Simulation Modeling for Human Community and Agricultural Landuse

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ABSTRACT

The Mediterranean Landscape Dynamics (MEDLAND) project seeks to better understand the impacts of early agropastoral activities on human societies. A hybrid agent and landscape simulation model is being developed to meet the project goals. The human and landscape models serve as both provider and consumer in this hybrid model. The devised approach allows these models to interact with one another while providing flexibility for either model to be changed in a systematic fashion. In this paper, we describe the MEDLAND simulation and detail models of human population growth as governed via their interactions with landscape. The agents, landscape, and the interaction models are developed as a combination of atomic, coupled, and cellular models realized in the DEVSJAVA environment.

1 INTRODUCTION

The Mediterranean Landscape Dynamics project brings together researchers from diverse disciplines including Anthropology, Computer Science, Geography, and Geological Sciences to study the long-term impacts of human agropastoral land use in the Mediterranean Basin from the beginnings of agriculture in the Neolithic through the rise of early cities in the Bronze Age [1]. The initial model focuses on the Jordan Valley from the middle of the Early Bronze Age I to the middle of the Early Bronze Age II - III (c.a. 3350 B.C. - 2450 B.C.). Through the use of Geographic Information Systems (GIS) technology and agent modeling, this initial model focuses on the investigation of three major themes of human land use: 1) The effects of growth in agropastoral economies on biodiversity; 2) subsequent land use intensification and diversification and its impacts on landscape vulnerability and resilience; and 3) the sustainability of human maintained ecosystems. Other goals include examining the effects of land degradation on subsequent settlement patterns and investigating how changes in agricultural practices affect the productivity of crops and of the landscape. The group is also interested in examining whether or not periods of village abandonment may be explained by climate change or human-caused degradation of the landscape. Finally, by placing model villages in locations provided by archeological findings, it may be possible to study the potential for conflict between competing villages as they grow.

Two types of models are being used to meet these goals: A human aspect model and a landscape model. The human model contains the simulation agents and all of the objects with which the agent must directly interact. The landscape model encompasses all of the landscape and climate objects in the simulation that an agent cannot directly influence, such as rainfall and vegetation growth. Initial archaeological and ethnographical data from human settlements of the region and time periods under study is being used to develop a first generation set of models. The landscape model is being built using this known data (such as topography, human settlement locations, and vegetation during specific time frames) as the core of its contents. The simulation models for environmental changes are based upon this data and inputs provided from the human model. For example, ground slope and elevation impacts on water run off and soil erosion calculations. Furthermore, as the human agent removes natural vegetation for agricultural activities, input data will be provided to the landscape model to revise former soil erosion calculations.

While data is available, it is incomplete. Thus, the landscape and human agent models can only be developed based on partial facts and hypothesized knowledge. While the measure of correctness for the simulation cannot be exact, the simulation experiments will still be useful for testing hypotheses. Thus, the human and landscape models are being designed around what data is available and how human and landscape interactions may have occurred. Domain experts will examine the simulation results to determine if they are consistent with the known data within a certain margin of error and are at all probable within the studied region and time periods.

1.1 Requirements

The initial human model represents a human population within the Jordan Valley from the middle of the Early

Bronze Age I to the middle of the Early Bronze Age II - III. This model represents both sedentary and non-sedentary human populations that manage crops, orchards and animal herds and works to meet two basic agent goals: survival and reproduction. Accomplishing these goals requires that the agents interact with the landscape to cultivate crops and orchards and to use land for animal husbandry. The model also maintains a consideration of human social structure from the levels of the individual, household, village, and society. In this scenario, consideration does not imply representation. Some or all of the components of this structure may be implicit in abstract form from within a higher-level model(s) or may be emergent from the interactions of lower-level components. The agents must also be capable of interacting with other agents and of working within specified rule sets that yield simulation results consistent with data models developed from anthropological sources.

From a combined human and landscape modeling perspective, a major goal of the project is to create a design that can be used for other scenarios of human land use with minimal changes to an agent's rule sets and its underlying simulation environment. The goal is to enable variables within rules to be modified as easily as possible and will also provide a general interface to the landscape model that allows the use of different data sets. To achieve this, the human aspect model is being developed in phases. Each subsequent phase will build upon the last and will revise the model as required to meet project goals. The first phase involves developing a model that represents the sedentary humans that manage crops only. Impacts of pastoral activities and orchard cultivation are abstracted into variables, inserted as disturbances, or ignored in this initial phase. An initial landscape model is being developed [2] with its underlying GRASS [3] environment and is being studied for extension to support integration with agent-based modeling environments such as DEVSJAVA [4]. While the initial landscape model is being created, a simplified landscape model — in comparison to those represented in GRASS — is being used to exercise the human model during its initial phase simulations.

2 RELATED WORK

Three related research projects were examined during the development of the agent-based models. The first is Epstein and Axtell's *Growing Artificial Societies: Social Science from the Bottom Up*. The devised environment, called Sugarscape, is an agent-based model that tightly couples the agents and the environment in which they act. To survive, agents act in tribes and must collect resources. The environment is simplistic with enough inserted variability to exercise the agents capabilities [5].

The second research project called "*Social Science Applications of Discrete Event Simulation: A DEVS Artificial Society*" [6, 7] uses the concepts of the Sugarscape model. It uses the cellular DEVS modeling approach [8] and extends it to simulate agents. In this approach, the agents are attributes of the cell structure, thus resulting in tight coupling between agent and environment.

In a more recent project called Village [9], concepts separating agents and landscape are developed into models to simulate landuse in Southwest United States spanning several hundred years [9, 10]. In this work, the landscape data provides input on which their agents could act. The landscape attributes were more dynamic but still strongly tied to the agent-model on which the focus of the project lies.

Numerous other projects have been carried out to study various aspects of agents and landscape dynamics (e.g., [11-14]). Similarly, a variety of simulation environments have also been developed. Two examples are Ascape [15] and DEVSJAVA. The former is based on object-oriented software design concepts and the latter on system-theoretic, component-based modeling. Both of these environments are realized using the Java programming language. Ascape provides a suite of model components and user interfaces to simulate dynamics similar to those of Sugarscape. DEVSJAVA offers a basis where agents are modeled as atomic and coupled models and the landscape is specified as Cellular DEVS [4, 8]. In this project, our aim is to develop a modeling environment where the humans are modeled in DEVS and the landscape is modeled using GRASS.

For this project, however, we use the DEVSJAVA environment to realize the composition concept for integrating agents, landscape, and interactions described below.

3 A THREE-FACETED MODELING APPROACH

To support combined modeling of human activities and landscape/climate processes, it is useful to develop a modeling framework which can support modular model development and composition [2, 16]. Such a modeling framework is key for developing and experimenting with complex simulation models. A key challenge in developing heterogeneous models is not only to support different modeling approaches to be used, but also to ensure that they interact in a well-defined fashion. For hybrid simulation of agents and physical processes, a rigorous modeling framework must support (i) separate modeling of humans and landscape dynamics and (ii) their (internal and external) interactions [17].

A variety of modeling approaches exists (e.g., agent-oriented, discrete-event, and logic-based) that are well suited for representing different types and aspects of human activities. The degree of complexity supported by these approaches varies significantly. For example, the basic modeling element in agent-based and discrete-event approaches is an agent (i.e., object) which may be combined to represent complex decision making. These agents are relatively simple and well suited for capturing common reactive human-like activities. In contrast, logic-based decision-making is concerned with representing intricate forms of reasoning including planning in partially known situations using different types of logical calculi and belief revision approaches (for example, see [18]). Human-like modeling approaches can be extended to varying degrees to support decision making under uncertainty.

Despite their differences, the above human decision-making modeling approaches can be viewed as being alike in comparison with modeling of physical dynamics of landscape and climate. The dynamics of subsurface, surface, and climate processes are generally modeled as continuous and/or discrete-time formulas. In particular, environmental changes, fluid flows, and natural processes are generally described using (partial) differential equations or their discrete-time counterparts.

An important abstraction that has been introduced is the distinction between *managed* and *unmanaged* resources . Their role in separating agent and landscape/climate models is key for succinctly modeling their interactions.

Based on the above separation of concerns between human activities and natural processes, it is useful to develop models for humans, landscape/climate, and their interactions. Given the partitioning of human actions and the physical world, a key decision is to determine suitable agent, landscape/climate, and interaction model abstractions such that their combinations can represent their known dynamics as well as revealing some likely hidden dynamics.

3.1 Agent Modeling

Agent models are conceptualized to represent individual and collective human roles and activities. Four basic abstractions are devised. First, the collection of agent models must exhibit population growth and decline. Second, some agent models must be able to manipulate managed resources such as crops. Third, agent models may exchange managed resources among each other. Fourth, some agent models activities affect unmanaged resources belonging to landscape dynamics. The degree of sophistication for each of these abstractions can result in simple to complex activities with actions that are either internal or external to the human agent model. For example, a family's agricultural activities may be modeled without modeling rules for exchanging managed resources with other families. In contrast, the modeling of a human society (which may entail things like social hierarchy and group management of resources) requires more complex interaction rules that govern the behavior within the agent as well as the interactions between them.

These kind of agent models can be developed using Discrete Event System Specification formalism [8]. A key advantage of this modeling framework is its support for cellular modeling (i.e., Cellular DEVS [4, 13]). It is useful to define an abstract representation of the landscape for the agents. The cellular DEVS model abstraction can serve as a surrogate for detailed landscape processes expressed in GRASS. The cellular model contains simple physical process dynamics for data derived from a complex model developed in the GRASS Geographical Information System (GIS).

3.2 Landscape/Climate Modeling

Surface and subsurface dynamics and climate processes can be described in terms of some attributes. Each attribute (or set of attributes) is assigned to two-dimensional and three-dimensional (cellular) space/time grids as supported by environments such as GRASS. The values of these attributes can be derived from physics-based models of dynamics (e.g., rate of change for soil fertility or water flow in a basin). The physical laws of landscape and climate processes are responsible for changes in unmanaged resources such as water availability and vegetation growth. These models, similar to agent models, can be developed based on first principles of physics, chemistry, and biology, for example. Instead, models can also be simple – e.g., tabular data representing vegetation index based on location and time. A piece of land may be abstracted as unmanaged with respect to the landscape model or managed with respect to the agent model. This separation helps to model the agent and landscape interactions as described next.

The landscape model being developed in GRASS contains a multi-level data set representing different features of the landscape under study. It will also be capable of running complex algorithms to study the impacts of landscape changes (e.g., water erosion) and climate.

3.3 Interaction Modeling

As noted above, the interactions among agent and landscape/climate models can be complex due to differences between modeling approaches. To support systematic interactions between these models, a separate, explicit, model supporting data exchange and control of the agent and landscape models can be introduced. The main responsibility of an interaction model is to describe agent and landscape interactions with one another and thus how agents can affect unmanaged resources (e.g., landscape) and conversely how the landscape limits the agents' activities.

This model is aimed to provide appropriate abstractions for handling complexity that arises due to data types, their mappings, and exchange frequency under some type of control (for details see [19]). We can identify which agent attributes and actions are to be communicated with the landscape model. Aside from data exchange, this model can specify how frequently the agent model receives data from the landscape model or conversely how often agent actions may change the landscape (e.g., cultivation every other year).

In the next section, we describe a scheme to support interactions between agents and landscape cells. This interaction scheme utilizes the coupling of (atomic, coupled, and cell) components supported by the DEVS framework.

4 HUMAN MODEL SPECIFICATION

In the previous section, we described our overall modeling framework for the project. In the rest of the paper, we detail the development of the human agent model where the landscape/climate model is abstracted to two-dimensional cellular DEVS models. An important part of developing reusable models is to understand the logic behind their creation. As such, we have provided some detailed explanations regarding the model development below.

The human model is being developed using DEVS along with its cellular extension. The human model is an assembly of models that provide an agent and an environment in which the agent can perform. Specifically, in the first phase of this project, there are three types of models in the system – *household*, *village*, and *landscape* [16]. A household is used to represent the human agent and multiple households are associated with a village. A village represents the land required to house the village inhabitants and any other communal areas. The cellular landscape is a collection of landscape cells which provide a two-dimensional representation of the households' environment. Each cell is a structure that contains abstractions of portions of the data in the landscape model needed for the household to make informed decisions.

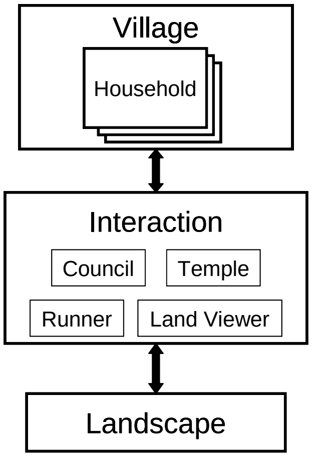

Figure 1. Human Landscape Simulation Model

Figure 1 depicts a configuration of the set of models used for simulating human-landscape dynamics. The *Council* and *Temple* support interactions among households and villages. The *Land Viewer* and *Runner* facilitate interactions between villages and landscape cells. These four models (collectively called the Interaction model) use an address messaging scheme to facilitate hierarchical communications between villages and landscape models without excessive couplings.

Resources have been divided into two categories based on the separation between landscape and human models as defined above. The first is unmanaged resources. This category includes all things in the environment that exist without human intervention and that, typically, the human only has indirect influence on. For example, water sources and soil are unmanaged resources. They may impact the agent and the agent may indirectly change their values based upon land cultivation, but they exist with or without the agent. The landscape will have a direct impact on these resources.

The second type of resource is the managed resource. These resources are directly created and managed by the agent. Managed resources, such as crops, are considered an attribute of the agent. The landscape model may have indirect influence on the managed resources. For instance, the amount of rainfall (an unmanaged resource) will impact the yield of a household's managed crops.

4.1 Villages

As mentioned above, villages in the first phase are simple objects that have no logic associated with them. The purpose of the village is to simplify the identification of a group of households and prevent them from cultivating residential segments of land. The land occupied by people as residence must be accounted for when considering a total land use impact. It would be cumbersome to rely on household models to maintain a contiguous, centralized group of cells that they could reside on but not cultivate given that a 1-to-many relation exists between land cells and households for village location representation. A village object maintains this dynamic *housing area* as a property and can expand or contract the area as population grows or declines. Further, since villages play an important role in modeling higher levels of complexity (e.g., community to community), they are integral to modeling of social interactions and landuse (see the Future Work section, below).

The Village is a coupled model consisting of a finite number of households. For the sake of convenience, the Village model contains the Council and the Temple models (see Figure 1). The Council maintains the number of households, the total village population, and the location of the village and supports dynamic coupling and decoupling to the households in the village. The Temple distributes incoming messages to the appropriate receiving household within the village. This enables households to move from village-to-village while also reducing the need to manage couplings directly between the households and landscape.

4.2 Households

A household is an atomic model representing a collection of individuals working together as a family. It is also the agent within the simulation. The household is the best choice to represent the human agent based upon the level of data available and the appropriateness of data for studying long-term dynamics of human settlements [20]. The data exists mainly at the village level – where the village was, the major roles a village played, the size of the village population, population growth, etc. However, it is known that most decisions were made at a household level. Households banded together as a village in an effort to increase the chance of survival for each family. Given that decisions were made at a household level, it would not be useful to model the agent at the level of the village since it severely restricts modeling important human and landscape interactions. Modeling at the level of the individual would not be appropriate either due to lack of detailed data that can describe the actions of the individual. In particular, it would be difficult to validate simulation models since it is impractical to obtain evidence to either support or deny simulated results.

Placing the agent at the household level enables the model to deal with interactions between groups of people living together and supporting one another. Further, while data is not explicit in defining households in great detail, adequate data can be interpolated from village-level data to support the creation of a model at this level.

Note that while the household represents multiple people, all with the same goals and capabilities, it is a singular agent. Each household has a *population* attribute that represents the number of family members within that household. Additionally, each household *belongs* to a specific village and knows the village location.

Based upon our initial goals, the household's first principle is survival with minimal work. Its secondary goal is growth. With these two core items, rule sets have been defined that drive the household's behavior in the initial phase. The household's primary rules are:

- Each person requires equal amounts of food each year.
- The amount of managed land is directly proportional to the population.
- All land has value; manage the highest valued land first.
- The amount of food yield is proportional to the amount of land cultivated.
- Cultivate only enough to sustain the current population.
- If less land is cultivated than the maximum that can be managed, reserve the rest as fallow.
- Growth occurs when the difference between yield and need exceeds a threshold value.

Secondary rules are:

- If the cultivated land equals less than half of what can be managed; cultivate up to half to gain excess yield for growth.
- Revise the expectation of next year's yield based upon this year's yield.
- The value of cultivated land will decline each year.
- The value of fallowed land will increase each year.
- There is a limit to how far a household will travel from the village to manage land.

In support of these rule sets, key state variables can be identified in the household model. They are:

- Population: the number of people in the household. This value may be randomly determined initially. It dictates both the amount of food required and the maximum amount of land that can be managed to meet that need.
- Amount of Cultivated/Fallowed Land: This is initially zero. When the household starts, it begins by surveying the area around it and attempting to cultivate the best land to meet its initial needs.
- Yield from Cultivated Land: While the amount of yield is proportional to the amount of cultivated land, the yield calculation is highly dependent upon the soil value of the land cultivated. This soil value, while impacted by a household's management, is mainly derived from environmental variables that lie outside of a household's control.
- Cultivation Range: this is a concept as much as it is a variable, as it exists in the model both as a derived value and a hard line. The further away from the village that a landscape cell is, the less valuable it is to the household. There is also currently a hard limit beyond which the household can not see. This serves as a control structure as the model is being developed and tested.

Within the confines of an agent paradigm, the household is best described as a reactive agent. The inputs it receives are both the yield and its current population. From these, it calculates how much land is required to survive. It compares the values of the unmanaged land that it "senses" each year to what it is currently managing and executes a cultivation plan. "Plan" in this case not being a series of steps but a singly-executed approach. If this approach fails, it revises the failed portion of the approach and tries again. Since the household does retain some world information throughout the year to improve performance of error management it cannot be considered a purely reactive agent. It should also be noted that no world knowledge is provided *a priori*. In fact, it is possible for the household to repeatedly try and survey land beyond the boundaries of the simulation when the village is close to the cell boundaries. It is the job of the Land Viewer to manage these errant messages.

Time management for a household is conducted in year's. Each year, the household has three main phases. In the first phase, the household calculates the yield from each of its cultivated lands. The second phase is population management where the population is adjusted based upon the relationship between the yield and need. The last phase is land management. The household first reassess its need based upon an expectation derived from last year's yield. It then examines it's current managed land holdings and evaluates unmanaged, surrounding land. The household then formulates a management plan and executes it. When models interact, the DEVS formalism only allows one interaction at a time – in a nondeterministic fashion. Thus, contention over land grabbing is handled by a first-come, first-served approach requiring that any loosing household(s) revise their plan(s). Once management is complete, the next year begins and the household reaps the benefits of its plan.

A key factor in enabling the household to survive while performing minimal work is the concept of land value. Land value represents the household's interpretation of how much benefit may be gained from land in terms of agriculture, minus the amount of work required to manage it. An agent will calculate a land value, L, at time *t* for each cell it considers based upon the cell's maximum soil value, $sv_{\max}$, its current soil value, sv_t, the distance from the village to the cell, *d*, and preparation costs, *p*, at that time to cultivate the land.

$$L(t) = (c_1 \times sv_{\max}) - (c_2 \times (sv_{\max} - sv_t)) - (c_3 \times d) - (c_4 \times p(t))$$

The function $p(t)$ is dependant upon the current vegetation at time *t*. A straight linear valuation is planned for the initial phase but this may be modified later as land attributes such as slope are added to the models. Constants c_n are weighting constants that reflect the importance of the variable in the agent's decision. The values of each constant are as follows: $c_1 = 20.0$, $c_2 = 5.0$, $c_3 = 1.0$, and $c_4 = 1.0$. The value of c_3 is meant to limit the distance agents travel to cultivate land and is based upon the cell size chosen. So, using a 0.5 ha (~70m × ~70m) cell size, to limit most activity within 7 km (~110 cell lengths), a value for $c_3 = 1.0$ should suffice. The constant c_4 is currently 1.0 since the linear land type costs can be scaled accordingly.

Assuming all cell soil values are initially equal and have the same maximum, the intended outcome is for the households to cultivate the closest land first and, as the soil value drops, let it lie fallow and cultivate new land nearby. When this cell's value drops, the desired behavior is to see the household return to the fallow land since its soil value would have increased and the cost to prepare fallow land will be less than the cost to prepare previously uncultivated land. To facilitate this, each year the household revises its estimate of the land it is managing and seeks new information to determine the value of the unmanaged land surrounding it. It then cultivates the most valuable land. Any remaining managed land is retained as fallowed holdings, up to the maximum it can manage.

As previously stated, the amount of land that a household can tend is limited by its population. Data shows that there was an average of 1.36 ha / person, with a range of 0.8 ha / person to 1.9 ha / person, for people in the area under study. The current assumption is that half this value was fallowed and half was cultivated. Further, there is some additional land within each half that was used for trade. The specific values required for survival and trade are still being researched. This half-value can still be used, however. In later phases of this project, herding will be modeled and this surplus crop will be traded for other goods, such as meat. While the input from the meat is not currently modeled, this value can still be approached as a requirement; the utilization of the surplus will be left unmodeled.

4.3 Landscape Cell

A landscape cell is also an atomic model. One that encapsulates a small portion of the terrain being studied. All of the landscape cells are contained within a coupled model called the Landscape.

Each landscape cell has an attribute describing its *contents* (wild, cultivated, or housing; for instance). Every landscape cell will also have some (soil) fertility (nominal) value assigned to it. The maximum soil value is highest value that the cell's current soil value can obtain. Current and maximum are confined to a range of 0 to 5. A value of 0 indicates that nothing will grow. A value of 5 indicates extremely fertile soil where crops will grow well above average. The values and their meaning are kept relatively simple as to capture what a person of that time might be able to deduce by examining the soil (i.e. is it unusable, very poor, poor, average, good, or very good?).

The granularity of the area that a cell represents is dependant upon resource interaction and the smallest area occupied by a village or household. In the initial phase, a size of 0.5 ha will be used based upon data that indicates that this was the smallest plot of land used for housing in a village. If this number changes then the crop yield per cell will change as will the amount of land that an household will own. However, given the relation between these two elements, the overall yield to the household will remain the same. The final number will be decided once the landscape model is complete.

Since it is not an agent, the landscape cell has no goals. However, it does have behaviors and these behaviors are governed by some overarching rules. These rules are:

- Maintain a soil value that represents an abstraction of the data in the landscape model.
- Revise the soil value based upon household actions.
- When cultivated, provide a yield based upon soil value.

To support these rules, the landscape cell has three key state variables. They are:

- Size: Every cell represents a portion of the landscape. To properly calculate any yield, the value must be scaled proportionately.
- Soil Value: The soil value may be either static or dynamic over the course of the simulation. It operates with a range from 0 to a set maximum soil value. The largest the maximum soil value can be is 5. This soil value accounts for all of the environmental factors affecting the landscape cell and the yield is proportional to the soil value. Under normal circumstances, when a household cultivates a cell, the soil value declines each year it is cultivated. If the cell is fallowed, then the value increases until it reaches the maximum.
- Status: All landscape cells that start out unoccupied by villages start as "wild". If a village occupies a cell, then the status will be "residence". The cell status will change to "cultivated" or "fallowed" when managed by a household. If a household releases a cell, its status will become "fallowed" as it can not return to wild once cleared for cultivation. The status of a cell will impact the soil value and the cell's response should a household or village attempt to manage it.

5 SIMULATION ENVIRONMENT

The DEVSJAVA simulation environment is being used to simulate the households, village, and landscape models. Both cell-based landscape and agent-based human modeling in DEVSJAVA share a common "atomic" and "coupled" theory which offers combined agent/landscape simulation modeling. This simulation environment is particularly attractive if the cellular landscape specification is relatively simple – each cell contains dynamics that can be specified using a set of state changes due to internal and external stimuli (events) and captured in a two-dimensional space. Furthermore, as discussed in Section 3, it is important to have an abstract two-dimensional landscape grid representing detailed models of vegetation and terrain that are to be developed using GRASS.

6 SIMULATION EXPERIMENTS

The goal of the Phase I simulations is to demonstrate that the models are correct – not accurate. By correct, we mean that the underlying logic is sound, error free, and provides results that indicate the system is controlled, the general behavior can be predicted, and the results are possible, if not probable, for the domain.

The initial study of the human model focuses on a single village with 5 households. Each household had an initial population of 6 people. Five simulations were run with homogeneous, static maximum soil values for all landscape cells. The values used were 1, 2, 3, 4, and 5 for each run, respectively. The village was placed in the center of a cell grid with enough cells to support the population. The actions of the households and the growth of the population were studied for each simulation to examine the household's response to soil values.

The second set of simulations repeated the first in the modification of soil values. However, only soil values 1, 3, and 5 were used and the number of cells available to all households varied from below what is required to sustain the population to well above it. The actions of the households and the growth of the population were evaluated to determine how the households respond to a lack or abundance of land at varying soil values.

The third set of simulations held the maximum soil value of all landscape cells steady at soil values of 1, 3, and 5. The initial household populations were varied as were the land available to the households. These runs ensured that the households could manage varying populations under different conditions.

Success for the above simulations was the ability of the model to reach a steady state relatively quickly. Steady state for this system is defined as when both the population and the number of cultivated lands becomes constant. For minimal soil values, this meant that the household would have to maximize its cultivation with minimal loss of population. Using an average soil value of 3, the household should avoid over and underestimation of need and demonstrate no population change. When the household was faced with maximum soil values, it needed to show that it could quickly decrease its cultivated lands with minimal increase in population. In all cases, the households were able to achieve a steady state. When provided with enough cells to support the population, this occurred within 3 years. A lack of cells forced population loss even at the highest soil value and required as many as 8 years before the system settled. The results of these simulations indicate the households can successfully survive with minimal work.

For the next set of simulations, logic was added to the landscape cells to enable them to modify their current soil values based upon household management. In addition, logic in the household was revised to estimate this change. The result was an emergent behavior in which the households cultivated the nearest land first, let it lie fallow, and then cultivated new land the next year. For the third year, the households swapped cultivated and fallowed and continued. In the cases where the soil value was at minimum and all available managed land had to be cultivated, if there more than an adequate number of cells to support the population, the households would release their cultivated lands and cultivate new ones each year.

Two final simulations were run. For the first, logic was added to support the secondary goal of growth. To meet this goal, the households always cultivate up to half of their allocated managed lands (leaving the other half for fallowed). When soil values exceed average, the population grew very quickly in a positive direction. This capability will be very useful when additional concepts such as a granary and trading are introduced into the model.

The final simulation tested the ability of the household to manage its population under constantly changing soil values. A step-function was added to the landscape to enable it to modify its current soil value every year. It was designed to cycle between 1 and the maximum soil value, incrementing/decrementing by 1 each year. The simulations were conducted using different values for the household's expectation weight. The results revealed the impact of the weight in the responsiveness of the household. In some cases, the population followed the soil value cycle very closely. In others, the population reached a plateau slightly above and below the initial value as the soil value reached its minimum or maximum values.

7 CONCLUSIONS AND FUTURE WORK

A set of simulation results have demonstrated that the models are correct and the approach is feasible. In these simulations, the households have shown the ability to manage land given their prescribed capability within the environment provided to achieve the goal of survival with minimal effort. Under changing conditions, the households have maintained an orderly and successful management approach toward meeting their goals. Lastly, the system has shown that under favorable environmental conditions, the households can meet their secondary goal of growth. In summary, Phase I has demonstrated that our current approach using DEVS and designing against the data currently available is, thus far, a feasible approach to a solution.

The next phase of the project objective is to integrate the human agent model described in Section 4 with a detailed landscape model developed in GRASS. The landscape model data will be mapped into abstract data sets in the landscape cells in the Human Agent model and will drive soil values directly. Any changes made by the households will then be sent to the landscape model. At this stage, we will begin developing simulations for accuracy against known data.

In the latter phases, the plan is to add complex social dynamics into the model. Kinship, marriage, and trade are being examined as potential candidates. Household and communal granaries may be added to aid in modeling social interactions. Management of orchards and animal husbandry are also important modeling prospects. Along with animal husbandry, non-sedentary and semi-sedentary populations can be added to the model. Further, the households may be given a choice of crops, each with its own tradeoffs in terms of yield and work required. For instance, annual versus perennial crops and orchard crops. In the remainder of this project, the scope of the model is planned to be expanded to a regional scale (the Mediterranean Basin).

To achieve the overall goal of this project with respect to the understanding of human land use in the eastern Mediterranean Basin and the western Mediterranean Basin from the Neolithic through the Bronze Age time periods, the approach and the models need to be further investigated to support transitioning from one time period to the next.

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