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Simulation of Natural and Social Process Interactions: An Example from Bronze Age Mesopotamia

John H. Christiansen
Argonne National Laboratory

Mark Altaweel
University of Chicago/Argonne National Laboratory

ABSTRACT
New multi-model simulations of Bronze Age Mesopotamian settlement system dynamics, using advanced object-based simulation frameworks, are addressing fine-scale interaction of natural processes (crop growth, hydrology, etc.) and social processes (kinship-driven behaviors, farming and herding practices, etc.) on a daily basis across multi-generational model runs. Key components of these simulations are representations of initial settlement populations that are demographically and socially plausible, and detailed models of social mechanisms that can produce and maintain realistic textures of social structure and dynamics over time. The new simulation engine has broad applicability and is also being used to address modern problems such as agroeconomic sustainability in Southeast Asia. The paper describes the simulation framework and presents results of initial studies highlighting its social system representations.

Keywords: multi-model simulations; agent-based; holistic; environment and social interactions; complex adaptive systems; Mesopotamia

Introduction

The University of Chicago's Oriental Institute and Argonne National Laboratory are embarked upon a five-year research project sponsored by the National Science Foundation's Biocomplexity in the Environment initiative (NSF Grant No. 0216548). The principal thrust of the project is the use of advanced computer modeling and simulation techniques to examine the dynamic processes underlying and driving the development and sustainability or demise of settlement systems in both the rain-fed northern and irrigated southern regions of ancient Mesopotamia during the Bronze Age (3200-1200 BC). Because Mesopotamia offers a temporally deep array of data drawn from many different sources, it is an ideal test case for the study of long-term human-environmental interactions. Nevertheless, it is our goal to develop a simulation structure that can be adapted for examining both modern and ancient societies in various environmental settings.

Our paper will briefly outline the advanced computer simulation architectures that make this project feasible, and will describe how data obtained from textual, ethnographic, and archaeological sources are being incorporated within our simulation engine. The computer modeling approach for several of the key natural and social processes and their interactions will be described, with particular emphasis on some of the early social process representations. We will then identify the chief defining parameters for a simple northern Mesopotamian village modeling scenario, and will describe some of the preliminary results from our initial pilot studies.

Project Overview

A major goal of our project is the construction of a new multidisciplinary, agent-based dynamic software object model that can concurrently represent both the natural processes and the societal processes at work in the Bronze Age Mesopotamian simulation domain, at levels of fidelity and detail that make it feasible to represent heterogeneous process interactions over a useful range of spatial and temporal scales. An equally important project goal is to develop a simulation engine that can serve as an open framework within which researchers can explore alternative models and hypotheses and observe their models' performance, interactions, and sensitivities.

The Oriental Institute and Argonne have developed, and are presently elaborating upon, models of settlement systems in the rain-fed (northern) and irrigated (southern) zones of Syria and Iraq, using the household as a fundamental modeling unit.

The basic objective of the rain-fed zone model is to allow for the scaling up of a settlement from a single household to a village, and ultimately an urban center, with its appropriate array of subsidiary and neighboring settlements. Agrarian production (specifically in light of environmental stresses) and social interaction are modeled in considerable detail, reflecting the potentially strong significance of feedback processes, non-linear behavior mechanisms and some degree of self-organization in Bronze Age settlement systems (Wilkinson, 2000b). Emphasis is placed on the development of the household model and its transformation into higher-order settlements. Everyday decisions in farming (when to plant, whether to fallow or crop annually) essential to community survival, as well as social factors such as the pooling of resources, are being incorporated. The social systems representation is being expanded to include mechanisms that allow for the growth of social differentiation that enable some households to grow and others to become subordinate.

In southern Iraq, the presence of a network of anastomosing rivers and distributary canals makes for a markedly different cultural landscape than the rain-fed north. The rich patchwork of environments in the south not only supplies a rich subsistence base but also provides a convenient "low-friction" means of distribution of surpluses (Adams, 1981). Influences of environmental stresses, population changes, and resource competition will be included in the modeling representation, particularly as these relate to impacts on settlement patterns in the south. Thus far, our simulation pilot studies have been focused on settlement in northern Mesopotamia, and this paper will focus on that region.

The Simulation Framework

We are utilizing Argonne's Dynamic Information Architecture System (DIAS) (Christiansen, 2000a), an advanced, object based computer simulation framework, as the underpinning for a dynamic object model of the social/physical world of ancient Mesopotamia. The DIAS infrastructure has made it feasible to build and manipulate complex simulation scenarios in which many thousands of objects can interact via dozens to hundreds of concurrent dynamic processes. We are also using Argonne's Framework for Addressing Cooperative Extended Transactions (FACET; Christiansen, 2000b), a facility for constructing flexible and expressive agent-based object models of social behavior patterns. By using FACET models to implement social behaviors of individuals and organizations within the context of larger DIAS-based natural systems simulations, it has become possible to conveniently address a broad range of issues involving interaction and feedback among natural and social processes.

In essence, DIAS and FACET are enabling technologies for a new, holistic and intuitive approach to complex systems modeling that takes full advantage of advances in both agent-based societal modeling and physics-based natural systems modeling. Their use greatly facilitates progress toward the ambitious goals for complex quantitative simulation that we have set for this effort. Argonne's GeoViewer geospatial display and analysis toolkit (Lurie, Sydelko and Taxon, 2002) provides another valuable component of the simulation system's software infrastructure.

Over the five-year span of the project, modeling studies will encompass spatial scales and granularities that will range from single households and their individual members and resources, to individual hamlets, villages, towns with supporting satellite villages, regional constellations of such towns, and, finally, to the entire Fertile Crescent, with rain-fed northern and irrigated southern Mesopotamian settlements linked via hydrological and meteorological processes, and by social processes such as interactions between settlements and nomads. The project's simulation framework prototype has been named "ENKIMDU," after the ancient Sumerian god of agriculture and irrigation. ENKIMDU simulations address natural processes (weather, crop growth, hydrology, soil evolution, population dynamics, etc.) and societal processes (farming and herding practices, kinship-driven behaviors, trade, etc.) interweaving on a daily basis across multi-decadal to multi-generational runs. Software objects representing the salient components of the simulation domain are resolved and modeled at the level of individual persons and households, and individual cropped/fallowed fields, herds, and flocks. This fine temporal resolution and fine granularity in resolving the objects and agents in the simulation domain is essential to our bottom-up modeling approach, with its search for higher-order structure as emergent behavior of an ecology of simpler households. Figure 1 provides a simplified view of the ancient Mesopotamian simulation domain, with major classes of entity (Field, Household, etc.) exhibiting dynamic behaviors (vegetation growth, irrigation practices, etc.) that are implemented in ENKIMDU by an ensemble of simulation models, such as the U.S. Department of Agriculture's SWAT model (Arnold, Srinivasin and Williams, 1998; Arnold and Allen, 1992). SWAT is a recently released modeling suite that addresses growth of crops and other vegetation, soil evolution and degradation, moisture and heat exchange with the atmosphere, water and wind erosion, and distributed hydrology.

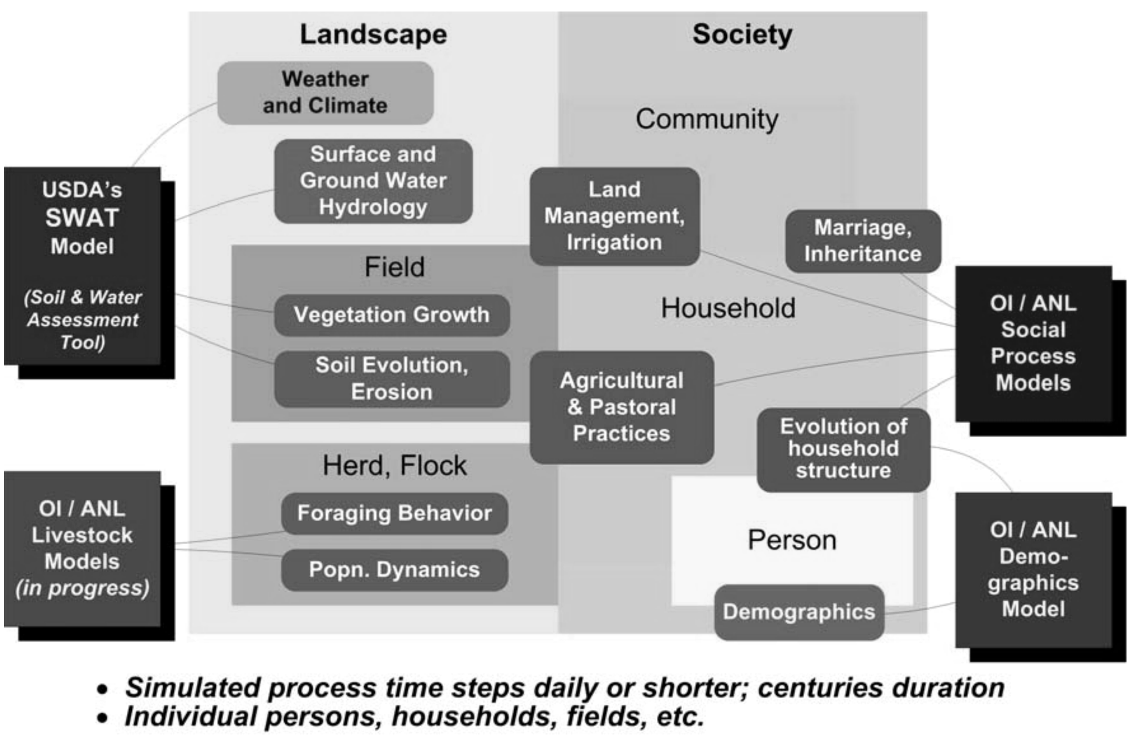

Figure 1. Simplified Schematic View of the Object Modeling Approach

The full list of processes addressed by the SWAT model is extensive, and includes:

- Hydrology: surface runoff and ponding; drainage routing at individual field to watershed scale; percolation and water table dynamics; lateral subsurface flow; evaporation; snowmelt; and precipitation recharge.
- Meteorology: daily agricultural weather, via a Markov Chain stochastic weather generator that is driven by data tables of climatological means and extremes.
- Soil Evolution: soil temperature dynamics; water and wind erosion, deflation, etc.
- Nutrient Cycling Dynamics: nitrogen and phosphorus balance.
- Vegetation Growth: canopy and root development; evapotranspiration; water budget; nutrient uptake; growth constraints (by moisture, temperature, nutrient levels, etc.); harvest yield, with constraints as above; dormancy; effects of pests; and effects of grazing and browsing by livestock.
- Human Interventions: tillage effects (leveling, plowing, planting, harrowing, harvesting, etc.); irrigation; and fertilizer application.

For the initial phases of our project we have made use of the SWAT model functionality for all of the many physical processes it represents. As the project progresses, however, we will need to decompose the SWAT functionality into separate processes that can be accepted or declined individually by the relevant ENKIMDU domain objects, in order to allow project investigators to substitute alternative models/processes to implement domain object dynamic behaviors. Simulation model components to represent the elements of social behavior identified in Figure 1 are being built with the aid of the FACET modeling framework, using its extensive built-in facilities for modeling and tracking resource management and conflict resolution dynamics. Examples of the layout of some of the FACET models that have been built thus far are shown in Figure 2.

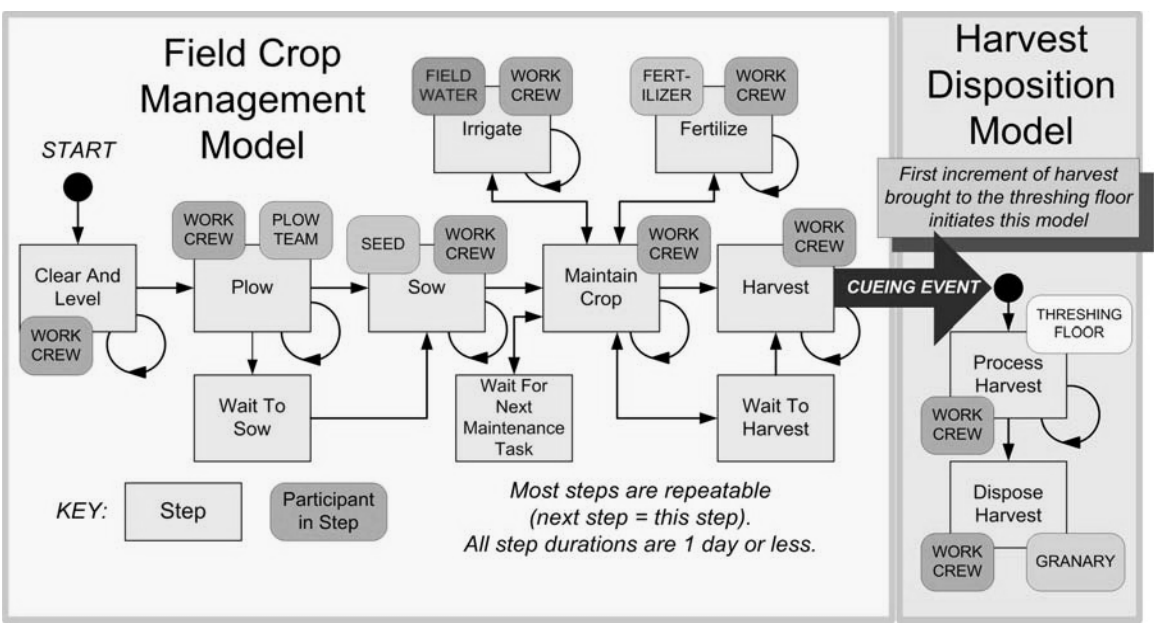

Figure 2. Two FACET Models for Agricultural Practices

Each Step in these FACET-based models is somewhat like a scene in a play, with a required (though often variable) cast of actors, who must provide the appropriate resources (labor, use of equipment, supplies, etc.) to enable the task to be performed. The flow from Step to Step is generally deterministic, yet can be quite mutable, with action sequences diverted or preempted by outside events. Although work crews are required as participants for most tasks, the details of the work crew requirements are generally different for each step, tailored to the needs of the task.

Interactions between natural and societal processes in the ENKIMDU system occur in many forms and modes, as both sorts of process impinge upon the same domain entities. An example is provided in Figure 3, which depicts the flow of information swirling around a simulation software object representing a single agricultural field. Landscape natural processes (as modeled by SWAT) cause changes in the state of the field, as do anthropogenic tillage processes, here modeled by a household's Field Crop Management Model (see Figure 2). In turn, the altered state of the field object due to natural processes (e.g., ripening grain, waterlogged soil, etc.) can induce changes in the household's behavior, and interventions by the household can propagate across the landscape.

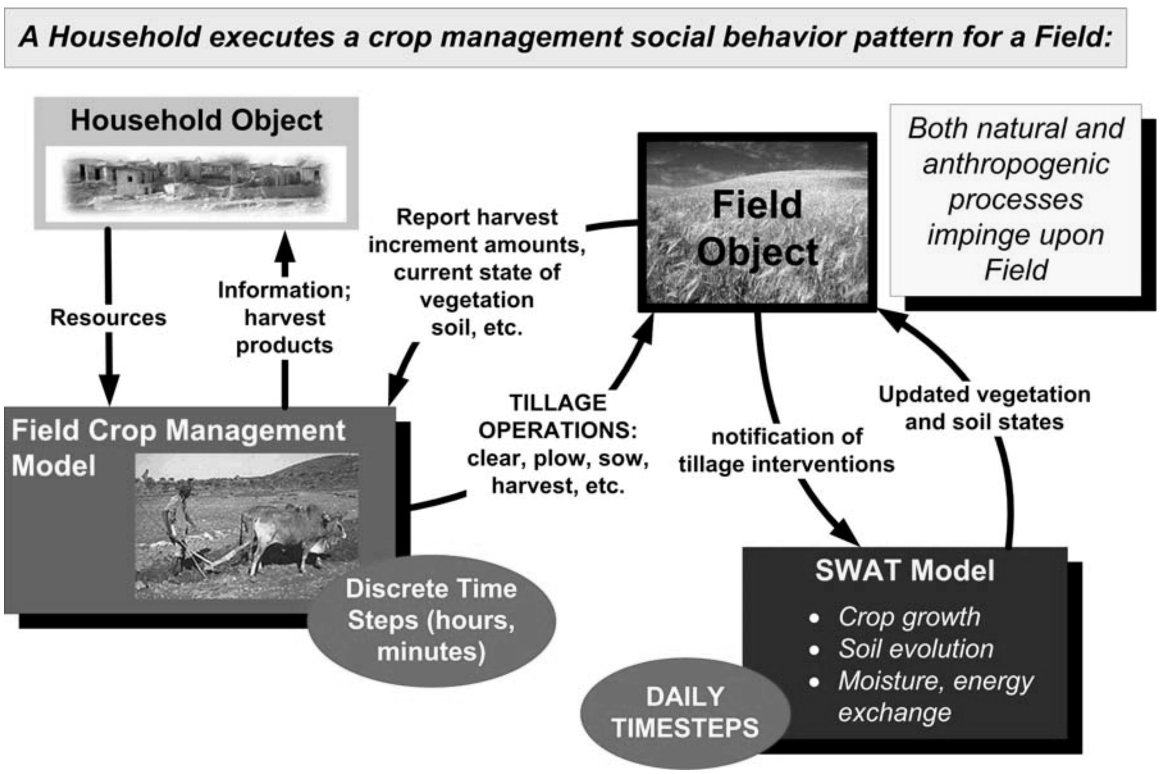

Figure 3. An Example of Modeled Natural / Social Process Interactions

The introduction of pastoralism into the ENKIMDU system, currently in progress, is bringing with it a great many more opportunities for heterogeneous, inter-process interaction. Herds and flocks change and are changed by the landscape, and interact in many complex ways with the communities that tend them.

Sheep and goats are the primary animals to be modeled in village pastoralism. Different strategies were practiced regarding pastoralism in ancient Mesopotamia. A village could use animal herds primarily for economic and nutritional security and/or increasing energy input. Thus, a village may choose to use animals to supplement its caloric intake and/or have animals available to deal with potential food stress situations. Animal products, such as skins and wool, were also very important for local consumption and economic exchange, and will be included in the simulation. Animals also provide fuel products and fertilizer (Redding, 1981). At Tell Beydar, the ancient urban site and its associated area that we are using as the archetype for the modeled landscape in our pilot studies, pastoralism was a major component of the local economy (van Lerberghe, 1996). Models are being constructed to address the salient natural and social processes related to local extensive pastoralism, including:

- Demographics and population dynamics of the herds/flocks under various levels and types of management;

- Species-dependent ruminant foraging behaviors, including plant biomass removal; trampling of vegetation, and deposition of manure; and

- The diverse tasks undertaken by the households to maintain, exploit, and perhaps increase their herds and flocks, including herding, milking, slaughtering, and collecting wool and hair.

In addition, the simulated households' repertoires of coping mechanisms and other adaptive behaviors are being expanded substantially to encompass exchange of animals for grain or other needed commodities, and adaptive shifts in household emphasis between agricultural and pastoral components.

Modeling Representation of Demographics and Household Structure and Dynamics

The simulation system includes mechanisms for construction of demographic and household components that are needed to characterize the initial population. This includes the creation of individuals who are in turn members of households, which are subsets of clan and tribal affiliations. Looking at Medieval and ancient demographic data from the Mediterranean region, we are able to reasonably estimate demographic trends in the pre-industrial Mediterranean world. Remarkably, results from Medieval Tuscany match well with census data from Ptolemaic Egypt (Bagnall and Frier, 1994; Herlihy and Klapisch-Zuber 1985). This data also matches closely with Coale and Demeny's model life tables (Coale and Demeny, 1966), for Model West Levels 2 (for males) and 4 (for females). We created demographic algorithms that can produce populations of "Person" objects for our simulations that are consistent with the Coale and Demeny model. This creates a population with relatively high death rates at very young and old ages, and a life expectancy at birth in the mid to early twenties for males and females respectively. The probability of male births is slightly higher than female (51 vs. 49 percent), although, like the other initial demographic algorithms, this assumption could be changed in future simulations. Furthermore, high birth rates (average of approximately six children per woman) are given; however, a high number of children die before they produce offspring (Bagnall and Frier, 1994). The settlement population created can be large (thousands) or small (a single household), depending on the specific simulation context. Simulated persons are given unique reference numbers and randomly assigned names to allow us to trace family history throughout a model run.

Figure 4 shows some of the population results, using the demographic sub-model just described, from a 100-year pilot study using the ENKIMDU simulator to represent a northern Mesopotamian village based loosely on site data from the Tell Beydar site.

Social interactions in the ancient Near East very often occurred at the household level (Stone, 1981), so that level of simulation granularity is of great interest to us. Once we have created demographically consistent populations of unrelated individuals, our population generation sub-model assigns individuals to households and establishes kinship connections. In our model, household census data from rural Ptolemaic Egypt were used to initially reconstruct the percentages of household types encountered in a rural society. This data source does match well with historical records from other similar regions (i.e. Medieval Tuscany) (Herlihy and Klapisch-Zuber, 1985). Future simulations may employ other data sets, particularly if detailed census data from Mesopotamia become available. We represent five basic household types found in the Near East in ancient periods (see Figure 5) : single person households, households without kin-related members, and nuclear, extended, and multiple family households. We have constructed these households based on the definitions provided by Bagnall and Frier (Bagnall and Frier, 1994). From the Near East, it appears that multiple family households may have been preferred; however, various physical and social factors may have prevented many households from achieving their ideal patrilocal type (Schloen, 2001).

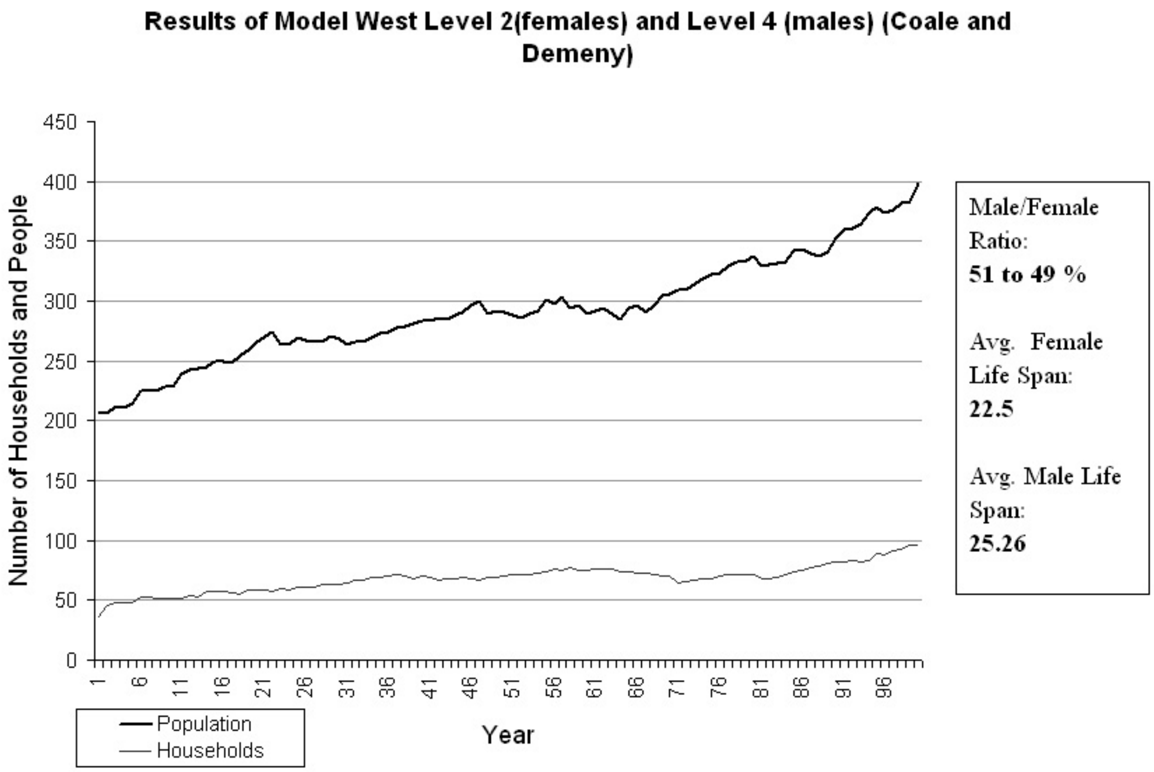

Figure 4. Example Modeled 100-Year Population Trajectory

Within the simulation's household types there are variations, such as conjugal pairs that have no offspring (a type of nuclear family) or a couple residing in a virilocal household with the parent or parents of the husband present. All of these variations represent examples one may encounter in ancient Near Eastern societies (Bagnall and Fryer, 1994). The dynamics of the simulated settlement population reflect both the inherent demographic reproductive and mortality rates (Coale and Demeny, 1966) and the social mores such as those related to marriage age, remarriage, etc. Other factors such as economic and health stress, (e.g., famine and disease) further affect population growth and household structure and dynamics. Demographic effects of disasters and sustained periods of high stress can be understood from historical examples; sub-models that can represent such stresses will soon be integrated into the simulation framework.

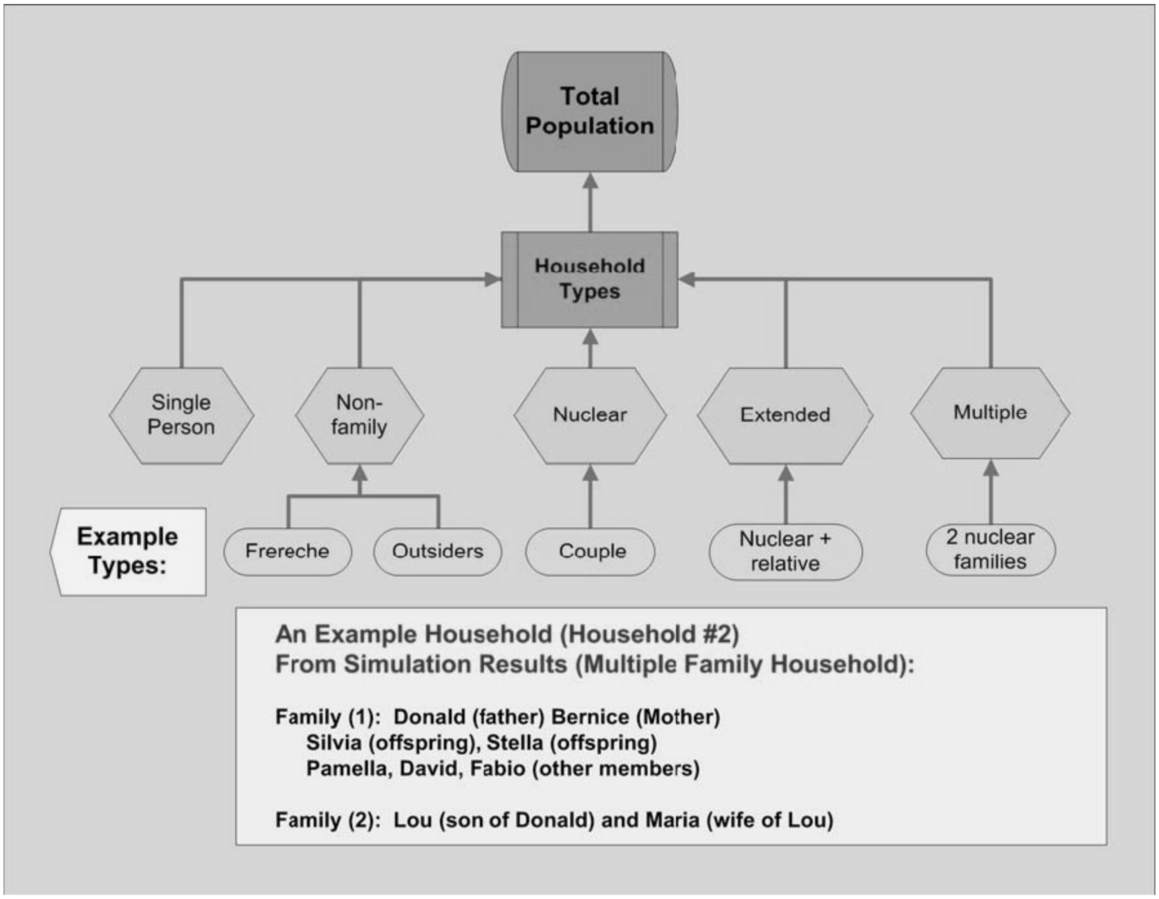

Figure 5. Household Types from Ptolemaic Egyptian Census Data

Figure 6 represents a 20-year episode in the existence of a single household, (the same household identified at the bottom of Figure 5) drawn directly from a 100-year pilot run of the ENKIMDU system for the “Tell Beydar-like” modeled village mentioned earlier. In Figure 6, the incidents that drive household evolution are called out in the simulation years in which they occurred. Clearly, the life history of this household was quite turbulent; given the prevailing death rates, this can be expected to be closer to the norm than to the exception.

Behaviors and decisions of households are influenced by natural and social circumstances such as low crop yields, endogamous or exogamous marriage patterns, and high rates of death. In the Near East, patrilineal cousin marriages were a common occurrence; however, exogamous marriage patterns were also common and may have been preferred in cases were there is an economic benefit or social motivation (e.g., conflict resolution). Limited economic exchanges and transfers, such as payment of bride price and dowry, reflect some of the other behavioral traits associated with the simulation’s marriage patterns (Holly, 1989). In the present ENKIMDU framework, when there is an exchange of goods among households, the transfer of items is only limited to grain and inheritable shares in a community-held cache of agricultural fields. With the future construction of an economic and more developed exchange system, household behavior can be further developed. Thus, as we create more complex social behavior in the simulation, household behavior and structure can be more representative of historical results known from Mesopotamia.

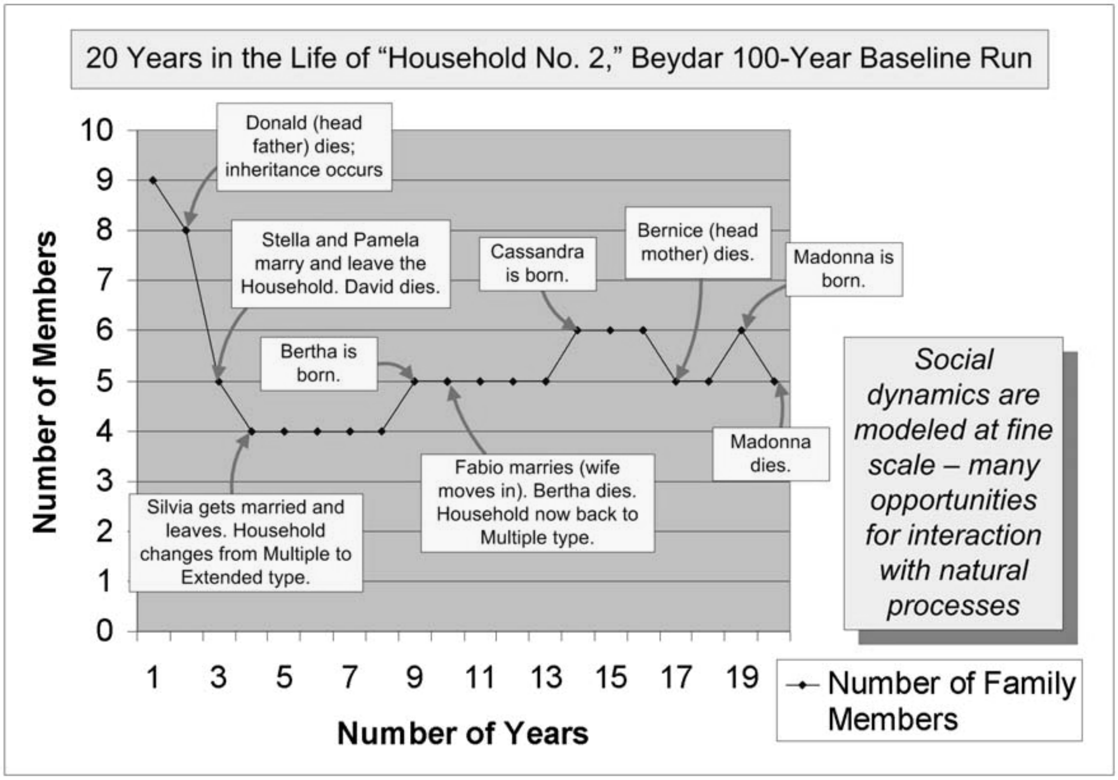

Figure 6. A Modeled Household Evolves over 20 Years

Many of the day-to-day labor activities of a Near Eastern village are planned and executed at the household level (Sweet, 1974). Accordingly, households are the agents that organize labor tasks, such as planting, harvesting, and herding of animals, in our model runs. Strength of social and kinship ties is important in creating and modulating behavioral options for the simulated social agents. In times of economic stress, a household may look to other kin-related households for assistance. Inheritance decisions are based on an individual's relationship with other consanguines as well as social position in society (e.g. a male getting a smaller inheritance than his elder brother) (Roth, 1997). Other households may increase their influence in the community through patronage (Saller, 1994; Schloen, 2001). This could be one mechanism that the simulation could use to form and sustain elites in a society.

Communities and their component households can also be influenced by changes brought about by the migration and movement of people between settlements, and can in many cases adaptively alter their lifestyles (e.g. nomadic vs. sedentary behavior) in response to stress. Such dynamics can be a major factor in replenishing or depleting a local population (Grossman, 1992). Thus, as we move from a closed system model of a north Mesopotamian village to a more complex regional model, we can begin to see how households are influenced by regional behavioral dynamics and outside populations. In the future, slaves and temporary migrants will also be modeled into the settlements. This, however, can only be developed with more complex exchange and economic behaviors integrated into the simulation, since slaves and migrant workers were important agents in ancient economies. Nevertheless, as we begin to look at various landscapes and time periods, different ensembles of social behaviors will be modeled, with different regions having varying and diachronic customs. Many of these different regions will also interact with each other as cultures across the Mesopotamian landscape come into contact.

Initial Pilot Studies for the Beydar Area

Tell Beydar, which has provided much of the data for the initial pilot study outlined in this paper, is located in the Wadi `Awaidj within the Khabur basin of northern Syria. It is a 26 hectare site that was heavily occupied during the Bronze age (3rd and 2nd millennium BC) (Wilkinson, 2000b). Some of the texts that we have used to help define or bound attributes and behaviors of our model settlement originate from this site. In many respects, the Beydar area is typical of northern Mesopotamia, where rain-fed agriculture (with average annual rainfall near 300 mm) is the norm, and drought and periods of environmental stress can be common occurrences. The landscape is undulating, with a basalt plateau lying west of the site (Wilkinson, 2000b). The site layout is illustrated in Figure 7.

The modeled field layout, though algorithmically created, seems reasonably representative of the texture of observed and inferred field mosaics appropriate to the period of interest. Modeled soil characteristics are based upon regional field studies (van Liere, 2003). Other important "baseline" modeling assumptions and parameterizations are noted in the Figure. The musha' system (Schaebler, 2001) mentioned in the figure is a community-level mechanism for periodically reallocating crop fields to households by lottery, based on "field shares" held by each household. Individuals or households can model it as an alternative form of land tenure to ownership.

Some early modeling results for this "Tell Beydar-like" village will now be discussed. The model output that is shown in this section is intended simply to illustrate the sorts of question that can perhaps be addressed, and to hint at the sorts of insights that may eventually be obtainable, through simulation systems such as ENKIMDU. The preliminary results reported here should in no way be construed as answering any questions, though to the project team they have been extraordinarily successful in provoking questions. Although only a very limited subset of the known natural and social dynamic mechanisms are being represented, the modeled settlement is already capable of exhibiting behavior that is subtle and intriguing.

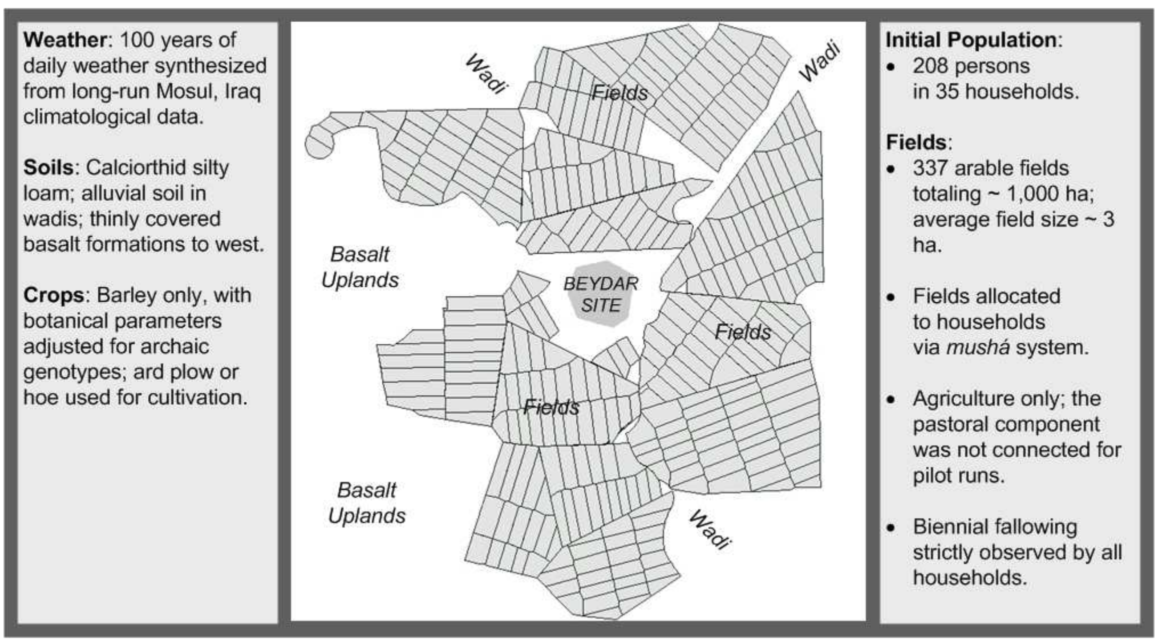

Figure 7. Modeled Village and Surrounding Fields

Figure 8 shows the village's annual average barley yield in the context of annual rainfall for a 100-year baseline simulation. The two parameters seem fairly well correlated, as would be expected. It is interesting to note that the yields appear to decline systematically over the first fifty years of cultivation before leveling off. The simulated village practiced biennial fallowing, with fallow fields left bare of vegetation; no manure or supplemental water was applied, and there was no intercropping with species other than barley. The results in Figure 8 reflect daily updates to the state of each of the 337 fields in the modeled settlement's surround, for 100 years of simulation: thus, in all, over 12 million daily field state updates are incorporated in the yield results.

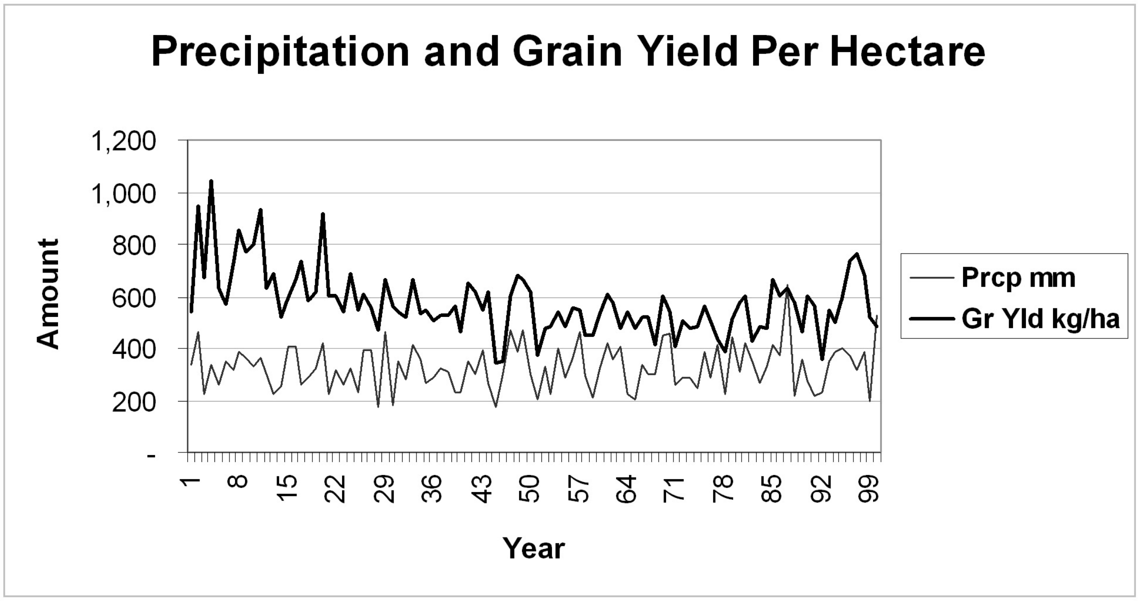

Figure 8. 100-Year Baseline Run: Barley Yield vs. Precipitation

Figure 9 presents the 100-year baseline trajectories of some additional parameters related to food production and distribution. The top two traces show total barley yield in kilograms and total village food requirement (expressed in kilograms of barley, assuming 250 kg barley per adult male per year, adjusted for gender and age of all members of the population). Although there were some bad years, there were seldom two or more in a row, and overall the village appeared to have been able to feed itself. The third trace, below the other two, requires a bit of explanation. It represents the amount of food required for consumption in each household that could not be met from that household's own grain stores, summed over all households in the settlement. Thus, if we can make the simple (though unsupported) assumption that the community will have sought to support all of its households, the deficit could be considered as an indicator of the degree of cooperation (food sharing) that would have been needed to accomplish this. It should be noted that, in the pilot study, all households attempt to farm; farming is the only sustainability option open to them in the scenarios we have modeled. (This limitation is soon to be eased when the pastoral component is added to the simulation framework.) The fraction of crops brought to harvest tends to be less than one for a number of reasons, chief among them being inadequate labor to complete cultivation tasks, often due to deaths in the household. Again, it is simplistically assumed for the pilot runs that households are entirely responsible for their own field cultivation; no such help is received for other households – this must be borne in mind lest these results be over-interpreted.

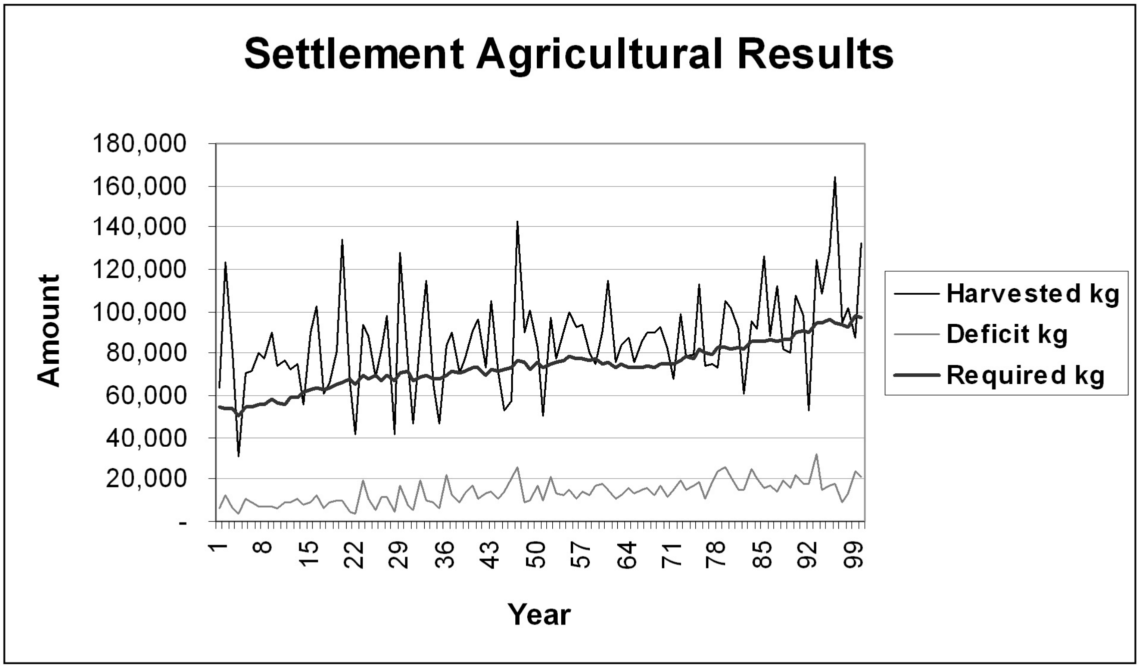

Figure 9. 100-Year Baseline Run: Food Production and Distribution

Figure 10 provides some further information regarding the unevenness in the measures of self-sufficiency across households. The “fraction of households self-sufficient” trace is the result of counting a household as self-sufficient in a given year only if it never came up short in feeding itself from its own grain supply; in general only about half of the households appear to have met this condition. The “fraction of grain needs met within households” trace indicates that, in general, the average household could provide about 80 percent of its own food. An intriguing follow-up question might be: who is providing the largesse? Are the same households or types of households always overproducing? What characterizes such households? Such questions will be near the top of our agenda when we revisit this scenario with a more thoroughly developed representation of social agent dynamics.

The last 100-year history we will show, in Figure 11, presents variations in a collection of demographic variables for the households in our simulated settlement. In addition to births, deaths, marriages and total number of households over time, the figure indicates number of people who moved from one household to another each year. Potential reasons for such a move modeled in the simulation could include a wife joining a new husband in his current household, forming a new household by splitting from a multiple household, being taken in by relatives after dissolution of one’s own household, etc.

In addition to the 100-year baseline run just discussed, we have launched a number of exploratory runs to test the sensitivity of the simulated landscape and settlement system to perturbations in various parameters. Highlights of these sensitivity tests are very briefly summarized below.

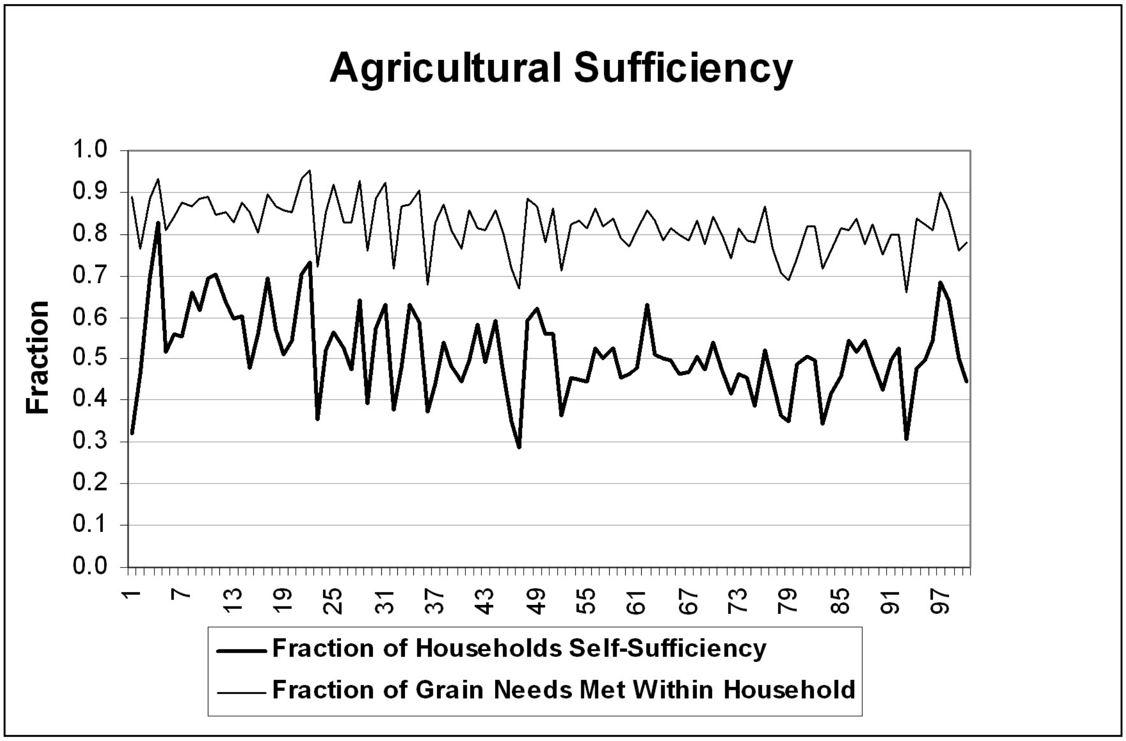

Figure 10. 100-Year Baseline Runs: Indicators of Production Efficiency

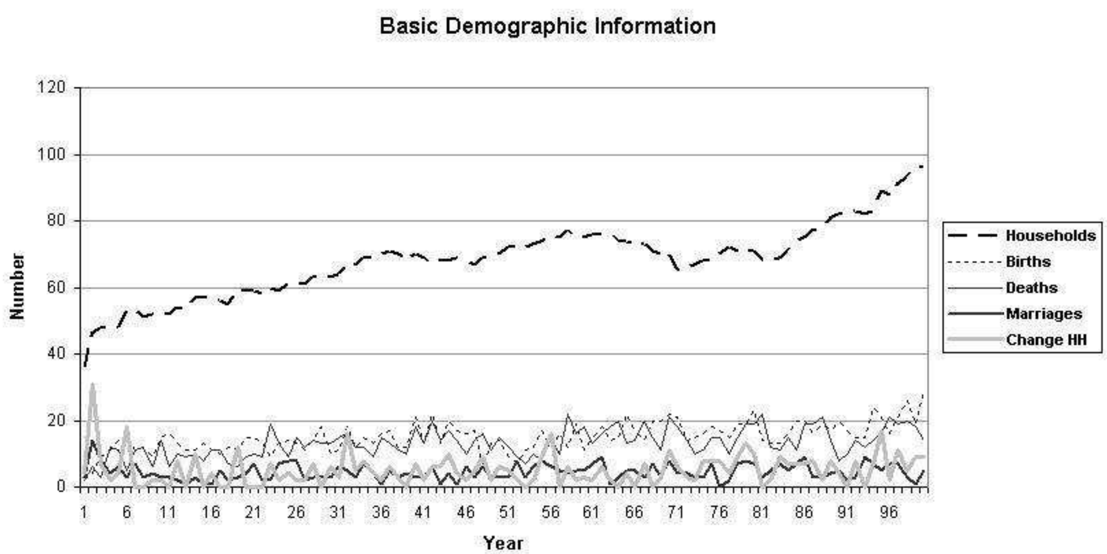

Figure 11. 100-Year Baseline Runs: Demographic Indicators

Short Sensitivity Test Simulations for Tell Beydar

I. <u>Rainfall</u>
This is a test of the effects of uniform 10 percent reduction in precipitation. The 100-year baseline run was repeated with average rainfall reduced from 328 to 296 mm/yr.

Results:

- Average barley yield was reduced 1.7 percent (from 553 kg/ha to 544 kg/ha)
- Average harvest sufficiency (yield/need) was reduced 1.9 percent (from 1.105 to 1.084)
- A 10 percent reduction to 296 mm/yr did not appear to stress barley unduly, from which we can tentatively deduce that the community may be sustainable (at least with respect to cereal production) even at the lower climatological mean rainfall level.

II. <u>Resources</u>
This is a test of the effects of constraints on availability of plow teams.
In the base case, it was assumed that there was a plow team for every household. We ran two additional cases: 0.5 and 0.25 plow teams per household. In all of the simulation results presented here, plow teams were assumed to be a resource that was managed at the community (not household) level. Households needing to plow a field in preparation for planting queue up for the next available plow team. Once they obtain access to a plow team, they may have continued use of it until the field is plowed, at which time the plow team goes back into the resource pool. If the previous user has more fields than one to plow, it must get back in the queue.

Results:

- In the 0.5 case, reduced availability of plow teams had a negligible effect on agricultural productivity.
- In the 0.25 case, reduced availability of plow teams had a very substantial effect: average harvest sufficiency dropped 12.3 percent (from 1.38 down to 1.21); fraction of crops abandoned increased from 2.3 percent (baseline) to 16.7 percent.

These runs appear to point out the existence of a hidden constraint on agricultural productivity: in our simulations, with a plow team assumed for every four households, some households are unable to complete plowing before the winter rains begin, are therefore late getting seed into the ground, and have a reduced or failed harvest as a result. There is evidently no such production bottleneck if only two households have to share each plow team. It is worth pointing out that this insight gained by running complex adaptive system simulations may not have been obtainable in any other way (other than by field trials); it is certainly not immediately apparent from the data we have on agricultural task productivity rates and task schedules for the ancient Mesopotamian agricultural year that a bottleneck will manifest itself at a plow team ratio of 0.25, but not at 0.5.

III. <u>Household Evolution</u>
This is a test of the effects of varying household cohesiveness. We implemented this test by imposing more restrictive preconditions for allowing multiple households to divide.

Results:

- Settlement population was 3 percent higher in the “more cohesive” case.
- Settlement average harvest sufficiency was 2 percent lower in the “more cohesive” case.

- The proportion of household food needs met within each household was reduced by 11 percent in the "more cohesive" case.

This preliminary result, if substantiated, contradicted our intuition that a few larger households might manage their resources more efficiently than many smaller ones. This is another intriguing result that we will want to revisit and test as we improve the fidelity and power of our ENKIMDU simulation framework.

Next Steps for the Project

Planned project activities for the upcoming project year include:

• Full incorporation of the pastoral component, including localized extensive livestock management (sheep and goats). Milk, wool, meat and livestock manure will enter the equation. Herd/flock foraging behaviors, with fine-scale interactions with the landscape, will be modeled. Herd/flock population dynamics (both natural and managed) will be simulated.

• Explicit modeling of other household sustaining activities: tending kitchen gardens, gathering wild foods, etc.

• More robust representation of the dynamics of exchange, with evolving networks of reciprocity and trust.

• More differentiation in persons' roles and activities within their households and communities.

In addition, we plan to expand scale of simulations to sub-regional (~ 50 km) with multiple settlements, and will add some cross-settlement interactions.

For Southern Mesopotamia, we plan to produce adjusted or alternative representations of the processes we've described, as appropriate, and add process models for "new" elements such as irrigation, canal maintenance, riverine bulk transport, etc.

Summary

Our preliminary pilot study results point to the potential usefulness of the ENKIMDU simulation engine for understanding complex socio-environmental mechanisms that affected the historical and social evolution of ancient Mesopotamia.
By explicitly representing dynamics of both societal and natural processes within the same multidisplinary, holistic simulation, ENKIMDU should be able to provide a new level of insights into the behaviors of real-world complex systems.

ENKIMDU is on its way to being able to examine society-scale questions, such as long-term sustainability of settlement systems, as well as issues more relevant at the level of households and individuals. This ability to give highly informative aspects of agency makes ENKIMDU useful for social scientists with varied interests in the components of societies. More importantly, the ability of the simulation chassis to incorporate disparate forms of social theories makes it a potentially useful tool for scholars with different theoretical backgrounds. As we continue to expand ENKIMDU's capabilities, even more complex agent behaviors can be represented and measured to see their impacts on social change.

Finally, we hope to be successful in adapting and employing ENKIMDU, supported by the DIAS and FACET simulation frameworks, to other societies in varied temporal, cultural, and environmental settings. We have taken the first steps along this path in a new project in which we are adapting and expanding ENKIMDU to address agroeconomic sustainability and resource planning issues for modern agricultural villages in Thailand.

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Biographies

John Christiansen (jhc@anl.gov) is Deputy Director of the Advanced Simulation Technologies Center at Argonne National Laboratory. Mr. Christiansen’s research over the past decade has focused on the development of flexible simulation frameworks that can be used to build very large, multidisciplinary complex adaptive system simulations, in applications that cover a wide range of domains and disciplines, including the natural and social sciences as well as health care and logistics. He is the creator of the ENKIMDU simulation engine and inventor of the DIAS and FACET modeling frameworks that support it.

Mark Altaweel is a recent PhD graduate from the University of Chicago. He is trained as an archaeologist specializing in the ancient Near East. Currently, he is working at Argonne National Laboratory as a research scientist assisting in the creation of ENKIMDU. He has worked in numerous countries in the Near East, and his primary interests are in the Bronze and Iron Ages of Mesopotamia. He can be reached at maltaweel@anl.gov or mraltawe@uchicago.edu.

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