

# Addressing the Structures and Dynamics of Modeled Human Ecologies

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## Abstract

Archaeologists studying varying facets of social behavior, particularly researchers exploring interactions between environmental and social processes, have begun incorporating computer modeling techniques in their research. Among the popular approaches, agent-based methodologies are used to obtain new insights and test theoretical assumptions for a variety of archaeological problems. However, the utility of agent-based modeling has been questioned. Criticisms primarily focus on the reductionist qualities and lack of theoretical flexibility of agent-based modeling to archaeological research. This paper addresses these criticisms by presenting a holistic agent-based modeling approach that allows for multiple models written in various computer languages and modeling systems to interact simultaneously and is accommodating to different theoretical perceptions. Simulation scenarios, results, and insights reflect an ancient Mesopotamian domain.

## 1 Introduction

With recent technological advancements as well as archaeologists increasingly researching complex interactions between social (e.g., economic exchange, marriage patterns, agricultural practices) and natural behaviors (e.g., hydrology, climate, human disease), or what can be termed as “socio-ecological” behaviors or “human ecodynamics” (Braudel 1980:31; Butzer 1982:230; Kirch 2005:409-410), scholars are applying simulation tools in order to obtain new research insights and test theoretical assumptions. One common approach in studying socio-ecological dynamics is agent-based modeling. In this approach, an “agent” is a simulation entity characterized by autonomous behavior, usually operating with the knowledge of local rules, and often responding to local conditions (Epstein and Axtell 1996:7; Lansing 2002:284-285). In addition, agents can be distinguished from other entities that can express behavior by the fact that agents have some cognitive, decision-making abilities (Wooldridge and Jennings 1995:128).

Despite the popularity of agent-based modeling, there has been criticism of how it has been applied in the social sciences. One common criticism is agent-based methodologies often represent agents or other simulation objects (e.g., fauna, flora, and other entities) as oversimplifications, having limited behavioral expression and detail compared to their real world counterparts. Another criticism is agent-based approaches can sometimes be inflexible in defining agent and object relationships. In other words, the specific parameters that relate an agent to the larger simulated society may require significant recoding in order to change from one domain or scenario to another. This results in an approach that is limited in expressing varying ideas and social-theoretical perspectives.

These criticisms seem to suggest that agent-based modeling may not sufficiently address detailed archaeological problems that involve complex behavior, much less be accommodating to a wide variety of theoretical approaches. Though these outlined critical points can be said to have merit, they can be addressed by applying a holistic agent-

based simulation approach that is flexible to integrating a wide variety of behavioral models and defining object parameters and relationships. One current object-oriented platform applying this holistic approach is ENKIMDU, a simulation chassis named after the Mesopotamian god of agriculture and canals. Example scenarios executed in this platform can, in fact, demonstrate that the platform’s simulation tools can enable complex interactions between diverse social and environmental models relevant for past societies. In addition, ENKIMDU allows users to easily define simulation object parameters and create object relationships suitable for a given domain.

To begin this paper, and in order to show how agent-based modeling developed to its current state, a brief history of modeling and simulation as it relates to archaeology and anthropology will be given. Based on this historical development, a presentation on the benefits and identified pitfalls of applying agent-based approaches to archaeological and anthropological problems will then be given. Later, the holistic approach used in ENKIMDU will be presented to demonstrate how the identified problems of agent-based approaches can be addressed. Examples of different social and environmental models as they related to the economic health of a modeled society will be presented. The goal of these examples is to show how a researcher can address the criticisms outlined for agent-based modeling.

## 2 Brief History of Modeling and Simulation in Archaeology

Since the early emergence of computational approaches to archaeology and anthropology, scholars began incorporating behavioral modeling and simulation in studying anthropogenic processes. From at least the late 1960s and early 1970s, researchers began employing system-dynamics (Forrester 1968) models in order to better perceive possibilities for specific past events such as the collapse of the

Maya (Hosler et al. 1977:554). The main criticism of this system-dynamics approach in archaeology is that it proved to be too homogeneous in capturing social phenomena, as large-scale societies and social units were treated as non-differentiated entities. In short, individuals, households, and heterogeneous social units within a society were neglected by this approach.

By the early 1990s, archaeologists and anthropologists in the United States and Europe began to apply agent-based modeling, or individual-based modeling as it is called in Europe, in their research. One reason for this interest was related to the perceived applicability of object-oriented programming, initially developed by Dahl and Nygaard (Dahl and Nygaard 1966:671) and others. In more recent software development practice (e.g., Wirfs-Brock et al. 1990), the problem domain, at least as applied to modeling, is divided into objects representing the principal elements that comprise the domain. Information describing the domain is assigned as attributes of the domain objects. Each object maintains information on its current state through the object parameters, with access to state variables regulated. In ENKIMDU and other object-oriented simulation systems, the domain objects are also responsible for expressing their own dynamic behaviors.

In archaeology and anthropology, some of the early and better known agent-based researchers include Doran (e.g., Doran et al. 1994), Biskowski (e.g., Biskowski 1992), Kohler (e.g., Kohler and Van West 1996), and Lansing (e.g., Lansing 2002). In general, agent-based approaches have proven to be popular with many archaeologists and anthropologists seeking to find higher order system behavior, such as social change in communities, through behavioral changes and adaptation of constituent agents (e.g., households and individuals).

### **3 Benefits and Problems of Agent-Based Modeling**

Some of the benefits of agent-based approaches have been highlighted by Epstein and Axtell in their influential book *Growing Artificial Societies* (Epstein and Axtell 1996), which demonstrates how numerous higher order social phenomena can be determined by investigating the behavioral outcomes of constituent agents. For example, large-scale political fallout and evolutionary biology in human populations can be understood by investigating behavioral choices of specific individuals within a larger population. In Epstein and Axtell's framework, a general pattern of behavior and traits can be observed for an entire population, but understanding how observed behavior and traits emerge can only be achieved by studying the components of that population. Their use of agent-based modeling accounts for behavior at a given time and space for the simulation actors, allowing these factors to be significant in how agents apply their behavior. Because of the characteristics of agent-based modeling, this form of modeling has been accepted as a more flexible methodology than system-dynamic and other behavioral modeling approaches. Agent-based modeling allows researchers to not only formulize a theoretical

framework, but it gives scholars the ability to test that framework in an artificial environment appropriate for the studied society (Conte and Gilbert 1995:5).

Nevertheless, the application of agent-based modeling in the social sciences, including applying this approach to the study of ancient societies, has included some significant critique. One primary criticism is essentially the same criticism that many applied to system-dynamics approaches. Specifically, agent-based methodologies fail to capture significant details that are required to accurately represent social or natural processes. Agent-based methods often reduce agents, such as a person, as well as other entities into objects that are associated with limited behavioral expression, and not allow for numerous concurrent processes and variable factors to be incorporated into the overall simulation (Richardson 2003). In other words, although real world behavioral processes in the social and natural sciences are highly complex and varied, many approaches are simply too reductionist in representing behavior. This lack of behavioral representation, therefore, limits the number of variables and behavioral detail one can use to study in order to better understand a specific phenomenon that is impacted by numerous processes.

A second criticism is that agent-based approaches, including platforms constructed for research, can sometimes be inflexible in defining agent and object relationships (Gilbert 1995:146), unless there is a significant amount of recoding. As a result, the simulation structure can be limited in theoretical applicability. To be an effective research tool, agent-based methods must be applicable to various theoretical approaches. For example, agent-based modeling has often emphasized that social phenomena emerge strictly from individuals, but established social norms of a given society might be ignored or minimized as factors that shape and constrain individual behaviors (Gilbert 1995:146; Lawson 1997:137). Some researchers may prefer that simulated behaviors of individuals be influenced by agent households as well as the larger community and society, which can be simulation objects that provide the social rules and data needed by the agent. In summary, the specific parameters that relate an agent to the larger simulation (i.e., the computational domain and objects) can be very diverse, depending on the theoretical framework used.

### **4 Holistic Modeling: A New Approach to Agent-Based Modeling**

The development of ENKIMDU has been constructed, in part, to address some of the shortcomings associated with agent-based approaches. ENKIMDU can be described as a simulation platform that was initially made to study Bronze Age (3000-1200 BC) Mesopotamia, with more recent adaptations made to investigate modern agro-economic behaviors in modern Thailand villages. This system can integrate numerous types of behavioral models that represent the actions of multiple types of social (e.g., households, communities, and other agents) and natural (e.g., fauna, landscapes, atmosphere, etc.) entities. The tools that give ENKIMDU its functionality can assist in not only addressing the

problems associated with agent-based modeling, but introduce a holistic way of modeling socio-ecological behavior. Figure 1 shows the primary system tools, examples of models and analysis tools, and types of data incorporated into ENKIMDU that allow it to have relatively unique functionality and be able to address a Bronze Age Mesopotamia domain. The descriptions that follow will introduce some of the characteristics that are enabled by the software, and indicate how these characteristics can address the identified shortcoming of agent-based methodologies.

#### 4.1 Flexibility and Scalability to Model Incorporation

Capturing sufficient behavioral detail in the social systems that archaeologists seek to study can be a major challenge. One particular model may have the necessary components to be highly complex in representing a specific behavior, but that same model might be insufficiently flexible to alternative perspectives for the represented behavior. As discussed, many behaviors in the real world can be described as open processes that are impacted by numerous concurrent processes, while, in fact, many agent-based systems are built or used as closed software systems that do not adequately represent complex behavioral interactions.

One way to approach the identified modeling problems just mentioned is to create a system that can build upon other modeling efforts. By allowing a modeling approach to incorporate models built by others, researchers can take

advantage of existing expertise in various domains (e.g., soil scientists, agronomists, physicists) and create modeling platforms that can be more inclusive of complex and diverse behaviors that impact a given dynamic. One system that can facilitate this approach is the Dynamic Information Architecture System (DIAS), a domain-free object-oriented modeling chassis used to create multi-model and distributed simulations such as ENKIMDU (Christiansen and Altaweel 2006:210). The DIAS tool, built using the Java programming language, allows researchers to not only create various models of social and natural behaviors, but it enables models built in various computer languages (e.g., C, C++, Fortran) and modeling platforms (e.g., Swarm and RePast) to be integrated into one overriding architecture. Domain objects, often representing agents and other entities that display behavior, have abstract references to models integrated in the platform; however, models are neither directly linked to objects nor made to interact directly with other models. This provides researchers an ability to apply modeled behaviors at needed time scales and more easily replace and scale up modeling efforts, as models can be added, extracted, or replaced without adversely affecting the overall simulation structure. If models were directly linked to entities displaying behavior or allowed to communicate with other models, a given simulation structure would then be very difficult to change without substantial recoding. Models generally represent a particular theoretical framework or approach that might not encapsulate a behavior that is universally accepted. An approach that allows models to be substituted

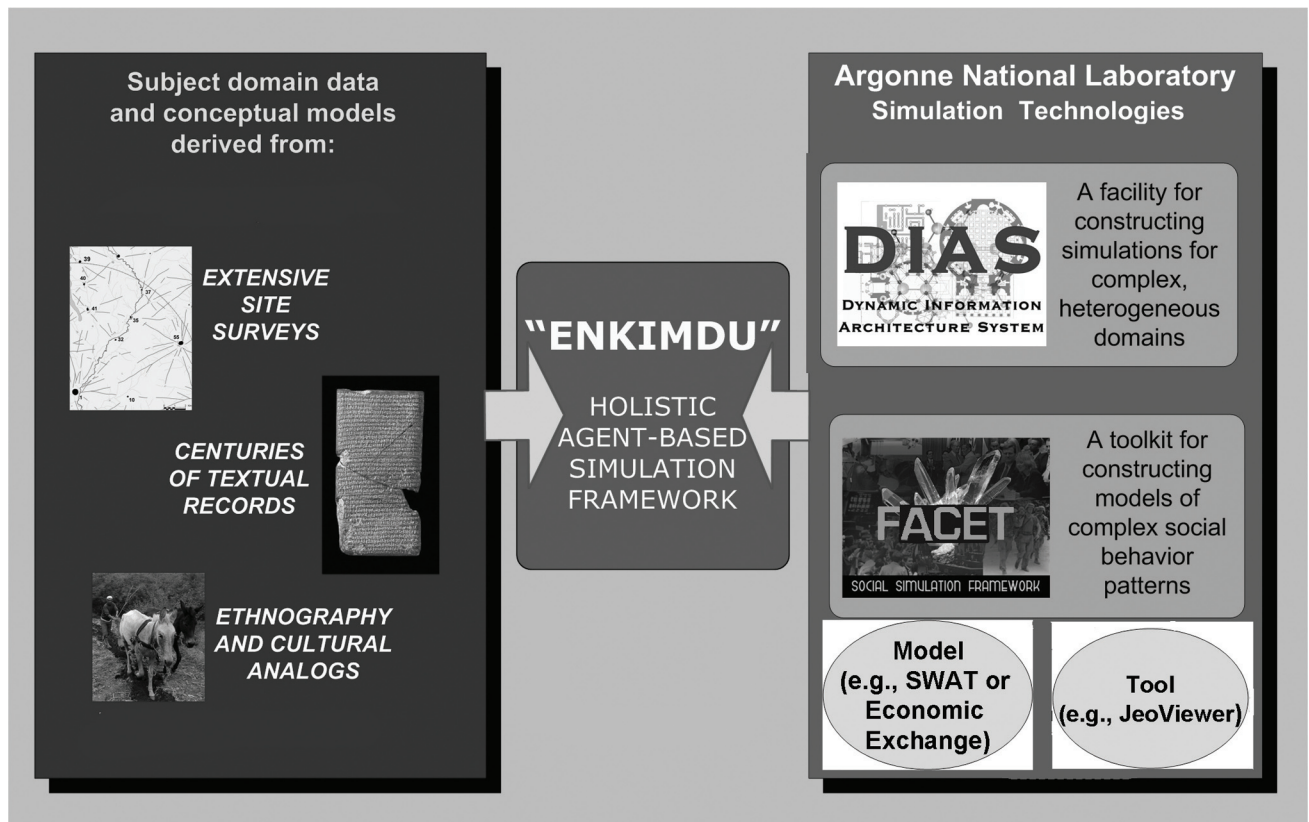


Figure 1. Image showing data examples and software that makeup ENKIMDU. DIAS and FACET, a modeling tool coupled into DIAS, are the main tools that enable ENKIMDU's functionality. In addition, various external tools and models can be integrated into ENKIMDU using DIAS.



and integrated when needed enables object parameters to be evolved by potentially very different modeling approaches. Thus, a structure that enables model entities to control data flow between models and enact models when needed makes the system accommodating to very different theoretical perspectives.

## 4.2 Representation of Time

The limited ability to express behavior at variable periods or instances within a simulation can hinder the utility of integrating multiple models. Agent-based simulations that are time-step, implying that behavioral actions always occur at specified equal temporal intervals, do not have the option to express behavior at variable time instances that might be needed based on contextual information derived from different models. A time-step approach can still be useful for some questions; however, it is generally inflexible for representing most socio-ecological behaviors. As soon to be shown, a far more flexible approach is to allow for a discrete event simulation (Fisherman 2001:24), whereby simulation context allows for behavioral processes to occur at appropriate time scales. This is a very important consideration for highly heterogeneous simulation domains such as those addressed by ENKIMDU, since diverse social and environmental processes typically proceed at different rates, and the interactions of multiple behaviors may require processes to execute at variable times.

Simulations that make use of discrete events are generally classifiable as either *event-driven* or *process-oriented*. ENKIMDU can be classified as a process-oriented discrete event simulation system, since events convey contextual information among agents and other domain entities, but do not attempt to prescribe the actions that the receiving entities should take. Rather, the decision of which behavior to implement and any given time can be made through the entity/agent. One way discrete event simulations are handled in DIAS-based simulation tools is to allow specified parameter states (e.g., biomass, social status, weight) to automatically trigger models to launch, enabling behavior to occur at time intervals that are often varied and sensitive to contextual changes. In summary, discrete events allow behavior to be expressed at timescales more comparable to observed behavior.

## 4.3 Expressing Behaviors of Multiple Entities

Certain models needed in holistic simulations may require multiple types of agents and entities to interact and share information. DIAS includes a tool called the Framework for Addressing Cooperative Extended Transactions (FACET; shown in Figure 1 as a tool used in ENKIMDU), which allows for flexible and expressive agent-based behavioral models (Christiansen 2000). Fundamentally, each FACET model instance enables extended and interactive transactions among various types of entities such as person, organization, and agricultural field through models of behavioral action. Multiple types of entities can concurrently implement

and be affected by various behavioral interaction processes in given model steps, allowing the formation of feedback relationships between all involved entities in any process within the model. This type of model essentially enables social entities (i.e., agents) to interact with other social or natural entities, allowing one or more of these entities to evolve their parameters.

In FACET models, each entity may manage its own internal behavior, such as natural processes that control biological functions in humans, and at the same time interacting agents and entities can share information to enable a particular process. In addition, resources needed by agents can be used to determine their ability to participate in a behavioral step. Agents involved in a FACET model are removed from the possibility of participating in other behaviors, that is, if other behaviors require them to physically be at another location. FACET models also allow for the creation of exceptions, which give behaviors mutability to alternative processes. An example FACET model of agricultural behavior will be presented shortly, demonstrating how multiple entities may interact in this type of model.

## 4.4 Integration of Numerous Types of Tools

Another significant aspect of DIAS is that it can incorporate different computational tools. This is important particularly for analyzing the results of complex multi-model agent-based systems. One possible reason why agent-based approaches have generally been limited in representing agent behavior is that complex heterogeneous behavioral patterns are difficult to analyze. Behaviors are often reduced to simple processes in order for the researcher to more easily comprehend behavioral outputs within a simulation. On the other hand, by allowing for different types of research tools to analyze different spatial, temporal, and behavioral scales, then the amount of data produced and variables within the simulation can be more tractable. For example, the ENKIMDU platform utilizes a standalone geospatial tool called JeoViewer, which can be used as a tool for spatial analysis and display of modeled entities (Lurie et al. 2002:108). JeoViewer allows different entities to display their various parameter states at any given period in a simulation, and with a simple click of the mouse one can interpret how particular entities may change in that period. Statistical tools can, in addition, be integrated into the environment to allow for runtime and post-runtime analysis. In summary, as entities behave and evolve their parameter states, these entities can be viewed in a spatial context and statistically analyzed in relationship to other entities and the simulation environment. Figure 2 is an example of JeoViewer being incorporated into ENKIMDU.

## 4.5 Object Relationships and Parameter Flexibility

The discussion up to this point has not addressed how modeling tools address the problem of creating flexible parameter structures that allow agents and different entities to reference other domain specific agents and objects that may provide

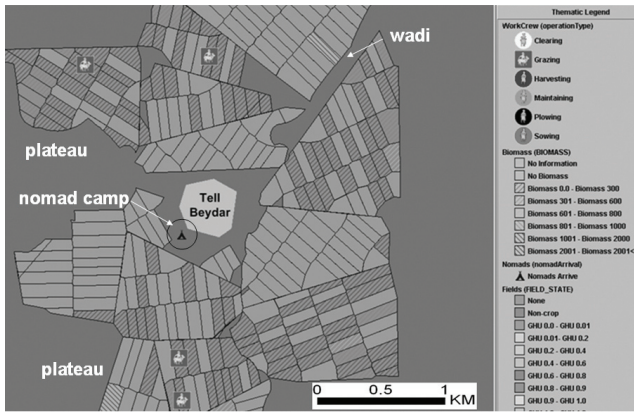


Figure 2. Figure displaying a JeoViewer screenshot of an ENKIMDU scenario that includes a modeled settlement, named Tell Beydar, surrounded by its agricultural fields. The image displays livestock groups grazing near the settlement with a nomadic camp residing nearby in a period after the harvest during the summer. As seen on the image, each field is treated uniquely by the applied models. The key on the right of the image displays biomass and growing heat units (GHU), a measure used to track crop maturity.

particular data to enable or impact a certain process (i.e., social or environmental behavior). To a large extent, this problem has been more related to theoretical application and design than inherent technical flaw in modeling approaches. In DIAS, the parameter relationship problem is remedied by having open-ended and easy to change parameter definitions (i.e., objects or primitives used to define parameters) that allow the user/modeler to define how agents relate to their social setting as well as how their physical setting is associated with other objects and data influencing the given environment. Figure 3 shows some of the current social entities and agents in ENKIMDU, including an example display of the relationships between these objects. In this case, each entity and agent does behave autonomously; on the other hand, by allowing the researcher to easily link object relationships, then specific data in an object can be made to impact various object behaviors. For instance, individuals can have references to their households as well as the larger community and society, which are objects that provide the social rules and data needed by the individual agent to influence a decision impacted by cultural constraints. An individualistic perspective, on the other hand, may limit or omit community and societal links in agent decisions. From a modeling perspective, having flexible parameter relationships allows researchers to create a simulation structure more adaptable to alternative theoretical ideas that may relate objects and parameters differently.

## 5 Examples and Results from ENKIMDU

The following examples and results will help to show that ENKIMDU has the necessary capabilities to address the identified criticisms against agent-based modeling. The examples are not meant to demonstrate a particular reality that occurred in Mesopotamian societies; rather, the results will show particular insights that can be gained and the

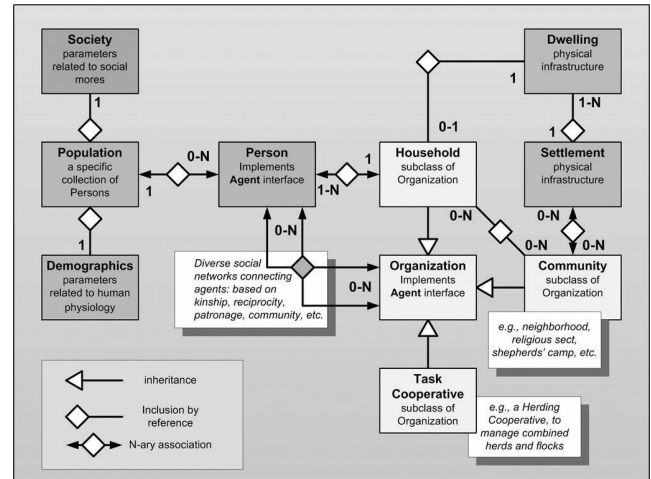


Figure 3. Schema showing example object relationships within ENKIMDU.

heuristic capabilities of a holistic agent-based approach as applied on perceived past behaviors. Very specific details of modeling results, data inputs used, and validity of the models presented cannot be given in this paper, but readers are encouraged to investigate other works (Altaweel in press; Christiansen and Altaweel 2006) that do provide more information. The examples to be presented should not be taken as arguments for particular social theories regarding Mesopotamia societies, although a specific theoretical framework may be used.

### 5.1 Agricultural Productivity

As in many other past societies, ancient Mesopotamia settlements heavily depended on agrarian products. Figure 4 shows a condensed schema diagram of FACET anthropogenic agricultural model employed in ENKIMDU. This model has been designed to accommodate social behaviors in Mesopotamia (Altaweel in press) and other societies (Townsend 1995; IRRI 2006).

Essentially, the model is several submodels that are rule-based and dependent on localized and agent-specific variables. Agents participating in agriculture can be either organizations, such as households, or individuals. Different steps in the overall model include the preparation of crop seedlings, distribution of water and fertilizer, plowing, planting, maintaining fields, harvesting, and processing the harvest. Numerous agents and types of entities, including agricultural fields and households, can be made to interact through this model. Agent behavior and ability can be bounded by available resources and ability to participate during any step. This includes availability of tools used, labor and time costs of performing a certain function, access to particular organic inputs employed on fields, and agents being present to participate in a given behavior. Environmental actions such as climate and the movement of water can also impact human decision making. For instance, an agent interpreting that a field can be irrigated given its proximity to water could use this information to decide to irrigate a given area using the irrigation submodel, as shown

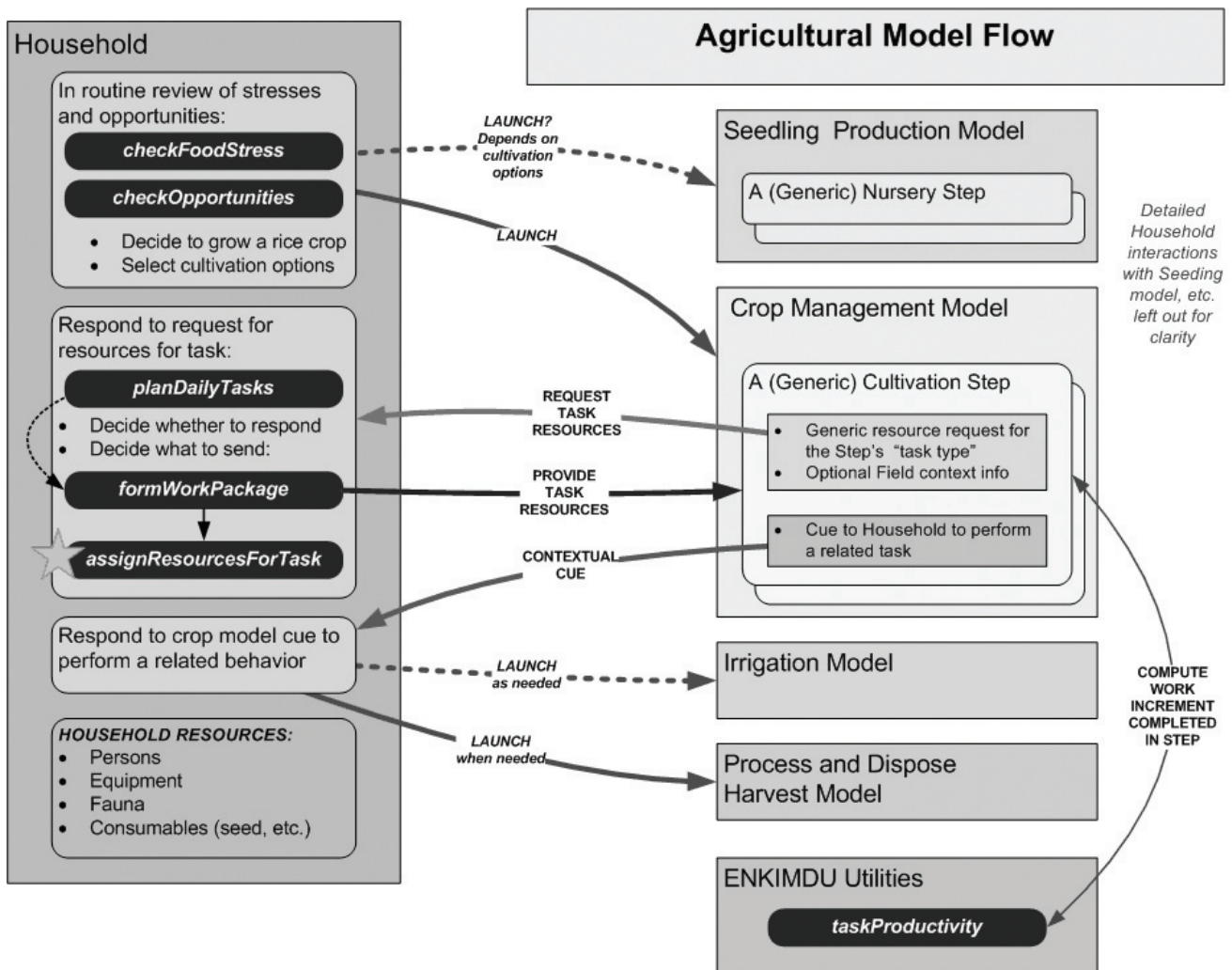


Figure 4. Figure showing the basic schema of the FACET anthropogenic agricultural model, which is comprised of several submodels.

in the pseudocode representation:

```

//irrigation submodel for a specific field
irrigate() {
  //get agent in model
  a = getAgent()

  //f is a field object instance
  f = getField()

  //get agent resources, called r
  r=a.getResources()

  //irrigated area left
  fieldArea = f.getIrrigationAreaLeft()

  //get how much time left to work
  t=workTimeRemaining()

  //time left
  workTimeLeft=fieldArea*r.irrigationRateOfWork()

  //water amount function of time
  waterAmount=r.getIrrigationAmount(t)

  //SWAT irrigation amount
  f.setIrrigationAmount(waterAmount);

  //irrigation is usually relatively quick,
  //but check time
  if(workTimeLeft>t) then
    areaFinished=t*r.irrigationRateOfWork()

    //amount finished
    f.setIrrigatedArea(areaFinished)

    //go home, back later
    return
  else //finish today

    timeFinished=fieldArea*r.irrigationRateOfWork()
    t=t-timeFinished

    //finished for now
    f.setIrrigatedAreaLeft(0)

  end-if
}

```



Agents can begin to alter the landscape through such behaviors as the removal of biomass, inundation of agricultural fields, and types of fertilizer used. In fact, actions such as maintenance of agricultural fields through irrigation, weeding, and harvesting crops contribute to the evolution of soil and vegetation properties, resulting in agents having an impact on how the local ecology evolves.

The model used for many of the physical environmental behaviors that include the evolution of soil and vegetation properties is the Soil Water Assessment Tool (SWAT), which can model behaviors that include evapotranspiration, erosion, hydrology, plant phenology, and other aspects related to soil and water processes (Arnold et al. 1998:74; Christiansen and Altaweel 2006:212). This model is written in Fortran90 and has been in continuous development by numerous specialists in the environmental sciences for more than 15 years. As for weather modeling, SWAT's weather generator or an integrated mesoscale weather model, an example being the MM5 model used by climatologists (Dorband et al. 1998), can be used in ENKIMDU to see how regional and local weather may impact the modeled landscape. Other models can be simultaneously coupled, including models replicating livestock behaviors that allow individual animals to remove biomass, trample on vegetation, and create field inputs through manure. In any case, it is the coupling of environmental and anthropogenic models together that can allow researchers to investigate variable processes that may impact a physical landscape. Each field becomes a nexus of physical and cultural activity that not only changes the field's parameters (e.g., biomass, soil properties), but subsequent environmental and social behaviors are in part determined by the evolved states of the fields and larger landscape. Agents, in essence, make decisions to perform specific agricultural actions in large part due to the combined social and natural processes affecting agricultural fields. Despite these concurrent processes, the anthropogenic and physical models never interact directly, rather data for the models are derived through the involved entities. Thus, SWAT obtains its model data from the fields and other environmental objects, while the anthropogenic model uses fields and agents.

Figure 5 shows the results of the anthropogenic FACET model as it is used along with SWAT over a 100-year scenario. In this case, the aggregate grain yields from fields around the settlement shown in Figure 2 are displayed. Barley crop was grown, with parameters for barley used by SWAT to model its growth.

The scenario was relatively favorable for agriculture, with rainfall averaging over 300 mm over 100 years. Despite these favorable conditions, grain yields were progressively lower, which can be explained, to a large extent, by deteriorating soil conditions (Altaweel forthcoming). In this scenario, manuring and irrigation were limited; with a lack of nutrient inputs, long-term soil degradation was inevitable.

The point in this example is that declining yields tend to impoverish or leave many sedentary households grain deficient and on the edge of collapse, forcing many of them to abandon the settlement over time, and resulting in only a slight population expansion over the 100-year simulation period (Figure 6). Other modeled commodities, including

textiles, silver, and livestock, are also in short supply due to the households' inability to obtain sufficient grain to use for trade. In fact, Figure 6 shows the percentages of various goods owned by households in Year 100, and these results show that no household has a large percentage of multiple items, indicating the settlement had little wealth differentiation.

## 5.2 Economic Exchange

ENKIMDU does not only model agricultural activities in Mesopotamia, but economic, political, religious, and other cultural behaviors are all either incorporated or will be shortly. As for economic exchange, complex trade networks between different nomadic and settled communities were a major part of the social landscape of the Middle East (Barth 1961:98-99; Cribb 1991). These exchange relationships often involved kin related households and clans that had settled and nomadic elements at different periodic stages. By interacting complex exchange models with the physical and social models related to agricultural, as shown previously, the relationship between economic exchange and agriculture can be studied in detail.

Although no scholar can claim that they fully understand the dynamics of exchange between nomadic and

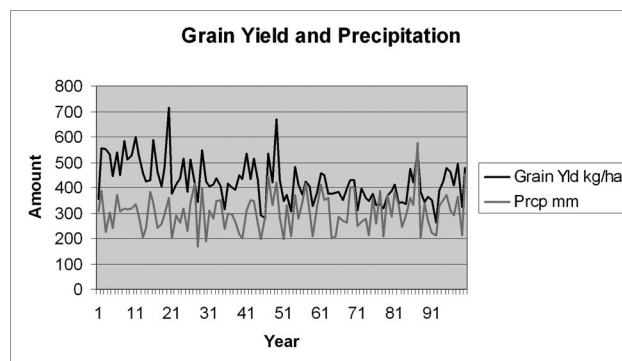


Figure 5. Graph showing barley yield values for a 100-year scenario.

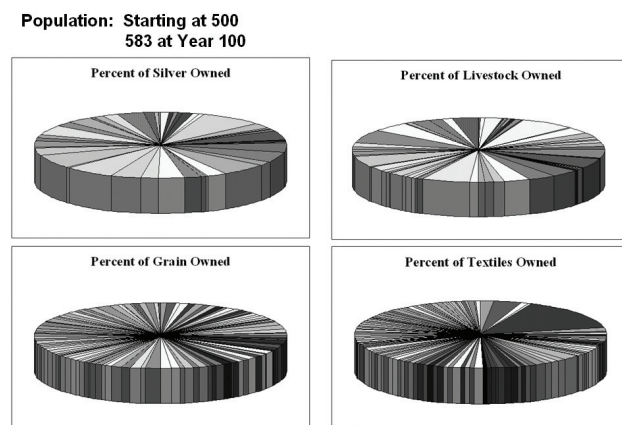


Figure 6. Pie charts showing the distribution of different commodities owned by sedentary households in the settlement at Year 100. Each pie slice represents one household.

settled communities in the past, holistic agent-based modeling and simulation can at least be used as a heuristic tool in order to investigate different economic relationships and possibly provide insights to formulate new questions. For instance, Figure 7 shows a model of exchange that utilizes agent utility functions (Hogg and Jennings 2000:308) and allows for flexible context driven decisions made by nomad or settler agents. Factors such as religion or other social circumstances can affect agent decisions regarding items they attempt to accumulate. Agents can evaluate different exchange items and quantities by using their context maps, which provide relevant information that include market conditions and value of items, more immediate needs for specific goods (e.g., grain needed for food), and general economic goals. The variables for economic goals incorporate both agent desires based on economic practice and wants as well as cultural influences, such as preferring to exchange with old trade partners, relevant for the larger community (Barth 1961:99). Each agent attempts to obtain the commodity of greatest benefit for their utility function at a given time; however, each item and its quantity requested are evaluated by other agents who must consider exchanges based on their own utility function. The general algorithm used for evaluating the utility of a given commodity is stated as follows (1), though alternative functions can be swapped easily using the abstract reference to models that

DIAS incorporates. Essentially, the data from the context maps (e.g., market conditions, needs, and goals) are used as weighted values that affect a given commodity's utility evaluation.

$$x_i = m_i + n_i + g_i$$

where  $m$  ( $m_i = p_i * w_i$ ) is weight ( $w$ ) of market price ( $p$ ) for an item ( $i$ ),  $n$  ( $n_i = d_i * y_i$ ) is weight ( $y$ ) of agent needs ( $d$ ) for an item ( $i$ ), and  $g$  ( $g_i = v_i * z_i$ ) is weight ( $z$ ) of agent goals ( $v$ ) relative to an item ( $i$ ). (1)

$$U(x_i) = 1 / (1 + e^{-x_i})$$

where  $U$  is the utility and  $x$  represents the aggregate weighted values for an item ( $i$ ).

If the item of greatest benefit to one of the agents cannot be obtained from the other agents, then other items that provide significant benefit are sought after. When an exchange is finally made, that is when the specific exchange offer is satisfactory to all parties, the next appropriate time to look for further exchanges can be determined by the agents. In

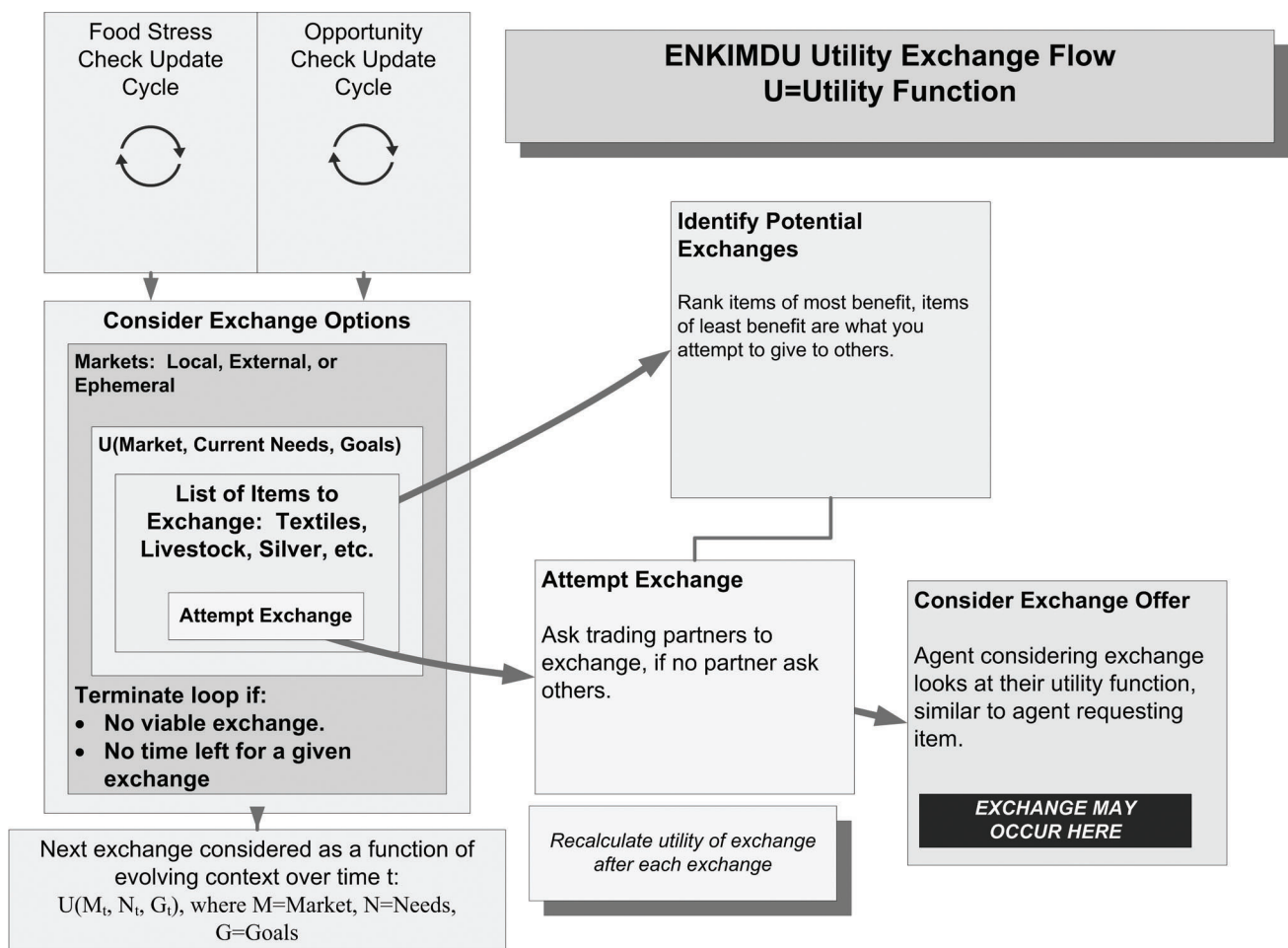


Figure 7. Image showing an exchange model schema incorporating agent utility functions. Agents evaluate a given exchange opportunity for an item by looking at the given market, specific needs, and overall economic goals at a given time.



a similar manner to the previous agriculture model, the timing of particular actions, in this case agents attempting to exchange, are driven by discrete events based on agent choice, enabling the agents to control when behaviors are implemented. Thus, agents attempt to exchange items at varying temporal scales, enabling the utility model to be relevant for a given time, as shown in Figure 7's schema.

For scenarios involving exchange between nomad and sedentary communities, the nomadic community arrives at the settlement, exchanges with the settlement households, and then leaves the settlement area; all of these behaviors occur at roughly the same time each modeled year. Modeling results reflect an exchange relationship between the specific communities at a given time of annual interaction over the period of a simulation. In most scenarios, commodities such as dairy products, textiles, and silver are initially in less demand by the nomadic community and are traded to the settlement. The nomadic community generally desires to obtain grain and livestock from the settlement community. Nevertheless, exchanges vary depending on circumstances, including how much of various items are possessed by the nomad and sedentary households at a given time. To aid in analysis, modeling results of exchanges can be displayed as diaries or summaries for individual households at any given point in a simulation, which can be very telling in detailing

specific household exchange dynamics. Examples of a nomad household and sedentary household are displayed respectively in Figures 8 and 9.

As for overall modeling results, one scenario had a nomadic group that interacted with the settlement, shown in Figure 2, in the early summer around June, or roughly the time of harvest. The long-term effect on the sedentary households was that a few of these households, and one in particular, were able to use their surplus grain to become wealthier through goods obtained from nomads and other sedentary households (Figure 10).

In the scenario, grain yields did not change from the declining yields shown earlier. Since these households were able to trade with the nomads and other sedentary households, many sedentary household agents had potential trading partners that could provide desired or needed items. During the early parts of the simulation, many sedentary households did, in fact, accumulate numerous goods, in large part due to the exchanges with the nomads. At the time of an increasing food crisis, goods, with the general exception of grain, obtained from the nomads by the sedentary households were exchanged to obtain grain from other sedentary households. Nevertheless, after many years of low harvest yields, numerous sedentary households were in a dire economic condition, with almost all households having limited

## HOUSEHOLD NUMBER 108 DIARY FOR YEAR 21

**Head:** Hal551(15) 4 Member(s):

**Mo:** Eva340(44) **Off:**(Rocko554(15) ) (Mo= mother, Off=offspring)

Hal551(15) Fabio623(13)

Close Kin: MU:142 (Mother's uncle)

**Exchange Partners:** 1 2 102 84 110 16 61 8 97 118 130 28 86 131 129 25 111 142  
(Exchange partner household numbers)

**Resources:** field shares: 7.1 stored grain: 504.8 kg 15.3 kg textiles

319 > Grain gift of **24.3** kg received from m uncle ( H142 )

322 > Processed grain harvest to storage:**820.4** kg

322 > Provided **3.8** kg grain to Gambinos#1 in exchange for **0.4** kg sheep milk

322 > Provided **2.1** kg grain to Gambinos#2 in exchange for **0.3** kg textiles

323 > Provided **7.2** kg grain to Gambinos#1 in exchange for **0.8** kg sheep milk

323 > Provided **2.1** kg grain to Gambinos#2 in exchange for **0.3** kg textiles

324 > Provided **3.8** kg grain to Gambinos#1 in exchange for **0.5** kg textiles

324 > Provided **103.5** kg grain to H60 in exchange for **0.1** kg silver

Figure 9. This sedentary household diary indicates economic exchange and various events occurring to the household during a given year. In this case, the diary shows events between Day 319 and Day 324. In the Mesopotamian scenarios, the year begins on August 1 (Day 1). Information above the dark horizontal line reflects conditions in the household on August 1. This information includes household members' names, ages, the exchange and kin networks shown by the household numbers in those networks, and resources owned.

## Gambinos – Nomad Household # 1 Year 21 Summary

Members: 11

### Resources

Sheep: 67 Goats: 32

Wool: 34.9 kg Goat Hair: 10 kg

Silver: 0.7 kg Dairy: 29.5 kg

Exchanges: 3 (new partners)

8 (old partners)

Textiles sold: 2.5 kg

Textiles bought: 4.4 kg

Livestock bought: 1

Silver sold: .07 kg

Dairy sold: 21.3 kg

Grain bought: 40.5 kg

Figure 8. Image showing the exchange summary of a nomad household, called Gambinos and designated as Nomad Household 1, during Year 21. Resources held by the nomad household prior to contact with sedentary households in that year are shown above the dark line.

quantities of grain. In fact, by over exchanging grain in the earlier part of the simulation, when grain yields were higher, sedentary households were in an economically weaker position in the latter half of the scenario compared to the same time interval in the previous scenario with no nomads. The primary result was only a few households had sufficient grain supplies for their needs, allowing these household to be better able to exchange for different goods. At the end of the simulation, one household, Household #29, was able to

amass the largest percentage of several commodities in the settlement community by using wealth in one category to obtain goods in other categories. But because of the general impoverishment of most households, numerous households were forced to leave the settlement.

In a different scenario, the timing of the economic interaction was changed to the spring, or over a month prior to harvest, and all other variables were left unchanged. In this case, sedentary households generally became net importers of grain rather than exporters, due to the fact that in almost every year grain, immediately before the harvest, was in high demand. This enabled these households to be more sustainable even as agricultural yields declined, mainly because more grain was going into the settlement rather than out of it. The net result of this scenario was that many sedentary households were economically healthier at Year 100 than the previous scenario (Figure 11). In fact, the settlement population was at 686 individuals in Year 100, indicating the general health of the settlement, as few households emigrated from the settlement. Households, nevertheless, were not economically equal; rather, Household #66 can be seen to own very large percentages of several commodity categories by Year 100, at even larger percentages than seen in the previous case. This indicates that with more grain in the settlement community, a wealthy household was better able in this scenario than the last to use wealth in one category (i.e., grain) to obtain other goods from other agents. Simply stated, stronger grain security, or a strategy to obtain more

Population: Starting at 500  
528 at Year 100

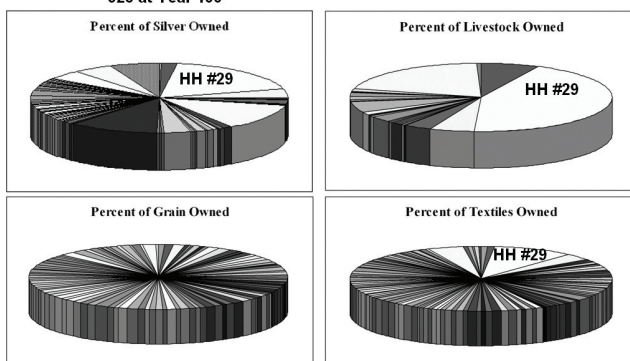


Figure 10. Pie charts indicating the distribution of commodities in the modeled community at Year 100 for the scenario that has nomads interacting with the settlement in the early summer. Each slice represents a sedentary household.

Population: 500 at beginning  
686 at Year 100

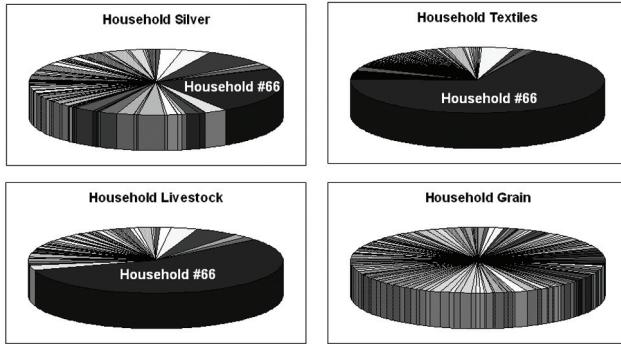


Figure 11. Pie charts indicating the distribution of commodities in the sedentary community at Year 100 for the scenario with nomads interacting with the settlement in the spring. As in the other scenarios, each slice represents a sedentary household.

grain, enhances the ability to have greater wealth in a variety of commodities.

## 6 Conclusion

Although the holistic model integration approach outlined in this paper has shown substantial promise in providing modeling results that can address many important archaeological questions at multiple scales of detail, clearly no modeling approach can claim that it can completely represent socio-ecological systems and behaviors in a given society. Nevertheless, the approach and benefits outlined in this paper can allow researchers to 1) make far more sophisticated modeling tools that integrate numerous behaviors and data and 2) enable various theoretical perspectives to be addressed. In essence, the modeling approach presented addresses the two main criticisms outlined against agent-based modeling.

The integration and interaction of sophisticated social and natural behavior models enabled this study to investigate how socio-ecological behaviors may affect a particular social development of the studied society. In the examples presented, the modeled settlement was seen to be impoverished when it did not have the ability to interact with other communities. With the interaction of a second social group, the nomads, two cases were seen, with one resulting in better overall economic circumstances and the other in weaker economic circumstances for the settlement. In those cases, certain households were shown to benefit more due to the presence of the nomads. Anthropogenic and environmental models related to agriculture showed that yield averages would inevitably decline, but the exchange model indicated that under proper circumstances, in this case it was the timing of when exchanges occurred, a settlement could have enough grain. The best overall strategy for the settlement was to obtain grain from the nomads and limit the amount of grain leaving the settlement.

By not directly integrating domain objects and models, portability and ease of reuse of models and objects to alternative scenarios can be enabled, allowing for a greater

flexibility to different domain problems and theoretical perspectives. The structure presented makes it easier to scale up an effort as more models and objects are added, or models can be replaced by other similar models to test alternative theoretical perspectives. In addition, behavioral outputs from models, sometimes built in different languages and platforms, can be made to impact other implemented models at different time scales, such as the agricultural and exchange models discussed. Flexible and easy to change parameter relationships within the framework insure that appropriate object and data references can be maintained for the given study domain, allowing the agents and entities in question to be more easily adaptable to the behaviors and attributes relevant for the research problem and theoretical approach. In summary, the tools and methods presented enable significant insights relevant for a variety of theoretical perspectives and topical interests, provided that rigorous testing and validation are applied.

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