 3-- Death aftermath

;; At the present time, this block merely removes associated farms and households from the map/landscape when the last household resident dies. E
;; survivors, for example, children whenever both parents have died.

update-household-size
ask households
[
  if householdSize = 0 ;<= 1 ; this is a stop-gap to avoid households of size 1 or 0; later versions will be "if householdSize = 0" and other mecht
  [
    ask patch farmx farmy [set ocfarm 0]
    if any? persons with [personHouseholdID = [householdID] of myself]
    [
      ask persons with [personHouseholdID = [householdID] of myself][die]
    ]
    ask patch-here [set ochousehold ochousehold - 1]
    die
  ]
]

end

;-----

to move-persons-with-household

;This method checks to make sure that each person trying to move has one house and only one house. It also ensures they move with the household i
let household-site households with [householdID = [personHouseholdID] of myself]
  ifelse any? household-site
  [
    ifelse (count household-site) = 1
    [
      move-to one-of households with [householdID = [personHouseholdID] of myself]
      set personX [pxcor] of households with [householdID = [personHouseholdID] of myself]
      set personY [pycor] of households with [householdID = [personHouseholdID] of myself]
    ]
    [print "Check data file; there is more than one household with this agent's householdID!" ]
  ]
  [ die ; There are no household sites left. Do nothing.
  ]

end

;-----

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;; AGRICULTURAL METHODS ;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to find-farm-and-settlement
; This method finds a spot for a household and its associated farm. The household spot will be a pre-existing location or it can be a new one. Th
; location of a household is its settlement; multiple households can occupy the same settlement space. Only one farm (which is linked to a
; specific household) can occupy a particular space.
let searchCount 0
let siteNeeded? true
let xh 0
let yh 0

ifelse length potfarms > 0
[
  set bestfarm determine-best-farm
  if bestfarm = nobody
  [
    ask persons with [personHouseholdID = [householdID] of myself] [die]
    ask patch-here [set ochousehold ochousehold - 1]
    die
  ]

let bestYield [baseYield] of bestfarm ; NOTE: "baseYield" is the realized output of a plot
set farmX [pxcor] of bestfarm
set farmY [pycor] of bestfarm
set farmplot bestfarm
ask patch farmX farmY [set ocfarm 1]
if (count patches with [waterSource? = true and ocfarm = 0 and (baseYield < bestYield)] > 0) ; the criterion is to find cells with water availa
; farmed and are in a zone that is less productive than the zc
; best farm plot is located

[
  ask min-one-of patches with [waterSource? = true and ocfarm = 0 and (baseYield < bestYield)] [distance bestfarm] ; find the spot with these
; to the farm that has just been c

[
  ifelse distance bestfarm <= waterSourceDistance ; if the spot is within the waterSourceDistance from the new farm plot,
  [set xh pxcor set yh pycor set siteNeeded? false] ; set the local variables xh and xy to the coordinates of the identified patch
  [set siteNeeded? true] ; and set the boolean to false; otherwise, keep the boolean at true
]
]
]
]

```

```

]
if siteNeeded? = false
[
  ask min-one-of patches with [ocfarm = 0 and hydro <= 0] [distancexy xh yh] ; if a suitable farmplot has been found, find a nearby patch w
  ; hydrology and choose that as the household location
  [
    set xh pxcor set yh pycor set ochousehold ochousehold + 1 ; this adds a household to the patch and allows us to keep track of settleme
  ]
]
]
if siteNeeded? = true ; no settlement was found in the previous block
[
  ; this block of code finds the closest patch without a farm, and if that is within than the maximum waterSource distance,
  ; set the coordinates of the farm to be that patch. Note: bestYield is the best farm's "baseYield" (adjusted).
  ; The constraint in the previous block is that the potential settlement site has a base yield lower than the base yield of the best farm
  ; plot and that it is not occupied by a farm and is within the maximum waterSource distance. In this block, the household can occupy
  ; a more fertile patch (base yield > bestYield) because there is nothing else available.

  ask min-one-of patches with [ocfarm = 0] [distance bestfarm]
  [
    ifelse distance bestfarm <= waterSourceDistance
    [
      set xh pxcor set yh pycor
      set siteNeeded? false
    ]
    [set siteNeeded? true]
  ]
  if siteNeeded? = false
  [
    ask min-one-of patches with [ocfarm = 0 and hydro <= 0] [distancexy xh yh] ; if a suitable farmplot has been found, find a nearby patch w
    ; hydrology and choose that as the household location
    [
      set xh pxcor set yh pycor set ochousehold ochousehold + 1; this adds a household to the patch and allows us to keep track of settlemet
    ]
  ]
]
if siteNeeded? = true ; still no settlement has been found
[
  ; this block of code finds the closest patch without a farm, even if it is a higher base yield than bestYield and outside the waterSource c
  ask min-one-of patches with [ocfarm = 0] [distance bestfarm]
  [
    set xh pxcor set yh pycor
    set siteNeeded? false
  ]
]
if siteNeeded? = false
[
  ask min-one-of patches with [ocfarm = 0 and hydro <= 0] [distancexy xh yh] ; if a suitable farmplot has been found, find a nearby patch w
  ; hydrology and choose that as the household location
  [
    set xh pxcor set yh pycor set ochousehold ochousehold + 1; this adds a household to the patch and allows us to keep track of settlemet
  ]
]
]

if siteNeeded? = true
[ ; type "I am household number: " type householdID type "It is year: " type year type "There are no suitable household sites available. I am
  ask patch farmx farmy [set ocfarm 0]
  if any? persons with [personHouseholdID = [householdID] of myself]
  [
    ask persons with [personHouseholdID = [householdID] of myself][die]
  ]
  ask patch-here [set ochousehold ochousehold - 1]
  die
]
]

; The following block of statements actually move households that have successfully identified new farms and settlements and increments the r
set householdX xh
set householdY yh
set xcor householdX
set ycor householdY
ask patch-here [set ochousehold ochousehold + 1]

]

[ ; This is the else part of the ifelse sitesAvailable? (i.e., no sites are available anywhere on the space). All people within the household c
if houseIsNew? = false
[
  ask patch farmx farmy [set ocfarm 0]
  if any? persons with [personHouseholdID = [householdID] of myself]
  [
    ask persons with [personHouseholdID = [householdID] of myself] [die]
  ]
  ask patch-here [set ochousehold ochousehold - 1]
]
]
die
]
end
]

;-----
to determine-potfarms
; This method identifies a list of potential farm locations to use during initialization. When first made, farms are given random locations,
; but must move to available sites. These sites are patches not already occupied by a farm or settlement and where the base yield (the adjusted

```

```

; yield) is higher than the minimum amount of food needed by the farm's household.
set potfarms []
ask patches with [(zone != "Empty") and (ocfarm = 0) and (ochohousehold = 0) and (baseYield >= minHouseholdNutriNeed)]
  [set potfarms lput self potfarms]
end

;-----

to-report determine-best-farm ; this method finds the closest suitable farm on the list of potential farms; the starting distance (distancetns)
  ; just puts constraints on the search space

set bestfarm nobody
let existingfarm patch farmX farmY
let distancetns 1000
foreach potfarms
[
  ask ? [
    if ((distance existingfarm < distancetns) and (baseYield > [householdNutriNeed] of myself))
    [
      set bestfarm self
      set distancetns distance existingfarm
    ]
  ]
]
if length potfarms > 0 [set potfarms remove bestfarm potfarms]
report bestfarm
end

;-----

to estimate-harvest ; this method calculates the expected level of food available to a household based on current stocks of maize and
  ; the estimate of the next year's harvest (equal to the actual production during the current year)

ask households [
  let total 0
  let ys yearsOfStock - 1
  while [ys > -1]
  [
    set total total + item ys agedCornStocks
    set ys ys - 1
  ]
  set availableCorn total + lastHarvest
]
end

;-----

to harvest-consumption
; The first block of this method calculates the base yield for each cell (i.e., adjusts the natural yield to account for spatial variation in
; productivity and crop loss). It then estimates the actual harvest of a household and updates the stocks of maize available in storage. The second
; block of code calculates the amount of nutrients a household can derive from the available maize.

ask patches [set baseYield (yield * quality * harvestAdjustment)]
ask households
[
  set lastHarvest [baseYield] of patch farmX farmY * (1 + ((random-normal 0 1) * harvestVariance))
  set agedCornStocks replace-item 2 agedCornStocks (item 1 agedCornStocks)
  set agedCornStocks replace-item 1 agedCornStocks (item 0 agedCornStocks)
  set agedCornStocks replace-item 0 agedCornStocks lastHarvest
  set householdNutriShortfall householdNutriNeed
  set householdAge householdAge + 1
]

; BLOCK 2

ask households
[
  let ys yearsOfStock
  while [ys > -1]
  [
    ifelse ((item ys agedCornStocks) >= householdNutriShortfall)
    [
      set agedCornStocks replace-item ys agedCornStocks (item ys agedCornStocks - householdNutriShortfall)
      set householdNutriShortfall 0
    ]
    [
      set householdNutriShortfall (householdNutriShortfall - item ys agedCornStocks)
      set agedCornStocks replace-item ys agedCornStocks 0
    ]
  ]
  set ys ys - 1
]
]
end

;-----

to water
; define for each location when water is available

ifelse ((year >= 280 and year < 360) or (year >= 800 and year < 930) or (year >= 1300 and year < 1450)) [set streamsExist? true][set streamsExist?
ifelse ((year >= 420 and (year < 560)) or ((year >= 630) and (year < 680)) or ((year >= 980) and (year < 1120)) or ((year >= 1180) and (year <
[set alluviumExist? true][set alluviumExist? false]

ask patches [

```

```

set waterSource? false
if ((alluviumExist? = true) and ((zone = "General") or (zone = "North") or (zone = "Mid") or (zone = "Kinbiko"))) [set waterSource? true]
if ((streamsExist? = true) and (zone = "Kinbiko")) [set waterSource? true]
]
; Consistent with the paleoenvironmental data, the following patches always have water regardless of the climate conditions.
ask patch 72 114 [set waterSource? true]
ask patch 70 113 [set waterSource? true]
ask patch 69 112 [set waterSource? true]
ask patch 68 111 [set waterSource? true]
ask patch 67 110 [set waterSource? true]
ask patch 66 109 [set waterSource? true]
ask patch 65 108 [set waterSource? true]
ask patch 65 107 [set waterSource? true]

ask waterpoints [
if typewater = 2 [ask patch xcor ycor [set waterSource? true]]
if typewater = 3 [if (year >= startdate and year <= enddate) [ask patch xcor ycor [set waterSource? true]]]
]

if mapview = "waterSource?" [
ask patches [
ifelse waterSource? = true [set pcolor blue] [set pcolor white]
]
]
end

;-----
to update-ALHV-personNutriNeed

;; Newborns are assumed to have 35% of the adult personal nutritional need. This need increases linearly with age until age 16 when all ages are a

ifelse age < fertilityAge
[set personNutriNeed personBaseNutriNeed * (0.35 + (0.65 * (age / fertilityAge)))]
[set personNutriNeed personBaseNutriNeed]
end

;-----
to update-ALHV-householdNutriNeed

let house-members persons with [personHouseholdID = [householdID] of myself]
if any? house-members
[set householdNutriNeed sum [personNutriNeed] of house-members]

end

;-----
to update-household-size
ask households
[
set householdSize count persons with [personHouseholdID = [householdID] of myself]
]
end

;-----
;;; DISPLAY AND DATA COLLECTION METHODS ;;;
;-----

to map-settlements ; This method allows easier visualization of the locations of simulated farms and settlements
; Note: the variable "nrh" keeps track of the number of simulated households on a patch, but the present model is not set up to
; We are keeping it in the model because it may prove to be useful later.

ask patches [set nrh 0]
ask households
[
ask patch-here [set nrh nrh + 1]
]
if mapview = "occup"
[
ask patches
[
ifelse ochousehold > 0
[set pcolor red]
[set pcolor black]

ifelse ocfarm = 1
[set pcolor yellow]
[set pcolor black]
]
]
]
end

;-----
to archaeological-population ; This method converts the input location coordinates of archaeological settlements to the appropriate map location ar
; them on the map. It also adjusts their size according to the number of households at each settlement.

ask archsettlements
[
if (typeset = 1) [
set nrhouseholds 0
]
]

```

```

ifelse (year >= startdate and year < enddate)
[
  set hidden? false ;; this statement determines whether the archaeological data appears on the map.

  ;; The following two blocks are direct translations from the original AA model and the equations used are a consequence of the way the arch
  if year > mediandate
  [
    if (year != mediandate)
    [
      set nrhouseholds ceiling (baselinehouseholds * (enddate - year) / (enddate - mediandate))
      if nrhouseholds < 1 [set nrhouseholds 1]
    ]
  ]
  if year <= mediandate
  [
    if (mediandate != startdate)
    [
      set nrhouseholds ceiling (baselinehouseholds * (year - startdate) / (mediandate - startdate))
      if nrhouseholds < 1 [set nrhouseholds 1]
    ]
  ]
]
[set hidden? true]
set archTotHouseholds archTotHouseholds + nrhouseholds
set archsettlementX (24.5 + (meterEast - 2392) / 93.5) ; these two statements are the location translation function for the coordinate
set archsettlementY (45 + (37.6 + (meterNorth - 7954) / 93.5))
; The 45 above is not included in the corrections made in the Ascape version. We suspect this is a conversion specifically for the
; Netlogo map setup.
set xcor int archsettlementX
set ycor int archsettlementY
;; set size nrhouseholds ;; Janssen's version of the original model adjusted the size of archaeological settlements by the number of households
; the size of archaeological settlements will be included in the future.
]
end

;-----

to plot-counts
let ageList []
let harvestList []
let cornList []
set-current-plot "Population"
set-current-plot-pen "simHouseholds"
plot (totHouseholds)
set-current-plot-pen "archHouseholds"
plot (archTotHouseholds)
; set-current-plot-pen "simPersons"
; plot (totPopSize)

ask households
[
  set ageList lput householdAge ageList
  set harvestList lput lastHarvest harvestList
  set cornList lput availableCorn cornList
]
set-current-plot "Household Age"
histogram ageList
set-current-plot "Household Harvest"
histogram harvestList
set-current-plot "Household Available Maize"
histogram cornList
end

;-----

to update-annual-output
plot-counts
write-to-annual-file
end

to write-to-annual-file
file-open "ALHVbaselineJ-PNN-285-HA-1.0-Repetition.csv"
file-type (word behaviorspace-run-number ", ")
file-type (word year ", ")
file-type (word totFertRate ", ")
file-type (word minFertilityAge ", ")
file-type (word maxFertilityAge ", ")
file-type (word minFertilityEndsAge ", ")
file-type (word maxFertilityEndsAge ", ")
file-type (word minDeathAge ", ")
file-type (word maxDeathAge ", ")
file-type (word personBaseNutriNeed ", ")
file-type (word harvestAdjustment ", ")
file-type (word harvestVariance ", ")
file-type (word archTotHouseholds ", ")
file-type (word totHouseholds ", ")
file-print (word totPopSize ", ")
file-close
end

```

```

;; ALHV-AGED_MORT MODEL CODE

patches-own [value watersource? zone apdsi hydro quality maizeZone yield baseYield ofcfarm ocfarm household nrh]
breed [households household ]
breed [archsettlements archsettlement] ; archaeological occupation
breed [waterpoints waterpoint]
breed [persons person]

archsettlements-own [archsettlementX archsettlementY SARG meterNorth meterEast startdate enddate mediandate typeset sizeset description roomcount e

waterpoints-own [waterpointX waterpointY sarg meternorth metereast typewater startdate enddate]

households-own [

householdID ; ID of a household; assigned at the time a household is formed
householdX householdY ; location of the household on the space
householdSize ; the number of persons assigned to a household
householdAge ; self-explanatory, initialized at age 0
householdNutriNeed ; combined nutritional needs of all agents within a household
householdNutriShortfall ; difference between the estimated nutrients available and the household nutrition need
farmX farmY ; location of the household's associated farm on the space
farmplot ; a household's farmplot; assigned after finding the best farm in findFarmAndSettlement methc
lastHarvest ; yield of the most recent harvest
availableCorn ; estimate of the maize that will be available the following year; combines existing stock ar
agedCornStocks ; stores of maize from harvests of the previous two years; each year retains its identity
houseIsNew? ; boolean to indicate whether a house is newly built
deathInHousehold? ; boolean to indicate whether a death has occurred in a household in the current step
]

persons-own [

; GENERAL CHARACTERISTICS
personID ; ID of a person; assigned at initialization or birth
personX personY ; location of a person on the space
natalCommunity ; site at which the person was born; 1 = Long House Valley, 5 = outside male
residence ; site at which the person is living; 1 = Long House Valley
personHouseholdID ; the household to which a person is assigned
clanID ; ID of a person's clan; assigned at initialization or birth, newborns are assigned their mot
sex age ; age and sex, assigned at initialization or birth; values for persons formed at initializati
headOfHousehold? ; boolean that indicates whether a person is head of her household
eldestChild? ; boolean that indicates whether a person is the eldest child (male or female); used to deter
married ; indicates marital status; 0 = never married, 1 = currently married, 2 = unmarried widow or
mateID ; the personID of a person's mate
numChildren ; the number of children born to a person
eventCategory ; designates when an individual experiences a birth (1), dies (2), migrates out (3), or migra
eventCause ; designates the specific cause of a demographic event. Codes begin with the number assigned
; the reflects the specific cause is added. Present causes include: 10 (birth cause is self-e
; 30 (adult male), 31 (reproductive female), 32 (post-reproductive female), 33 (male child),
; 42 (no wife available for a widower), 43 (never-married male unable to marry within the val
; 40 (other cause for migration).

houseNeeded? ; set false when agent is born or initialized, set true when a female begins the process of f
wifeChecked? ; used in find-new-wife to determine whether a re-marrying male has already tried to select a

personNutriNeed ; the nutritional requirements of a person, based on age and sex
personNutriShortfall ; the amount of personal nutritional need that is not being met by the available maize

; DEMOGRAPHIC VARIABLES
fertility ; age-specific probability that a female gives birth in any particular year
fertilityAge ; set at initialization for adults; for younger agents, chosen at initialization or birth
; from range determined by min- and maxFertilityAge
fertilityEndsAge ; chosen females at initialization or hatching (outside males and newborns) from range determ
mortality ; age-specific probability that an agent dies in any particular year

birthAge ; a list that holds the ages at which a person's children are born; the first element is the
; deathAge ; chosen at initialization or hatching (outside males and newborns) from range determined by
]

globals [

;; INTERFACE VARIABLES
; harvestAdjustment ; a variable in the original AA model that reflects actual vs. maximum possible
; harvestVariance ; a variable in the original AA model that reflects spatial variation in yields
; mapview ; a chooser that allows the user to view different types of data on the map
; archaeologyview ; a switch that allows the user to control whether archaeological sites are see
; personBaseNutriNeed ; the amount of food needed per adult; initialized at 160 kg in AA model
; minFertilityAge maxFertilityAge ; boundaries of age range within which a female can reproduce
; minFertilityEndsAge maxFertilityEndsAge ; boundaries of age range for end of female reproductive period
; minDeathAge maxDeathAge ; boundaries of age range during which agents die
; numClans ; number of clans in the population

;; HOUSEHOLD VARIABLES

householdIDindex ; a variable to keep track of numbering for new households
minHouseholdNutriNeed ; the minimum value for a household's nutritional need; required for the determ
; because households need this when they are first made; changed each step to t
householdMinInitialCorn householdMaxInitialCorn ; boundaries of the range of maize stocks available at initialization of a hous
totHouseholds ; simulated number of households
archTotHouseholds ; the number of archaeological households at a given time; based on archaeologi
weddingMaizeGift ; the proportion of the stored maize of the parent household given to a new dau

;; PERSON VARIABLES
personIDindex ; a variable to keep track of numbering for new persons
age-specificFertility ; a list giving age-specific fertility values (15-19, 20-24, 25-29, 30-34, 35-3

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age-specificMortality ; a list giving age-specific mortality values (0-1, 1-4, 5-9, 5-year age classe
;; SUMMARY DEMOGRAPHIC VARIABLES
totPopSize ; total number of persons at any time
ageDistribution ; a list that gives the number of persons in each age class in the population c
starveDistribution ; a list that gives the number of persons in each age class who die by starvati
totStarvations ; total number of persons who starve in a given year

;; FIND FARM AND HOUSEHOLD LOCATION VARIABLES
potfarms ; list of potential farm sites
bestfarm ; the best farm site available
streamsexist? alluviumexist? ; self-explanatory booleans
watersourceDistance ; the maximum distance in number of cells an agent likes to live away from wate
yearsOfStock ; number of years maize can be stored = 2 years

;; MISCELLANEOUS VARIABLES
year ; year of the simulation
environment-data ; empirical data read into the program
apdsi-data ; empirical data read into the program
map-data ; empirical data read into the program
settlements-data ; empirical data read into the program
water-data ; empirical data read into the program
]

;;;;;;;;;;;;;
;;; SETUP AND GO METHODS ;;;
;;;;;;;;;;;;;

to setup ; initialize the parameters and variables of the model and download the datafiles
clear-all
; set-default-shape settlements "tile log" ; Simulation settlements not used in present version
set-default-shape archsettlements "tile stones"
set-default-shape households "house"
set-default-shape persons "person"
load-map-data
set streamsexist? false
set alluviumexist? false
set year 800 ; initial year
ask patches
[
set watersource? false
set quality ((random-normal 0 1) * harvestVariance) + 1.0 ; assigns a measure to a patch that is used below to introduce spatial heterogeneity
if (quality < 0) [set quality 0]
]
set watersourceDistance 16.0 ; maximum distance between a household and water source
; set harvestAdjustment 0.56 ; (slider) 0.56 is Janssen's default value
; set harvestVariance 0.40 ; (slider) 0.40 is the default value in both the Ascape and Janssen versions
; set personBaseNutriNeed 160 ; (slider) an adult needs 160 kg of food (maize) each year; children's need will be determined by their age at initi
; set minFertilityAge 15 ; (slider) minimum age when persons reach maturity and can marry, form new households, and reproduce. Value set to be cor
; set maxFertilityAge 15 ; (slider) maximum age at which reproduction can start; the present settings of min- and maxFertilityAge mean there is no
; set minFertilityEndsAge 48 ; (slider) minimum age at menopause, Coale-Trussell standard does not allow fertility beyond age 50
; set maxFertilityEndsAge 50 ; (slider) maximum age at menopause, Coale-Trussell standard does not allow fertility beyond age 50
; set minDeathAge 51 ; (slider) minimum age at death (= 16 years plus minDeathAge in Janssen)
; set maxDeathAge 57 ; (slider) maximum age at death (= 16 years plus maxDeathAge in Janssen)
set householdIDindex 1 ; needed to assign IDs to new households
set personIDindex 1 ; needed to assign IDs to new person agents
set weddingMaizeGift 0.33 ; proportion of parents' maize given to new household by parent household at marriage of a daughter
set yearsOfStock 2 ; number of years maize can be stored
set minHouseholdNutriNeed 800 ; initialization value of a household's nutrition need; calculated subsequently from the individual nutritional nee
set householdMinInitialCorn 2000 ; lower bound of possible maize stock at initialization of a household
set householdMaxInitialCorn 2400 ; upper bound of possible maize stock at initialization of a household
set age-specificFertility [0.263 0.294 0.276 0.253 0.206 0.107 0.015] ; the values listed here are from the Coale-Trussell standard model with a
; are 15-19, 20-24, 25-29, 30-34, 35-39, 40-44, and 45-49; Coale-Trussell s
; the default values are from Weiss' MT 35.0-65.0 life table; age groups ar
; 15-19, 20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64, 65-
; 10-14, ..., 75-79, 80+
set age-specificMortality [0.1670 0.1050 0.0800 0.0523 0.0897 0.0912 0.0927 0.0942 0.0957 0.0972 0.0988 0.1004 0.1311 0.1824 0.2493 0.3450 0.4746
; the starve distribution vector has the year in the first element, followed by the num
; aged 0-1, 1-4, 5-9, 10-14, ..., 75-79, 80+

; If sensitivity analyses are being run, paired variables that are being studied need to be set at the same values. The appropriate line below for
; set maxFertilityAge minFertilityAge
; set maxFertilityEndsAge minFertilityEndsAge
; set maxDeathAge minDeathAge

ask archsettlements [set hidden? true] ; if true, don't show archaeological sites
water ; calculate water availability for initial time step
calculate-yield
ask patches [set baseYield yield * quality * harvestAdjustment] ; NOTE: "yield" is the natural output of a plot; "baseYield" is the output adjust
; heterogeneity among patches within a productive zone, and harvest adjustment, which reflects crc

determine-potfarms ; makes a list of the possible farm sites given the land quality and space available
set archTotHouseholds 14 ; initialization of the same number of simulation households as there are archaeological households in the data
create-households archTotHouseholds [init-households] ; creates the same number of simulation households as archaeological households, imbues the
; and places them on the landscape in suitable locations
set householdIDindex archTotHouseholds + 1 ; sets the household index so that the first household created after setup will be the next consecuti
init-persons
calculate-age-distribution
ask households [update-householdSize]
set totHouseholds count households
set totPopSize count persons
set totStarvations 0
estimate-harvest
map-settlements

```

```

setup-annualDataFile
; setup-demogDataFile
  setup-popDistributionFile
  setup-starveDistributionFile
write-to-annual-file
write-to-popdist-file
write-to-starvedist-file
reset-ticks
end

;-----
to go ; core procedure of the model, which defines the cycle of activities each year
set archTotHouseholds 0
; set totHouseholds 0
set year year + 1
set starveDistribution [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
set starveDistribution replace-item 0 starveDistribution year
set totStarvations 0
calculate-age-distribution
ask persons [
  set eventCategory 0
  set eventCause 0
]
ask households [
  set houseIsNew? false
  set deathInHousehold? false
]
calculate-yield
if archaeologyview [archaeological-population] ; this statement governs how the archaeological data are shown on the map; whether they are shown
; by a slider on the interface

harvest-consumption
ALHV-death
ask households
[
  if (deathInHousehold? = true)
  [
    type "Household " type householdID print " has experienced a death."
    death-aftermath
  ]
]

map-settlements
ask households
[
  update-householdSize
  update-ALHV-householdNutriNeed
estimate-harvest
set minHouseholdNutriNeed personBaseNutriNeed * 2 ; minHouseholdNutriNeed is assumed to be the need of a household with two adults in it
ask households
[
  if (availableCorn < householdNutriNeed)
  [
    determine-potfarms
    ask patch farmX farmY [set ocfarm 0] ; this statement codes for abandonment of the present farmplot; in the next statement a new plot is soug
    find-farm-and-settlement
  ]
]
ask persons
[
  set age age + 1
  if (sex = 0 and age > 20 and married = 0) ; This statement forces males who are unable to find a first wife by age 21 to leave the valley in se
  [
    set eventCategory 4
    set eventCause 43
; write-to-demog-file
    die
  ]
  if (sex = 0 and married = 2) [type "Error: I am agent " type personID print ". I am a widower who should have died or left the valley."]
  find-age-specific-fertility
  find-age-specific-mortality
  update-ALHV-personNutriNeed
  move-persons-with-household ; the positioning of this method call here ensures that all persons in households that need to move because of inad
; resources do, in fact, move to the new household location. Movement because of demographic events is completed at
; those events. Placing the method call here seems to be more efficient than calling it in find-farm-and-settlement
; method is an observer method, not a person method and so we would have to repeatedly cycle through ALL persons wh
; household changed locations. The placement here moves all agents that have changed households at the same time.
]
determine-potfarms

; the following block sets conditions on marriage and childbirth
ask persons [
  if ((married = 0) and (sex = 1) and (age >= fertilityAge) and (age <= fertilityEndsAge) and (headOfHousehold? = false)) [find-mate]
  if ((sex = 1) and (married = 1) and (age >= fertilityAge) and (age <= fertilityEndsAge) and (random-float 1.0 < fertility)) [produce-babies]
]

ask households
[
  update-householdSize
  update-ALHV-householdNutriNeed
]
set totHouseholds count households
set totPopSize count persons
water ; re-assess the availability of water in each cell of the map
map-settlements
update-annual-output

```



```

if year = 1350 [stop]
tick
end

;-----

to load-map-data
; load spatially explicit data to populate the landscape with a map of different types of land cover
ifelse ( file-exists? "Map.txt" )
[
set map-data []
file-open "Map.txt"
while [ not file-at-end? ]
[
set map-data sentence map-data (list (list file-read))
]
file-close
]
[ user-message "There is no Map.txt file in current directory!" ]

clear-patches
clear-turtles
let yy 119
let xx 0

; The numbers after each "? =" below are values given to each patch during the process of converting actual map data to a rasterized form that ca
; into the model. This will likely be changed once we incorporate the available Netlogo GIS extension.

foreach map-data [ [?] ->
ask patch xx yy [set value first ?1]
if first ?1 = 0 [ask patch xx yy [set pcolor black set zone "General" set maizeZone "Yield_2"]] ; General Valley
if first ?1 = 10 [ask patch xx yy [set pcolor red set zone "North" set maizeZone "Yield_1"]] ; North Valley
if first ?1 = 15 [ask patch xx yy [set pcolor white set zone "North Dunes" set maizeZone "Sand_dune"]] ; North Valley ; Dunes
if first ?1 = 20 [ask patch xx yy [set pcolor gray set zone "Mid" ifelse (xx <= 74) [set maizeZone "Yield_1"][set maizeZone "Yield_2"]]] ; Mid Va
if first ?1 = 25 [ask patch xx yy [set pcolor white set zone "Mid Dunes" set maizeZone "Sand_dune"]] ; Mid Valley ; Dunes
if first ?1 = 30 [ask patch xx yy [set pcolor yellow set zone "Natural" set maizeZone "No_Yield"]] ; Natural
if first ?1 = 40 [ask patch xx yy [set pcolor blue set zone "Uplands" set maizeZone "Yield_3"]] ; Uplands Arable
if first ?1 = 50 [ask patch xx yy [set pcolor pink set zone "Kinbiko" set maizeZone "Yield_1"]] ; Kinbiko Canyon
if first ?1 = 60 [ask patch xx yy [set pcolor white set zone "Empty" set maizeZone "Empty"]] ; Empty
ifelse yy > 0 [set yy yy - 1][set xx xx + 1 set yy 119] ]

; SARG (Southwestern Archaeological Research Group) number, meters north, meters east, start date, end date, median date (1950 - x), type, size,
ifelse ( file-exists? "settlements.txt" )
[
set settlements-data []
file-open "settlements.txt"
while [ not file-at-end? ]
[
set settlements-data sentence settlements-data (list (list file-read file-read file-read file-read file-read file-read file-read file-read fi
)
file-close
]
[ user-message "There is no settlements.txt file in current directory!" ]

foreach settlements-data [ [?] ->
create-archsettlements 1 [
set SARG first ?1
set meterNorth item 1 ?1
set meterEast item 2 ?1
set startdate item 3 ?1
set enddate item 4 ?1
set mediandate (1950 - item 5 ?1)
set typeset item 6 ?1
set sizeset item 7 ?1
set description item 8 ?1
set roomcount item 9 ?1
set elevation item 10 ?1
set baselinehouseholds last ?1 ] ]

; number, meters north, meters east, type, start date, end date
ifelse ( file-exists? "water.txt" )
[
set water-data []
file-open "water.txt"
while [ not file-at-end? ]
[
set water-data sentence water-data (list (list file-read file-read file-read file-read file-read file-read))
]
file-close
]
[ user-message "There is no water.txt file in current directory!" ]

foreach water-data [ [?] ->
create-waterpoints 1 [
set sarg first ?1
set meterNorth item 1 ?1
set meterEast item 2 ?1
set typewater item 3 ?1
set startdate item 4 ?1
set enddate item 5 ?1 ] ]

; This block of code converts the input coordinates for each waterpoint to the simulation map coordinates so that they will appear on the map in
ask waterpoints [
set xcor 24.5 + int ((meterEast - 2392) / 93.5)
set ycor 45 + int (37.6 + ((meterNorth - 7954) / 93.5))
set hidden? true

```

```

]
elseif ( file-exists? "adjustedPDSI.txt" )
[
  set apdsi-data []
  file-open "adjustedPDSI.txt"
  while [ not file-at-end? ]
  [
    set apdsi-data sentence apdsi-data (list file-read)
  ]
  file-close
]
[ user-message "There is no adjustedPDSI.txt file in current directory!" ]

; The 15 file-read statements below refer to the structure of the data, which consists of three values for each of the five environment zones for
; Only the hydrology data (the second of the three values per environment zone) are used in the program.
elseif (file-exists? "environment.txt")
[
  set environment-data []
  file-open "environment.txt"
  while [not file-at-end?]
  [
    set environment-data sentence environment-data (list (list file-read file-read file-read file-read file-read file-read file-read file-read fil
      file-read file-read file-read file-read file-read))
  ]
  file-close
]
[ user-message "There is no environment.txt file in current directory!" ]

ask patches [set ocfarm 0 set ochothousehold 0] ; all patches are initialized as vacant (i.e., with no farms or households on them)
end

;-----
to calculate-yield
; calculate the yield (unadjusted) and whether water is available for each patch based on the adjusted PDSI and the presence of a suitable water
; table level (indicated by the hydrologic data).

; The following 6 lines indicate where in the apdsi-data file to find the specific values for each environment for a particular year.
; In the apdsi-data file, all values are placed linearly in a single line. The apdsi values for north and kinbiko are identical to each other, as
; are the values for natural and upland. This is consistent with what is published in the article in the Kohler and Gumerman volume (Dean et al.
let generalapdsi item (year - 200) apdsi-data
let northapdsi item (1100 + year) apdsi-data
let midapdsi item (2400 + year) apdsi-data
let naturalapdsi item (3700 + year) apdsi-data
let uplandapdsi item (3700 + year) apdsi-data
let kinbikoapdsi item (1100 + year) apdsi-data

; The following 6 lines indicate the location of the hydrology data for each environment in a given year. Note: item 1 is actually the second ite
; in a row of the environment data. Natural and upland have identical hydrology values, although at specific times the values are overridden in t
; program to reflect the rare times when the two differ.
let generalhydro item 1 (item (year - 382) environment-data)
let northhydro item 4 (item (year - 382) environment-data)
let midhydro item 7 (item (year - 382) environment-data)
let naturalhydro item 10 (item (year - 382) environment-data)
let uplandhydro item 10 (item (year - 382) environment-data)
let kinbikohydro item 13 (item (year - 382) environment-data)

; See Dean et al. (2000) in the Kohler and Gumerman volume for explanation of zone identification and yield calculation.
ask patches [
  if zone = "General" [set apdsi generalapdsi]
  if zone = "North" [set apdsi northapdsi]
  if zone = "Mid" [set apdsi midapdsi]
  if zone = "Natural" [set apdsi naturalapdsi]
  if zone = "Upland" [set apdsi uplandapdsi]
  if zone = "Kinbiko" [set apdsi kinbikoapdsi]

  if zone = "General" [set hydro generalhydro]
  if zone = "North" [set hydro northhydro]
  if zone = "Mid" [set hydro midhydro]
  if zone = "Natural" [set hydro naturalhydro]
  if zone = "Upland" [set hydro uplandhydro]
  if zone = "Kinbiko" [set hydro kinbikohydro]

  if (maizeZone = "No_Yield" or maizeZone = "Empty") [set yield 0]
  if (maizeZone = "Yield_1") [
    if (apdsi >= 3.0) [set yield 1153]
    if (apdsi >= 1.0 and apdsi < 3.0) [set yield 988]
    if (apdsi > -1.0 and apdsi < 1.0) [set yield 821]
    if (apdsi > -3.0 and apdsi <= -1.0) [set yield 719]
    if (apdsi <= -3.0) [set yield 617]]

  if (maizeZone = "Yield_2") [
    if (apdsi >= 3.0) [set yield 961]
    if (apdsi >= 1.0 and apdsi < 3.0) [set yield 824]
    if (apdsi > -1.0 and apdsi < 1.0) [set yield 684]
    if (apdsi > -3.0 and apdsi <= -1.0) [set yield 599]
    if (apdsi <= -3.0) [set yield 514]]

  if (maizeZone = "Yield_3") [
    if (apdsi >= 3.0) [set yield 769]
    if (apdsi >= 1.0 and apdsi < 3.0) [set yield 659]
    if (apdsi > -1.0 and apdsi < 1.0) [set yield 547]
    if (apdsi > -3.0 and apdsi <= -1.0) [set yield 479]
    if (apdsi <= -3.0) [set yield 411]]

```

```

if (maizeZone = "Sand_dune") [
  if (apdsi >= 3.0) [set yield 1201]
  if (apdsi >= 1.0 and apdsi < 3.0) [set yield 1030]
  if (apdsi > -1.0 and apdsi < 1.0) [set yield 855]
  if (apdsi > -3.0 and apdsi <= -1.0) [set yield 749]
  if (apdsi <= -3.0) [set yield 642]]

if mapview = "yield" [set pcolor (40 + baseYield / 140)]
]
end

;-----

to init-households
; this method is for initialization of the founding households only; new households are initialized in the build-house method. Besides creating th
; initial households, this method calls a different method (find-farm-and-settlement) to actually assign a spot for each household's farming plot

set size 3
set color brown
set householdID householdIDindex
let initPotfarms patches with [maizeZone = "Sand_dune" and ocfarm = 0]
let farmLoc one-of initPotfarms
set farmX [pxcor] of farmLoc set farmY [pycor] of farmLoc
set householdX random 80 set householdY random 120
set bestfarm self
set agedCornStocks []
set agedCornStocks fput (householdMinInitialCorn + random-float (householdMaxInitialCorn - householdMinInitialCorn)) agedCornStocks
set agedCornStocks fput (householdMinInitialCorn + random-float (householdMaxInitialCorn - householdMinInitialCorn)) agedCornStocks
set agedCornStocks fput (householdMinInitialCorn + random-float (householdMaxInitialCorn - householdMinInitialCorn)) agedCornStocks
set farmplot self
set householdAge 0
set householdNutriNeed 0
set householdSize 0
set houseIsNew? false
set deathInHousehold? false
set lastHarvest 0
determine-potfarms
find-farm-and-settlement

set xcor householdX
set ycor householdY
set householdIDindex householdIDindex + 1
end

;-----

to init-persons ; this method is for initialization of the founding population only; new births are initialized in the produce-babies method. Sever
; of census-based populations are available for input into the model. Each CensusPop file contains different founding populations a
; founding populations form the bases for different files to allow incorporation of different clan structures. The number of found
; each file is indicated by the designation "?c" at the end of the file, where ? refers to the actual clan number. NOTE: the number
; present is a file that is being used by the model must be set on the slider on the interface.
ifelse ( file-exists? "CensusPop5-7c.txt" )
[
file-open "CensusPop5-7c.txt"
; The following code reads in all the data in the file. Each line of data contains the values for 13 attributes per agent in the order listed b
while [not file-at-end?]
[
let items read-from-string (word "[" file-read-line "]")
; items is a temporary list of variables read in as string but converted to the appropriate variable type. "Word" concatenates
; the brackets to the line being read in, because list arguments need to be in brackets (see Netlogo user manual).
create-persons 1 [
set personIDindex personIDindex + 1
set size 2
set color green
set personID item 0 items
set natalCommunity item 1 items
set residence item 2 items
set personHouseholdID item 3 items
set clanID item 4 items
set sex item 5 items
set age item 6 items
set headOfHousehold? item 7 items
set eldestChild? item 8 items
set married item 9 items
set fertilityAge item 10 items
set mateID item 11 items
set numChildren item 12 items

ask persons [
ifelse any? households with [householdID = [personHouseholdID] of myself]
[move-persons-with-household]
[
print "An agent was created (i.e., characteristics were read in from the input file), but the corresponding household does not exist.
die
]
]

ifelse headOfHousehold? = 0 [set headOfHousehold? false][set headOfHousehold? true]
ifelse eldestChild? = 0 [set eldestChild? false][set eldestChild? true]
set houseNeeded? false
set deathAge minDeathAge + random (maxDeathAge - minDeathAge)
if fertilityAge = 0 [set fertilityAge minFertilityAge + random (maxFertilityAge - minFertilityAge)]

ifelse sex = 1

```

```

[set fertilityEndsAge minFertilityEndsAge + random (maxFertilityEndsAge - minFertilityEndsAge)]
[set fertilityEndsAge 80] ; All males are given a fertilityEndsAge of 80, which in this version of the model is the maximum age.
; Females are determining all fertility anyway, so the specific value is not important.

set birthAge [] ; birthAge is a list of the ages at which a person has a child; it is initialized here with only the person's ID and sex.
set birthAge lput personID birthAge ; children for the initial population because we would have to calculate all that information and
set birthAge lput sex birthAge
set eventCategory 0
set eventCause 0
find-age-specific-fertility
find-age-specific-mortality
update-ALHV-personNutriNeed
set personNutriShortfall 0

; The following block of code calculates the household's nutrition need by adding up the personal need of each assigned agent,
; it calculates the size of the household, and determines its age from the age of the eldest child.
ask households with [householdID = [personHouseholdID] of myself]
[
  set householdNutriNeed householdNutriNeed + [personNutriNeed] of myself
  if [eldestChild?] of myself = true [set householdAge [age] of myself + 1]
  ; The household age is assumed to be the age of the eldest child + 1 because of the length of gestation time (i.e., the
  ; eldest child was most likely born more than a year after the formation of the household)
]
]
]
file-close
]
[ user-message "The person file called is not in the current directory!" ]
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;; DEMOGRAPHIC METHODS ;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to calculate-age-distribution
set ageDistribution [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
set ageDistribution replace-item 0 ageDistribution year
set ageDistribution replace-item 1 ageDistribution count persons with [age >= 0 and age < 1]
set ageDistribution replace-item 2 ageDistribution count persons with [age >= 1 and age < 5]
set ageDistribution replace-item 3 ageDistribution count persons with [age >= 5 and age < 10]
set ageDistribution replace-item 4 ageDistribution count persons with [age >= 10 and age < 15]
set ageDistribution replace-item 5 ageDistribution count persons with [age >= 15 and age < 20]
set ageDistribution replace-item 6 ageDistribution count persons with [age >= 20 and age < 25]
set ageDistribution replace-item 7 ageDistribution count persons with [age >= 25 and age < 30]
set ageDistribution replace-item 8 ageDistribution count persons with [age >= 30 and age < 35]
set ageDistribution replace-item 9 ageDistribution count persons with [age >= 35 and age < 40]
set ageDistribution replace-item 10 ageDistribution count persons with [age >= 40 and age < 45]
set ageDistribution replace-item 11 ageDistribution count persons with [age >= 45 and age < 50]
set ageDistribution replace-item 12 ageDistribution count persons with [age >= 50 and age < 55]
set ageDistribution replace-item 13 ageDistribution count persons with [age >= 55 and age < 60]
set ageDistribution replace-item 14 ageDistribution count persons with [age >= 60 and age < 65]
set ageDistribution replace-item 15 ageDistribution count persons with [age >= 65 and age < 70]
set ageDistribution replace-item 16 ageDistribution count persons with [age >= 70 and age < 75]
set ageDistribution replace-item 17 ageDistribution count persons with [age >= 75 and age < 80]
set ageDistribution replace-item 18 ageDistribution count persons with [age >= 80]
end

to-report find-starve-list-item
let itemno 99
if (age >= 0 and age < 1) [set itemno 1]
if (age >= 1 and age < 5) [set itemno 2]
if (age >= 5 and age < 10) [set itemno 3]
if (age >= 10 and age < 15) [set itemno 4]
if (age >= 15 and age < 20) [set itemno 5]
if (age >= 20 and age < 25) [set itemno 6]
if (age >= 25 and age < 30) [set itemno 7]
if (age >= 30 and age < 35) [set itemno 8]
if (age >= 35 and age < 40) [set itemno 9]
if (age >= 40 and age < 45) [set itemno 10]
if (age >= 45 and age < 50) [set itemno 11]
if (age >= 50 and age < 55) [set itemno 12]
if (age >= 55 and age < 60) [set itemno 13]
if (age >= 60 and age < 65) [set itemno 14]
if (age >= 65 and age < 70) [set itemno 15]
if (age >= 70 and age < 75) [set itemno 16]
if (age >= 75 and age < 80) [set itemno 17]
if (age >= 80 ) [set itemno 18]
report itemno
end

to find-mate
; This method determines who the mate of an eligible unmarried woman will be. In order to marry she must be able to build a new house. In the blc
; calls the build-house method, if she successfully builds a house, she sets several person variables, including mateID, which is the personID of
; has chosen. She then asks that person to set his mateID to her personID, his householdID to her householdID, and his married status to 1 ("curr
; also removed from their previous households and move into their newly assigned household.

set houseNeeded? true
let potential-mates persons with [(sex = 0) and (age >= minFertilityAge) and ((age >= [age] of myself - 10) and (age <= [age] of myself + 20))
and (headOfHousehold? = false) and ((married = 0) or (married = 2)) and (clanID != [clanID] of myself) and (personHouseholdID != [personHouseh

; This method first looks for a mate from within the community. If a suitable mate cannot be found, the marry-outsider method is called.
ifelse any? potential-mates
[

```

```

build-house ; A female looking for a mate has to have a house available in order to marry. If a house can be built, the variable houseNeeded? is
; false in build-house. If she cannot build a house (e.g., if there is no space available and houseNeeded? is still true, she remain
; and will look for a husband in the next time tick.
ifelse houseNeeded? = false
[
set married 1
set headOfHousehold? true

let possible-mate one-of potential-mates
set mateID [personID] of possible-mate
ask possible-mate
[
set mateID [personID] of myself
set personHouseholdID [personHouseholdID] of myself
set married 1
]
ask persons with [personHouseholdID = [personHouseholdID] of myself]
[
move-persons-with-household
]
]
[set houseNeeded? false] ; This is the else part of ifelse houseNeeded?. houseNeeded? is set to false because in this situation a female cannot
; stays in her existing house (and so does not need a new house).
]
[
print "No mates are available. I am going to marry an outsider."
marry-outsider ; This is the else part of ifelse any? potential-mates
]
end

;-----

to marry-outsider
; This method creates a potential mate for a woman when no others are available in the community. It is done to guarantee
; that a woman who comes of age or who loses her husband by death can make a new household. This is needed to keep this model
; equivalent to the original model, which had no constraints on fissioning other than finding suitable farm land.
; Eventually this method may involve finding a mate from another community rather than just creating one (when more than one
; community is incorporated into the model).

hatch-persons 1 [
set personID personIDindex
set personHouseholdID [personHouseholdID] of myself ; This is a fail-safe to make sure that the calling agent does, in fact, marry
; the agent being created. That agent should already have the same personHouseholdID,
; however, since it is a clone of the calling agent.

set natalCommunity 5 ; 5 is an arbitrary ID to designate an unspecified outside community

;The following four statements ensure that the designated spouse does not come from the same clan
let tempClan random numClans
while [(tempClan = 0) or (tempClan = [clanID] of myself)]
[set tempClan random numClans]
set clanID tempClan

set sex 0
ifelse [age] of myself < 21
[set age 16 + random 6]
[set age [age] of myself + (-5 + random 11)]
set color blue
set size 2
set headOfHousehold? false
set married 0 ; the actual act of marriage occurs further below in this method
set mateID 0
set numChildren 0 ; Since we are creating these males, we assume they have no children; in later versions outside males will have their own

;
set deathAge minDeathAge + random (maxDeathAge - minDeathAge)
set fertilityAge age
set fertilityEndsAge 80 ; All males are given a fertilityEndsAge of 80, which in this version of the model is the maximum age.
; Females are determining all fertility anyway, so the specific value is not important.

set birthAge [] ; birthAge is a list of the ages at which a person has a child; it is initialized here with only the person's ID and sex.
set birthAge lput personID birthAge
set birthAge lput sex birthAge
find-age-specific-fertility
find-age-specific-mortality
set personNutriNeed personBaseNutriNeed
set personNutriShortfall 0
]
set personIDindex personIDindex + 1 ; this increments the personIDindex so that the next newly created agent has a unique ID number

; Because of the way outside-mates are created, their personHouseholdID must be the same as the calling agent and their natal community must be c
; All other constraints here are the same as those for potential mates in the find-mate method.
let outside-mates persons with [(sex = 0) and (age >= fertilityAge) and ((age >= [age] of myself - 10) and (age <= [age] of myself + 20))
and (headOfHousehold? = false) and ((married = 0) or (married = 2)) and (clanID != [clanID] of myself) and (personHouseholdID = [personHousehold
and (natalCommunity != [natalCommunity] of myself)]

; The following process is the same as that for the find-mate method.
ifelse any? outside-mates
[
build-house
ifelse houseNeeded? = false
[
set married 1
set headOfHousehold? true
let new-mate one-of outside-mates
set mateID [personID] of new-mate
ask new-mate

```

```

[
  set mateID [personID] of myself
  set personHouseholdID [personHouseholdID] of myself
  set married 1
  set eventCategory 3
  set eventCause 30 ; mate is a migrant whose new wife is marrying for the first time
; write-to-demog-file
]
ask persons with [personHouseholdID = [personHouseholdID] of myself]
[
  move-persons-with-household
]
]
[set houseNeeded? false]
]
[print "I made a new man. I should have a husband, but something went wrong! Please help!"]
end

;-----

to remarry ; this method is called in the death aftermath method after a person (male or female) has been widowed
if sex = 0
[
  if any? other persons with [personHouseholdID = [personHouseholdID] of myself][reassign-to-clan] ; family members of a widower move in with
  find-next-wife ; members of their own clan,rather than s
]
]
if sex = 1
[
  ifelse age > fertilityEndsAge ; only widows within the reproductive span are allowed to remarry
  [
    type "Agent " type personID type " is a widow above FEA. Her household ID is " type personHouseholdID print ". She is calling this in the rem
  ]
  [
    find-next-husband
  ]
]
]
end

;-----

to find-next-husband ; this method allows a newly widowed woman of reproductive age to find a suitable husband. If one is not available in the vall
; following the same constraints as in the find-mate and marry-outsider methods, except that at this time she already has a hc
; build one) and her new husband moves in with her.
let potential-husbands persons with [(sex = 0) and (age >= minFertilityAge) and (age >= [age] of myself - 10)
and (headOfHousehold? = false) and ((married = 0) or (married = 2)) and (clanID != [clanID] of myself) and (personHouseholdID != [personHouseh

; This method first looks for a mate from within the community. If a suitable mate cannot be found, an outsider is brought in.
ifelse any? potential-husbands
[
  set married 1

  let possible-husband one-of potential-husbands
  set mateID [personID] of possible-husband
  ask possible-husband
  [
    set mateID [personID] of myself
    set personHouseholdID [personHouseholdID] of myself
    set married 1
    move-persons-with-household
  ]
]
]
[
  hatch-persons 1 [
; print "A husband is being found in another community!"
    set personID personIDindex
    set personHouseholdID [personHouseholdID] of myself ; This is a fail-safe to make sure that the calling agent does, in fact, marry
    ; the agent being created. That agent should already have the same personHouseholdID,
    ; however, since it is a clone of the calling agent.

    set natalCommunity 5 ; 5 is an arbitrary ID to designate an unspecified outside community

    ;The following four statements ensure that the designated spouse does not come from the same clan
    let tempClan random numClans
    while [(tempClan = 0) or (tempClan = [clanID] of myself)]
      [set tempClan random numClans]
    set clanID tempClan

    set sex 0
    ifelse [age] of myself < 21
    [set age 16 + random 6]
    [set age [age] of myself + (-5 + random 11)]
    set color blue
    set size 2
    set headOfHousehold? false
    set married 0 ; the actual act of marriage occurs further below in this method
    set mateID 0
    set numChildren 0 ; Since we are creating these males, we assume they have no children; in later versions outside males will have their own

; set deathAge minDeathAge + random (maxDeathAge - minDeathAge)
    set fertilityAge age

    ifelse sex = 1
    [set fertilityEndsAge minFertilityEndsAge + random (maxFertilityEndsAge - minFertilityEndsAge)]
    [set fertilityEndsAge 80] ; All males are given a fertilityEndsAge of 80, which in this version of the model is the maximum age.
    ; Females are determining all fertility anyway, so the specific value is not important.

```

```

    set birthAge [] ; birthAge is a list of the ages at which a person has a child; it is initialized here with only the person's ID and sex.
    set birthAge lput personID birthAge
    set birthAge lput sex birthAge
    find-age-specific-fertility
    find-age-specific-mortality
    set personNutriNeed personBaseNutriNeed
    set personNutriShortfall 0
  ]
set personIDindex personIDindex + 1 ; this increments the personIDindex so that the next newly created agent has a unique ID number
; Because of the way outside-husbands are created, their personHouseholdID must be the same as the calling agent and their natal community must be
; All other constraints here are the same as those for potential mates in the find-mate method.
let outside-husbands persons with [(sex = 0) and (age >= fertilityAge) and (age >= [age] of myself - 10)
and (headOfHousehold? = false) and ((married = 0) or (married = 2)) and (clanID != [clanID] of myself) and (personHouseholdID = [personHousehol
and (natalCommunity != [natalCommunity] of myself)]
; The following process is the same as that for a potential husband from within the community.
ifelse any? outside-husbands
[
  set married 1
  let new-husband one-of outside-husbands
  set mateID [personID] of new-husband
  ask new-husband
  [
    set mateID [personID] of myself
    set married 1
    set eventCategory 3
    set eventCause 30 ; mate is a migrant whose new wife has been widowed
; write-to-demog-file
move-persons-with-household
  ]
]
; This is the else-part of if any? outside husbands. At present, there will always be an outside husband because we are making them, but in fut
; versions of the model we will need to put our code for what happens if a female cannot find any suitable mate here.
]
; find outside male
ask households with [householdID = [personHouseholdID] of myself]
[
  update-householdSize
  update-ALHV-householdNutriNeed
]
end
]
;-----
to find-next-wife ; this method allows a newly widowed man to find a suitable wife. This is the only situation in the simulation where males are al
; from within the valley can either already be heads of households or they can be never married, in which case they must first be
; in the find-mate method). If the widower finds a suitable mate, he moves into her household by himself (any other household men
; wife's death are reassigned prior to this in the death aftermath method). If he cannot find a suitable mate, he dies/leaves the

let potential-wives persons with [(sex = 1) and (age >= minFertilityAge) and ((married = 0) or (married = 2)) and (clanID != [clanID] of myself
and (personHouseholdID != [personHouseholdID] of myself)]
let newWifeFound? false
let possibleWife nobody
let countWives 0
ask potential-wives [set wifeChecked? false]

ifelse any? potential-wives
[
  set countWives count potential-wives
  while [countWives > 0 and not newWifeFound?]
  [
    set possibleWife one-of potential-wives with [wifeChecked? = false]
    ask possibleWife
    [
      set wifeChecked? true
      ifelse headOfHousehold?
      [ask myself [set newWifeFound? true]]
      [
        set houseNeeded? true
        build-house
        if houseNeeded? = false [ask myself [set newWifeFound? true]]
      ]
    ]
    set countWives countWives - 1
  ]
]

ifelse newWifeFound?
[
  set mateID [personID] of possibleWife
  set married 1
  set personHouseholdID [personHouseholdID] of possibleWife
  ask possibleWife
  [
    set mateID [personID] of myself
    set married 1
    set headOfHousehold? true
  ]
  ask persons with [personHouseholdID = [personHouseholdID] of myself]
  [
    move-persons-with-household
  ]
]
[
  set eventCategory 4
  set eventCause 41

```

```

; write-to-demog-file
die
] ; this is the death/migration of a man who could not find a wife even though women were available (because the potential wives could not be
]
[
set eventCategory 4
set eventCause 42
; write-to-demog-file
die
] ; this is the death/migration of a man who could not find any available women
end
;-----
to reassign-to-clan ; this method is used to reassign survivors to another household within their own clan. Three classes of survivors can be reass
; household where the head of household (female) dies; the husband tries to remarry, b) a widow above reproductive age and all
; who have been orphaned.
let reassigned-group no-turtles ; the following statements allow us to omit a surviving husband from the group to be reassigned -- he tries to re
ifelse (sex = 0) and (married = 2)
[set reassigned-group other persons with [personHouseholdID = [personHouseholdID] of myself]]
[set reassigned-group persons with [personHouseholdID = [personHouseholdID] of myself]]

let clan-checker one-of reassigned-group ; any agent in the reassigned group can direct the choice of which new household to move to
ask reassigned-group
[
if clanID != [clanID] of clan-checker
[
print "Error: Multiple clans are represented in this reassigned group. Check methods!"
]
]
let possible-newHeadHouse persons with [(personHouseholdID != [personHouseholdID] of clan-checker) and (clanID = [clanID] of clan-checker) and he
ifelse any? possible-newHeadHouse
[
let newHeadHouse one-of possible-newHeadHouse ; a random household that has a head of household in the same clan as the survivors is chosen
ask reassigned-group
[
set personHouseholdID [personHouseholdID] of newHeadHouse
move-persons-with-household
]
ask households with [householdID = [personHouseholdID] of newHeadHouse]
[
update-householdSize
update-ALHV-householdNutriNeed
]
]
[
ask reassigned-group
[
set eventCategory 4
set eventCause 44 ; clan household not available
; write-to-demog-file
die
]
]
]
end
;-----
to build-house
; This method is our ALHV fission method. It is called when a women tries to marry and creates a new household, fills the
; maize stocks with a gift from the parent household, and finds a spot for the household's farming plot and settlement.

ask households with [householdID = [personHouseholdID] of myself]
[
hatch 1
[
set size 3
set color red
set householdID householdIDindex
set householdAge 0
set householdNutriNeed personBaseNutriNeed * 2 ; this initializes the householdNutriNeed; the actual value will be calculated as persons move
set householdSize 0
set lastHarvest 0
set houseIsNew? true
set deathInHousehold? false
]
]
ask households with [householdID = householdIDindex]
[
determine-potfarms ; this needs to be called to ensure the potfarms list is up-to-date whenever a new house is built
find-farm-and-settlement
]

; If the house that is created above cannot find a suitable farming plot and settlement in the find-farm-and-settlement method, it dies and there
; will be no household with the householdID designated above in the hatch block. If that is the case, nothing further happens, which means that
; the calling agent continues to be part of her original household (i.e., her personHouseholdID is only changed in the block below where a new hous
; is designated, and that household is given the maize gift from the parents before her personHouseholdID is changed so that the parent household c
; still be identified).
let newHouse households with [householdID = householdIDindex]
ifelse any? newHouse
[
give-maize-gift (newHouse)
set houseNeeded? false
set personHouseholdID householdIDindex
set householdIDindex householdIDindex + 1
]
[

```



```

; No suitable location was found for new house. Do nothing.
]
end

;-----

to give-maize-gift [newHousehold]
; This method takes a user-designated proportion of the corn stocks from a parent household and give it to the daughter's newly created household

ask households with [householdID = [personHouseholdID] of myself]
[
let ysParent yearsOfStock
while [ysParent > -1]
[
set agedCornStocks replace-item ysParent agedCornStocks ((1 - weddingMaizeGift) * (item ysParent agedCornStocks))
set ysParent ysParent - 1
]
]
ask newHousehold
[
let ysNew yearsOfStock
while [ysNew > -1]
[
set agedCornStocks replace-item ysNew agedCornStocks ((weddingMaizeGift / (1 - weddingMaizeGift)) * (item ysNew agedCornStocks))
set ysNew ysNew - 1
]
]
end

;-----

to produce-babies
hatch-persons 1 [
set personID personIDindex
set age 0
let sex-prob random-float 1.0
ifelse sex-prob < 0.5
[set sex 0]
[set sex 1]
set headOfHousehold? false
set married 0
set mateID 0
set numChildren 0
ifelse ([numChildren] of myself = 0) [set eldestChild? true][set eldestChild? false]

; set deathAge minDeathAge + random (maxDeathAge - minDeathAge)
set fertilityAge minFertilityAge + random (maxFertilityAge - minFertilityAge)

ifelse sex = 1
[set fertilityEndsAge minFertilityEndsAge + random (maxFertilityEndsAge - minFertilityEndsAge)]
[set fertilityEndsAge 80] ; All males are given a fertilityEndsAge of 80, which in this version of the model is the maximum age.
; Females are determining all fertility anyway, so the specific value is not important.

set birthAge [] ; birthAge is a list of the ages at which a person has a child; it is initialized here with only the person's ID and sex.
set birthAge lput personID birthAge
set birthAge lput sex birthAge
find-age-specific-fertility
find-age-specific-mortality
update-ALHV-personNutriNeed
set personNutriShortfall 0
ask households with [householdID = [personHouseholdID] of myself]
[
set householdNutriNeed householdNutriNeed + [personNutriNeed] of myself
]
]
set numChildren numChildren + 1
set birthAge lput age birthAge ; this adds the age of the mother at the birth of this child to her birth age list
set eventCategory 1
set eventCause 10
; write-to-demog-file
ask persons with [personID = [mateID] of myself]
[
set numChildren numChildren + 1
set birthAge lput age birthAge ; this adds the age of the father at the birth of this child to his birth age list
set eventCategory 1
set eventCause 10
; write-to-demog-file
]

set personIDindex personIDindex + 1 ; this increments the personIDindex so that the next newly created agent has a unique ID number
end

;-----

to find-age-specific-fertility ; the specific values indicated in the comments below are from the original ALHV disaggregate model
ifelse ((age >= 0 and age < fertilityAge) or age >= fertilityEndsAge) [set fertility 0.00] ; 0.000
[
ifelse sex = 1
[
if (age >= fertilityAge and age < 20) [set fertility item 0 age-specificFertility] ; 0.094
if (age >= 20 and age < 25) [set fertility item 1 age-specificFertility] ; 0.256
if (age >= 25 and age < 30) [set fertility item 2 age-specificFertility] ; 0.256
if (age >= 30 and age < 35) [set fertility item 3 age-specificFertility] ; 0.208
]
]
]

```



```

        set mateID 0
    ]
}
ask youngest
[
    type "Agent " type personID type " is about to die from starvation. Age: " type age type " Sex: " type sex type " householdID: " print
    ask households with [householdID = [personHouseholdID] of myself] [set deathInHousehold? true]
    set eventCategory 2
    set eventCause 21
    let starveClass find-starve-list-item
    let newStarveCount item starveClass starveDistribution + 1
    set starveDistribution replace-item starveClass starveDistribution newStarveCount
    set totStarvations totStarvations + 1
;
    write-to-demog-file
    die
]
update-householdSize
update-ALHV-householdNutriNeed
]
]
update-householdSize
update-ALHV-householdNutriNeed
]
end
end

```

to age-specific-dying

; At the present time this method only considers death by old age, which is assumed to occur within the same user-defined age range for all agents, they don't die before reaching their designated death age. If an agent dying of old age is married, the method also changes the marital state of

```

ask persons
[
    let deathHouseholdID personHouseholdID
    if random-float 1.0 < mortality
    [
        if married = 1
        [
            ask persons with [mateID = [personID] of myself]
            [
                type "Agent " type personID type ": My spouse is about to die. My age is " type age type ". Sex: " type sex type " householdID: " pri
                ifelse (sex = 1 and age > fertilityEndsAge) ; females above reproductive age are assigned a marital status of 3 to prevent remarriage,
                [
                    set headOfHousehold? false
                    set married 3
                ]
                [set married 2]
                set mateID 0
            ]
        ]
        ask households with [householdID = [personHouseholdID] of myself]
        [
            set householdNutriShortfall householdNutriShortfall - [personNutriNeed] of myself
            set deathInHousehold? true
        ]
;
        type "Agent " type personID type " is about to die. Age: " type age type " Sex: " type sex type " householdID: " print personHouseholdID
        set eventCategory 2
        set eventCause 20 ; at the present time, cause 10 is any death other than by starvation
;
        write-to-demog-file
        die
        ask households with [householdID = deathHouseholdID]
        [
            update-householdSize
            update-ALHV-householdNutriNeed
        ]
    ]
]
end
end

```

to death-aftermath ; This method deals with any issues that arise as a consequence of someone dying, including relocation of survivors (e.g., chil
; whenever both parents have died), removal of households if the last person dies or moves to a new house as a consequence of s
; If one member of a married couple dies, the method initiates specific widow or widower behavior methods; if both spouses die,
; survivors to a new household is called. Households and the individuals within them can also die when a household is not able
; new location if forced to move; this process is modeled within the findFarmAndSettlement method.

```

update-householdSize
ifelse householdSize > 1
[
    let widowed persons with [(personHouseholdID = [householdID] of myself) and (married = 2)] ; widows above reproductive age are not allowed to
; marital status (3) and are excluded from this wid
    if any? widowed
    [
        ask widowed [remarry]
    ]
    if not any? persons with [(personHouseholdID = [householdID] of myself) and (married = 1)] ; this ensures that the composition of households
; altered except for the removal of the dying age
; then household reassignment of survivors must e
    [
        if any? persons with [personHouseholdID = [householdID] of myself]
        [
            ask one-of persons with [personHouseholdID = [householdID] of myself] [reassign-to-clan] ; this situation involves orphans and post-ferti

```

```

]
update-householdSize
update-ALHV-householdNutriNeed
]
[
update-householdSize
if householdSize = 1
[
let last-resident persons with [personHouseholdID = [householdID] of myself]
ask last-resident
[
if (married = 0 or married = 3) [reassign-to-clan]
if (married = 2) [remarry]
]
]
]
end

;-----

to move-persons-with-household ; this method checks to make sure that each person trying to move has one and only one assigned household, and then
; it ensures that they move with the household if the latter changes location
let household-site households with [householdID = [personHouseholdID] of myself]
ifelse any? household-site
[
ifelse (count household-site) = 1
[
move-to one-of households with [householdID = [personHouseholdID] of myself]
set personX [pxcor] of households with [householdID = [personHouseholdID] of myself]
set personY [pycor] of households with [householdID = [personHouseholdID] of myself]
]
[
print "Check data file; there is more than one household with this agent's householdID!"
]
]
[
print "Check data file; there is no household associated with this agent's householdID!"
die
]
end

;-----

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;; AGRICULTURAL METHODS ;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to find-farm-and-settlement
; This method finds a spot for a household and its associated farm. The household spot might be a pre-existing location or it can be a new one. T
; location of a household is its settlement; multiple households can occupy the same settlement space. Only one farm (which is linked to a
; specific household) can occupy a particular space.
let searchCount 0
let siteNeeded? true
let xh 0
let yh 0
ifelse length potfarms > 0
[
set bestfarm determine-best-farm
if bestfarm = nobody [
ask persons with [personHouseholdID = [householdID] of myself]
[
set eventCategory 4
set eventCause 41
; write-to-demog-file
die
]
ask patch-here [set ohousehold ohousehold - 1]
die
]
let bestYield [baseYield] of bestfarm ; NOTE: "baseYield" is the realized output of a plot
set farmX [pxcor] of bestfarm
set farmY [pycor] of bestfarm
set farmplot bestfarm
ask patch farmX farmY [set ocfarm 1]
if (count patches with [watersource? = true and ocfarm = 0 and (baseYield < bestYield)] > 0) ; the criterion is to find cells with water availa
; farmed and are in a zone that is less productive than the zc
; best farm plot is located
[
ask min-one-of patches with [watersource? = true and ocfarm = 0 and (baseYield < bestYield)] [distance bestfarm] ; find the spot with these
; to the farm that has just been c
[
ifelse distance bestfarm <= watersourceDistance ; if the spot is within the watersource distance from the new farm plot,
[set xh pxcor set yh pycor set siteNeeded? false] ; set the local variables xh and yh to the coordinates of the identified patch
[set siteNeeded? true] ; and set the boolean to false; otherwise, keep the boolean at true
]
]
if siteNeeded? = false
[
ask min-one-of patches with [ocfarm = 0 and hydro <= 0] [distancexy xh yh] ; if a suitable farmplot has been found, find a nearby patch w
; hydrology and choose that as the household location
[
set xh pxcor set yh pycor set ohousehold ohousehold + 1 ; this adds a household to the patch and allows us to keep track of settleme
]
]
]
]
end

```

```

]
]
if siteNeeded? = true ; no settlement was found in the previous block
[
; this block of code finds the closest patch without a farm, and if that is within the maximum watersource distance,
; set the coordinates of the farm to be that patch. Note: bestYield is the best farm's "baseYield" (adjusted).
; The constraint in the previous block is that the potential settlement site has a base yield lower than the base yield of the best farm
; plot and that it is not occupied by a farm and is within the maximum watersource distance. In this block, the household can occupy
; a more fertile patch (baseYield > bestYield) because there is nothing else available.

ask min-one-of patches with [ocfarm = 0] [distance bestfarm]
[
  ifelse distance bestfarm <= watersourceDistance
  [
    set xh pxcor set yh pycor
    set siteNeeded? false
  ]
  [set siteNeeded? true]
]
if siteNeeded? = false
[
  ask min-one-of patches with [ocfarm = 0 and hydro <= 0] [distancecx y xh yh] ; if a suitable farmplot has been found, find a nearby patch w
  ; hydrology and choose that as the household location
  [
    set xh pxcor set yh pycor set ohousehold ohousehold + 1 ; this adds a household to the patch and allows us to keep track of settlem
  ]
]
]
if siteNeeded? = true ; still no settlement has been found
[
; this block of code finds the closest patch without a farm, even if it is a higher base yield than bestYield and outside the watersource d
ask min-one-of patches with [ocfarm = 0] [distance bestfarm]
[
  set xh pxcor set yh pycor
  set siteNeeded? false
]
]
if siteNeeded? = false
[
  ask min-one-of patches with [ocfarm = 0 and hydro <= 0] [distancecx y xh yh] ; if a suitable farmplot has been found, find a nearby patch w
  ; hydrology and choose that as the household location
  [
    set xh pxcor set yh pycor set ohousehold ohousehold + 1 ; this adds a household to the patch and allows us to keep track of settlem
  ]
]
]
if siteNeeded? = true
[
  ask patch farmx farmy [set ocfarm 0]
  if any? persons with [personHouseholdID = [householdID] of myself]
  [
    ask persons with [personHouseholdID = [householdID] of myself] [
      set eventCategory 4
      set eventCause 41
      write-to-demog-file
      die
    ]
  ]
  ask patch-here [set ohousehold ohousehold - 1]
  die
]
]

; The following block of statements actually moves households that have successfully identified new farms and settlements, and increments the
; occupying the chosen patch
set householdX xh
set householdY yh
set xcor householdX
set ycor householdY
ask patch-here [set ohousehold ohousehold + 1]
]
; The following block is the else part of ifelse siteNeeded? -- there are available sites on the space, but no suitable settlement is found,
; leave the valley (either through death or eventually migration).
[
  if (houseIsNew? = false)
  [
    ask patch farmx farmy [set ocfarm 0]
    if any? persons with [personHouseholdID = [householdID] of myself]
    [
      ask persons with [personHouseholdID = [householdID] of myself]
      [
        set eventCategory 4
        set eventCause 41
        write-to-demog-file
        die
      ]
    ]
    ask patch-here [set ohousehold ohousehold - 1]
    die
  ]
]
]
end

```

```

;-----
to determine-potfarms

```

```

; This method identifies a list of potential farm locations to use during initialization. When first made, farms are given random locations,

```

```

; but must move to available sites. These sites are patches not already occupied by a farm or settlement and where the base yield (the adjusted
; yield) is higher than the minimum amount of food needed by the farm's household.
set potfarms []
ask patches with [(zone != "Empty") and (ocfarm = 0) and (ochosehold = 0) and (baseYield >= minHouseholdNutriNeed)]
  [set potfarms lput self potfarms]
end

;-----

to-report determine-best-farm ; this method finds the closest suitable farm on the list of potential farms; the starting distance (distancetns)
; just puts constraints on the search space
set bestfarm nobody
let existingfarm patch farmX farmY
let distancetns 1000
foreach potfarms
  [ [?1] ->
    ask ?1 [
      if ((distance existingfarm < distancetns) and (baseYield > [householdNutriNeed] of myself))
      [
        set bestfarm self
        set distancetns distance existingfarm
      ]
    ]
  ]
if length potfarms > 0 [set potfarms remove bestfarm potfarms]
report bestfarm
end

;-----

to estimate-harvest ; this method calculates the expected level of food available to a household based on current stocks of maize and
; the estimate of the next year's harvest (equal to the actual production during the current year)
ask households [
  let total 0
  let ys yearsOfStock - 1
  while [ys > -1]
  [
    set total total + item ys agedCornStocks
    set ys ys - 1
  ]
  set availableCorn total + lastHarvest
]
end

;-----

to harvest-consumption
; The first block of this method calculates the base yield for each cell (i.e., adjusts the natural yield to account for spatial variation in
; productivity and crop loss). It then estimates the actual harvest of a household and updates the stocks of maize available in storage. The sec
; block of code calculates the amount of nutrients a household can derive from the available maize.

ask patches [set baseYield (yield * quality * harvestAdjustment)]
ask households
[
  set lastHarvest [baseYield] of patch farmX farmY * (1 + ((random-normal 0 1) * harvestVariance))
  set agedCornStocks replace-item 2 agedCornStocks (item 1 agedCornStocks)
  set agedCornStocks replace-item 1 agedCornStocks (item 0 agedCornStocks)
  set agedCornStocks replace-item 0 agedCornStocks lastHarvest
  set householdNutriShortfall householdNutriNeed
  set householdAge householdAge + 1
]

; BLOCK 2

ask households
[
  let ys yearsOfStock
  while [ys > -1]
  [
    ifelse ((item ys agedCornStocks) >= householdNutriShortfall)
    [
      set agedCornStocks replace-item ys agedCornStocks (item ys agedCornStocks - householdNutriShortfall)
      set householdNutriShortfall 0
    ]
    [
      set householdNutriShortfall (householdNutriShortfall - item ys agedCornStocks)
      set agedCornStocks replace-item ys agedCornStocks 0
    ]
  ]
  set ys ys - 1
]
]
end

;-----

to water
; define for each location when water is available
ifelse ((year >= 280 and year < 360) or (year >= 800 and year < 930) or (year >= 1300 and year < 1450)) [set streamsexist? true][set streamsexist
ifelse ((year >= 420) and (year < 560)) or ((year >= 630) and (year < 680)) or ((year >= 980) and (year < 1120)) or ((year >= 1180) and (year <
[set alluviumexist? true][set alluviumexist? false]

ask patches [
  set watersource? false

```

```

    if ((alluviumexist? = true) and ((zone = "General") or (zone = "North") or (zone = "Mid") or (zone = "Kinbiko"))) [set watersource? true]
    if ((streamsexist? = true) and (zone = "Kinbiko")) [set watersource? true]
]
; Consistent with the paleoenvironmental data, the following patches always have water, regardless of any other conditions
ask patch 72 114 [set watersource? true]
ask patch 70 113 [set watersource? true]
ask patch 69 112 [set watersource? true]
ask patch 68 111 [set watersource? true]
ask patch 67 110 [set watersource? true]
ask patch 66 109 [set watersource? true]
ask patch 65 108 [set watersource? true]
ask patch 65 107 [set watersource? true]

ask waterpoints [
  if typewater = 2 [ask patch xcor ycor [set watersource? true]]
  if typewater = 3 [if (year >= startdate and year <= enddate) [ask patch xcor ycor [set watersource? true]]]
]

if mapview = "watersource?" [
  ask patches [
    ifelse watersource? = true [set pcolor blue] [set pcolor white]
  ]
]
end

;-----

to update-ALHV-personNutriNeed
; Newborns are assumed to have 35% of the adult personal nutritional need; this need increases linearly with age until age
; 16, when all agents are assumed to be adults
ifelse age < fertilityAge
[set personNutriNeed personBaseNutriNeed * (0.35 + (0.65 * (age / fertilityAge)))]
[set personNutriNeed personBaseNutriNeed]
end

;-----

to update-ALHV-householdNutriNeed
let house-members persons with [personHouseholdID = [householdID] of myself]
if any? house-members
[set householdNutriNeed sum [personNutriNeed] of house-members]
end

;-----

to update-householdSize
set householdSize count persons with [personHouseholdID = [householdID] of myself]
if householdSize = 0
[
  ask patch farmX farmY [set ocfarm 0]
  ask patch-here [set ochousehold ochousehold - 1]
  die
]
end

;-----

;;;;;;;;;;;;;
;;; DISPLAY AND DATA COLLECTION METHODS ;;;
;;;;;;;;;;;;;

to map-settlements ; this method allows easier visualization of the locations of simulated farms and settlements
; Note: the variable "nrh" keeps track of the number of simulated households on a patch, but the present model is not set up
; to map the simulated settlement size and so the variable is not used. We are keeping it in the model because it may prove to b
ask patches [
  set nrh 0
;   if ocfarm = 1
;     [set pcolor orange]
]
ask households
[
  ask patch-here [set nrh nrh + 1]
]
if mapview = "occup"
[
  ask patches
  [
    ifelse ochousehold > 0
    [set pcolor red]
    [set pcolor black]

    ifelse ocfarm = 1
    [set pcolor orange]
    [set pcolor black]
  ]
]
end

;-----

to archaeological-population ; This method converts the input location coordinates of archaeological settlements to the appropriate map location ar
; them on the map. It also adjusts their size according to the number of households at each settlement.

```

```

ask archsettlements
[
  if (typeset = 1) [
    set nrhouseholds 0
    ifelse (year >= startdate and year < enddate)
    [
      set hidden? false ; this statement controls whether the archaeological data show up on the map

      ; The following two blocks are a direct translation from the original AA model. The equations used are a consequence of the way
      ; the data are recorded in the SARG database.
      if year > mediandate
      [
        if (year != mediandate)
        [
          set nrhouseholds ceiling (baselinehouseholds * (enddate - year) / (enddate - mediandate))
          if nrhouseholds < 1 [set nrhouseholds 1]
        ]
      ]
      if year <= mediandate
      [
        if (mediandate != startdate)
        [
          set nrhouseholds ceiling (baselinehouseholds * (year - startdate) / (mediandate - startdate))
          if nrhouseholds < 1 [set nrhouseholds 1]
        ]
      ]
    ]
    [set hidden? true]
    set archTotHouseholds archTotHouseholds + nrhouseholds
    set archsettlementX (24.5 + (meterEast - 2392) / 93.5) ; these two statements are the location translation function for the coordinate
    set archsettlementY (45 + (37.6 + (meterNorth - 7954) / 93.5))
    ; The 45 above is not included in the corrections made in the Ascape version. We suspect this is a conversion specifically for the
    ; Netlogo map setup.
    set xcor int archsettlementX
    set ycor int archsettlementY
  ;   set size nrhouseholds ; Janssen's version of the original model adjusted the size of archaeological settlements by the number of household
  ;   ; at some time periods, overwhelms the map. A better way to represent the size of such settlements will be included
  ]
end

;-----

to plot-counts
let ageList []
let harvestList []
let cornList []
set-current-plot "Population"
set-current-plot-pen "simHouseholds"
plot (totHouseholds)
set-current-plot-pen "archHouseholds"
plot (archTotHouseholds)
set-current-plot-pen "simPersons"
plot (totPopSize)

ask households
[
  set ageList lput householdAge ageList
  set harvestList lput lastHarvest harvestList
  set cornList lput availableCorn cornList
]
set-current-plot "Household Age"
histogram ageList
set-current-plot "Household Harvest"
histogram harvestList
set-current-plot "Household Available Maize"
histogram cornList
end

;-----

to update-annual-output
plot-counts
write-to-annual-file
if (year mod 50 = 0)
[
  write-to-popdist-file
  write-to-starvedist-file
]
end

;-----

to setup-annualDataFile
if (not file-exists? "ALHVagedmort-annual.csv") [
  file-open "ALHVagedmort-annual.csv"
  file-print "PARAMETERS, "
  file-type "minFertilityAge, "
  file-type "maxFertilityAge, "
  file-type "minFertilityEndsAge, "
  file-type "maxFertilityEndsAge, "
;   file-type "minDeathAge, "
;   file-type "maxDeathAge, "
  file-type "fert 15-19, "
  file-type "fert 20-24, "
  file-type "fert 25-29, "

```



```

file-type "fert 30-34, "
file-type "fert 35-39, "
file-type "fert 40-44, "
file-type "fert 45+, "
file-type "personBaseNutriNeed, "
file-type "harvestAdjustment, "
file-print "harvestVariance, "

file-type (word minFertilityAge ", ")
file-type (word maxFertilityAge ", ")
file-type (word minFertilityEndsAge ", ")
file-type (word maxFertilityEndsAge ", ")
; file-type (word minDeathAge ", ")
; file-type (word maxDeathAge ", ")
file-type (word item 0 age-specificFertility ", ")
file-type (word item 1 age-specificFertility ", ")
file-type (word item 2 age-specificFertility ", ")
file-type (word item 3 age-specificFertility ", ")
file-type (word item 4 age-specificFertility ", ")
file-type (word item 5 age-specificFertility ", ")
file-type (word item 6 age-specificFertility ", ")
file-type (word personBaseNutriNeed ", ")
file-type (word harvestAdjustment ", ")
file-print (word harvestVariance ", ")

file-type "mort 0-1, "
file-type "mort 1-4, "
file-type "mort 5-9, "
file-type "mort 10-14, "
file-type "mort 15-19, "
file-type "mort 20-24, "
file-type "mort 25-29, "
file-type "mort 30-34, "
file-type "mort 35-39, "
file-type "mort 40-44, "
file-type "mort 45-49, "
file-type "mort 50-54, "
file-type "mort 55-59, "
file-type "mort 60-64, "
file-type "mort 65-69, "
file-type "mort 70-74, "
file-type "mort 75-79, "
file-print "mort 80+, "

file-type (word item 0 age-specificMortality ", ")
file-type (word item 1 age-specificMortality ", ")
file-type (word item 2 age-specificMortality ", ")
file-type (word item 3 age-specificMortality ", ")
file-type (word item 4 age-specificMortality ", ")
file-type (word item 5 age-specificMortality ", ")
file-type (word item 6 age-specificMortality ", ")
file-type (word item 7 age-specificMortality ", ")
file-type (word item 8 age-specificMortality ", ")
file-type (word item 9 age-specificMortality ", ")
file-type (word item 10 age-specificMortality ", ")
file-type (word item 11 age-specificMortality ", ")
file-type (word item 12 age-specificMortality ", ")
file-type (word item 13 age-specificMortality ", ")
file-type (word item 14 age-specificMortality ", ")
file-type (word item 15 age-specificMortality ", ")
file-type (word item 16 age-specificMortality ", ")
file-print (word item 17 age-specificMortality ", ")
file-print " "

file-type "Run number,"
file-type "Year,"
file-type "Arch Households,"
file-type "Sim Households,"
file-print "Sim People,"
file-close
]
end

;-----

to setup-demogDataFile
if (not file-exists? "ALHVagedmort-demogData.csv") [
file-open "ALHVagedmort-demogData.csv"
file-print "PARAMETERS, "
file-type "minFertilityAge, "
file-type "maxFertilityAge, "
file-type "minFertilityEndsAge, "
file-type "maxFertilityEndsAge, "
; file-type "minDeathAge, "
; file-type "maxDeathAge, "
file-type "fert 15-19, "
file-type "fert 20-24, "
file-type "fert 25-29, "
file-type "fert 30-34, "
file-type "fert 35-39, "
file-type "fert 40-44, "
file-type "fert 45+, "
file-type "personBaseNutriNeed, "
file-type "harvestAdjustment, "
file-print "harvestVariance, "

file-type (word minFertilityAge ", ")

```

```

file-type (word maxFertilityAge ", ")
file-type (word minFertilityEndsAge ", ")
file-type (word maxFertilityEndsAge ", ")
; file-type (word minDeathAge ", ")
; file-type (word maxDeathAge ", ")
file-type (word item 0 age-specificFertility ", ")
file-type (word item 1 age-specificFertility ", ")
file-type (word item 2 age-specificFertility ", ")
file-type (word item 3 age-specificFertility ", ")
file-type (word item 4 age-specificFertility ", ")
file-type (word item 5 age-specificFertility ", ")
file-type (word item 6 age-specificFertility ", ")
file-type (word personBaseNutriNeed ", ")
file-type (word harvestAdjustment ", ")
file-print (word harvestVariance ", ")
file-print ""

```

```

file-type "Run number, "
file-type "Year, "
file-type "Event Category, "
file-type "Event Cause, "
file-type "PersonID, "
file-type "Sex, "
file-type "Age, "
file-type "Household, "
file-type "Clan, "
file-print "MateID, "
file-close

```

```

]
end

```

```

;-----
to setup-popDistributionFile
if (not file-exists? "ALHVagedmort-popDist.csv") [
file-open "ALHVagedmort-popDist.csv"
file-print "POPULATION AGE DISTRIBUTION, "
file-print "PARAMETERS, "
file-type "minFertilityAge, "
file-type "maxFertilityAge, "
file-type "minFertilityEndsAge, "
file-type "maxFertilityEndsAge, "
; file-type "minDeathAge, "
; file-type "maxDeathAge, "
file-type "fert 15-19, "
file-type "fert 20-24, "
file-type "fert 25-29, "
file-type "fert 30-34, "
file-type "fert 35-39, "
file-type "fert 40-44, "
file-type "fert 45+, "
file-type "personBaseNutriNeed, "
file-type "harvestAdjustment, "
file-print "harvestVariance, "

file-type (word minFertilityAge ", ")
file-type (word maxFertilityAge ", ")
file-type (word minFertilityEndsAge ", ")
file-type (word maxFertilityEndsAge ", ")
; file-type (word minDeathAge ", ")
; file-type (word maxDeathAge ", ")
file-type (word item 0 age-specificFertility ", ")
file-type (word item 1 age-specificFertility ", ")
file-type (word item 2 age-specificFertility ", ")
file-type (word item 3 age-specificFertility ", ")
file-type (word item 4 age-specificFertility ", ")
file-type (word item 5 age-specificFertility ", ")
file-type (word item 6 age-specificFertility ", ")
file-type (word personBaseNutriNeed ", ")
file-type (word harvestAdjustment ", ")
file-print (word harvestVariance ", ")
file-print ""

file-type "Run number, "
file-type "Year, "
file-type "0 to 1, "
file-type "1 to 4, "
file-type "5 to 9, "
file-type "10 to 14, "
file-type "15 to 19, "
file-type "20 to 24, "
file-type "25 to 29, "
file-type "30 to 34, "
file-type "35 to 39, "
file-type "40 to 44, "
file-type "45 to 49, "
file-type "50 to 54, "
file-type "55 to 59, "
file-type "60 to 64, "
file-type "65 to 69, "
file-type "70 to 74, "
file-type "75 to 79, "
file-type "80+, "
file-print "total pop, "
file-close

```

```

]
end

```

```

;-----
to setup-starveDistributionFile
  if (not file-exists? "ALHVagedmort-starveDist.csv") [
    file-open "ALHVagedmort-starveDist.csv"
    file-print "STARVATION AGE DISTRIBUTION, "
    file-print "PARAMETERS, "
    file-type "minFertilityAge, "
    file-type "maxFertilityAge, "
    file-type "minFertilityEndsAge, "
    file-type "maxFertilityEndsAge, "
;   file-type "minDeathAge, "
;   file-type "maxDeathAge, "
    file-type "fert 15-19, "
    file-type "fert 20-24, "
    file-type "fert 25-29, "
    file-type "fert 30-34, "
    file-type "fert 35-39, "
    file-type "fert 40-44, "
    file-type "fert 45+, "
    file-type "personBaseNutriNeed, "
    file-type "harvestAdjustment, "
    file-print "harvestVariance, "

    file-type (word minFertilityAge ", ")
    file-type (word maxFertilityAge ", ")
    file-type (word minFertilityEndsAge ", ")
    file-type (word maxFertilityEndsAge ", ")
;   file-type (word minDeathAge ", ")
;   file-type (word maxDeathAge ", ")
    file-type (word item 0 age-specificFertility ", ")
    file-type (word item 1 age-specificFertility ", ")
    file-type (word item 2 age-specificFertility ", ")
    file-type (word item 3 age-specificFertility ", ")
    file-type (word item 4 age-specificFertility ", ")
    file-type (word item 5 age-specificFertility ", ")
    file-type (word item 6 age-specificFertility ", ")
    file-type (word personBaseNutriNeed ", ")
    file-type (word harvestAdjustment ", ")
    file-print (word harvestVariance ", ")
    file-print ""

    file-type "Run number, "
    file-type "Year, "
    file-type "0 to 1, "
    file-type "1 to 4, "
    file-type "5 to 9, "
    file-type "10 to 14, "
    file-type "15 to 19, "
    file-type "20 to 24, "
    file-type "25 to 29, "
    file-type "30 to 34, "
    file-type "35 to 39, "
    file-type "40 to 44, "
    file-type "45 to 49, "
    file-type "50 to 54, "
    file-type "55 to 59, "
    file-type "60 to 64, "
    file-type "65 to 69, "
    file-type "70 to 74, "
    file-type "75 to 79, "
    file-type "80+, "
    file-print "total starved, "
    file-close
  ]
end

;-----

to write-to-annual-file
  file-open "ALHVagedmort-annual.csv"
  file-type (word behaviorspace-run-number ", ")
  file-type (word year ", ")
  file-type (word archTotHouseholds ", ")
  file-type (word totHouseholds ", ")
  file-print (word totPopSize ", ")
  file-close
end

;-----

to write-to-demog-file
  file-open "ALHVagedmort-demogData.csv"
  file-type (word behaviorspace-run-number ", ")
  file-type (word year ", ")
  file-type (word eventCategory ", ")
  file-type (word eventCause ", ")
  file-type (word personID ", ")
  file-type (word sex ", ")
  file-type (word age ", ")
  file-type (word personHouseholdID ", ")
  file-type (word clanID ", ")
  file-print (word mateID ", ")
  file-close

```

end

```
to write-to-popdist-file
  file-open "ALHVagedmort-popDist.csv"
  file-type (word behaviorspace-run-number ", ")
  file-type (word year ", ")
  file-type (word item 1 ageDistribution ", ")
  file-type (word item 2 ageDistribution ", ")
  file-type (word item 3 ageDistribution ", ")
  file-type (word item 4 ageDistribution ", ")
  file-type (word item 5 ageDistribution ", ")
  file-type (word item 6 ageDistribution ", ")
  file-type (word item 7 ageDistribution ", ")
  file-type (word item 8 ageDistribution ", ")
  file-type (word item 9 ageDistribution ", ")
  file-type (word item 10 ageDistribution ", ")
  file-type (word item 11 ageDistribution ", ")
  file-type (word item 12 ageDistribution ", ")
  file-type (word item 13 ageDistribution ", ")
  file-type (word item 14 ageDistribution ", ")
  file-type (word item 15 ageDistribution ", ")
  file-type (word item 16 ageDistribution ", ")
  file-type (word item 17 ageDistribution ", ")
  file-type (word item 18 ageDistribution ", ")
  file-print (word totPopSize ", ")
  file-close
end
```

end

```
to write-to-starvedist-file
  file-open "ALHVagedmort-starveDist.csv"
  file-type (word behaviorspace-run-number ", ")
  file-type (word year ", ")
  file-type (word item 1 starveDistribution ", ")
  file-type (word item 2 starveDistribution ", ")
  file-type (word item 3 starveDistribution ", ")
  file-type (word item 4 starveDistribution ", ")
  file-type (word item 5 starveDistribution ", ")
  file-type (word item 6 starveDistribution ", ")
  file-type (word item 7 starveDistribution ", ")
  file-type (word item 8 starveDistribution ", ")
  file-type (word item 9 starveDistribution ", ")
  file-type (word item 10 starveDistribution ", ")
  file-type (word item 11 starveDistribution ", ")
  file-type (word item 12 starveDistribution ", ")
  file-type (word item 13 starveDistribution ", ")
  file-type (word item 14 starveDistribution ", ")
  file-type (word item 15 starveDistribution ", ")
  file-type (word item 16 starveDistribution ", ")
  file-type (word item 17 starveDistribution ", ")
  file-type (word item 18 starveDistribution ", ")
  file-print (word totStarvations ", ")
  file-close
end
```

end

```
;; ALHV-MESA MODEL CODE
```

```
patches-own [value watersource? zone apdsi pdsi hydro quality maizeZone yield baseYield ocfarm ochousehold nrh patchRegion ;LVH = 1, BM = 2, border ]
```

```
breed [households household ]  
; breed [archsettlements archsettlement] ; archaeological occupation  
breed [waterpoints waterpoint]  
breed [persons person]
```

```
extensions [profiler]
```

```
; archsettlements-own [archsettlementX archsettlementY SARG meterNorth meterEast startdate enddate mediandate typeset sizeset description roomcount]
```

```
waterpoints-own [waterpointX waterpointY sarg meternorth metereast typewater startdate enddate]
```

```
households-own [
```

```
householdID ; ID of a household; assigned at the time a household is formed  
householdX householdY ; location of the household on the space  
householdSize ; the number of persons assigned to a household  
householdAge ; self-explanatory, initialized at age 0  
householdNutriNeed ; combined nutritional needs of all agents within a household  
householdNutriShortfall ; difference between the estimated nutrients available and the household nutrition need  
farmX farmY ; location of the household's associated farm on the space  
farmplot ; a household's farmplot; assigned after finding the best farm in findFarmAndSettlement methc  
lastHarvest ; yield of the most recent harvest  
availableCorn ; estimate of the maize that will be available the following year; combines existing stock ar  
agedCornStocks ; stores of maize from harvests of the previous two years; each year retains its identity  
houseIsNew? ; boolean to indicate whether a house is newly built  
siteNeeded? ; boolean to indicate whether a household has been able to find farm or settlement site  
deathInHousehold? ; boolean to indicate whether a death has occurred in a household in the current step  
HHregion ; indicates which region a household is situated, LVH = 1, BM = 2, border = 0  
HHmatchIndex ; allows for matching households with persons during initialization  
]
```

```
persons-own [
```

```
; GENERAL CHARACTERISTICS
```

```
personID ; ID of a person; assigned at initialization or birth  
personX personY ; location of a person on the space  
natalCommunity ; site at which the person was born; 1 = Long House Valley, 5 = outside male  
residence ; site at which the person is living; 1 = Long House Valley  
personHouseholdID ; the household to which a person is assigned  
clanID ; ID of a person's clan; assigned at initialization or birth, newborns are assigned their mot  
sex age ; age and sex, assigned at initialization or birth; values for persons formed at initializati  
headOfHousehold? ; boolean that indicates whether a person is head of her household  
eldestChild? ; boolean that indicates whether a person is the eldest child (male or female); used to deter  
married ; indicates marital status; 0 = never married, 1 = currently married, 2 = unmarried widow or  
mateID ; the personID of a person's mate  
numChildren ; the number of children born to a person  
vitalCategory ; designates when an individual experiences a birth (1), dies (2),  
migrationCategory ; designate when an individual migrates in (3), or migrates out (4)  
vitalCause ; vital and migration cause designate the specific cause of a demographic event. Codes begin  
; and a second digit that reflects the specific cause is added. The letter indicates the area  
; Present causes include: 10V (birth cause is self-evident), 21V (starvation), 20V (other cau  
; 30V (adult male), 31V (reproductive female), 32V (post-reproductive female), 33V (male chil  
; 42V (no wife available for a widower), 43V (never-married male unable to marry within the v  
; household region anywhere),  
; 40V (other cause for migration).
```

```
houseNeeded? ; set false when agent is born or initialized, set true when a female begins the process of f  
wifeChecked? ; used in find-new-wife to determine whether a re-marrying male has already tried to select a
```

```
personNutriNeed ; the nutritional requirements of a person, based on age and sex  
personNutriShortfall ; the amount of personal nutritional need that is not being met by the available maize
```

```
; DEMOGRAPHIC VARIABLES
```

```
fertility ; age-specific probability that a female gives birth in any particular year  
fertilityAge ; set at initialization for adults; for younger agents, chosen at initialization or birth  
; from range determined by min- and maxFertilityAge  
fertilityEndsAge ; chosen females at initialization or hatching (outside males and newborns) from range determ  
mortality ; age-specific probability that an agent dies in any particular year
```

```
birthAge ; a list that holds the ages at which a person's children are born; the first element is the  
personRegion ; the region in which a person lives, LVH = 1, BM = 2, border = 0  
]
```

```
globals [
```

```
;; INTERFACE VARIABLES
```

```
; harvestAdjustment ; a variable in the original AA model that reflects actual vs. maximum possible  
; harvestVariance ; a variable in the original AA model that reflects spatial variation in yields  
; mapview ; a chooser that allows the user to view different types of data on the map  
; archaeologyview ; a switch that allows the user to control whether archaeological sites are seen  
; personBaseNutriNeed ; the amount of food needed per adult; initialized at 160 kg in AA model  
; minFertilityAge maxFertilityAge ; boundaries of age range within which a female can reproduce  
; minFertilityEndsAge maxFertilityEndsAge ; boundaries of age range for end of female reproductive period  
; numClans ; number of clans in the population  
; mesaAdjustment ; allows for increased yields in all mesa areas, this may need to be turned on
```

```
;; HOUSEHOLD VARIABLES
```

```
householdIDindex ; a variable to keep track of numbering for new households  
personHouseholdMatch ; a variable that allows households and the persons within them to be matched a  
minHouseholdNutriNeed ; the minimum value for a household's nutritional need; required for the determ
```

```

householdMinInitialCorn householdMaxInitialCorn
totHH valleyHH mesaHH
archTotHH archValleyHH archMesaHH
weddingMaizeGift

;; PERSON VARIABLES
personIDindex ; a variable to keep track of numbering for new persons
age-specificFertility ; a list giving age-specific fertility values (15-19, 20-24, 25-29, 30-34, 35-3
age-specificMortality ; a list giving age-specific mortality values (0-1, 1-4, 5-9, 5-year age classe

;; SUMMARY DEMOGRAPHIC VARIABLES
totPopSize valleyPopSize mesaPopSize ; total number of persons at any time
vAgeDistribution ; a list that gives the number of persons in each age class in the valley durin
mAgeDistribution ; a list that gives the number of persons in each age class on the mesa during
totAgeDistribution ; a list that gives the number of persons in each age class in the population c

;; FIND FARM AND HOUSEHOLD LOCATION VARIABLES
vPotfarms mPotfarms ; list of potential farm sites, v = valley, m = mesa
vBestfarm mBestfarm ; the best farm site available, v = valley, m = mesa
streamsexist? alluviumexist? ; self-explanatory booleans
watersourceDistance ; the maximum distance in number of cells an agent likes to live away from wate
yearsOfStock ; number of years maize can be stored = 2 years

;; MISCELLANEOUS VARIABLES
year ; year of the simulation
environment-data ; empirical data read into the program
apdsi-data ; empirical data read into the program for LHV environment
pdsi-data ; empirical data read into the program for Black Mesa environment
LHV-archpop ; empirical data read into the program for LHV (population estimates by year)
Mesa-archPop ; empirical data read into the program for the mesa (population estimates by ye
map-data ; empirical data read into the program
settlements-data ; empirical data read into the program
water-data ; empirical data read into the program
]

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;; SETUP AND GO METHODS ;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to profile
  setup
  profiler:start
  repeat 550 [go]
  profiler:stop
  print profiler:report
  profiler:reset
end

to setup ; initialize the parameters and variables of the model and download the datafiles
  clear-all
  ; set-default-shape archsettlements "tile stones"
  set-default-shape households "house"
  set-default-shape persons "person"
  ask patches with [pxcor >= 0 and pxcor < 80] [set patchRegion 1]
  ask patches with [pxcor > 80] [set patchRegion 2]
  ask patches with [pxcor = 80] [set pcolor gray set patchRegion 0]
  load-ALHV-map-data
  load-mesa-map-data
  archaeological-population
  set streamsexist? false
  set alluviumexist? false
  set year 800 ; initial year
  ask patches
  [
    set watersource? false
    set quality ((random-normal 0 1) * harvestVariance) + 1.0 ; assigns a measure to a patch that is used below to introduce spatial heterogeneity
    if (quality < 0) [set quality 0]
  ]
  set watersourceDistance 16.0 ; maximum distance between a household and water source
  ; set harvestAdjustment 1.0 ; (slider) 0.56 is Janssen's default value
  ; set harvestVariance 0.40 ; (slider) 0.40 is the default value in both the Ascape and Janssen versions
  ; set personBaseNutriNeed 285 ; (slider) an adult needs 285 kg of food (maize) each year; children's need will be determined by their age at initi
  ; set mesaAdjustment 1.3 ; (slider) This value was estimated by looking at average family composition of the Black Mesa starting population, avera
  ; and their nutritional need taking into account increased mesa soil productivity (see daily notes from 9-14-17 for more
  ; set minFertilityAge 15 ; (slider) minimum age when persons reach maturity and can marry, form new households, and reproduce. Value set to be cor
  ; set maxFertilityAge 15 ; (slider) maximum age at which reproduction can start; the present settings of min- and maxFertilityAge mean there is no
  ; set minFertilityEndsAge 48 ; (slider) minimum age at menopause, Coale-Trussell standard does not allow fertility beyond age 50
  ; set maxFertilityEndsAge 50 ; (slider) maximum age at menopause, Coale-Trussell standard does not allow fertility beyond age 50
  set householdIDindex 1 ; needed to assign IDs to new households
  set personHouseholdMatch 1 ; to match households to person agents
  set personIDindex 1 ; needed to assign IDs to new person agents
  set weddingMaizeGift 0.33 ; proportion of parents' maize given to new household by parent household at marriage of a daughter
  set yearsOfStock 2 ; number of years maize can be stored
  set minHouseholdNutriNeed 800 ; initialization value of a household's nutrition need; calculated subsequently from the individual nutritional nee
  set householdMinInitialCorn 2000 ; lower bound of possible maize stock at initialization of a household
  set householdMaxInitialCorn 2400 ; upper bound of possible maize stock at initialization of a household
  set age-specificFertility [0.263 0.294 0.276 0.253 0.206 0.107 0.015] ; the values listed here are from the Coale-Trussell standard model with a
  ; are 15-19, 20-24, 25-29, 30-34, 35-39, 40-44, and 45-49; Coale-Trussell s
  set age-specificMortality [0.1670 0.1050 0.0800 0.0523 0.0897 0.0912 0.0927 0.0942 0.0957 0.0972 0.0988 0.1004 0.1311 0.1824 0.2493 0.3450 0.4746
  ; [0.1286 0.0809 0.0616 0.0403 0.0691 0.0702 0.0714 0.0725 0.0737 0.0748 0.0761 0.0773 0.1009 0.1404 0.1920 0.2657 0.3654 1.0000]]

```

```

; the default values are from Weiss' MT 35.0-65.0 life table; age groups ar
; 15-19, 20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64, 65-

set totAgeDistribution [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
set vAgeDistribution [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
set mAgeDistribution [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
; the age distribution vector has the year in the first element, followed by the numbers of individuals aged 0-1, 1-4, 5-9,
; 10-14, ..., 85-89, 90+

; If sensitivity analyses are being run, paired variables that are being studied need to be set at the same values. The appropriate line below for
; set maxFertilityAge minFertilityAge
; set maxFertilityEndsAge minFertilityEndsAge

; ask archsettlements [set hidden? false] ; if true, don't show archaeological sites
water ; calculate water availability for initial time step

calculate-valley-yield
calculate-mesa-yield

ask patches [set baseYield yield * quality * harvestAdjustment] ; NOTE: "yield" is the natural output of a plot; "baseYield" is the output adjust
; heterogeneity among patches within a productive zone, and harvest adjustment, which reflects csc

determine-potfarms ; makes a list of the possible farm sites given the land quality and space available
set archValleyHH 14 ; initialization of the same number of simulation households as there are archaeological households in the data
set archMesaHH 26 ; ; initialization of the same number of simulation households as there are archaeological households in the data

; The model as it is formulated now requires that A CREATE HOUSEHOLD STATEMENT MUST BE PAIRED WITH A CREATE PERSON STATEMENT. EACH PAIR OF STATEM
create-households archValleyHH [init-valley-households] ; creates the same number of simulation households as archaeological households in the va
; and places them on the landscape in suitable locations

init-valley-persons
set personHouseholdMatch 1 ; this resets the variable and must be included whenever a new region is initialized

create-households archMesaHH [init-mesa-households] ; creates the same number of simulation households as archaeological households in the mesa,
; and places them on the landscape in suitable locations

init-mesa-persons

set householdIDindex archValleyHH + archMesaHH + 1 ; sets the household index so that the first household created after setup will be the next cc
; if additional regions are added, total household numbers should be included in this statement

set totAgeDistribution calculate-age-distribution (0) ; 0 refers to the total population
set vAgeDistribution calculate-age-distribution (1) ; 1 is the region designation for LHV
set mAgeDistribution calculate-age-distribution (2) ; 2 is the region designation for the mesa
ask households [update-householdSize]

set totHH count households
set totPopSize count persons

set valleyHH count households with [HHregion = 1]
set valleyPopSize count persons with [personRegion = 1]

set mesaHH count households with [HHregion = 2]
set mesaPopSize count persons with [personRegion = 2]

estimate-harvest
map-settlements
setup-annualDataFile
setup-demogDataFile
setup-popDistributionFile "ALHV-mesa-PopDistValley.csv" "VALLEY"
setup-popDistributionFile "ALHV-mesa-PopDistMesa.csv" "MESA"
setup-popDistributionFile "ALHV-mesa-PopDistTotal.csv" "TOTAL"

write-to-annual-file
write-to-popdist-file "ALHV-mesa-popDistValley.csv" vAgeDistribution valleyPopSize
write-to-popdist-file "ALHV-mesa-popDistMesa.csv" mAgeDistribution mesaPopSize
write-to-popdist-file "ALHV-mesa-popDistTotal.csv" totAgeDistribution totPopSize

reset-ticks
end

;-----
to go ; core procedure of the model, which defines the cycle of activities each year
; ask persons [type "I am person " type personID type " and I am a " print sex]
set archValleyHH 0
set archMesaHH 0
set year year + 1

set totAgeDistribution calculate-age-distribution (0)
set vAgeDistribution calculate-age-distribution (1)
set mAgeDistribution calculate-age-distribution (2)

ask persons [
set vitalCategory 0
set migrationCategory 0
set vitalCause "0"
set migrationCause "0"
]

```

```

ask households [
  set houseIsNew? false
  set deathInHousehold? false
]

calculate-valley-yield
calculate-mesa-yield

; if archaeology-view? [archaeological-population] ; this statement governs how the archaeological data are shown on the map; whether they are shown
; by a slider on the interface

harvest-consumption
ALHV-death
ask households
[
  if (deathInHousehold? = true)
  [
    type "Household " type householdID print " has experienced a death."
    death-aftermath
  ]
]

map-settlements
estimate-harvest
set minHouseholdNutriNeed personBaseNutriNeed * 2 ; minHouseholdNutriNeed is assumed to be the need of a household with two adults in it
ask households
[
  if (availableCorn < householdNutriNeed)
  [
    determine-potfarms
    ask patch farmX farmY [set ocfarm 0] ; this statement codes for abandonment of the present farmplot; in the next statement a new plot is sought
    find-farm-and-settlement
  ]
]
ask persons
[
  set age age + 1
  if (sex = 0 and age > 20 and married = 0) ; This block forces males to leave the study area if they are not chosen as a mate by any valley or mesa
  [
    set migrationCategory 4
    set migrationCause "43X"
    write-to-demog-file
    die
  ]

  if (sex = 0 and married = 2) [type "Error: I am agent " type personID print ". I am a widower who should have died or left the study area."]

  find-age-specific-fertility
  find-age-specific-mortality
  update-ALHV-personNutriNeed
; move-persons-with-household; the positioning of this method call here ensures that all persons in households that need to move because of inadequate
; resources do, in fact, move to the new household location. Movement because of demographic events is completed at
; those events. Placing the method call here seems to be more efficient than calling it in find-farm-and-settlement
; method is an observer method, not a person method and so we would have to repeatedly cycle through ALL persons with
; household changed locations. The placement here moves all agents that have changed households at the same time.
]
determine-potfarms

; the following block sets conditions on marriage and childbirth
ask persons [
  if ((married = 0) and (sex = 1) and (age >= fertilityAge) and (age <= fertilityEndsAge) and (headOfHousehold? = false))[find-mate]

  if ((sex = 1) and (married = 1) and (age >= fertilityAge) and (age <= fertilityEndsAge) and (random-float 1.0 < fertility)) [produce-babies]
]

ask households
[
  update-householdSize
  update-ALHV-householdNutriNeed
; if (householdID = "VH1") or (householdID = "VH2") [type "Go, post demog. Step FINAL. Household size is " type householdSize type "NutriNeed: "
]

set totHH count households
set totPopSize count persons

set valleyHH count households with [HHregion = 1]
set valleyPopSize count persons with [personRegion = 1]

set mesaHH count households with [HHregion = 2]
set mesaPopSize count persons with [personRegion = 2]

water ; re-assess the availability of water in each cell of the map
map-settlements
update-annual-output
if year = 1350 [stop]
tick
end

;-----
to load-ALHV-map-data
; load spatially explicit data to populate the landscape with a map of different types of land cover
ifelse ( file-exists? "valleyMap.txt" )
[
  set map-data []
]

```



```

file-open "valleyMap.txt"
while [ not file-at-end? ]
[
  set map-data sentence map-data (list (list file-read))
]
file-close
]
[ user-message "There is no valleyMap.txt file in current directory!" ]

; clear-patches
; clear-turtles
let yy 119
let xx 0

; The numbers after each "? =" below are values given to each patch during the process of converting actual map data to a rasterized form that ca
; into the model. This will likely be changed once we incorporate the available Netlogo GIS extension.

foreach map-data [ [?] ->
ask patch xx yy [set value first ?1]
if first ?1 = 0 [ask patch xx yy [set pcolor black set zone "General" set maizeZone "Yield_2"]] ; General Valley
if first ?1 = 10 [ask patch xx yy [set pcolor red set zone "North" set maizeZone "Yield_1"]] ; North Valley
if first ?1 = 15 [ask patch xx yy [set pcolor white set zone "North Dunes" set maizeZone "Sand_dune"]] ; North Valley ; Dunes
if first ?1 = 20 [ask patch xx yy [set pcolor gray set zone "Mid" ifelse (xx <= 74) [set maizeZone "Yield_1"][set maizeZone "Yield_2"]]] ; Mid Va
if first ?1 = 25 [ask patch xx yy [set pcolor white set zone "Mid Dunes" set maizeZone "Sand_dune"]] ; Mid Valley ; Dunes
if first ?1 = 30 [ask patch xx yy [set pcolor yellow set zone "Natural" set maizeZone "No_Yield"]] ; Natural
if first ?1 = 40 [ask patch xx yy [set pcolor blue set zone "Uplands" set maizeZone "Yield_3"]] ; Uplands Arable
if first ?1 = 50 [ask patch xx yy [set pcolor pink set zone "Kinbiko" set maizeZone "Yield_1"]] ; Kinbiko Canyon
if first ?1 = 60 [ask patch xx yy [set pcolor brown set zone "Empty" set maizeZone "Empty"]] ; Empty
ifelse yy > 0 [set yy yy - 1][set xx xx + 1 set yy 119 ]

; SARG (Southwestern Archaeological Research Group) number, meters north, meters east, start date, end date, median date (1950 - x), type, size,
; ifelse ( file-exists? "vSettlements.txt" )
; [
;   set settlements-data []
;   file-open "vSettlements.txt"
;   while [ not file-at-end? ]
;   [
;     set settlements-data sentence settlements-data (list (list file-read file-read file-read file-read file-read file-read file-read file-read f
;   ]
;   file-close
; ]
; [ user-message "There is no vSettlements.txt file in current directory!" ]

; foreach settlements-data [ [?] ->
; create-archsettlements 1 [
;   set SARG first ?1
;   set meterNorth item 1 ?1
;   set meterEast item 2 ?1
;   set startdate item 3 ?1
;   set enddate item 4 ?1
;   set mediantdate (1950 - item 5 ?1)
;   set typeset item 6 ?1
;   set sizeset item 7 ?1
;   set description item 8 ?1
;   set roomcount item 9 ?1
;   set elevation item 10 ?1
;   set baselinehouseholds last ?1
;   set settlementRegion 1
; ] ]

; ask archsettlements [set settlementRegion 1

; number, meters north, meters east, type, start date, end date
ifelse ( file-exists? "vWater.txt" )
[
  set water-data []
  file-open "vWater.txt"
  while [ not file-at-end? ]
  [
    set water-data sentence water-data (list (list file-read file-read file-read file-read file-read file-read))
  ]
  file-close
]
[ user-message "There is no vWater.txt file in current directory!" ]

foreach water-data [ [?] ->
create-waterpoints 1 [
  set sarg first ?1
  set meterNorth item 1 ?1
  set meterEast item 2 ?1
  set typewater item 3 ?1
  set startdate item 4 ?1
  set enddate item 5 ?1 ] ]

; This block of code converts the input coordinates for each waterpoint to the simulation map coordinates so that they will appear on the map in
ask waterpoints [
  set xcor 24.5 + int ((meterEast - 2392) / 93.5)
  set ycor 45 + int (37.6 + ((meterNorth - 7954) / 93.5))
  set hidden? true
]

ifelse ( file-exists? "adjustedPDSI.txt" )
[
  set apdsi-data []
  file-open "adjustedPDSI.txt"
  while [ not file-at-end? ]
  [

```

```

    set apdsi-data sentence apdsi-data (list file-read)
  ]
  file-close
]
[ user-message "There is no adjustedPDSI.txt file in current directory!" ]

; The 15 file-read statements below refer to the structure of the data, which consists of three values for each of the five environment zones for
; Only the hydrology data (the second of the three values per environment zone) are used in the program.
ifelse (file-exists? "vEnvironment.txt")
[
  set environment-data []
  file-open "vEnvironment.txt"
  while [not file-at-end?]
  [
    set environment-data sentence environment-data (list (list file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read file-read))
  ]
  file-close
]
[ user-message "There is no vEnvironment.txt file in current directory!" ]

ask patches [set ocfarm 0 set ochothousehold 0] ; set patchRegion 1 ; all patches are initialized as vacant (i.e., with no farms or households on the
end

;-----

to load-mesa-map-data
  ; load spatially explicit data to populate the landscape with a map of different types of land cover
  ifelse ( file-exists? "MesaMap2.txt" )
  [
    set map-data []
    file-open "MesaMap2.txt"
    while [ not file-at-end? ]
    [
      set map-data sentence map-data (list (list file-read))
    ]
    file-close
  ]
  [ user-message "There is no MesaMap2.txt file in current directory!" ]

; clear-patches
; clear-turtles
let yy 119
let xx 81

; The numbers after each "? =" below are values given to each patch during the process of converting actual map data to a rasterized form that ca
; into the model. This will likely be changed once we incorporate the available Netlogo GIS extension.

foreach map-data [ ?1] ->
ask patch xx yy [set value first ?1]
if first ?1 = 0 [ask patch xx yy [set pcolor brown set zone "Empty" set maizeZone "Empty"]] ; Empty
if first ?1 = 5 [ask patch xx yy [set pcolor blue set zone "Water" set maizeZone "Empty"]] ; Water paths
if first ?1 = 10 [ask patch xx yy [set pcolor green set zone "General" set maizeZone "Yield_1"]] ; General Valley
  ifelse yy > 0 [set yy yy - 1][set xx xx + 1 set yy 119] ]

ifelse ( file-exists? "BlackMesaPDSI.txt" )
[
  set pdsi-data []
  file-open "BlackMesaPDSI.txt"
  while [ not file-at-end? ]
  [
    set pdsi-data sentence pdsi-data (list file-read)
  ]
  file-close
]
[ user-message "There is no BlackMesaPDSI.txt file in current directory!" ]

ask patches [ set ocfarm 0 set ochothousehold 0] ; set patchRegion 2; all patches are initialized as vacant (i.e., with no farms or households on th
end

;-----

to calculate-valley-yield
  ; calculate the yield (unadjusted) and whether water is available for each patch based on the adjusted PDSI and the presence of a suitable water
  ; table level (indicated by the hydrologic data).

  ; The following 6 lines indicate where in the apdsi-data file to find the specific values for each environment for a particular year.
  ; In the apdsi-data file, all values are placed linearly in a single line. The apdsi values for north and kinbiko are identical to each other, as
  ; are the values for natural and upland. This is consistent with what is published in the article in the Kohler and Gumerman volume (Dean et al.
  let generalapdsi item (year - 200) apdsi-data
  let northapdsi item (1100 + year) apdsi-data
  let midapdsi item (2400 + year) apdsi-data
  let naturalapdsi item (3700 + year) apdsi-data
  let uplandapdsi item (3700 + year) apdsi-data
  let kinbikoapdsi item (1100 + year) apdsi-data

  ; The following 6 lines indicate the location of the hydrology data for each environment in a given year. Note: item 1 is actually the second ite
  ; in a row of the environment data. Natural and upland have identical hydrology values, although at specific times the values are overridden in t
  ; program to reflect the rare times when the two differ.
  let generalhydro item 1 (item (year - 382) environment-data)
  let northhydro item 4 (item (year - 382) environment-data)
  let midhydro item 7 (item (year - 382) environment-data)

```

```

let naturalhydro item 10 (item (year - 382) environment-data)
let uplandhydro item 10 (item (year - 382) environment-data)
let kinbikohydro item 13 (item (year - 382) environment-data)

; See Dean et al. (2000) in the Kohler and Gumerman volume for explanation of zone identification and yield calculation.
ask patches with [patchRegion = 1] [
  if zone = "General" [set apdsi generalapdsi]
  if zone = "North" [set apdsi northapdsi]
  if zone = "Mid" [set apdsi midapdsi]
  if zone = "Natural" [set apdsi naturalapdsi]
  if zone = "Upland" [set apdsi uplandapdsi]
  if zone = "Kinbiko" [set apdsi kinbikoapdsi]

  if zone = "General" [set hydro generalhydro]
  if zone = "North" [set hydro northhydro]
  if zone = "Mid" [set hydro midhydro]
  if zone = "Natural" [set hydro naturalhydro]
  if zone = "Upland" [set hydro uplandhydro]
  if zone = "Kinbiko" [set hydro kinbikohydro]

  if (maizeZone = "No_Yield" or maizeZone = "Empty") [set yield 0]
  if (maizeZone = "Yield_1") [
    if (apdsi >= 3.0) [set yield 1153]
    if (apdsi >= 1.0 and apdsi < 3.0) [set yield 988]
    if (apdsi > -1.0 and apdsi < 1.0) [set yield 821]
    if (apdsi > -3.0 and apdsi <= -1.0) [set yield 719]
    if (apdsi <= -3.0) [set yield 617]]

  if (maizeZone = "Yield_2") [
    if (apdsi >= 3.0) [set yield 961]
    if (apdsi >= 1.0 and apdsi < 3.0) [set yield 824]
    if (apdsi > -1.0 and apdsi < 1.0) [set yield 684]
    if (apdsi > -3.0 and apdsi <= -1.0) [set yield 599]
    if (apdsi <= -3.0) [set yield 514]]

  if (maizeZone = "Yield_3") [
    if (apdsi >= 3.0) [set yield 769]
    if (apdsi >= 1.0 and apdsi < 3.0) [set yield 659]
    if (apdsi > -1.0 and apdsi < 1.0) [set yield 547]
    if (apdsi > -3.0 and apdsi <= -1.0) [set yield 479]
    if (apdsi <= -3.0) [set yield 411]]

  if (maizeZone = "Sand_dune") [
    if (apdsi >= 3.0) [set yield 1201]
    if (apdsi >= 1.0 and apdsi < 3.0) [set yield 1030]
    if (apdsi > -1.0 and apdsi < 1.0) [set yield 855]
    if (apdsi > -3.0 and apdsi <= -1.0) [set yield 749]
    if (apdsi <= -3.0) [set yield 642]]

  if mapview = "yield" [set pcolor (40 + baseYield / 140)]
]
end

;-----
to calculate-mesa-yield
; calculate the yield (unadjusted) for each patch based on the PDSI value

; The following 6 lines indicate where in the apdsi-data file to find the specific values for each environment for a particular year.
; In the apdsi-data file, all values are placed linearly in a single line. The apdsi values for north and kinbiko are identical to each other, as
; are the values for natural and upland. This is consistent with what is published in the article in the Kohler and Gumerman volume (Dean et al.

;let annualpdsi 0

;ifelse item (year - 800) pdsi-data < 0 [
;  let pdsiToAverage []
;  let increment 0
;
;  repeat (pdsiBufferYears) [
;    if ((year - 800 - increment) >= 0 ) [
;      set pdsiToAverage fput item (year - 800 - increment) pdsi-data pdsiToAverage
;      set increment increment + 1
;    ]
;  ]
;  set annualpdsi mean pdsiToAverage + 2
;]
;
; set annualpdsi item (year - 800) pdsi-data + 2 ]

ask patches with [patchRegion = 2] [
  if zone = "General" [set pdsi item (year - 800) pdsi-data]
  if zone = "Water" [set pdsi item (year - 800) pdsi-data]

  if (maizeZone = "Empty") [set yield 0]

  if (maizeZone = "Yield_1") [
    if (pdsi >= 3.0) [set yield 961 * mesaAdjustment]
    if (pdsi >= 1.0 and pdsi < 3.0) [set yield 824 * mesaAdjustment]
    if (pdsi > -1.0 and pdsi < 1.0) [set yield 684 * mesaAdjustment]
    if (pdsi > -3.0 and pdsi <= -1.0) [set yield 599 * mesaAdjustment ]
    if (pdsi <= -3.0) [set yield 514 * mesaAdjustment]]

  if mapview = "yield" [set pcolor (40 + baseYield / 140)]
]
end

```

```

;-----
to init-valley-households
; this method is for initialization of the founding households only; new households are initialized in the build-house method. Besides creating th
; initial households, this method calls a different method (find-farm-and-settlement) to actually assign a spot for each household's farming plot

set size 3
set color brown
set householdID (word "VH" householdIDindex)
set HHregion 1
set HHmatchIndex personHouseholdMatch
let initVpotfarms patches with [patchRegion = 1 and maizeZone = "Sand_dune" and ocfarm = 0]
let farmLoc one-of initVpotfarms
set farmX [pxcor] of farmLoc set farmY [pycor] of farmLoc
set householdX random 80 set householdY random 120
; type " I am householdID: " type householdID type " I am located at" type householdX print householdY
set vBestfarm self
set agedCornStocks []
set agedCornStocks fput (householdMinInitialCorn + random-float (householdMaxInitialCorn - householdMinInitialCorn)) agedCornStocks
set agedCornStocks fput (householdMinInitialCorn + random-float (householdMaxInitialCorn - householdMinInitialCorn)) agedCornStocks
set agedCornStocks fput (householdMinInitialCorn + random-float (householdMaxInitialCorn - householdMinInitialCorn)) agedCornStocks
set farmplot self
set householdAge 0
set householdNutriNeed 0
set householdSize 0
set houseIsNew? false
set deathInHousehold? false
set lastHarvest 0
determine-potfarms
find-farm-and-settlement
; type " I am householdID: " type householdID type " I am located at" type householdX print householdY
set xcor householdX
set ycor householdY
set personHouseholdMatch personHouseholdMatch + 1
set householdIDindex householdIDindex + 1

end

;-----

to init-valley-persons ; this method is for initialization of the founding population only; new births are initialized in the produce-babies method
; of census-based populations are available for input into the model. Each CensusPop file contains different founding populations a
; founding populations form the bases for different files to allow incorporation of different clan structures. The number of found
; each file is indicated by the designation "?c" at the end of the file, where ? refers to the actual clan number. NOTE: the number
; present is a file that is being used by the model must be set on the slider on the interface.
ifelse ( file-exists? "valleyPop.txt" ) ; original name of this file was CensusPop5-7c.txt
[
file-open "valleyPop.txt"
; The following code reads in all the data in the file. Each line of data contains the values for 13 attributes per agent in the order listed b
while [not file-at-end?]
[
let items read-from-string (word "[" file-read-line "]")
; Items is a temporary list of variables read in as string but converted to the appropriate variable type. "Word" concatenates
; the brackets to the line being read in, because list arguments need to be in brackets (see Netlogo user manual).
create-persons 1 [
set personIDindex personIDindex + 1
set size 2
set color violet
set personID item 0 items
set natalCommunity item 1 items
set residence item 2 items
set personHouseholdID item 3 items
set clanID item 4 items
set sex item 5 items
set age item 6 items
set headOfHousehold? item 7 items
set eldestChild? item 8 items
set married item 9 items
set fertilityAge item 10 items
set mateID item 11 items
set numChildren item 12 items
set personRegion 1
set personID word "VP" personID
if mateID != 0 [set mateID word "VP" mateID]

ask self [
match-persons-with-HH
move-persons-with-household]

ifelse headOfHousehold? = 0 [set headOfHousehold? false][set headOfHousehold? true]
ifelse eldestChild? = 0 [set eldestChild? false][set eldestChild? true]
set houseNeeded? false

if fertilityAge = 0 [set fertilityAge minFertilityAge + random (maxFertilityAge - minFertilityAge)]

ifelse sex = 1
[set fertilityEndsAge minFertilityEndsAge + random (maxFertilityEndsAge - minFertilityEndsAge)]
[set fertilityEndsAge 80] ; All males are given a fertilityEndsAge of 80, which in this version of the model is the maximum age.
; Females are determining all fertility anyway, so the specific value is not important.

set birthAge [] ; birthAge is a list of the ages at which a person has a child; it is initialized here with only the person's ID and sex.
set birthAge lput personID birthAge ; children for the initial population because we would have to calculate all that information and
set birthAge lput sex birthAge
set vitalCategory 0
set migrationCategory 0

```

```

set vitalCause "0"
set migrationCause "0"
find-age-specific-fertility
find-age-specific-mortality
update-ALHV-personNutriNeed
set personNutriShortfall 0

; The following block of code calculates the household's nutrition need by adding up the personal need of each assigned agent,
; it calculates the size of the household, and determines its age from the age of the eldest child.
ask households with [householdID = [personHouseholdID] of myself]
[
  set householdNutriNeed householdNutriNeed + [personNutriNeed] of myself
  if [eldestChild?] of myself = true [set householdAge [age] of myself + 1]
  ; The household age is assumed to be the age of the eldest child + 1 because of the length of gestation time (i.e., the
  ; eldest child was most likely born more than a year after the formation of the household)
]
]
]
file-close
]
[ user-message "The person file called is not in the current directory!" ]
end

-----
to init-mesa-households
; this method is for initialization of the founding households only; new households are initialized in the build-house method. Besides creating th
; initial households, this method calls a different method (find-farm-and-settlement) to actually assign a spot for each household's farming plot

set size 3
set color red
set householdID (word "MH" householdIDindex)
set HHregion 2
set HHmatchIndex personHouseholdMatch
let initMpotfarms patches with [(patchRegion = 2) and (maizeZone = "Yield_1") and (ocfarm = 0)]
let farmLoc one-of initMpotfarms
set farmX [pxcor] of farmLoc set farmY [pycor] of farmLoc
set householdX 81 + random (225 - 81) set householdY random 120
; type " I am householdID: " type householdID type " I am located at" type householdX print householdY
set mBestfarm self
set agedCornStocks []
set agedCornStocks fput (householdMinInitialCorn + random-float (householdMaxInitialCorn - householdMinInitialCorn)) agedCornStocks
set agedCornStocks fput (householdMinInitialCorn + random-float (householdMaxInitialCorn - householdMinInitialCorn)) agedCornStocks
set agedCornStocks fput (householdMinInitialCorn + random-float (householdMaxInitialCorn - householdMinInitialCorn)) agedCornStocks
set farmplot self
set householdAge 0
set householdNutriNeed 0
set householdSize 0
set houseIsNew? false
set deathInHousehold? false
set lastHarvest 0
determine-potfarms
find-farm-and-settlement
; type " I am householdID: " type householdID type " I am located at" type householdX print householdY
set xcor householdX
set ycor householdY
set personHouseholdMatch personHouseholdMatch + 1
set householdIDindex householdIDindex + 1

end

-----
to init-mesa-persons ; this method is for initialization of the founding population only; new births are initialized in the produce-babies method.
; of census-based populations are available for input into the model. Each CensusPop file contains different founding populations a
; founding populations form the bases for different files to allow incorporation of different clan structures. The number of found
; each file is indicated by the designation "?c" at the end of the file, where ? refers to the actual clan number. NOTE: the number
; present is a file that is being used by the model must be set on the slider on the interface.
ifelse ( file-exists? "mesaPop.txt" ) ; original name of this file was Mcensuspop1220
[
  file-open "mesaPop.txt"
  ; The following code reads in all the data in the file. Each line of data contains the values for 13 attributes per agent in the order listed b
  while [not file-at-end?]
  [
    let items read-from-string (word "[" file-read-line ")")
    ; Items is a temporary list of variables read in as string but converted to the appropriate variable type. "Word" concatenates
    ; the brackets to the line being read in, because list arguments need to be in brackets (see Netlogo user manual).
    create-persons 1 [
      set personIDindex personIDindex + 1
      set size 2
      set color orange
      set personID item 0 items
      set natalCommunity item 1 items
      set residence item 2 items
      set personHouseholdID item 3 items
      set clanID item 4 items
      set sex item 5 items
      set age item 6 items
      set headOfHousehold? item 7 items
      set eldestChild? item 8 items
      set married item 9 items
      set fertilityAge item 10 items
      set mateID item 11 items
      set numChildren item 12 items
      set personRegion 2
      set personID word "MP" personID
      if mateID != 0 [set mateID word "MP" mateID]
    ]
  ]
]

```

```

ask self [
  match-persons-with-HH
  move-persons-with-household]

ifelse headOfHousehold? = 0 [set headOfHousehold? false][set headOfHousehold? true]
ifelse eldestChild? = 0 [set eldestChild? false][set eldestChild? true]
set houseNeeded? false
if fertilityAge = 0 [set fertilityAge minFertilityAge + random (maxFertilityAge - minFertilityAge)]

ifelse sex = 1
[set fertilityEndsAge minFertilityEndsAge + random (maxFertilityEndsAge - minFertilityEndsAge)]
[set fertilityEndsAge 80] ; All males are given a fertilityEndsAge of 80, which in this version of the model is the maximum age.
; Females are determining all fertility anyway, so the specific value is not important.

set birthAge [] ; birthAge is a list of the ages at which a person has a child; it is initialized here with only the person's ID and sex.
set birthAge lput personID birthAge ; children for the initial population because we would have to calculate all that information and
set birthAge lput sex birthAge
set vitalCategory 0
set vitalCause "0"
set migrationCategory 0
set migrationCause "0"
find-age-specific-fertility
find-age-specific-mortality
update-ALHV-personNutriNeed
set personNutriShortfall 0

; The following block of code calculates the household's nutrition need by adding up the personal need of each assigned agent,
; it calculates the size of the household, and determines its age from the age of the eldest child.
ask households with [householdID = [personHouseholdID] of myself]
[
  set householdNutriNeed householdNutriNeed + [personNutriNeed] of myself
  if [eldestChild?] of myself = true [set householdAge [age] of myself + 1]
  ; The household age is assumed to be the age of the eldest child + 1 because of the length of gestation time (i.e., the
  ; eldest child was most likely born more than a year after the formation of the household)
]
]
]
file-close
]
[ user-message "The person file called is not in the current directory!" ]
end

;-----
to match-persons-with-HH

let potentialHH households with [HHregion = [personRegion] of myself]
; type "The household set is for agent: " type personID type " is " print potentialHH
; type "Agent " type personID type " is trying to find a new household and is in match-person-with-HH." type " Their mate's ID is: " print mateID
ifelse any? potentialHH with [HHmatchIndex = [personHouseholdID] of myself]
[
  ifelse (count potentialHH with [HHmatchIndex = [personHouseholdID] of myself] = 1)
  [
    let personHome one-of potentialHH with [HHmatchIndex = [personHouseholdID] of myself]
    set personHouseholdID [householdID] of personHome
;
;
    if personRegion = 1 [set personHouseholdID word "VH" personHouseholdID]
    if personRegion = 2 [set personHouseholdID word "MH" personHouseholdID]

  ]
  [type "An agent was created and multiple households have personHouseholdID. Check code."
  ]
]
[
; print "An agent was created (i.e., characteristics were read in from the input file), but the corresponding household does not exist
die
]
; type "Agent " type personID type " has been matched with household: " print personHouseholdID
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;; DEMOGRAPHIC METHODS ;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to-report calculate-age-distribution [ageDistChoice]

let population nobody
ifelse (ageDistChoice = 0) [set population persons] [set population persons with [personRegion = ageDistChoice]]

let ageDistribution [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
set ageDistribution replace-item 0 ageDistribution year
set ageDistribution replace-item 1 ageDistribution count population with [age >= 0 and age < 1]
set ageDistribution replace-item 2 ageDistribution count population with [age >= 1 and age < 5]
set ageDistribution replace-item 3 ageDistribution count population with [age >= 5 and age < 10]
set ageDistribution replace-item 4 ageDistribution count population with [age >= 10 and age < 15]
set ageDistribution replace-item 5 ageDistribution count population with [age >= 15 and age < 20]
set ageDistribution replace-item 6 ageDistribution count population with [age >= 20 and age < 25]
set ageDistribution replace-item 7 ageDistribution count population with [age >= 25 and age < 30]
set ageDistribution replace-item 8 ageDistribution count population with [age >= 30 and age < 35]
set ageDistribution replace-item 9 ageDistribution count population with [age >= 35 and age < 40]
set ageDistribution replace-item 10 ageDistribution count population with [age >= 40 and age < 45]
set ageDistribution replace-item 11 ageDistribution count population with [age >= 45 and age < 50]
set ageDistribution replace-item 12 ageDistribution count population with [age >= 50 and age < 55]
set ageDistribution replace-item 13 ageDistribution count population with [age >= 55 and age < 60]
set ageDistribution replace-item 14 ageDistribution count population with [age >= 60 and age < 65]

```

```

set ageDistribution replace-item 15 ageDistribution count population with [age >= 65 and age < 70]
set ageDistribution replace-item 16 ageDistribution count population with [age >= 70 and age < 75]
set ageDistribution replace-item 17 ageDistribution count population with [age >= 75 and age < 80]
set ageDistribution replace-item 18 ageDistribution count population with [age >= 80 and age < 85]
set ageDistribution replace-item 19 ageDistribution count population with [age >= 85 and age < 90]
set ageDistribution replace-item 20 ageDistribution count population with [age >= 90]

report ageDistribution
end

;-----

to find-mate
; This method determines who the mate of an eligible unmarried woman will be. In order to marry she must be able to build a new house. In the blc
; calls the build-house method, if she successfully builds a house, she sets several person variables, including mateID, which is the personID of
; has chosen. She then asks that person to set his mateID to her personID, his householdID to her householdID, and his married status to 1 ("curr
; also removed from their previous households and move into their newly assigned household.

set houseNeeded? true

let valley-pot-mates persons with [(personRegion = 1) and (sex = 0) and (age >= minFertilityAge) and ((age >= [age] of myself - 10) and (age <= [a
and (headOfHousehold? = false) and ((married = 0) or (married = 2)) and (clanID != [clanID] of myself) and (personHouseholdID != [personHousehc

let mesa-pot-mates persons with [(personRegion = 2) and (sex = 0) and (age >= minFertilityAge) and ((age >= [age] of myself - 10) and (age <= [a
and (headOfHousehold? = false) and ((married = 0) or (married = 2)) and (clanID != [clanID] of myself) and (personHouseholdID != [personHousehc

let local-pot-mates no-turtles
let other-pot-mates no-turtles
let mates-anywhere no-turtles
let possible-mate nobody

if personRegion = 1 [
set local-pot-mates valley-pot-mates
set other-pot-mates mesa-pot-mates]

if personRegion = 2 [
set other-pot-mates valley-pot-mates
set local-pot-mates mesa-pot-mates]

set mates-anywhere (turtle-set local-pot-mates other-pot-mates)

ifelse any? mates-anywhere [
; type " Person : " type personID print " has trying to marry and is about to call build-house."
build-house ; A female looking for a mate has to have a house available in order to marry. If a house can be built, the variable houseNeeded? is
; false in build-house. If she cannot build a house (e.g., if there is no space available and houseNeeded? is still true, she remain
; and will look for a husband in the next time tick. ; This method first looks for a mate from within the community. If a suitable
; found, she looks in the other region before calling marry outsider.

ifelse houseNeeded? = false [
; type " Person : " type personID print " has successfully built a house."
set married 1
set headofHousehold? true

ifelse any? local-pot-mates
[set possible-mate one-of local-pot-mates]
; type "I am a new wife, person " type personID type " trying to find husband and there are local males available."
[set possible-mate one-of other-pot-mates
;type "I am a new wife, person " type personID type " trying to find husband and there are no local males available."
]
set mateID [personID] of possible-mate
; type "I am a new wife, person " type personID type " and have found a husband. He is person " print mateID
ask possible-mate
[
set mateID [personID] of myself
set personHouseholdID [personHouseholdID] of myself
set married 1
if personRegion != [personRegion] of myself [
set migrationCategory 3
if personRegion = 1 [set migrationCause "31V"]
if personRegion = 2 [set migrationCause "31M"]
write-to-demog-file
]
]

ask persons with [personHouseholdID = [personHouseholdID] of myself]
[
move-persons-with-household
]

]

[set houseNeeded? false] ; This is the else part of ifelse houseNeeded?. houseNeeded? is set to false because in this situation a female cannot
; stays in her existing house (and so does not need a new house).

[
marry-outsider ; This is the else part of ifelse any? mates-anywhere
]
end

;-----

to marry-outsider

```

```
; This method creates a potential mate for a woman when no others are available in the community. It is done to guarantee
; that a woman who comes of age or who loses her husband by death can make a new household. This is needed to keep this model
; equivalent to the original model, which had no constraints on fissioning other than finding suitable farm land.
; Eventually this method may involve finding a mate from another community rather than just creating one (when more than one
; community is incorporated into the model).
```

```
hatch-persons 1 [
  set personRegion [personRegion] of myself
  if personRegion = 1 [set personID (word "VOP" personIDindex)]; valley outside person (new man created by valley woman)
  if personRegion = 2 [set personID (word "MOP" personIDindex)]; mesa outside person (new man created by mesa woman)
  set personHouseholdID [personHouseholdID] of myself ; This is a fail-safe to make sure that the calling agent does, in fact, marry
  ; the agent being created. That agent should already have the same personHouseholdID,
  ; however, since it is a clone of the calling agent.

  set natalCommunity 5 ; 5 is an arbitrary ID to designate an unspecified outside community

  ;The following four statements ensure that the designated spouse does not come from the same clan
  let tempClan random numClans
  while [(tempClan = 0) or (tempClan = [clanID] of myself)]
    [set tempClan random numClans]
  set clanID tempClan

  set sex 0
  ifelse [age] of myself < 21
  [set age 16 + random 6]
  [set age [age] of myself + (-5 + random 11)]
  set color blue
  set size 2
  set headOfHousehold? false
  set married 0 ; the actual act of marriage occurs further below in this method
  set mateID 0
  set numChildren 0 ; Since we are creating these males, we assume they have no children; in later versions outside males will have their own

  set fertilityAge age
  set fertilityEndsAge 80 ; All males are given a fertilityEndsAge of 80, which in this version of the model is the maximum age.
  ; Females are determining all fertility anyway, so the specific value is not important.

  set birthAge [] ; birthAge is a list of the ages at which a person has a child; it is initialized here with only the person's ID and sex.
  set birthAge lput personID birthAge
  set birthAge lput sex birthAge
  find-age-specific-fertility
  find-age-specific-mortality
  set personNutriNeed personBaseNutriNeed
  set personNutriShortfall 0
]
```

```
set personIDindex personIDindex + 1 ; this increments the personIDindex so that the next newly created agent has a unique ID number
```

```
; Because of the way outside-mates are created, their personHouseholdID must be the same as the calling agent and their natal community must be the same
; All other constraints here are the same as those for potential mates in the find-mate method.
```

```
let outside-mates persons with [(sex = 0) and (age >= fertilityAge) and ((age >= [age] of myself - 10) and (age <= [age] of myself + 20))
and (headOfHousehold? = false) and ((married = 0) or (married = 2)) and (clanID != [clanID] of myself) and (personHouseholdID = [personHouseholdID]
of myself) and (natalCommunity != [natalCommunity] of myself)]
```

```
; The following process is the same as that for the find-mate method.
```

```
ifelse any? outside-mates
```

```
[ ; type " Person : " type personID print " has trying to marry an outsider and is about to call build-house."
  build-house
  ifelse houseNeeded? = false
```

```
[ ; type " Person : " type personID print " is trying to marry an outsider and successfully built a house."
```

```
set married 1
set headOfHousehold? true
let new-mate one-of outside-mates
set mateID [personID] of new-mate
ask new-mate
[
  set mateID [personID] of myself
  set personHouseholdID [personHouseholdID] of myself
  set married 1
  set migrationCategory 3
  set migrationCause "30X" ; mate is a migrant whose new wife is marrying for the first time
  write-to-demog-file
]
ask persons with [personHouseholdID = [personHouseholdID] of myself]
```

```
[
  move-persons-with-household
]
```

```
]
[set houseNeeded? false]
]
[print "ERROR. I made a new man. I should have a husband, but something went wrong! Please help!"]
```

```
end
```

```
;-----
```

```
to remarry ; this method is called in the death aftermath method after a person (male or female) has been widowed
```

```
if sex = 0
[
  if any? other persons with [personHouseholdID = [personHouseholdID] of myself][reassign-to-clan] ; family members of a widower move in with
  ; members of their own clan, rather than s
  find-next-wife
]
if sex = 1
[
  ifelse age > fertilityEndsAge ; only widows within the reproductive span are allowed to remarry
```



```

]
  type "ERROR. Agent " type personID type " is a widow above FEA. Her household ID is " type personHouseholdID print ". She is calling this in
]
]
find-next-husband
]
]
end
end

;-----
to find-next-husband ; this method allows a newly widowed woman of reproductive age to find a suitable husband. If one is not available in the vall
; following the same constraints as in the find-mate and marry-outsider methods, except that at this time she already has a hc
; build one) and her new husband moves in with her.

let valley-pot-husbands persons with [(personRegion = 1) and (sex = 0) and (age >= minFertilityAge) and (age >= [age] of myself - 10)
and (headOfHousehold? = false) and ((married = 0) or (married = 2)) and (clanID != [clanID] of myself) and (personHouseholdID != [personHousehc

let mesa-pot-husbands persons with [(personRegion = 2) and (sex = 0) and (age >= minFertilityAge) and (age >= [age] of myself - 10)
and (headOfHousehold? = false) and ((married = 0) or (married = 2)) and (clanID != [clanID] of myself) and (personHouseholdID != [personHousehc

let local-pot-husbands no-turtles
let other-pot-husbands no-turtles
let husbands-anywhere no-turtles

if personRegion = 1 [
set local-pot-husbands valley-pot-husbands
set other-pot-husbands mesa-pot-husbands]

if personRegion = 2 [
set other-pot-husbands valley-pot-husbands
set local-pot-husbands mesa-pot-husbands]

set husbands-anywhere (turtle-set local-pot-husbands other-pot-husbands)

; This method first looks for a mate from within the region, then looks in another region. If a suitable mate cannot be found, an outsider is brc
ifelse any? husbands-anywhere [

; type "I am a widow with personID: " type personID print " I am looking for a new husband."

ifelse any? local-pot-husbands
[
set married 1

let possible-husband one-of local-pot-husbands
set mateID [personID] of possible-husband
ask possible-husband
[
set mateID [personID] of myself
set personHouseholdID [personHouseholdID] of myself
set married 1
; type " I am marrying a widowed woman from within my community. I am person number: " type personID type " My new wife is: " print mateID
]
ask persons with [personHouseholdID = [personHouseholdID] of myself] [move-persons-with-household]
]
; Because the husbands-anywhere is true and there was no suitable husband locally, we know there must be a husband in the other region. This f
set married 1

let possible-husband one-of other-pot-husbands
set mateID [personID] of possible-husband
ask possible-husband
[
set mateID [personID] of myself
set personHouseholdID [personHouseholdID] of myself
set married 1
set migrationCategory 3
if personRegion = 1 [set migrationCause "30V"]
if personRegion = 2 [set migrationCause "30M"]
move-persons-with-household
; type " I am marrying a widowed woman from outside of my community. I am person number: " type personID type " My new wife is: " print mateID
write-to-demog-file
]
]
]

; this occurs when there are no husbands available in either region
hatch-persons 1 [
set personRegion [personRegion] of myself
if personRegion = 1 [set personID (word "VOP" personIDindex)]; valley outside person (new man created by valley woman)
if personRegion = 2 [set personID (word "MOP" personIDindex)]; mesa outside person (new man created by mesa woman)
set personHouseholdID [personHouseholdID] of myself ; This is a fail-safe to make sure that the calling agent does, in fact, marry
; the agent being created. That agent should already have the same personHouseholdID,
; however, since it is a clone of the calling agent.

set natalCommunity 5 ; 5 is an arbitrary ID to designate an unspecified outside community

;The following four statements ensure that the designated spouse does not come from the same clan
let tempClan random numClans
while [(tempClan = 0) or (tempClan = [clanID] of myself)]
[set tempClan random numClans]
set clanID tempClan

set sex 0
ifelse [age] of myself < 21
[set age 16 + random 6]
[set age [age] of myself + (-5 + random 11)]
set color blue

```

```

set size 2
set headOfHousehold? false
set married 0 ; the actual act of marriage occurs further below in this method
set mateID 0
set numChildren 0 ; Since we are creating these males, we assume they have no children; in later versions outside males will have their own

set fertilityAge age

ifelse sex = 1
[set fertilityEndsAge minFertilityEndsAge + random (maxFertilityEndsAge - minFertilityEndsAge)]
[set fertilityEndsAge 80] ; All males are given a fertilityEndsAge of 80, which in this version of the model is the maximum age.
; Females are determining all fertility anyway, so the specific value is not important.

set birthAge [] ; birthAge is a list of the ages at which a person has a child; it is initialized here with only the person's ID and sex.
set birthAge lput personID birthAge
set birthAge lput sex birthAge
find-age-specific-fertility
find-age-specific-mortality
set personNutriNeed personBaseNutriNeed
set personNutriShortfall 0
]

set personIDindex personIDindex + 1 ; this increments the personIDindex so that the next newly created agent has a unique ID number

; Because of the way outside-husbands are created, their personHouseholdID must be the same as the calling agent and their natal community must be
; All other constraints here are the same as those for potential mates in the find-mate method.
let outside-husbands persons with [(sex = 0) and (age >= fertilityAge) and (age >= [age] of myself - 10)
and (headOfHousehold? = false) and ((married = 0) or (married = 2)) and (clanID != [clanID] of myself) and (personHouseholdID = [personHouseholdID]
and (natalCommunity != [natalCommunity] of myself)]

; The following process is the same as that for a potential husband from within the community.
if any? outside-husbands
[
set married 1
let new-husband one-of outside-husbands
set mateID [personID] of new-husband
ask new-husband
[
set mateID [personID] of myself
set married 1
set migrationCategory 3
set migrationCause "30X" ; mate is a migrant whose new wife has been widowed
write-to-demog-file
]
ask persons with [personHouseholdID = [personHouseholdID] of myself] [move-persons-with-household]
]
]
ask households with [householdID = [personHouseholdID] of myself]
[
update-householdSize
update-ALHV-householdNutriNeed
]
end

;-----
to find-next-wife ; this method allows a newly widowed man to find a suitable wife. This is the only situation in the simulation where males are allowed
; from within the valley can either already be heads of households or they can be never married, in which case they must first be
; in the find-mate method). If the widower finds a suitable mate, he moves into her household by himself (any other household men
; wife's death are reassigned prior to this in the death aftermath method). If he cannot find a suitable mate, he dies/leaves the

let valley-pot-wives persons with [(personRegion = 1) and (sex = 1) and (age >= minFertilityAge) and ((married = 0) or (married = 2)) and (clanID
and (personHouseholdID != [personHouseholdID] of myself)]

let mesa-pot-wives persons with [(personRegion = 2) and (sex = 1) and (age >= minFertilityAge) and ((married = 0) or (married = 2)) and (clanID
and (personHouseholdID != [personHouseholdID] of myself)]

let local-pot-wives no-turtles
let other-pot-wives no-turtles
let wives-anywhere no-turtles

let newWifeFound? false
let possibleWife nobody
let countWives 0
ask valley-pot-wives [set wifeChecked? false]
ask mesa-pot-wives [set wifeChecked? false]

if personRegion = 1 [
set local-pot-wives valley-pot-wives
set other-pot-wives mesa-pot-wives]

if personRegion = 2 [
set other-pot-wives valley-pot-wives
set local-pot-wives mesa-pot-wives]

set wives-anywhere (turtle-set local-pot-wives other-pot-wives)

ifelse any? wives-anywhere
[
; type "I am a widower with personID: " type personID print "I am looking for a new wife."
if any? local-pot-wives
[
set countWives count local-pot-wives
while [countWives > 0 and not newWifeFound?]
[

```

```

set possibleWife one-of local-pot-wives with [wifeChecked? = false]
ask possibleWife
[
set wifeChecked? true
ifelse [headOfHousehold?] of self
[ask myself [set newWifeFound? true]]
[
set houseNeeded? true
; type " Person : " type personID print " is trying to remarry and is about to call build-house."
build-house
if houseNeeded? = false [ask myself [set newWifeFound? true
]]
]]
]
set countWives count local-pot-wives with [wifeChecked? = false]
; We could change structure of this method to collect data about whether a man couldn't find a wife because there were no local women
; To distinguish between no local women and no local land we would have to make even more changes
if not newWifeFound? [ ; either there was no potential wife in local area or there were some but they couldn't build a house, so the widower will
if any? other-pot-wives
[
set countWives count other-pot-wives
while [countWives > 0 and not newWifeFound?]
[
set possibleWife one-of other-pot-wives with [wifeChecked? = false]
ask possibleWife
[
set wifeChecked? true
ifelse [headOfHousehold?] of self
[ask myself [set newWifeFound? true]]
[
set houseNeeded? true
; type " Person : " type personID print " is trying to remarry in someone from another region and is about to call build-house."
build-house
if houseNeeded? = false [ask myself [set newWifeFound? true]]
]]
]
set countWives count other-pot-wives with [wifeChecked? = false]
; We could change the structure of this method to collect data about whether a man couldn't find a wife because there were no other women
; To distinguish between no other women and no other land we would have to make even more changes
]
]
]
ifelse newWifeFound?
[
set mateID [personID] of possibleWife
set married 1
set personHouseholdID [personHouseholdID] of possibleWife
; type " I am a widower, person: " type personID type "I have found a new wife. Her ID is: " print mateID
if personRegion != [personRegion] of possibleWife
[
set migrationCategory 4
if personRegion = 1 [set migrationCause "41V"]
if personRegion = 2 [set migrationCause "41M"]
write-to-demog-file
set personRegion [personRegion] of possibleWife
;type "I am a widower who has found a new wife in another region. I am personID: " type personID type "My new wife is " print mateID
]
ask possibleWife
[
set mateID [personID] of myself
set married 1
set headOfHousehold? true
]
ask persons with [personHouseholdID = [personHouseholdID] of myself]
[
move-persons-with-household
]
]
]
; this category should not include migration as a result no women were available anywhere, it can only be the result of no land anywhere or a la
set migrationCategory 4
set migrationCause "41X"
set personHouseholdID word "TMM-" personHouseholdID
write-to-demog-file
die
]
[
;no wives available anywhere
set migrationCategory 4
set migrationCause "42X"
write-to-demog-file
die
]; this is the death/migration of a man who could not find any available women
end
-----;-----
to reassign-to-clan ; this method is used to reassign survivors to another household within their own clan. Three classes of survivors can be reass
; household where the head of household (female) dies; the husband tries to remarry, b) a widow above reproductive age and all
; who have been orphaned.
; type " We are from HH: " type personHouseholdID print " we are are being reassigned. "

```

```

let reassigned-group no-turtles ; the following statements allow us to omit a surviving husband from the group to be reassigned -- he tries to re
let newHeadHouse nobody

; Determined group to be reassigned
ifelse (sex = 0) and (married = 2)
[set reassigned-group other persons with [personHouseholdID = [personHouseholdID] of myself]]
[set reassigned-group persons with [personHouseholdID = [personHouseholdID] of myself]]

; Determines the clan-checker
let clan-checker one-of reassigned-group ; any agent in the reassigned group can direct the choice of which new household to move to
; ask clan-checker [type "I am the clan-checker. My ID is: " type personID type " My clan ID is: " type clanID type "My personHouseholdID is: " ]
ask reassigned-group
[
; type "I am in a reassigned group. My personID is: " type personID type " My clanID is: " type clanID type "My householdID is: " print personID
if clanID != [clanID] of clan-checker
[
print " Error: Multiple clans are represented in this reassigned group. Check methods!"
]
]
]

; Determines which new clan households are able to receive the reassigned-group. First looks in home region and then in neighboring area(s).
let possible-newHeadHouse persons with [(personRegion = [personRegion] of clan-checker) and (personHouseholdID != [personHouseholdID] of clan-checker)
and (clanID = [clanID] of clan-checker) and headOfHousehold?]

let possible-newRegionHeadHouse persons with [(personRegion != [personRegion] of clan-checker) and (personHouseholdID != [personHouseholdID] of clan-checker)
and (clanID = [clanID] of clan-checker) and headOfHousehold?]

ifelse any? possible-newHeadHouse [
set newHeadHouse one-of possible-newHeadHouse] ; a random household that has a head of household in the same clan as the survivors is chosen

[if any? possible-newRegionHeadHouse
[set newHeadHouse one-of possible-newRegionHeadHouse
; Group has to move to a clan household in a neighboring region, nothing available in home region
ask reassigned-group [
set migrationCategory 4
if personRegion = 1 [set migrationCause "44V"] ; clan household not available in the valley for valley persons
if personRegion = 2 [set migrationCause "44M"] ; clan household not available in the mesa for mesa persons
set personHouseholdID word "TRC-" personHouseholdID
write-to-demog-file
]
]
]
]
; Procedure for actual reassignment of reassigned groups.
ifelse (newHeadHouse != nobody) [
ask reassigned-group
[
set personHouseholdID [personHouseholdID] of newHeadHouse
move-persons-with-household
; type "I am in a reassigned group and have found a new home. My personID is: " type personID type " My new household is: " print personHouseholdID
]
ask households with [householdID = [personHouseholdID] of newHeadHouse]
[
update-householdSize
update-ALHV-householdNutriNeed
; if (householdID = "VH1") or (householdID = "VH2") [type "Reassign to clan. Household size is " type householdSize type "NutriNeed: " print householdSize]
]
]
; No clan household available anywhere in model regions.
[ask reassigned-group [
set migrationCategory 4
set migrationCause "44X" ; agent could not find a clan households anywhere and move on to another region (or die)
write-to-demog-file
die]
] ; persons who cannot find a new household in any region die

```

end

```

;-----
to build-house
; This method is our ALHV fission method. It is called when a women tries to marry and creates a new household, fills the
; maize stocks with a gift from the parent household, and finds a spot for the household's farming plot and settlement.
; type "Person: " type personID type " has personHouseholdID of " type personHouseholdID print " is at the beginning of build house"
let newHouse nobody
ask households with [householdID = [personHouseholdID] of myself]
[
; type "HouseholdID : " type householdID print " is going to clone itself."
hatch 1
[
set newHouse self
set size 3
; set color red
if HHregion = 1 [set householdID (word "VH" householdIDindex) set color brown]
if Hhregion = 2 [set householdID (word "MH" householdIDindex) set color red]
; set newHouseID householdID
; type " The newHouse ID is: " print newHouseID
; type "The newHouse is : " print newHouse
set householdAge 0
set householdNutriNeed personBaseNutriNeed * 2 ; this initializes the householdNutriNeed; the actual value will be calculated as persons move
set householdSize 0
set lastHarvest 0
set siteNeeded? true
set houseIsNew? true
set deathInHousehold? false
]
]
]

```

```

ask newHouse
[
; type "I am householdID : " type householdID print " and I am going to try to find a new farm and settlement."
determine-potfarms ; this needs to be called to ensure the potfarms list is up-to-date whenever a new house is built
find-farm-and-settlement
; type "I am householdID : " type householdID print " I have gone past find farm and settlement."
]

; If the house that is created above cannot find a suitable farming plot and settlement in the find-farm-and-settlement method, it dies and there
; will be no household with the householdID designated above in the hatch block. If that is the case, nothing further happens, which means that
; the calling agent continues to be part of her original household (i.e., her personHouseholdID is only changed in the block below where a new hous
; is designated, and that household is given the maize gift from the parents before her personHouseholdID is changed so that the parent household c
; still be identified).

ifelse newHouse != nobody
[
give-maize-gift (newHouse)
set houseNeeded? false
set personHouseholdID [householdID] of newHouse
set householdIDindex householdIDindex + 1
]
[
; No suitable location was found for new house. Do nothing.
]
end

-----

to give-maize-gift [newHousehold]
; This method takes a user-designated proportion of the corn stocks from a parent household and give it to the daughter's newly created household

ask households with [householdID = [personHouseholdID] of myself]
[
let ysParent yearsOfStock
while [ysParent > -1]
[
set agedCornStocks replace-item ysParent agedCornStocks ((1 - weddingMaizeGift) * (item ysParent agedCornStocks))
set ysParent ysParent - 1
]
]
]
ask newHousehold
[
let ysNew yearsOfStock
while [ysNew > -1]
[
set agedCornStocks replace-item ysNew agedCornStocks ((weddingMaizeGift / (1 - weddingMaizeGift)) * (item ysNew agedCornStocks))
set ysNew ysNew - 1
]
]
]
end

-----

to produce-babies
hatch-persons 1 [
set personRegion [personRegion] of myself
if personRegion = 1 [set personID (word "VP" personIDindex)]
if personRegion = 2 [set personID (word "MP" personIDindex)]
set age 0
let sex-prob random-float 1.0
ifelse sex-prob < 0.5
[set sex 0]
[set sex 1]
set headOfHousehold? false
set married 0
set mateID 0
set numChildren 0
ifelse ([numChildren] of myself = 0) [set eldestChild? true][set eldestChild? false]

set fertilityAge minFertilityAge + random (maxFertilityAge - minFertilityAge)

ifelse sex = 1
[set fertilityEndsAge minFertilityEndsAge + random (maxFertilityEndsAge - minFertilityEndsAge)]
[set fertilityEndsAge 80] ; All males are given a fertilityEndsAge of 80, which in this version of the model is the maximum age.
; Females are determining all fertility anyway, so the specific value is not important.

set birthAge [] ; birthAge is a list of the ages at which a person has a child; it is initialized here with only the person's ID and sex.
set birthAge lput personID birthAge
set birthAge lput sex birthAge
find-age-specific-fertility
find-age-specific-mortality
update-ALHV-personNutriNeed
set personNutriShortfall 0
ask households with [householdID = [personHouseholdID] of myself]
[
set householdNutriNeed householdNutriNeed + [personNutriNeed] of myself
]
]
]

```

```

set numChildren numChildren + 1
set birthAge lput age birthAge ; this adds the age of the mother at the birth of this child to her birth age list
set vitalCategory 1
if personRegion = 1 [set vitalCause "10V"]
if personRegion = 2 [set vitalCause "10M"]
; write-to-demog-file
ask persons with [personID = [mateID] of myself]
[
set numChildren numChildren + 1
set birthAge lput age birthAge ; this adds the age of the father at the birth of this child to his birth age list
set vitalCategory 1
if personRegion = 1 [set vitalCause "10V"]
if personRegion = 2 [set vitalCause "10M"]
; write-to-demog-file
]

set personIDindex personIDindex + 1 ; this increments the personIDindex so that the next newly created agent has a unique ID number
end

;-----

to find-age-specific-fertility ; the specific values indicated in the comments below are from the original ALHV disaggregate model
ifelse ((age >= 0 and age < fertilityAge) or age >= fertilityEndsAge) [set fertility 0.00] ; 0.000
[
ifelse sex = 1
[
if (age >= fertilityAge and age < 20) [set fertility item 0 age-specificFertility] ; 0.094
if (age >= 20 and age < 25) [set fertility item 1 age-specificFertility] ; 0.256
if (age >= 25 and age < 30) [set fertility item 2 age-specificFertility] ; 0.256
if (age >= 30 and age < 35) [set fertility item 3 age-specificFertility] ; 0.208
if (age >= 35 and age < 40) [set fertility item 4 age-specificFertility] ; 0.144
if (age >= 40 and age < 45) [set fertility item 5 age-specificFertility] ; 0.060
if (age >= 45 and age < fertilityEndsAge) [set fertility item 6 age-specificFertility] ; 0.012
]
[set fertility 1.0] ; the process of birth is governed by females. Males enter indirectly because a female must be married in order to have a
; fertility rate does not affect this process. Since all agents possess this variable, we must set it at something for ma
]
end

;-----

to find-age-specific-mortality
; The constants subtracted from each of these lines refers to the probability of death by starvation estimated from our experimental study
; using the demogUpdate version of the model. That model sets the maximum death age at 57, so we do not have estimates for older ages, but
; the values are so low, we just kept them the same throughout the longer life span modeled here. See the file "starvation study analysis.xlsx"
; for details on the experimental study. Because we are subtracting out the values for probability of starvation, the mortality rates
; calculated below give the age-specific probabilities of death due to all other causes.

if (age >= 0 and age < 1) [set mortality item 0 age-specificMortality - 0.038]
if (age >= 1 and age < 5) [set mortality ((item 1 age-specificMortality - 0.032) / 4.0)]
if (age >= 5 and age < 10) [set mortality ((item 2 age-specificMortality - 0.032) / 5.0)]
if (age >= 10 and age < 15) [set mortality ((item 3 age-specificMortality - 0.026) / 5.0)]
if (age >= 15 and age < 20) [set mortality ((item 4 age-specificMortality - 0.013) / 5.0)]
if (age >= 20 and age < 25) [set mortality ((item 5 age-specificMortality - 0.004) / 5.0)]
if (age >= 25 and age < 30) [set mortality ((item 6 age-specificMortality - 0.005) / 5.0)]
if (age >= 30 and age < 35) [set mortality ((item 7 age-specificMortality - 0.006) / 5.0)]
if (age >= 35 and age < 40) [set mortality ((item 8 age-specificMortality - 0.006) / 5.0)]
if (age >= 40 and age < 45) [set mortality ((item 9 age-specificMortality - 0.004) / 5.0)]
if (age >= 45 and age < 50) [set mortality ((item 10 age-specificMortality - 0.004) / 5.0)]
if (age >= 50 and age < 55) [set mortality ((item 11 age-specificMortality - 0.003) / 5.0)]
if (age >= 55 and age < 60) [set mortality ((item 12 age-specificMortality - 0.001) / 5.0)]
if (age >= 60 and age < 65) [set mortality ((item 13 age-specificMortality - 0.001) / 5.0)]
if (age >= 65 and age < 70) [set mortality ((item 14 age-specificMortality - 0.001) / 5.0)]
if (age >= 70 and age < 75) [set mortality ((item 15 age-specificMortality - 0.001) / 5.0)]
if (age >= 75 and age < 80) [set mortality ((item 16 age-specificMortality - 0.001) / 5.0)] ; in this life table, the mortality of 75-80 = 1,
; the value for probability of starving, which would be 0.001 in oth

if (age >= 80) [set mortality item 17 age-specificMortality]

; The above schedule (STUDY MORTALITY SCHEDULE 1) was taken from Weiss's model life table MT: 20.0-55.0 with an infant mortality of 0.233 (p. 12
; Memoir). This table was chosen because it gives what we think are reasonable values for total childhood mortality, the proportion of the
; American Antiquity population that lives beyond age 50, and the proportion of the population that lives beyond age 70. Total childhood mortality
; is 45%; Gurven et al. 2007 estimated 36% for present-day forager/horticultural populations, but it is reasonable to assume that mortality during
; study period was somewhat higher. This life table has 6.1% of the population over age 50 and 0.4% over age 70, which we think best approximates
; estimates of population derived from Southwestern skeletal samples (Nelson et al. 1994).

end

;-----

to ALHV-death
; This method is called near the beginning of the go method and governs the order in which different death processes are called. Only two process
; at the present time: starvation and age-specific dying. Eventually more specific causes of individual agent death will be included in this or a

let block-order random-float 1.0
ifelse block-order < 0.5
[
starve
age-specific-dying
]
[
age-specific-dying
starve
]
end

```

```

-----
to starve
; The underlying assumption about death by starvation is that the youngest will die first. We first determine if there is a household nutritional
; and if that is the case, we remove agents (youngest to oldest) until the nutritional need of the household is low enough that all needs can be
; existing maize stocks (i.e., householdNutriShortfall becomes <= 0). If an agent dying by starvation is married, the method also changes the mar
; of the surviving spouse.

  if any? households [
    ask households
  ]
  [
    if (householdNutriShortfall > 0)
    [
      let household-members persons with [personHouseholdID = [householdID] of myself]
      if any? household-members
      [
        while [householdNutriShortfall > 0]
        [
          let youngest min-one-of household-members [age]
          set householdNutriShortfall householdNutriShortfall - [personNutriNeed] of min-one-of household-members [age]
          if ([married] of youngest = 1)
          [
            ask persons with [mateID = [personID] of youngest]
            [
              ifelse (sex = 1 and age > fertilityEndsAge) ; females above reproductive age are assigned a marital status of 3 to prevent remarriage,
              [
                set married 3
                set headOfHousehold? false
              ]
              [set married 2]
              set mateID 0
            ]
          ]
          ask youngest
          [
            ask households with [householdID = [personHouseholdID] of myself] [set deathInHousehold? true]
            set vitalCategory 2
            if (personRegion = 1) [set vitalCause "21V"]
            if (personRegion = 2) [set vitalCause "21M"]
            write-to-demog-file
            die
          ]
          update-householdSize
          update-ALHV-householdNutriNeed
          ; if (householdID = "VH1") or (householdID = "VH2") [type "Starvation 1 (shortfall). Household size is " type householdSize type " NutriNe
          ]
        ]
      ]
    ]
  ]
end

```

```

-----
to age-specific-dying
; At the present time this method only considers death by old age, which is assumed to occur within the same user-defined age range for all agents,
; they don't die before reaching their designated death age. If an agent dying of old age is married, the method also changes the marital state of

ask persons
[
  let deathHouseholdID personHouseholdID
  if random-float 1.0 < mortality
  [
    if married = 1
    [
      ask persons with [mateID = [personID] of myself]
      [
        ifelse (sex = 1 and age > fertilityEndsAge) ; females above reproductive age are assigned a marital status of 3 to prevent remarriage,
        [
          set headOfHousehold? false
          set married 3
        ]
        [set married 2]
        set mateID 0
      ]
    ]
    ask households with [householdID = [personHouseholdID] of myself]
    [
      set householdNutriShortfall householdNutriShortfall - [personNutriNeed] of myself
      set deathInHousehold? true
    ]
    set vitalCategory 2
    if (personRegion = 1) [set vitalCause "20V"] ; at the present time, cause 10 is any death other than by starvation
    if (personRegion = 2) [set vitalCause "20M"]
    write-to-demog-file
    die
  ]
]
ask households with [deathInHousehold?]
[
  update-householdSize
  update-ALHV-householdNutriNeed
  ; if (householdID = "VH1") or (householdID = "VH2") [type "ASM 1. Household ID : " type householdID type "ASM 1 . Household size is " type hc
  ]
]

```

```

end
;-----
to death-aftermath ; This method deals with any issues that arise as a consequence of someone dying, including relocation of survivors (e.g., chil
; whenever both parents have died), removal of households if the last person dies or moves to a new house as a consequence of s
; If one member of a married couple dies, the method initiates specific widow or widower behavior methods; if both spouses die,
; survivors to a new household is called. Households and the individuals within them can also die when a household is not able
; new location if forced to move; this process is modeled within the findFarmAndSettlement method.

; if (householdID = "VH1") or (householdID = "VH2") [type "Death aftermath start. Household ID : " type householdID type " Household size is " t

ifelse householdSize > 1
[
  let widowed persons with [(personHouseholdID = [householdID] of myself) and (married = 2)] ; widows above reproductive age are not allowed to
; marital status (3) and are excluded from this wid
  if any? widowed
  [
    ask widowed [
      ; type " I am person: " type personID type " and I have been widowed. My person ID is : " print personID
      remarry]
    ]
  if not any? persons with [(personHouseholdID = [householdID] of myself) and (married = 1)] ; this ensures that the composition of households
; altered except for the removal of the dying age
; then household reassignment of survivors must e
  [
    if any? persons with [personHouseholdID = [householdID] of myself]
    [
      ask one-of persons with [personHouseholdID = [householdID] of myself] [reassign-to-clan]] ; this situation involves orphans and post-ferti
; reassign-to-clan and ensure that all household
  ]
]
if householdSize = 1
[
  let last-resident persons with [personHouseholdID = [householdID] of myself]
  ask last-resident
  [
    if (married = 0 or married = 3) [reassign-to-clan]
    if (married = 2) [remarry]
  ]
]
]
end
;-----

to move-persons-with-household ; this method checks to make sure that each person trying to move has one and only one assigned household, and then
; it ensures that they move with the household if the latter changes location
let household-site households with [householdID = [personHouseholdID] of myself]
ifelse any? household-site
[
  ifelse (count household-site) = 1
  [
    move-to one-of households with [householdID = [personHouseholdID] of myself]
    set personX [pxcor] of households with [householdID = [personHouseholdID] of myself]
    set personY [pycor] of households with [householdID = [personHouseholdID] of myself]
  ]
  [
    print "Check data file; there is more than one household with this agent's householdID!"
  ]
]
[
  print "Check data file; there is no household associated with this agent's householdID!"
  die
]
end
;-----

;;;;;;;;;;;;;
;;; AGRICULTURAL METHODS ;;;
;;;;;;;;;;;;;

;to find-new-farm-and-settlement
; if year != 800 [type "I am HH ID : " type householdID print " and I am needing a new place."]
;
; ifelse ((length vPotfarms + length mPotfarms) > 0)
; [
;   if HHregion = 1 [set siteNeeded? search-valley]
;   if HHregion = 2 [set siteNeeded? search-mesa]
;   if siteNeeded? = true [die]
; ]
; [die]
;
;end
;-----

```



```

to find-farm-and-settlement

; if year != 800 [type "I am householdID : " type householdID print " and I am in FFS."]
let numfarms (length vPotfarms + length mPotfarms)
; type "Numfarms = " print numfarms
ifelse (numfarms > 0)
[
  if HHregion = 1 [set siteNeeded? search-valley]
  if HHregion = 2 [set siteNeeded? search-mesa]
]
ifelse houseIsNew? = true
[
  type "Household : " type householdID print " is a new house that could not find a space in their home region and is going to die. "
  die
]
; ; this is the else

if siteNeeded? = true [
; type "Household : " type householdID print " is an established house and could not find a space in home region and is going to search the
  if HHregion = 1 [set siteNeeded? search-mesa]
  if HHregion = 2 [set siteNeeded? search-valley]
]

ifelse siteNeeded? = false [
  if any? persons with [personHouseholdID = [householdID] of myself]
  [
    ask persons with [personHouseholdID = [householdID] of myself]
    [
      set personRegion [HHregion] of myself
    ]
  ]
]

[
  ask patch farmx farmy [set ocfarm 0]
  if any? persons with [personHouseholdID = [householdID] of myself]
  [
    ask persons with [personHouseholdID = [householdID] of myself] [
      set migrationCategory 4
      set migrationCause "41X"
      write-to-demog-file
      die
    ]
  ]
  ask patch-here [set ochousehold ochousehold - 1]
  die ; This likely will stay when we get LS set up completely, because this is how the household itself gets removed from the region.
]

;
; if houseIsNew? = true [
; die]; This likely will stay when we get LS set up completely, because this is how the household itself gets removed from the region.
]

[
  if (houseIsNew? = false)
  [
    ask patch farmx farmy [set ocfarm 0]
    if any? persons with [personHouseholdID = [householdID] of myself]
    [
      ask persons with [personHouseholdID = [householdID] of myself]
      [
        type age print sex
        set migrationCategory 4
        set migrationCause "41X"
        write-to-demog-file
        die ; most likely to be moved to the master model when we get levelSpace set up completely
      ]
    ]
    ask patch-here [set ochousehold ochousehold - 1]
  ]
  die ; this likely will stay when we get levelSpace set up completely, because this is how the household itself is removed from the region
]

end

;-----
to-report search-valley
; This method finds a spot for a household and its associated farm. The household spot might be a pre-existing location or it can be a new one. T
; location of a household is its settlement; multiple households can occupy the same settlement space. Only one farm (which is linked to a
; specific household) can occupy a particular space.

set siteNeeded? true
let xh 0
let yh 0
if length vPotfarms > 0
[
  set vBestfarm determine-best-Vfarm

```

```

if vBestfarm != nobody [
let bestYield [baseYield] of vBestfarm ; NOTE: "baseYield" is the realized output of a plot
set farmX [pxcor] of vBestfarm
set farmY [pycor] of vBestfarm
set farmplot vBestfarm
ask patch farmX farmY [set ocfarm 1]
if (count patches with [watersource? = true and ocfarm = 0 and (baseYield < bestYield)] > 0) ; the criterion is to find cells with water available
; farmed and are in a zone that is less productive than the zone
; best farm plot is located
[
ask min-one-of patches with [watersource? = true and ocfarm = 0 and (baseYield < bestYield)] [distance vBestfarm] ; find the spot with the closest distance
; to the farm that has just been created
[
ifelse distance vBestfarm <= watersourceDistance ; if the spot is within the watersource distance from the new farm plot,
[set xh pxcor set yh pycor
ask myself [set siteNeeded? false
; type " I am household: " type householdID print " I have found a farm and settlement that meet criterion 1."
]
] ; set the local variables xh and xy to the coordinates of the identified patch

[ask myself [set siteNeeded? true
; type " I am household: " type householdID print " I have NOT found a farm and settlement that meet criterion 1."
]
] ; and set the boolean to false; otherwise, keep the boolean at true
]

if siteNeeded? = false
[
ask min-one-of patches with [ocfarm = 0 and hydro <= 0] [distancexy xh yh] ; if a suitable farmplot has been found, find a nearby patch with the closest distance
; hydrology and choose that as the household location
[
set xh pxcor set yh pycor set ochohousehold ochohousehold + 1 ; this adds a household to the patch and allows us to keep track of settlements
]
]
]

if siteNeeded? = true ; no settlement was found in the previous block
[
; this block of code finds the closest patch without a farm, and if that is within the maximum watersource distance,
; set the coordinates of the farm to be that patch. Note: bestYield is the best farm's "baseYield" (adjusted).
; The constraint in the previous block is that the potential settlement site has a base yield lower than the base yield of the best farm
; plot and that it is not occupied by a farm and is within the maximum watersource distance. In this block, the household can occupy
; a more fertile patch (baseYield > bestYield) because there is nothing else available.

ask min-one-of patches with [ocfarm = 0] [distance vBestfarm]
[
ifelse distance vBestfarm <= watersourceDistance
[
set xh pxcor set yh pycor
ask myself [set siteNeeded? false
; type " I am household: " type householdID print " I have found a farm and settlement that meet criterion 2."
]
]
[ask myself [set siteNeeded? true
; type " I am household: " type householdID print " I have NOT found a farm and settlement that meet criterion 2."
]]
]
if siteNeeded? = false
[
ask min-one-of patches with [ocfarm = 0 and hydro <= 0] [distancexy xh yh] ; if a suitable farmplot has been found, find a nearby patch with the closest distance
; hydrology and choose that as the household location
[
set xh pxcor set yh pycor set ochohousehold ochohousehold + 1 ; this adds a household to the patch and allows us to keep track of settlements
]
]
]

if siteNeeded? = true ; still no settlement has been found
[
; this block of code finds the closest patch without a farm, even if it is a higher base yield than bestYield and outside the watersource distance
ask min-one-of patches with [ocfarm = 0] [distance vBestfarm]
[
set xh pxcor set yh pycor
ask myself [set siteNeeded? false
; type " I am household: " type householdID print " I have found a farm and settlement that meet criterion 3."
]
]
]

if siteNeeded? = false
[
ask min-one-of patches with [ocfarm = 0 and hydro <= 0] [distancexy xh yh] ; if a suitable farmplot has been found, find a nearby patch with the closest distance
; hydrology and choose that as the household location
[
set xh pxcor set yh pycor set ochohousehold ochohousehold + 1 ; this adds a household to the patch and allows us to keep track of settlements
]
]
]
]

if siteNeeded? = false
[
set houseIsNew? false
set HHregion 1
set householdX xh
set householdY yh
]
]

```

```

set xcor householdX
set ycor householdY
ask patch-here [set ohousehold ohousehold + 1]
ask persons with [personHouseholdID = [householdID] of myself][move-persons-with-household]
ask persons with [personHouseholdID = [householdID] of myself and personRegion = 2] [set migrationCategory 4 set migrationCause "41M" write-t
]
]
report siteNeeded?
end

;-----
to-report search-mesa
; This method finds a spot for a household and its associated farm. The household spot might be a pre-existing location or it can be a new one. T
; location of a household is its settlement; multiple households can occupy the same settlement space. Only one farm (which is linked to a
; specific household) can occupy a particular space.

set siteNeeded? true
let xh 0
let yh 0
let MwatersourceDistance watersourceDistance
; set MwatersourceDistance 25.0
if length mPotfarms > 0
[
set mBestfarm determine-best-Mfarm
if mBestfarm != nobody [
let bestYield [baseYield] of mBestfarm ; NOTE: "baseYield" is the realized output of a plottatements about the existing household after w
set farmX [pxcor] of mBestfarm
set farmY [pycor] of mBestfarm
set farmplot mBestfarm
ask patch farmX farmY [set ocfarm 1]
if (count patches with [watersource? = true and ocfarm = 0 and (baseYield < bestYield)] > 0) ; the criterion is to find cells with water availa
; farmed and are in a zone that is less productive than the zc
; best farm plot is located

[
ask min-one-of patches with [watersource? = true and ocfarm = 0 and (baseYield < bestYield)] [distance mBestfarm] ; find the spot with thes
; to the farm that has just been c

[
ifelse distance mBestfarm <= MwatersourceDistance ; if the spot is within the watersource distance from the new farm plot,
[
set xh pxcor set yh pycor
ask myself [set siteNeeded? false
; type " I am household: " type householdID print " I have found a farm and settlement that meet criterion 1."
]
] ; set the local variables xh and xy to the coordinates of the identified patch
[ask myself [set siteNeeded? true
; type " I am household: " type householdID print " I have NOT found a farm and settlement that meet criterion 1."
]
]
]
; and set the boolean to false; otherwise, keep the boolean at true

if siteNeeded? = false
[
ask min-one-of patches with [ocfarm = 0 and zone != "Water"] [distancexy xh yh] ; if a suitable farmplot has been found, find a nearby pa
; and choose that as the household location

[
set xh pxcor set yh pycor set ohousehold ohousehold + 1 ; this adds a household to the patch and allows us to keep track of settleme
]
]
]

if siteNeeded? = true ; no settlement was found in the previous block
[
; this block of code finds the closest patch without a farm, and if that is within the maximum watersource distance,
; set the coordinates of the farm to be that patch. Note: bestYield is the best farm's "baseYield" (adjusted).
; The constraint in the previous block is that the potential settlement site has a base yield lower than the base yield of the best farm
; plot and that it is not occupied by a farm and is within the maximum watersource distance. In this block, the household can occupy
; a more fertile patch (baseYield > bestYield) because there is nothing else available.

ask min-one-of patches with [ocfarm = 0] [distance mBestfarm]
[
ifelse distance mBestfarm <= MwatersourceDistance
[
set xh pxcor set yh pycor
ask myself [set siteNeeded? false
; type " I am household: " type householdID print " I have found a farm and settlement that meet criterion 2."
]
]
[
ask myself [set siteNeeded? true
; type " I am household: " type householdID print " I have NOT found a farm and settlement that meet criterion 2."
]
]
]

if siteNeeded? = false
[
ask min-one-of patches with [ocfarm = 0 and zone != "Water"] [distancexy xh yh] ; if a suitable farmplot has been found, find a nearby th
; and choose that as the household location

[
set xh pxcor set yh pycor set ohousehold ohousehold + 1 ; this adds a household to the patch and allows us to keep track of settlem
]
]
]
]
]

```

```

if siteNeeded? = true ; still no settlement has been found
[
; this block of code finds the closest patch without a farm, even if it is a higher base yield than bestYield and outside the watersource c
ask min-one-of patches with [ocfarm = 0] [distance mBestfarm]
[
set xh pxcor set yh pycor
ask myself [set siteNeeded? false
; type " I am household: " type householdID print " I have found a farm and settlement that meet criterion 3."
]
]
if siteNeeded? = false
[
ask min-one-of patches with [ocfarm = 0 and zone != "Water"] [distancexy xh yh] ; if a suitable farmplot has been found, find a nearby pe
; and choose that as the household location
[
set xh pxcor set yh pycor set ochohousehold ochohousehold + 1 ; this adds a household to the patch and allows us to keep track of settlem
]
]
]
]

if siteNeeded? = false
[
set houseIsNew? false
set HHregion 2
set householdX xh
set householdY yh
set xcor householdX
set ycor householdY
ask patch-here [set ochohousehold ochohousehold + 1]
ask persons with [personHouseholdID = [householdID] of myself][move-persons-with-household]
ask persons with [personHouseholdID = [householdID] of myself and personRegion = 1] [set migrationCategory 4 set migrationCause "41V" write-t
]
]

report siteNeeded?

end

;-----

to determine-potfarms
; This method identifies a list of potential farm locations to use during initialization. When first made, farms are given random locations,
; but must move to available sites. These sites are patches not already occupied by a farm or settlement and where the base yield (the adjusted
; yield) is higher than the minimum amount of food needed by the farm's household.
set vPotfarms []
set mPotfarms []
ask patches with [(patchRegion = 1) and (zone != "Empty") and (ocfarm = 0) and (ochohousehold = 0) and (baseYield >= minHouseholdNutriNeed)]
[set vPotfarms lput self vPotfarms]
; type "The vPotfarms available are : " print vPotfarms
ask patches with [(patchRegion = 2) and (zone = "General") and (ocfarm = 0) and (ochohousehold = 0) and (baseYield >= minHouseholdNutriNeed)]
[set mPotfarms lput self mPotfarms]
; type "The mPotfarms available are : " print mPotfarms
end

;-----

to-report determine-best-Vfarm ; this method finds the closest suitable farm on the list of potential farms; the starting distance (distancetns)
; just puts constraints on the search space
set vBestfarm nobody
let existingfarm patch farmX farmY
let distancetns 1000
foreach vPotfarms
[ [?1] ->
ask ?1 [
if ((distance existingfarm < distancetns) and (baseYield > [householdNutriNeed] of myself))
[
set vBestfarm self
set distancetns distance existingfarm
]
]
]
if length vPotfarms > 0 [set vPotfarms remove vBestfarm vPotfarms]
report vBestfarm
end

;-----

to-report determine-best-Mfarm ; this method finds the closest suitable farm on the list of potential farms; the starting distance (distancetns)
; just puts constraints on the search space
set mBestfarm nobody
let existingfarm patch farmX farmY
let distancetns 1000
foreach mPotfarms
[ [?1] ->
ask ?1 [
if ((distance existingfarm < distancetns) and (baseYield > [householdNutriNeed] of myself))
[
set mBestfarm self
set distancetns distance existingfarm
]
]
]
]
if length mPotfarms > 0 [set mPotfarms remove mBestfarm mPotfarms]

```

```

    report mBestfarm
end
;-----

to estimate-harvest ; this method calculates the expected level of food available to a household based on current stocks of maize and
; the estimate of the next year's harvest (equal to the actual production during the current year)
ask households [
  let total 0
  let ys yearsOfStock - 1
  while [ys > -1]
  [
    set total total + item ys agedCornStocks
    set ys ys - 1
  ]
  set availableCorn total + lastHarvest
]
end

;-----

to harvest-consumption
; The first block of this method calculates the base yield for each cell (i.e., adjusts the natural yield to account for spatial variation in
; productivity and crop loss). It then estimates the actual harvest of a household and updates the stocks of maize available in storage. The second
; block of code calculates the amount of nutrients a household can derive from the available maize.

ask patches [set baseYield (yield * quality * harvestAdjustment)]
ask households
[
  set lastHarvest [baseYield] of patch farmX farmY * (1 + ((random-normal 0 1) * harvestVariance))
  set agedCornStocks replace-item 2 agedCornStocks (item 1 agedCornStocks)
  set agedCornStocks replace-item 1 agedCornStocks (item 0 agedCornStocks)
  set agedCornStocks replace-item 0 agedCornStocks lastHarvest
  set householdNutriShortfall householdNutriNeed
  set householdAge householdAge + 1
]

; BLOCK 2

ask households
[
  let ys yearsOfStock
  while [ys > -1]
  [
    ifelse ((item ys agedCornStocks) >= householdNutriShortfall)
    [
      set agedCornStocks replace-item ys agedCornStocks (item ys agedCornStocks - householdNutriShortfall)
      set householdNutriShortfall 0
    ]
    [
      set householdNutriShortfall (householdNutriShortfall - item ys agedCornStocks)
      set agedCornStocks replace-item ys agedCornStocks 0
    ]
  ]
  set ys ys - 1
]
end

;-----

to water
; define for each location when water is available
ifelse ((year >= 280 and year < 360) or (year >= 800 and year < 930) or (year >= 1300 and year < 1450)) [set streamsexist? true][set streamsexist
ifelse ((year >= 420 and (year < 560)) or ((year >= 630) and (year < 680)) or ((year >= 980) and (year < 1120)) or ((year >= 1180) and (year <
[set alluviumexist? true][set alluviumexist? false]

let currentPDSI item (year - 800) pdsi-data
let probWatersource 0

ask patches with [patchRegion = 1] [
  set watersource? false
  if ((alluviumexist? = true) and ((zone = "General") or (zone = "North") or (zone = "Mid") or (zone = "Kinbiko"))) [set watersource? true]
  if ((streamsexist? = true) and (zone = "Kinbiko")) [set watersource? true]
]
; Consistent with the paleoenvironmental data, the following patches always have water, regardless of any other conditions
ask patch 72 114 [set watersource? true]
ask patch 70 113 [set watersource? true]
ask patch 69 112 [set watersource? true]
ask patch 68 111 [set watersource? true]
ask patch 67 110 [set watersource? true]
ask patch 66 109 [set watersource? true]
ask patch 65 108 [set watersource? true]
ask patch 65 107 [set watersource? true]

ask patches with [patchRegion = 2] [
  set watersource? false
  if zone = "Water" [
    if (currentPDSI >= -1.0 and currentPDSI <= 1.0)
    [ set probWatersource 0.5 * (currentPDSI + 1)
      if (probWatersource >= random 1.0) [set watersource? true]
    ]
  ]

  if ((currentPDSI > 1.0)) [set watersource? true]
]
]

```

```

ask waterpoints [
  if typewater = 2 [ask patch xcor ycor [set watersource? true]]
  if typewater = 3 [if (year >= startdate and year <= enddate) [ask patch xcor ycor [set watersource? true]]]
]

if mapview = "watersource?" [
  ask patches [
    ifelse watersource? = true [set pcolor blue] [set pcolor white]
  ]
]
end

;-----

to update-ALHV-personNutriNeed
; Newborns are assumed to have 35% of the adult personal nutritional need; this need increases linearly with age until age
; 16, when all agents are assumed to be adults
ifelse age < fertilityAge
[set personNutriNeed personBaseNutriNeed * (0.35 + (0.65 * (age / fertilityAge)))]
[set personNutriNeed personBaseNutriNeed]
end

;-----

to update-ALHV-householdNutriNeed
let house-members persons with [personHouseholdID = [householdID] of myself]
if any? house-members
[set householdNutriNeed sum [personNutriNeed] of house-members]
end

;-----

to update-householdSize
set householdSize count persons with [personHouseholdID = [householdID] of myself]
if householdSize = 0
[
  ask patch farmX farmY [set ocfarm 0]
  ask patch-here [set ochousehold ochousehold - 1]
  die
]
end

;-----

;;;;;;;;;;;;;
;;; DISPLAY AND DATA COLLECTION METHODS ;;;
;;;;;;;;;;;;;

to map-settlements ; this method allows easier visualization of the locations of simulated farms and settlements
; Note: the variable "nrh" keeps track of the number of simulated households on a patch, but the present model is not set up
; to map the simulated settlement size and so the variable is not used. We are keeping it in the model because it may prove to b

ask patches [
  set nrh 0
;   if ocfarm = 1
;     [set pcolor orange]
]
ask households
[ ask patch-here [set nrh nrh + 1]
]
if mapview = "occup"
[
  ask patches
  [
    ifelse ochousehold > 0
    [set pcolor red]
    [set pcolor black]

    ifelse ocfarm = 1
    [set pcolor orange]
    [set pcolor black]
  ]
]
end

;-----

to archaeological-population

ifelse ( file-exists? "LHVarchHHCounts.txt" )
[
  set LHV-archpop []
  file-open "LHVarchHHCounts.txt"
  while [ not file-at-end? ]
  [
    set LHV-archpop sentence LHV-archpop (list file-read)
  ]
  file-close
]
[ user-message "There is no LHVarchHHcounts.txt file in current directory!" ]

ifelse ( file-exists? "mesaArchHHCounts.txt" )

```

```

[
  set Mesa-archpop []
  file-open "mesaArchHHCounts.txt"
  while [ not file-at-end? ]
  [
    set Mesa-archpop sentence Mesa-archpop (list file-read)
  ]
  file-close
]
[ user-message "There is no mesaArchHHcounts.txt file in current directory!" ]
end
;-----

;to archaeological-population ; This method converts the input location coordinates of archaeological settlements to the appropriate map location a
; ; them on the map. It also adjusts their size according to the number of households at each settlement.
; ask archsettlements
; [
;   if (typeset = 1) [
;     set nrhouseholds 0
;     ifelse (year >= startdate and year < enddate)
;     [
;       set hidden? false ; this statement controls whether the archaeological data show up on the map
;
;       ; The following two blocks are a direct translation from the original AA model. The equations used are a consequence of the way
;       ; the data are recorded in the SARG database.
;       if year > mediandate
;       [
;         if (year != mediandate)
;         [
;           set nrhouseholds ceiling (baselinehouseholds * (enddate - year) / (enddate - mediandate))
;           if nrhouseholds < 1 [set nrhouseholds 1]
;         ]
;       ]
;       if year <= mediandate
;       [
;         if (mediandate != startdate)
;         [
;           set nrhouseholds ceiling (baselinehouseholds * (year - startdate) / (mediandate - startdate))
;           if nrhouseholds < 1 [set nrhouseholds 1]
;         ]
;       ]
;     ]
;     [set hidden? true]
;     set archValleyHH archValleyHH + nrhouseholds
;     set archsettlementX (24.5 + (meterEast - 2392) / 93.5) ; these two statements are the location translation function for the coordinate
;     set archsettlementY (45 + (37.6 + (meterNorth - 7954) / 93.5))
;     ; The 45 above is not included in the corrections made in the Ascape version. We suspect this is a conversion specifically for the
;     ; Netlogo map setup.
;     set xcor int archsettlementX
;     set ycor int archsettlementY
;     set size nrhouseholds ; Janssen's version of the original model adjusted the size of archaeological settlements by the number of househol
;     ; at some time periods, overwhelms the map. A better way to represent the size of such settlements will be included
;   ]
; ]
;end

;-----

to plot-counts

set-current-plot "IndividualPopulations"
set-current-plot-pen "valleySimHouseholds"
plot (valleyHH)
set-current-plot-pen "valleyArchHouseholds"
set archValleyHH item (year - 800) LHV-archpop
plot (archValleyHH)
set-current-plot-pen "mesaSimHouseholds"
plot (mesaHH)
set-current-plot-pen "mesaArchHouseholds"
set archMesaHH item (year - 800) Mesa-archpop
plot (archMesaHH)

set-current-plot "TotalPopulations"
set-current-plot-pen "totalSimHouseholds"
plot (totHH)
set-current-plot-pen "totalArchHouseholds"
set archTotHH archValleyHH + archMesaHH
plot (archTotHH)

end

;-----

to update-annual-output
plot-counts
write-to-annual-file
; if (year mod 50 = 0)
; [
;   write-to-popdist-file "ALHV-mesa-popDistValley.csv" vAgeDistribution valleyPopSize
;   write-to-popdist-file "ALHV-mesa-popDistMesa.csv" mAgeDistribution mesaPopSize
;   write-to-popdist-file "ALHV-mesa-popDistTotal.csv" totAgeDistribution totPopSize
; ]
end
;-----

```

```

to setup-annualDataFile
  if (not file-exists? "ALHV-mesa-annData-idealruns.csv") [
    file-open "ALHV-mesa-annData-idealruns.csv"
    file-print "PARAMETERS, "
    file-type "minFertilityAge, "
    file-type "maxFertilityAge, "
    file-type "minFertilityEndsAge, "
    file-type "maxFertilityEndsAge, "
    file-type "fert 15-19, "
    file-type "fert 20-24, "
    file-type "fert 25-29, "
    file-type "fert 30-34, "
    file-type "fert 35-39, "
    file-type "fert 40-44, "
    file-type "fert 45+, "
    file-type "personBaseNutriNeed, "
    file-type "harvestAdjustment, "
    file-type "harvestVariance, "
    file-print "mesaAdjustment, "

    file-type (word minFertilityAge ", ")
    file-type (word maxFertilityAge ", ")
    file-type (word minFertilityEndsAge ", ")
    file-type (word maxFertilityEndsAge ", ")
    file-type (word item 0 age-specificFertility ", ")
    file-type (word item 1 age-specificFertility ", ")
    file-type (word item 2 age-specificFertility ", ")
    file-type (word item 3 age-specificFertility ", ")
    file-type (word item 4 age-specificFertility ", ")
    file-type (word item 5 age-specificFertility ", ")
    file-type (word item 6 age-specificFertility ", ")
    file-type (word personBaseNutriNeed ", ")
    file-type (word harvestAdjustment ", ")
    file-type (word harvestVariance ", ")
    file-print (word mesaAdjustment ", ")

    file-type "mort 0-1, "
    file-type "mort 1-4, "
    file-type "mort 5-9, "
    file-type "mort 10-14, "
    file-type "mort 15-19, "
    file-type "mort 20-24, "
    file-type "mort 25-29, "
    file-type "mort 30-34, "
    file-type "mort 35-39, "
    file-type "mort 40-44, "
    file-type "mort 45-49, "
    file-type "mort 50-54, "
    file-type "mort 55-59, "
    file-type "mort 60-64, "
    file-type "mort 65-69, "
    file-type "mort 70-74, "
    file-type "mort 75-79, "
    file-print "mort 80+, "

    file-type (word item 0 age-specificMortality ", ")
    file-type (word item 1 age-specificMortality ", ")
    file-type (word item 2 age-specificMortality ", ")
    file-type (word item 3 age-specificMortality ", ")
    file-type (word item 4 age-specificMortality ", ")
    file-type (word item 5 age-specificMortality ", ")
    file-type (word item 6 age-specificMortality ", ")
    file-type (word item 7 age-specificMortality ", ")
    file-type (word item 8 age-specificMortality ", ")
    file-type (word item 9 age-specificMortality ", ")
    file-type (word item 10 age-specificMortality ", ")
    file-type (word item 11 age-specificMortality ", ")
    file-type (word item 12 age-specificMortality ", ")
    file-type (word item 13 age-specificMortality ", ")
    file-type (word item 14 age-specificMortality ", ")
    file-type (word item 15 age-specificMortality ", ")
    file-type (word item 16 age-specificMortality ", ")
    file-print (word item 17 age-specificMortality ", ")
    file-print " "

    file-type "Run number, "
    file-type "Year, "
    file-type "Arch Valley Households, "
    file-type "Sim Valley Households, "
    file-type "Sim Valley People, "
    file-type "Sim Mesa Households, "
    file-type "Sim Mesa People, "
    file-type "Sim Total Households, "
    file-print "Sim Total People, "
    file-close
  ]
end

```

```

;-----
to setup-demogDataFile
  if (not file-exists? "ALHV-mesa-demogData.csv") [
    file-open "ALHV-mesa-demogData.csv"
    file-print "PARAMETERS, "
    file-type "minFertilityAge, "
    file-type "maxFertilityAge, "

```



```

file-type "minFertilityEndsAge, "
file-type "maxFertilityEndsAge, "
file-type "fert 15-19, "
file-type "fert 20-24, "
file-type "fert 25-29, "
file-type "fert 30-34, "
file-type "fert 35-39, "
file-type "fert 40-44, "
file-type "fert 45+, "
file-type "personBaseNutriNeed, "
file-type "harvestAdjustment, "
file-print "harvestVariance, "

file-type (word minFertilityAge ", ")
file-type (word maxFertilityAge ", ")
file-type (word minFertilityEndsAge ", ")
file-type (word maxFertilityEndsAge ", ")
file-type (word item 0 age-specificFertility ", ")
file-type (word item 1 age-specificFertility ", ")
file-type (word item 2 age-specificFertility ", ")
file-type (word item 3 age-specificFertility ", ")
file-type (word item 4 age-specificFertility ", ")
file-type (word item 5 age-specificFertility ", ")
file-type (word item 6 age-specificFertility ", ")
file-type (word personBaseNutriNeed ", ")
file-type (word harvestAdjustment ", ")
file-print (word harvestVariance ", ")
file-print ""

file-type "Run number, "
file-type "Year, "
file-type "Vital Category, "
file-type "Migration Category, "
file-type "Vital Cause, "
file-type "Migration Cause, "
file-type "PersonID, "
file-type "Sex, "
file-type "Age, "
file-type "Household, "
file-type "Clan, "
file-print "MateID, "
file-close
]
end

;-----

to setup-popDistributionFile [file-to-setup region]
if (not file-exists? file-to-setup) [
file-open file-to-setup
file-print word region " POPULATION AGE DISTRIBUTION, "
file-print "PARAMETERS, "
file-type "minFertilityAge, "
file-type "maxFertilityAge, "
file-type "minFertilityEndsAge, "
file-type "maxFertilityEndsAge, "
file-type "fert 15-19, "
file-type "fert 20-24, "
file-type "fert 25-29, "
file-type "fert 30-34, "
file-type "fert 35-39, "
file-type "fert 40-44, "
file-type "fert 45+, "
file-type "personBaseNutriNeed, "
file-type "harvestAdjustment, "
file-print "harvestVariance, "

file-type (word minFertilityAge ", ")
file-type (word maxFertilityAge ", ")
file-type (word minFertilityEndsAge ", ")
file-type (word maxFertilityEndsAge ", ")
file-type (word item 0 age-specificFertility ", ")
file-type (word item 1 age-specificFertility ", ")
file-type (word item 2 age-specificFertility ", ")
file-type (word item 3 age-specificFertility ", ")
file-type (word item 4 age-specificFertility ", ")
file-type (word item 5 age-specificFertility ", ")
file-type (word item 6 age-specificFertility ", ")
file-type (word personBaseNutriNeed ", ")
file-type (word harvestAdjustment ", ")
file-print (word harvestVariance ", ")
file-print ""

file-type "Run number, "
file-type "Year, "
file-type "0 to 1, "
file-type "1 to 4, "
file-type "5 to 9, "
file-type "10 to 14, "
file-type "15 to 19, "
file-type "20 to 24, "
file-type "25 to 29, "
file-type "30 to 34, "
file-type "35 to 39, "
file-type "40 to 44, "
file-type "45 to 49, "
file-type "50 to 54, "

```

```

file-type "55 to 59, "
file-type "60 to 64, "
file-type "65 to 69, "
file-type "70 to 74, "
file-type "75 to 79, "
file-type "80 to 84, "
file-type "85 to 89, "
file-type "90+, "
file-print "total pop, "
file-close
]
end

;-----

to write-to-annual-file
file-open "ALHV-mesa-annData-idealruns.csv"
file-type (word behaviorspace-run-number ", ")
file-type (word year ", ")
file-type (word archValleyHH ", ")
file-type (word valleyHH ", ")
file-type (word valleyPopSize ", ")
file-type (word mesaHH ", ")
file-type (word mesaPopSize ", ")
file-type (word totHH ", ")
file-print (word totPopSize ", ")
file-close
end

;-----

to write-to-demog-file
file-open "ALHV-mesa-demogData.csv"
file-type (word behaviorspace-run-number ", ")
file-type (word year ", ")
file-type (word vitalCategory ", ")
file-type (word migrationCategory ", ")
file-type (word vitalCause ", ")
file-type (word migrationCause ", ")
file-type (word personID ", ")
file-type (word sex ", ")
file-type (word age ", ")
file-type (word personHouseholdID ", ")
file-type (word clanID ", ")
file-print (word mateID ", ")
file-close
end

;-----

to write-to-popdist-file [write-to-file AgedDist popSize]
file-open write-to-file
file-type (word behaviorspace-run-number ", ")
file-type (word year ", ")
file-type (word item 1 AgedDist ", ")
file-type (word item 2 AgedDist ", ")
file-type (word item 3 AgedDist ", ")
file-type (word item 4 AgedDist ", ")
file-type (word item 5 AgedDist ", ")
file-type (word item 6 AgedDist ", ")
file-type (word item 7 AgedDist ", ")
file-type (word item 8 AgedDist ", ")
file-type (word item 9 AgedDist ", ")
file-type (word item 10 AgedDist ", ")
file-type (word item 11 AgedDist ", ")
file-type (word item 12 AgedDist ", ")
file-type (word item 13 AgedDist ", ")
file-type (word item 14 AgedDist ", ")
file-type (word item 15 AgedDist ", ")
file-type (word item 16 AgedDist ", ")
file-type (word item 17 AgedDist ", ")
file-type (word item 18 AgedDist ", ")
file-type (word item 19 AgedDist ", ")
file-type (word item 20 AgedDist ", ")
file-print (word popSize ", ")
file-close
end

```

VITA

Amy Warren was born in Minot, North Dakota to Denny and Diana Reynolds. After graduating from Bentonville High School in Bentonville, Arkansas, she attended the University of Arkansas-Fayetteville. She earned a Bachelor of Arts in Anthropology in May 2010, after spending a number of years out of academia. She is married to Randy Warren and has two daughters, Annabelle and Madeleine.

In Fall 2010, she started graduate work in Anthropology also at the University of Arkansas and graduated with a Master of Arts in 2012. During this program, she served as a graduate teaching assistant for both Introduction to Biological Anthropology and Human Physiology laboratories.

In Fall 2012, she began work on a doctoral degree in Anthropology at the University of Missouri-Columbia. During her time at the University of Missouri, she served as a graduate instructor for biological anthropology laboratories and as an NSF GK-12 Graduate STEM Fellow in K-12 Education, as well as the coordinator for the BGREEN environmental outreach and education program. During her graduate programs, she presented at multiple regional and national conferences, and participated in workshops and short courses both at MU and the Santa Fe Institute.

Upon the completion of coursework and comprehensive exams, she and her family returned to Arkansas. She served as part-time Anthropology faculty at the Northwest Arkansas Community College and as a teacher-naturalist at the Ozark Natural Science Center. Currently, she serves as the Assistant Director of Outreach and Summer Programs at the University of Arkansas College of Engineering.