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THE FERTILITY OF ASSUR'S LANDS: A STUDY OF AGRICULTURAL PRODUCTIVITY USING COMPUTER SIMULATION

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ABSTRACT

The city of Assur and its environs are located in a region that has long been considered an agriculturally marginal landscape. However, there have been few systematic studies that have looked at the productivity of this landscape using past methods of agriculture. This paper examines human and environmental interactions related to farming productivity of Assur's surrounding environs under three different scenarios. The results are obtained by applying new simulation technologies that incorporate ancient and modern sources of socio-environmental data. The benefits of this study not only help to show new insights in the agricultural capabilities of Assur's landscape under expected conditions in the past, but the results also show that the simulation technologies applied can be useful for testing a variety of ideas and theories related to ancient Mesopotamian societies. This study, therefore, is a test case in determining the capabilities of the simulation tools applied to addressing significant issues in ancient Mesopotamia.

KEYWORDS

Assur, landscape, agriculture, socio-environment, modeling, agent-based, simulation.

1. INTRODUCTION

Assur today is located in an agriculturally marginal landscape that receives low amounts of rainfall, and can experience prolonged periods of drought. Although one cannot be sure of the annual rainfall during ancient periods, the landscape can be assumed to have been marginal in many periods. The city's surrounding terrain, given its thin soils and rocky inclusions, further limits the area's agricultural capabilities. These limitations may have even contributed to the Assyrian kings' decisions to make the northern cities of Kalhu and Nineveh the capitals during the Neo-Assyrian period.

Assur's location next to the Tigris River likely enabled the city to receive provisions from distant areas. The long-distance roads dating to at least the Middle or Neo-Assyrian (1363-614 BC) and Arsacid (ca.1st and 2nd centuries AD) periods indicate that food may have been transported over land as well (Altaweel 2004). In fact, texts indicate that Assur was provisioned with grain and other types of food from different provinces (Freydank 1992). Nevertheless, given the uncertainties of maintaining political and economic control over external regions, Assur and its surrounding region would have likely attempted to produce as much agricultural goods as possible. Although the region is agriculturally limited, various strategies to increase farming productivity, including

irrigation and manuring, could have been applied. Ancient records, indeed, show that the Assyrian kings in the Middle Assyrian period did irrigate the landscape near Assur (Bagg 2000).

However, it is difficult to estimate how much cereal grain, which would have certainly been a main food staple for most of the inhabitants of the Assur region in many periods, could have been produced in the past. Recent developments in simulation technologies, nevertheless, enable researchers to produce more sophisticated and accurate estimates of agricultural productivity under various conditions in a given landscape. Researchers at Argonne National Laboratory as well as archaeologists and cuneiformists from the University of Chicago and University of Edinburgh have been able to produce long-term estimates of agricultural productivity for the region of Tell Beydar, located in modern Syria's Khabur Basin (Christiansen and Altaweel 2006; Wilkinson et al. forthcoming).

Similar approaches as used in the Tell Beydar region can be applied to Assur in order to achieve likely cereal agricultural yield estimates for its landscape. First, data sources from satellites, soil reports and observations, climate stations, and archaeological results can all be used to reconstruct a physical landscape and environment associated with Assur. For the purposes of this paper, this landscape will comprise a 10 kilometers radius surrounding the site. Throughout this paper this 10 km radius will simply be referred to as Assur's area or similar phrases. This designated area is not intended to imply that only this landscape could have provided Assur with grain; rather this region is an appropriate sample of the surrounding landscape near Assur. The environmental characteristics used for Assur's area are likely to be comparable to neighboring territories. As for anthropogenic processes and cultural characteristics involved in agriculture, historical and ethnographic data from different periods will be used to create and provide input for human behavioral models. For the purpose of this paper, archaic barley will be the crop modeled. The primary reason for this is that barley was and still is a major crop in agriculturally marginal regions in northern Mesopotamia.

Following the presentation of the models, the simulation technologies used will be discussed in order to show how they can be integrated to answer issues related to agricultural production. Results from three different simulation scenarios, termed the baseline, dry phase, and irrigation, will be presented. The different types of scenarios will help to test several common social and natural behaviors that could have occurred in Assur's landscape in many different periods. Thus, the goal of the paper is to provide possible results and insights into agricultural productivity and potential under certain conditions, but not claim that a simulation scenario necessarily represents a specific period or a result achieved in the past. In addition, the results can provoke new questions that relate to socio-environmental behavioral interactions, particularly how they may have shaped Assur and other past societies.

2. ENVIRONMENTAL DATA AND MODELING FOR ASSUR'S LANDSCAPE

Several existing environmental models can be used to investigate landscape processes for modern and ancient landscapes. One tool that has proven to be popular in modeling landscapes is the Soil and Water Assessment Tool (SWAT). This tool was developed for the United States Department of Agriculture to investigate landscape evolution as it relates to agricultural crop management. The modeling suite not only addresses modern crop plants, but it can be modified to model non-agricultural lands as

well as plants that may not be extensively used today, including ancient forms of barley and wheat (Arnold et al. 1998; Arnold and Allen 1992). The list of physical processes involved in landscape and agricultural modeling that can be executed in SWAT is extensive. Figure 1 shows some of the key behaviors that are included in SWAT. By incorporating the appropriate inputs for a given landscape and environment, SWAT can be used to model almost any landscape type. For Assur's landscape, the challenge is to determine what are the applicable landscape input parameters to make this model function¹. Some of these parameters will now be discussed.

Most studies concerning an ancient landscape's agricultural productivity, given the inadequacies of the data available, require that multiple sources of data be used from sometimes different periods and even settlement regions. Assur's landscape is no different. Satellite data have been among the more recent sources of data that is used to investigate its landscape (see Altaweel 2004 for examples). This source of data can indicate regions where agricultural activity was likely to have taken place as well as identify other landscape characteristics. By no means can satellite data be considered a perfect source for identifying all of the potential agricultural areas surrounding Assur; however, this form of data can illustrate clear landscape features that certainly would have affected agriculture. Figure 2 is a CORONA satellite image taken in the late 1960s that shows the general characteristics of this landscape. In this image, different terrains, including alluvial, rolling plains, and elevated regions can be identified (Altaweel 2004)². Figure 2 makes it clear that a large portion of the landscape near Assur can be described as plains and ridges. Alluvial areas, nevertheless, do form a significant portion near Assur, particularly to the north and east. Furthermore, many of the ridges and some of the surrounding area appear to have thin soils, since little vegetation can be seen in Figure 2³. This indicates that this type of terrain is clearly difficult to use for agriculture. Other satellite data, such as those produced by ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), appear to show similar results using infrared equipment. As for application in landscape modeling, satellite data enable the identification and location of landscape features, including their associated soil types, that can be incorporated into SWAT and the overall modeling effort that will be presented later.

Soil reports and observations from this region are needed to adequately describe and identify the contents of the soil types found in this region. Buringh and the British Admiralty Handbook both describe the surrounding region; they state that it can be characterized as an area with rich alluvial clays and silts near the Tigris, with reddish-brown gypsum loamy soils away from the river in the plains. Limestone ridges with heavy gypsum content are another characteristic of the landscape near Assur (e.g. Jebel Khanuqa and Jebel Mak-hul) (The British Admiralty 1944; Buringh 1960). Much of the region's subsurface, in fact, is composed of gypsum and limestone material. To the south of Assur, the soils can be characterized as being thin with mixed gypsum inclusions. The Makhmur region, just to the northeast, and areas to the north of Assur generally have deeper brown loamy soils, which are among the most fertile areas near Assur (Buringh 1960). For the most part, these soil characteristics help to confirm what was observed

¹ For a full listing of the input parameters needed to run the SWAT model see Neitsch et al. 2002.

² For further information and views of the landscape using CORONA and ASTER satellite imagery see Altaweel 2004.

³ Vegetation appears as darker shades on CORONA imagery; for further information on using photography to identify landscape features see Riley 1987 and Sabins 1997.

using the satellite sources, allowing some of the soil descriptions provided by the British Admiralty Handbook and Buringh to be spatially linked to the CORONA data.

The observations and descriptions by Buringh and the British Admiralty are nearly complete enough to create the main soil profiles used in a SWAT model. In order to fill some of the data voids, other comparable soil profiles that can be found in the Near East, particularly in neighboring Syria, can be used to characterize some of the inputs needed in the SWAT model, such as water permeability in a given soil type (van Liere 2003; Mulders 1969; Neitsch et al. 2002)⁴. Overall, the modeled soils include gypsum-limestone ridges/thin soil areas, rolling plains, and alluvial regions. The two main soil types modeled for agricultural lands were gypsiferous brown loamy soils and dark alluvial silts and clays. Ideally, the brown gypsiferous soils could have been further differentiated into deep brown soils to the north and east of Assur and shallow light brown soils to the south and west. However, given that the exact location of the brown soils was not clear for Assur's area, only one general soil type was used for the plains surrounding the alluvial soils near the Tigris.

Determining the ancient climate in any given period for the region of Assur is also difficult. Climate data from the last century, on the other hand, can give an indication of possible local climate conditions for past ancient periods. The nearest weather stations to Assur that have published data spanning over a few decades are Qayara and Beiji. These weather stations' monthly rainfall data, recorded between 1935-1957, can be used to recreate monthly averages over a year. In this case, the average of the two weather stations' monthly results can be used for the overall monthly averages at Assur. Other climatological data, such as wind speed and temperature, can be obtained from Mosul and Beiji (NOAA 2005). These and other data can be incorporated into SWAT's weather generator (Neitsch 2002). This weather generator uses a Markov process to derive daily and even hourly weather data input from the monthly averages, and this input can then be used within the SWAT model. Therefore, although the weather data used from the weather stations may only be monthly averages, these averages can help derive reasonable estimates of daily and hourly variations in weather, enabling climate variables to be constantly updated throughout the overall simulation. If actual daily and hourly weather data was available, this data can also be used as weather inputs. Overall, the weather stations' data used appear to be comparable to observations made by Andrae early last century for the Assur area (Andrae 1977). Some necessary data, on the other hand, can be derived within SWAT. For example, the coordinates of Assur's area assist in determining the effect that solar radiation has on the environment. Once all of these necessary data inputs are obtained, Assur's landscape can be modeled so that it is affected by the suitable weather conditions.

Archaeological data, although they often do not provide specific environmental data that can be used in modeling, can be useful in understanding general characteristics of the landscape. For instance, the size of settlements may suggest the capability of the landscape to provide for significant population sizes. Survey results, excavations, and visits to sites near Assur (within 15 km from the site) show that almost all the sites known in this region are less than 15 hectares. A few sites, such as Tell Akrah, Tell Khuwaish, and Tulul al-'Aqr (Kār-Tukultī-Ninūrta), do, however, seem to be more than 15 hectares (Ibrahim 1982; Mallowan and El-Amin 1950; Oates 1968). Nevertheless, many of these relatively large sites are near the Tigris, which suggests that much of the landscape away

⁴ Soil data from the Balikh region and other parts of the Jazirah in Syria (areas with less than 300 mm of rainfall) were used to assist in the reconstruction of soil profiles in the Assur area.

from the river was not suitable for sustaining large population concentrations. The road systems in the region of Assur also seem to suggest that agriculture was unstable. In contrast to sites near Nineveh further to the north, many sites near Assur, including Assur, do not have well-developed intra-regional road systems. Observed intra-regional hollow way systems are generally associated with settlements that had a significant and more stable agricultural component in their local economy (Wilkinson and Tucker 1995; van Liere and Lauffray 1954), while less developed intra-regional hollow ways may indicate that fields could not be farmed for long periods (Altaweel 2004).

The general environmental variables and inputs discussed form much of the primary data used to create a physical model of Assur's agricultural area. The environmental and archaeological data help to show that the landscape near Assur appeared to be limited in its agricultural potential. However, the anthropogenic characteristics that influence crop growth still need to be discussed in order to understand the potential of agriculture in Assur's region.

3. SOCIAL ASPECTS OF AGRICULTURE

Textual sources from Assur's area and nearby regions during the city's occupation certainly offer the best type of data needed in this study. This information not only provides information on the agricultural potential of the landscape, but textual data can help researchers to understand the social behavioral processes and cultural aspects associated with agriculture. Although textual data can be used to help reconstruct likely anthropogenic and cultural components in agricultural models, historical sources alone are often not sufficient to address all of the social behaviors and other cultural aspects involved in agriculture. Ethnographic sources can both add further detail and reinforce results as seen from historical documents. In the discussion to follow, ethnographic and historical sources discussed will represent the major components of the anthropogenic agricultural model that will be presented shortly. Other behaviors and characteristics that can be derived from historical or ethnographic sources, and are relevant to agriculture, will also be discussed.

Among other benefits, texts provide background information on how a given landscape may have been used by the local inhabitants. From several historical texts, it is clear that Assur's landscape was not only producing cereals such as wheat and barley, but gardens were also associated with the city (Wiggermann 2000; Bagg 2000). These gardens appear to have been irrigated, which suggests that many types of plants could not be kept alive without additional water (Bagg 2000). However, it is not clear which specific areas were irrigated, that is assuming the significantly large gardens were located outside of the city. Based on the geography of Assur's area, alluvial zones near the Tigris would have been likely locations for irrigation. In any case, the fact that texts mention irrigation and canal construction near Assur suggests that the local population did try to enhance the capabilities of the surrounding landscape.

One major input in agriculture is the amount of seed grain used in planting crops. The best evidence for seeding rates in northern Mesopotamia comes from Nuzi, located approximately 100 km to the east of Assur. Seeding rates from this site show that approximately 42 kg/ha of seed were used on field plots (Zaccagnini 1979). However, this number is disputed, and other data show that for barley grain, the common cereal crop in northern Mesopotamia for many periods, a rate closer to 70 kg/ha would have been more likely (van Driel 2000; Russell 1988).

During the Middle Assyrian period, a major cultural element implied by historical sources is the *pūru* (lot) system of communally sharing agricultural fields. This system contrasts with specific field ownership or management by individuals and households. In the *pūru* system, households own shares that give them rights to the community's fields; however, these rights are not specific to any particular field (Renger 1995; Postgate 1989). In many respects, this system is very similar to the Islamic system of *musha'*, which was a communal system of sharing access to agricultural fields (Schaebler 2001). At Assur, communal management of land could have been a common, but certainly not universal, system in some of the periods. In addition, in at least some periods, some of Assur's agricultural lands were likely to have been owned by the state or elite households, although this does not negate the likelihood that local common households performed most day-to-day activities in the fields (Freydank 1994). This would mean that the *pūru* system could have been retained by the households involved in agricultural production, even if ownership of the fields may have been held by other households or government officials. As for the agricultural impact of communally sharing fields, productivity at a given field can be significantly influenced from year-to-year by the fact that alternating households with varying labor capabilities may manage that field. For instance, a highly fertile field in the alluvial areas near the Tigris could be underutilized in a given year, as it is transferred to the care of a household unable to provide the necessary labor to fully utilize the field's productive capabilities.

Field plot sizes are another important model input in that this impacts how much labor would have been required for a given field. Among other examples, the ability to sufficiently sow an entire field or finish plowing before a certain time is impacted by the field's size. Texts from Kār-Tukultī-Ninūrta indicate that 1.8-14.4 hectare field plots can be a common range for many fields operated by households or work crews (Freydank 1980). As for the dimensions of many, although certainly not all, agricultural fields, texts (e.g. Zaccagnini 1979) and satellite and air photographs from the 1950s and 1960s suggest that rectangular and elongated shapes were common; perhaps a shape useful in limiting the number of times a plow needs to be turned.

Other historical and ethnographic data from the Near East and the Mediterranean region further assist in reconstructing anthropogenic processes and data that impacted the landscape. From these sources, it is clear that during the agricultural year households must clear and/or level, plow, sow, weed and maintain, and harvest their fields (Sweet 1974; Russell 1988). The labor and resources required for each of these tasks varies, depending on the requirements for a particular field. For instance, an average person may take up to 200 hours/ha to harvest a field, although this value may be different based on such factors as age and sex (Gallant 1991; Russell 1988). Additional data, from the Roman period and ethnographic sources from the northern parts of Jordan near modern Irbid, have provided information on the daily tillage capacity of plowing teams using the traditional symmetrical ard, an instrument similar to those used in northern Mesopotamia in ancient periods (Wiggermann 2000; Palmer 1998; Palmer and Russell 1993). Texts from Assur suggest that bulls or oxen were used for plowing the fields surrounding the city (van Driel 1995). Ethnographic data show that a team of two average oxen is able to till 0.3-0.4 hectares per 8-10 hour day (Russell 1988). In addition, a major component of ancient and modern agriculture in the Near East is the practice of fallowing. Biennial fallow, or even triennial fallow systems, can be assumed to have been practiced for dry environments similar to Assur's region (Wilkinson 1997). For the agricultural model applied, it was only assumed biennial fallow was practiced, though this can be altered in

future studies.

Many of the agricultural events appear to occur during specific periods in an agricultural cycle. The general timing of these events as observed in ethnography and textual sources can be used to drive anthropogenic models (Landsberger 1949; Sweet 1974). However, what is an even better method is to have human agents respond to changing conditions that cause them to perform a certain agricultural event. For instance, plowing appears to have been conducted by many farmers at least until the first rains or slightly later (Columella 1948; Russell 1988). This can be incorporated into the overall effort by having the human agents respond to not only the time of year in order to accomplish plowing, but humans in the simulation can be made to respond to events such as rainfall. Harvesting crops is another event that can use environmental conditions, such as level of crop maturity measured by Growing Heat Units (GHU), to initiate the harvest step by human agents.

For an anthropogenic modeling effort, it is vital to incorporate demography and household formation models in order to adequately represent household and individual parameters that related to agricultural labor as they evolve through time. As stated, households were often the main work crews associated with daily activities in farming. The households, therefore, will form the primary components of the work crew agents in the agricultural model to be presented. In the simulation, households have individuals with life parameters (e.g. reproductive rates and probability of death at a given age) that are determined by life table probabilities. For Assur's area, Coale and Demeny's Level 2 Model West and Level 4 Model West for males and females respectively were used (Coale and Demeny 1983). To a large extent, these life tables were useful since they approximate pre-industrial Near Eastern demographics as seen in historical texts (Bagnall and Frier 1984). For the agricultural model, the key demographic attributes used were age and sex, as these variables impact the types and amount of labor an average person may accomplish (Wilkinson et al. forthcoming)⁵.

Households in the simulation did attempt to form multiple family household types, as one would expect in the ancient Near East; however, relatively high death rates, particularly infant mortality, as well as general social stress often prevented households in achieving this ideal, similar to what can be observed in the ancient Near East (Schloen 2001). Although population dynamics are major factors in impacting agricultural productivity, specific population numbers for the Assur region are not addressed since they are not the primary concern of this article. For now, it is only important to note that a population was created and placed into households in order to work the agricultural fields.

Combining the cultural and socio-behavioral data sources, an anthropogenic model can be created for the practice of agriculture in the area of Assur. Figure 3 shows a schematic representation of this model, called the Field Crop Management Model⁶. The behavioral steps shown have different participants, named work crews, that represent households and other human labor. Resources such as plows and seed are implemented in appropriate behavioral steps. The rates that the different behavioral steps can be performed (e.g. plowing and sowing) were primarily derived from the epigraphic, historical, and ethnographic sources described earlier. When applicable, age and sex did impact these rates. After the crop model is complete, a second model that processes the

⁵ See Gallant 1991 for specific numerical values of average labor rates.

⁶ This schematic representation is a FACET model, a type of model that will be discussed shortly.

agricultural yield is launched. This model includes steps such as winnowing and threshing grain, data for which can be derived from ethnographic studies (Russell 1988). As for the overall impact to this study, the merger and interaction of the anthropogenic models with the physical environmental model described earlier will provide the results that will be presented.

4. SIMULATION FRAMEWORKS

In order to understand how one can simulate social and natural behaviors together, a brief discussion on the concepts of agent-based modeling as well as new approaches in modeling will be presented. The term agent-based modeling, or simulation, essentially means creating agents or other entities⁷, natural or human (e.g. households, people, animals, fields), that have autonomous behavior, usually performed with reference to local rules, and can respond to local conditions. This form of modeling is often referred to as a bottom up approach to modeling behavior, as agents and entities generally form components of larger systems (e.g. societies and landscapes) (Epstein and Axtell 1996). In archaeology, numerous projects have begun to use this approach in attempting to gain insights in past socio-environmental systems such as ancient landscapes and settlements (Kohler et al. 2000; Wilkinson et al. forthcoming).

Recent advancements in modeling and simulation technologies have made it feasible to integrate numerous types of natural and social models. The Dynamic Information Architecture System (DIAS) is a simulation platform that can integrate such models. This system is agent-based system, and allows any type of agent or entity to be coupled with one or more desired models of social and/or natural behavior (Christiansen and Altaweel 2006). Integrated within DIAS is the Framework for Addressing Cooperative Extended Transactions (FACET), a tool that can create models of social behavior that involve multiple types of agents and entities (Christiansen and Altaweel 2006; Christiansen 2000). Figure 3, in fact, shows this kind of model. In this case, multiple agents and entities, such as the work crews and agricultural fields, can interact with each other in defined steps of behavior. The entities and agents are called the "participants" in such models. In FACET models, the participants can apply their available resources, such as seed and plows, as they interact at variable time scales. The length and timing of interactions are determined by the context and capabilities of the involved participants. Thus, during the summer the human agents cannot plant new crops because there is not enough moisture on the field. On the other hand, if moisture was made available and the crops could withstand the heat, then the human agents can plant a crop.

When a FACET model is finished, other models, such as the Harvest Disposition Model seen in Figure 3, can be launched. Although the FACET models may appear deterministic and limited in their behavioral variation, they are mutable to different behaviors as the feedback received by the participants from various models, for instance the SWAT model, inform the participants to either forgo implementing a behavioral step or to alter the variable inputs in the subsequent step. Therefore, the result of the FACET model steps is that many of the participants' parameters (or distinctive attributes) are

⁷ An agent is a type of entity; however, agents are distinct from other entities in that they are able to display at least some level of ability to form and respond to perceptions, and adapt to, and possibly learn from, changing local environmental conditions and social stimuli. Humans and social groups generally form most computational agents.

transformed. For example, the human agents (the work crews) are made aware that they have received a harvest of a given amount after the harvest step. The SWAT model, on the other hand, in a simultaneous fashion with the FACET steps, evolves the parameters of the agricultural grain and fields (e.g. field biomass, field moisture content, etc.). The evolution of the landscape and crops as determined in SWAT not only informs the human agents on appropriate behavioral steps, but human behavior can also alter how the SWAT model performs its actions. For example, plowing and removal of vegetation from fields impacts how a given field will be modeled in SWAT. In this example, erosion may be promoted due to the removal of vegetation and plowing of the field. In summary, the DIAS framework allows for the integration of numerous entities and models of social and natural behavior that can concurrently operate and interact, allowing the DIAS chassis to be a very powerful tool for socio-environmental studies.

Furthermore, DIAS allows spatial display and analysis to be integrated with models of social and natural behavior, allowing researchers to adequately address issues in a spatial context. The geospatial tool integrated for this study is GeoViewer (Lurie, Sydelko, and Taxon 2002). In addition, each agent and entity can be given specific coordinates, allowing these objects to express their location and be displayed in GeoViewer.

Many aspects of the models and agents/entities described so far have been integrated into a DIAS tool called ENKIMDU. Argonne National Laboratory, the University of Chicago, and the University of Edinburgh⁸ have created ENKIMDU, a simulation framework that can be used to study ancient landscapes in Mesopotamia. Essentially, ENKIMDU is a library of agents and entities as well as models of social and natural behavior. Some of the tools incorporated in ENKIMDU, including SWAT and the other models described earlier, are shown in Figure 4. For the purposes of this study, certain aspects of the SWAT, anthropogenic, and demographic models in ENKIMDU were incorporated to study Assur and its surrounding landscape.

The DIAS approach incorporated in ENKIMDU and this study does differ from many other modeling approaches in that the agents/entities only refer to their behaviors (i.e. the models) abstractly. In other words, agents/entities know of their behaviors but actual behavioral models are located in a separate portion of the software, and different models can be swapped to represent the same behaviors. This allows modeling systems to be more flexible not only to different theoretical approaches, as various models can be implemented by the same or other types of agents/entities, but enables multiple models to be easily integrated, and permits an easy way to scale-up efforts in modeling and simulation. For instance, if the SWAT model was seen as inadequate for studying complex landscapes, and other models were more appropriate, then the agents and entities already included can be left unchanged and only the SWAT model would have to be replaced or complemented by other models. In another example, the FACET model for agriculture (the Field Crop Management Model) does not directly launch the Harvest Disposition Model; instead, the entities implement each model separately. These two models, therefore, never interact directly, even if they relate to each other. These characteristics make DIAS a new modeling platform that is uniquely able to integrate many different models and retain simulation flexibility to address virtually any theoretical

⁸ These institutions are collectively known as the MASS (Modeling Ancient Settlement Systems) group or team. This group is responsible for developing ENKIMDU using a National Science Foundation (NSF) Biocomplexity grant to study long-term socio-environmental issues of northern and southern Mesopotamian landscapes.

and research question.

5. SOCIO-ECOLOGICAL MODELING RESULTS

5.1. SCENARIO: "BASELINE"

At this point, many of the inputs used to run the social and natural models have been described. As mentioned earlier, the physical landscape this simulation uses is 10 km in radius. This landscape can be displayed using the GeoViewer tool described earlier (Figure 5). In the baseline simulation, there were 3243 total agricultural fields in the simulation, with 725 alluvial fields and 2518 fields in the plains⁹. All of these fields can be studied collectively or individually at different temporal levels. Individual hours, days, or entire crop cycles can, in short, be studied and observed at any point during a simulation. For example, Figure 6 shows a screen shot from GeoViewer during the harvest period in fields near Assur. In this example, GHU, a measure of crop majority, and biomass¹⁰ are among the outputs that can be spatially displayed. In this case, both these measures are affected by varying soil properties, human labor, and other human and natural factors affecting each field. For the purposes of this paper, however, the agricultural results will only be presented as aggregate data for the entire area.

The first simulation scenario, run for 55 years, was termed the "baseline" case because the environmental and social parameters for the models were made to represent what might be considered "average" circumstances, and this scenario served as the control for other scenarios to follow. In the baseline scenario, information described earlier such as the population's mortality and fertility levels, the agricultural techniques employed by the agents, and the soil characteristics were not changed. The weather variables, although they were made to represent an average year as based on data from weather stations, experienced volatility during the simulation. For example, rainfall ranged from 120 mm to 315 mm per year. However, the overall average over the simulation time span remained near 200 mm per year, an average approximating combined averages for the Qayara and Beiji weather stations (NOAA 2005).

Agricultural yield (kg/ha) results for this baseline case were simulated and divided into the plain and alluvial regions within the Assur area. Figure 7 shows the results for the plains and alluvial regions along with rainfall amounts. What the results generally show is that the alluvial terrain appeared to be 37 % (avg. 835 kg/ha over 55 years) more productive than the brown gypsiferous soils of the plains (avg. 526 kg/ha over 55 years), without applying any manuring, irrigation, or any other enhancements on the agricultural terrain. The higher yields in the alluvial areas are certainly expected due to the rich content and higher moisture levels of the soils. Looking at the yearly fluctuations in Figure 7, it is clear there is a high degree of variation in the modeled region. The alluvial areas were able to produce grain yields over 1200 kg/ha, while in the last year of the simulation the plains only averaged 296 kg/ha, indicating severe agricultural stress.

As seen in the overall yield produced, the alluvial areas were clearly more volatile than the plains, which can be expected since the alluvial soils had greater overall

⁹ Although 3243 fields were simulated, not all of the fields were used during each year since some fields remained fallow. The number of field shares per household was initially assigned based on the number of males in each household.

¹⁰ It should be noted that biomass refers to all plant materials, including grain yield. Therefore, biomass will be higher than agricultural yield.

capabilities in productivity (van Liere 2003). The plains, on the other hand, do seem to have had a long-term trend of gradual yield decline. In fact, in the first 25 years of the simulation the yield in the plains averaged 597 kg/ha, while in the last 30 years it averaged 468 kg/ha. Some of the likely explanations for this phenomenon are long-term soil water loss and gradual leaching of the soils that prevented higher yields. Wind erosion was also a factor in the simulation, as topsoil was removed during periods of low or no vegetation growth in the fields.

Given that crop growth is clearly affected by multiple factors, simulations in this and future studies can help further address the issue of sustained agricultural viability by uniquely testing some of the different input parameters affecting crop growth (e.g. rainfall, soil water content, soil nutrient content, etc.). For this simulation, it appears that rainfall's impact can often be correlated with agricultural yield for both the alluvial and plain areas. However, rainfall amounts do not always have a strong positive relationship with agricultural yield. In short, the results appear to be nonlinear in that agricultural yield is not always proportional to rainfall inputs. This indicates that other inputs were likely significant factors on agricultural yield, and these factors must be considered.

As stated, soil water content in the fields can affect overall agricultural yield. Even if rainfall was low, agricultural yield could still be relatively high if the soil moisture was sufficient. In fact, by practicing biennial fallow a field can still be productive due to the previous year's rains stored in the soil. Underground water sources can, in general, provide sufficient moisture. Year 14, for instance, was an above average year for barley yields in the plains (567 kg/ha), although the rainfall was only 173 mm. The alluvial areas had higher groundwater and soil moisture levels, which partially explains why the yields were higher in this area. Temperature and mineral content of soils certainly affect how barley matures. In fact, the overall results likely suggest that leaching of soil minerals may have contributed significantly to the gradual decline in productivity of the agricultural fields. Given that the soil nutrients were not replenished by any application of fertilizers added by the work crews, the constantly evolving field soil parameters gradually lost some fertility during the simulation. This is why leaching as well as the loss of soil moisture content were likely candidates. These and other possibilities of soil fertility loss, however, need to be studied further to see how much affect they had on crop growth. By having models that incorporate numerous variables that affect soil viability, studies can now adequately focus on the numerous reasons that may have led to agricultural decline.

Direct human action can also be seen to have had an impact on agricultural yield. One major input that affects agricultural productivity is labor, specifically the availability and capabilities of human labor. Insufficient plowing or field preparation can seriously undermine agricultural productivity, as shown by ethnographic sources. For instance, in the Near East multiple plowing is often conducted before crops can be planted (Russell 1988). If a field is planted late due to a delay in plowing or any other reason, then overall yield would be negatively affected. The same seems to be true in the simulation during certain years. Figure 8 shows the percentage of hectares defaulted in the alluvial regions, or a percent measure of all hectares employed for agriculture in the alluvial areas that were abandoned¹¹ due to insufficient labor inputs. Year 20, for example, shows that approximately 15 % of all cropped fields were abandoned during that year. This measure

¹¹ In all the simulations, a field was abandoned if it was not cleared, sufficiently plowed, and planted by the beginning of January.

not only indicates that many fields were abandoned, but the high percentage also indicates that many of the fields were planted relatively late in the year. Thus, labor constraints would cause some households to abandon their fields, while others would have finished field preparations relatively late in the agricultural cycle. Although the abandoned fields did not affect the overall yield average, certainly fields that were planted late impacted the overall yield. The average yield result for Year 20 was 704 kg/ha in the alluvial areas, even though the rainfall amount was above average (218 mm). Years 45 and 49 produced similar results, with 14 and 11 percent of the their fields abandoned respectively. In those years, the average yields in the alluvial zones were 667 kg/ha in Year 45 and 629 kg/ha in Year 49, with rainfall measuring 209 mm and 196 mm respectively. Even though this example only reflects results for grain yields in the alluvial zones, the points made in this example are also relevant for the plains, as these areas were undoubtedly impacted by labor shortages in certain years.

The relationship of labor to agricultural yield may seem to be obvious, but the factors limiting labor can be very diverse and complex. Some factors affecting labor inputs, and potentially limiting overall labor productivity, include death and ageing of household members, insufficient ability to access laborers from household members or kin¹², lack of access to plows¹³, and distance to fields from a home settlement¹⁴. Certainly a major factor affecting labor inputs is overall field size, with large fields requiring more labor. Therefore, fields that were relatively large in proportion to the labor available for work would be inadequately prepared in time to produce high yields. In general, the hectares defaulted result shows large variability from year-to-year in the provision of adequate labor. Households had to find the means to provide the necessary labor and resources for their fields, either using their social relationships within the community, including their kin networks, or their own capabilities. The consequence of not being able to meet agricultural labor requirements could, therefore, have a significant impact on the overall yield of the fields surrounding Assur.

For the most part, the agricultural output shows that the plains were likely to be relatively modest in productivity, while the alluvial areas are clearly more favorable for the production of grain. Although this scenario does not necessary represent a specific instance in the past, it does provide output that indicates some insights in the interplay of the numerous factors that would have certainly affected agricultural productivity. Even in this scenario, with variables near what could be considered the average for the Assur region, large fluctuations could be seen throughout. In many cases, this could be explained by the fluctuations in rainfall; however, as the labor example showed, other social and natural characteristics could significantly impact overall grain yields. In that case, labor shortages occurred for a number of reasons, ranging from death to lack of kin networks able to support struggling households. In summary, the results show the

¹² In all scenarios, a household can use patrilineal kin for labor assistance, that is if it lacks labor from its own members. Households can also pay others for their labor. However, in all these cases, the options may be unavailable for a number of reasons.

¹³ There was one plow for every two households in the simulation, thus households had to wait to gain access to plows.

¹⁴ For the purpose of this simulation, all human agents were located within 2 km from the fields they worked. Although this is not very distant, the farthest fields certainly would take longer to walk to, affecting the overall time that a work crew has for providing sufficient labor inputs in a day. In general, it is assumed that the farmers providing food for Assur and its region did not necessarily live in the city during the agricultural cycle.

nonlinear nature of agriculture and that numerous social and natural factors must be accounted for in order to properly measure agricultural yield in a given period. The next two scenarios will show how the addition of a behavior or change in a variable can affect agricultural capabilities in Assur's area.

5. 2. SCENARIO: "DRY PHASE"

In this second scenario, the average yearly rainfall amounts in the initial baseline simulation were reduced on average by 20 % during the entire simulation. This scenario represents a chronic case of low rainfall amounts during the entire scenario. All of the other parameters, including the time length of the scenario, remained the same as the original baseline.

Figure 9 shows the results for agricultural yield and rainfall amounts for this scenario. In this case, the alluvial areas averaged 539 kg/ha, while the plains were producing on average 351 kg/ha. The results indicate a large percentage difference between this scenario and the baseline, with a 35 % reduction in yield for the alluvial areas and 33% for the plains. This indicates that agricultural yield was disproportionately affected by the overall reduction of rainfall, in other words a far greater decrease in yield versus the decrease in rainfall percentage. In fact, in years when the agricultural yields were particularly low (300 kg/ha or lower), it is likely that a large quantity of the barley crop would have been of low quality, as grain heads are adversely affected by persistent stress (Samarah 2005).

Not only did the reduction of rainfall affect overall yield, but due to consecutive years of rainfall falling well below 200 mm, the overall soil water content dropped significantly. Although in the baseline scenario crop yields were sometimes higher in years of low rainfall, recurrent low rainfall amounts in this scenario limited productivity even in a biennial fallow system. During years of rainfall increasing to levels that can produce higher crop yields, the overall yields for both the alluvial regions and plains remained relatively low compared to the baseline. Year 27, for instance, had over 255 mm of rainfall, which was well above average for the scenario, but the average barley yield in the plains was only 352 kg/ha, or close to an average yield for the plains in this scenario. Part of the reason for this result is due to the fact that soil water content was significantly depleted from previous dry growing seasons. Furthermore, given that the soils are more porous in the plains, these areas tend to retain less water and lose soil nutrients to leaching, as described earlier. In short, particle size of the soils influenced the results observed (Brye 2003). Erosion also cannot be discounted as a significant influence in the plains. On the other hand, the alluvial areas had relatively high groundwater levels and soil particles that were less apt in promoting nutrient leaching, contributing to the sustainment of fertility in these soils.

This scenario suggests that under low rainfall conditions alternative cropping strategies may have been more appropriate to practice. For instance, one social induced mechanism that could have increased overall yields is triennial fallow, which can be used to conserve water content from two previous years prior to an agricultural cycle. Even in this strategy, however, leaching and other problems are likely to persist.

The overall results generally indicate that agricultural practice in this scenario would have produced many years of relatively low crop yields and/or crop yields that were of poor quality if rainfall was on average 20 % less than what can be considered the average rainfall for the Assur area. This is particularly apparent in the plains surrounding

Assur. Prolonged periods of low rainfall can be seen to have made it difficult for crops to rebound quickly when there is an improvement in rainfall amounts. Other factors mentioned in the last scenario, including labor constraints and soil leaching, would have certainly affected crop yields. As for the alluvial regions, these fields would have at least been more dependable in agricultural productivity even in relatively dry years.

5.3. SCENARIO: "IRRIGATION"

A third scenario run involved introducing irrigation as a practice for all alluvial fields in the Assur area and 337 fields in the plains. All of the plains were not irrigated simply due to the fact that this would have been unlikely in most periods, as topography of the region limits irrigation in these areas. Therefore, only a portion of fields in the plains, about 13% of the total for this field type, were irrigated in order to be tested for potential productivity under this condition. As for the nonirrigated agricultural fields in the plains, these fields were simply not included in the scenario. For all the simulated fields, all of the initial input parameters were kept the same as the baseline scenario with the exception of enabling irrigation during the agricultural sequence. During the agricultural cycle, there was approximately 240 mm of water applied to the simulated fields, and this water amount was divided and applied in equal increments from November to May. The crops were also nourished using the same rainfall parameters as the baseline scenario. In general, the result of irrigation insured that in every year adequate water sources were obtained to enable barley to grow properly. In fact, in many years crops received water amounts well above required levels.

Figure 10 shows the result of the scenario that ran for 55 years. In general, the plains produced an overall average of 627 kg/ha, an increase of 16 % from the baseline, while the alluvial region increased by 17 % to 1006 kg/ha. Similar to previous results, the plains produced a more limited range of agricultural yield, while the alluvial region showed the most potential for surplus. One observed phenomenon is that agricultural yield in the alluvial regions appeared to remain stable or trended slightly upward, while the plains still had a generally downward trend for the period of the scenario. These results are largely similar to the previous scenarios. In this scenario, the plains significantly decreased in productivity from an average of 686 kg/ha in the first 25 years versus an average of 569 kg/ha from Year 30 to Year 55. This shows that relative to the baseline scenario average, irrigation had a much greater benefit in the first half of the simulation, while the benefit was more minor in the last 25 years. The alluvial areas, on the other hand, appeared to maintain a greater capacity to retain soil nutrients and water that likely contributed to higher overall average yields in the last 25 years of the simulation (near 1100 kg/ha) versus the first 25 years (approximately 900 kg/ha). This tendency also appeared in the baseline scenario, although at lower yield averages, indicating that the higher yields sustained late into the irrigation scenario reinforce a similar observation in the baseline case.

What these results suggest is that irrigation can have long-term benefits for agriculture in the alluvial regions, while agriculture yield in the plains generally improves with greater water inputs. However, the plains still appear to be losing productivity as they are used more during the simulation, indicating that other factors besides water are likely causing the downward trend of agricultural production. Despite these intriguing results, only further testing can more definitively answer why the plains decline in fertility over the long-term and the alluvial areas appear to sustain higher yields. As for

future variations of this scenario, irrigation can be applied at only certain time intervals, rather than at constant amounts over several months. This may indicate that irrigation in specific growth stages of barley could significantly alter agricultural yield.

6. CONCLUSION

The results presented demonstrate that Assur's landscape could have been impacted by a variety of social and natural processes affecting the ancient city's potential agricultural productivity. One can assert that the results are limited in that only a few scenarios were actually conducted, and numerous natural and social variables were not sufficiently addressed. For example, a scenario testing the effects of fertilizers or allowing for more varied social mechanisms that can enable households to more easily improve labor efficiency could have been simulated. Furthermore, a number of the input parameters used in the simulation scenarios are debatable or unclear, as a portion of the data did not use universally accepted ancient or more modern sources.

Nevertheless, what was presented indicates that it is possible to construct modeling approaches that are spatially and temporally flexible and able to address a specific landscape. Different types of agricultural fields with different soil properties across Assur's landscape were simulated with temporal detail that allows for the investigation of agricultural processes as they occur at every minute, hour, day, or year during a simulation. The approach applied in this study demonstrates that by having the ability to integrate highly detailed social and natural models, the results produced can begin to reflect possible outcomes of past socio-environmental processes. Although none of the scenarios may have represented a comprehensive view of agriculture at Assur in a given period, the ability to test possible behavioral outcomes under varying circumstances makes the simulation approach presented useful for studying ancient Mesopotamian societies. Despite the data limitations in this study, the advantages of the simulation tools have helped to provide intriguing insights in the agricultural potential of Assur's landscape. In the different simulation scenarios presented, some of the insights gained include the observation that the plains declined in productivity over time, even when yield initially increased with irrigation. In the dry phase scenario, long-term limitations of rainfall appears to constrain the plains' ability to quickly rebound in years of higher rainfall. The alluvial terrain, on the other hand, showed much greater potential for agricultural yield in all the scenarios, with no loss of fertility over long periods. Even in relatively ideal circumstances, such as the baseline scenario, human labor can be a significant constraint in certain years. All of these insights would have been difficult to foresee without applying the simulation approaches discussed.

As stated, more detailed and insightful results could have been achieved by incorporating better data for the natural and social models, including more behavioral processes for the entities discussed, and adding more human and nonhuman actors that impact agriculture. Given that the specific results discussed are still preliminary, the major and more immediate achievement of this paper is the demonstration that numerous questions related to agriculture and other social and natural processes for past societies can be addressed to a high degree of fidelity using the flexibility and scalability of the presented simulation technologies. This allows questions such as agricultural productivity of a given landscape to be addressed in a more sophisticated manner than was previously possible. In fact, by extending the simulation tools to other major questions related to past Mesopotamian societies, scholars can be better able to test their

ideas and theories for those questions in order to achieve new insights. Ultimately, this author and his colleagues hope to be able to produce more thought provoking insights in both northern and southern Mesopotamian societies in several different periods using the same simulation approach outlined in this study.

6. ACKNOWLEDGEMENTS

This paper was partially made possible by the "Modeling Bronze Age Settlement Systems in a Dynamic Environment" project, a collaborative effort of the Oriental Institute and Department of Anthropology at the University of Chicago, the University of Edinburgh, and Argonne National Laboratory. This project is made possible by funding from the National Science Foundation Program: Dynamics of Coupled Natural and Human Systems (Grant No. 0216548). Further information regarding this project can be obtained at: <http://oi.uchicago.edu/OI/PROJ/MASS/Mass.htm>.

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SWAT Model

- Crop growth
- Soil evolution
- Soil moisture
- Evapotranspiration
- Landscape hydrology
- Temperature
- Rainfall
- Growing heat units
- Different plant coverage

Fig. 1. Figure showing the different types of physical / environmental processes modeled in SWAT

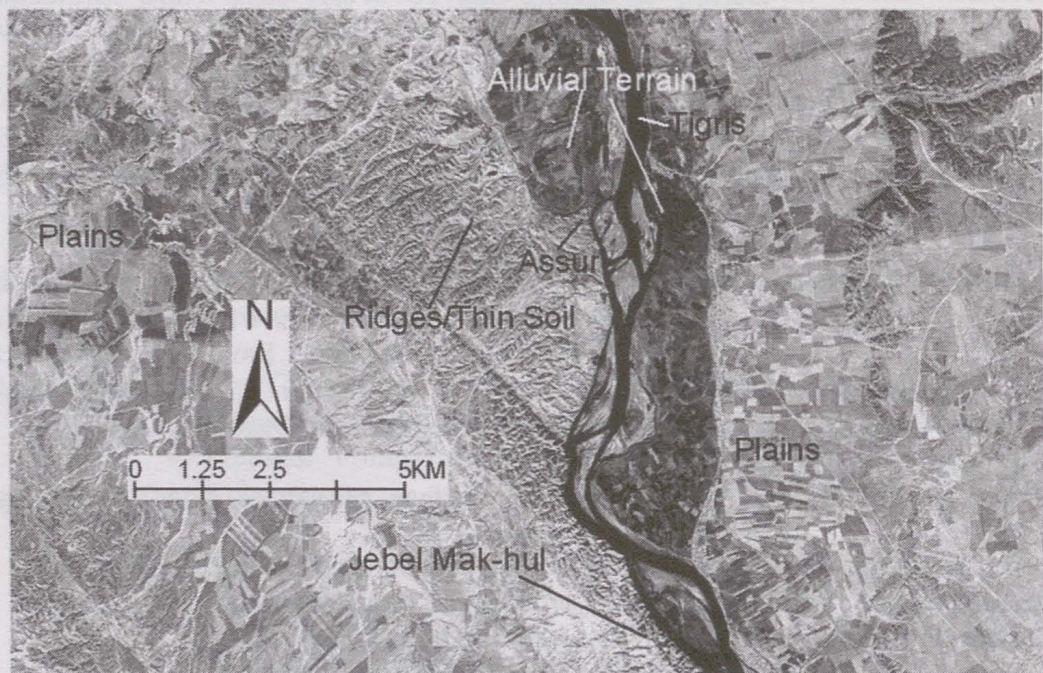


Fig. 2. CORONA December 1969 image showing Assur and its surrounding terrain. The main types of landscape coverages identified are the plains, alluvial regions, and elevated ridges or thin soil areas

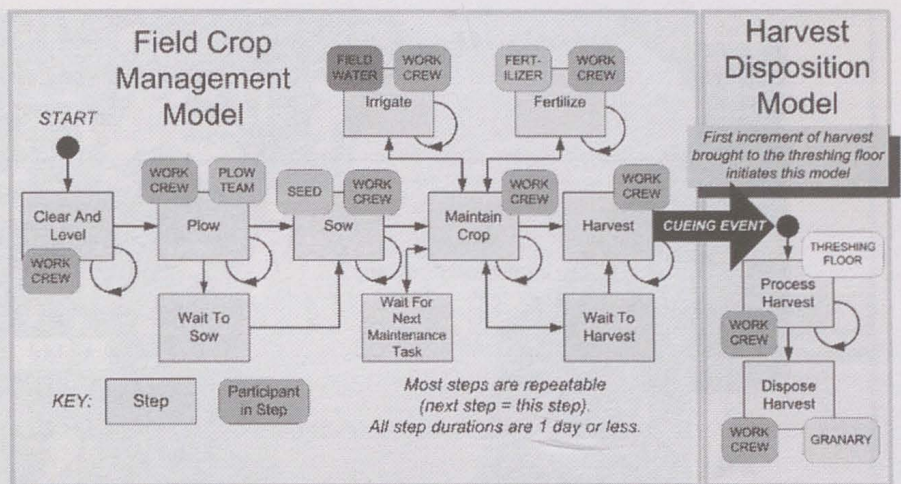


Fig. 3. FACET agricultural model (called the Field Crop Management Model) showing anthropogenic processes involved in producing grain. The model shows the different participants (work crews) and resources (seed and plow teams) that are used by the participants. After the harvest, a second model (Harvest Disposition Model) processes the agricultural yield

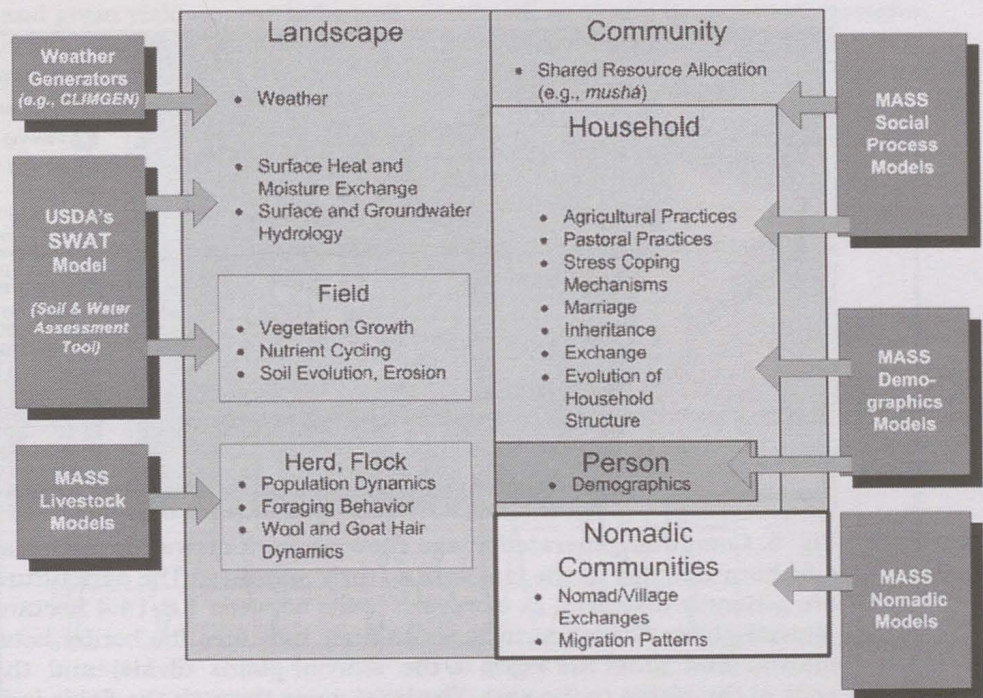


Fig. 4. Figure showing the agents/entities that are included in ENKIMDU, a number of which have been created by the MASS (Modeling Ancient Settlement Systems) team that includes Argonne National Laboratory, the University of Chicago, and the University of Edinburgh. Some of the behaviors represented in ENKIMDU are bulleted, and the associated types of models are shown as boxes on the edges of the image. In general, ENKIMDU can be used as a simulation library that can be modified to address different types of ancient Mesopotamian scenarios

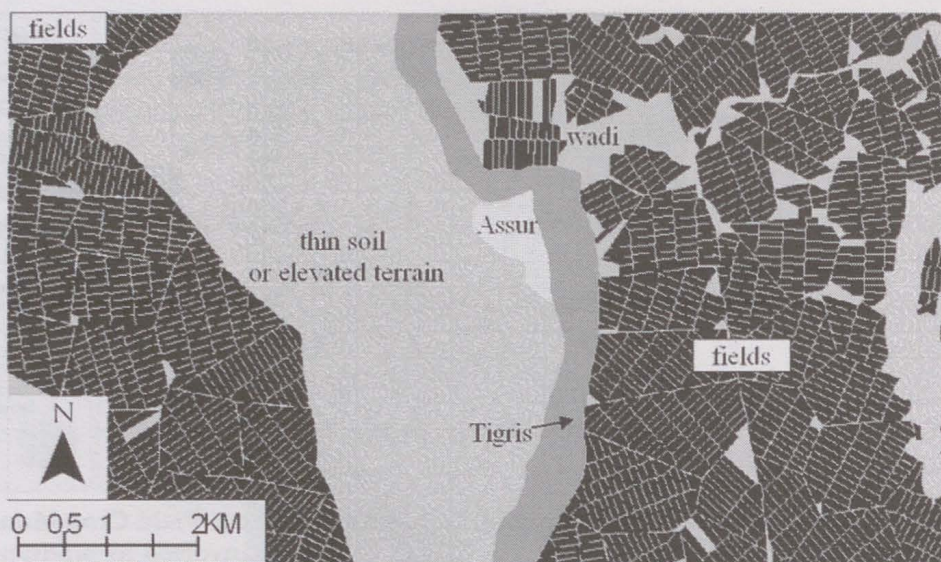


Fig. 5. Computer generated image showing some of the simulated Assur area. This image was derived using the spatial data discussed. Agricultural fields are shown as dark colored shapes, with thin soil and elevated terrains shown as gray and light gray features.

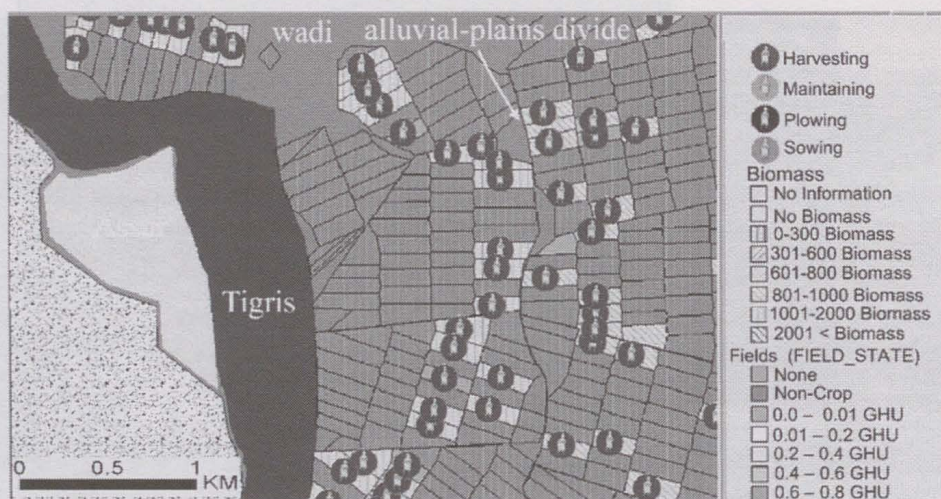


Fig. 6. Computer generated image showing work crews harvesting at a specific hour and day in the late spring/early summer. The agricultural fields are generally displayed as elongated fields between 1.8-14.4 hectares. The alluvial-plains divide (north to south line) indicates the border between the alluvial area (from the Tigris to the alluvial-plains divide) and the brown soils of the plains to the east. The lines going through the fields indicate biomass, while color on the fields display GHU, a cropmaturity measure. Most of the crops are at a 1.0-1.2 GHU stage, prompting the work crews to conduct harvest. As for biomass, the agricultural fields in the alluvial areas display generally higher numbers than the plains (1001-2000 vs. 801-1000 kg/hectare)

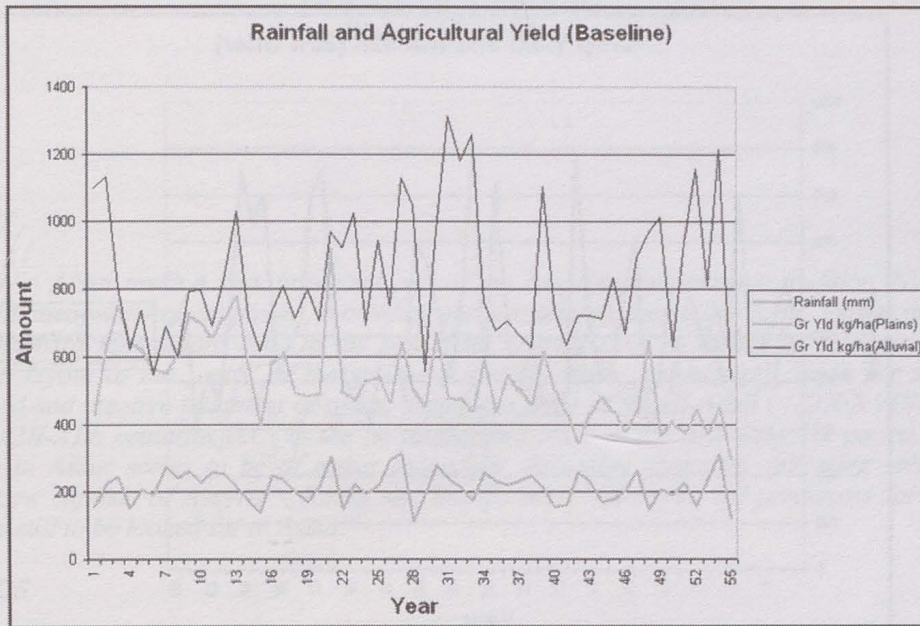


Fig. 7. Graph showing rainfall amounts in relation to barley yield in kg/ha for the alluvial and plain areas surrounding Assur. In many years, rainfall and grain yield appear to be well correlated, as would be expected; however, rainfall is often not linearly proportional to grain yield

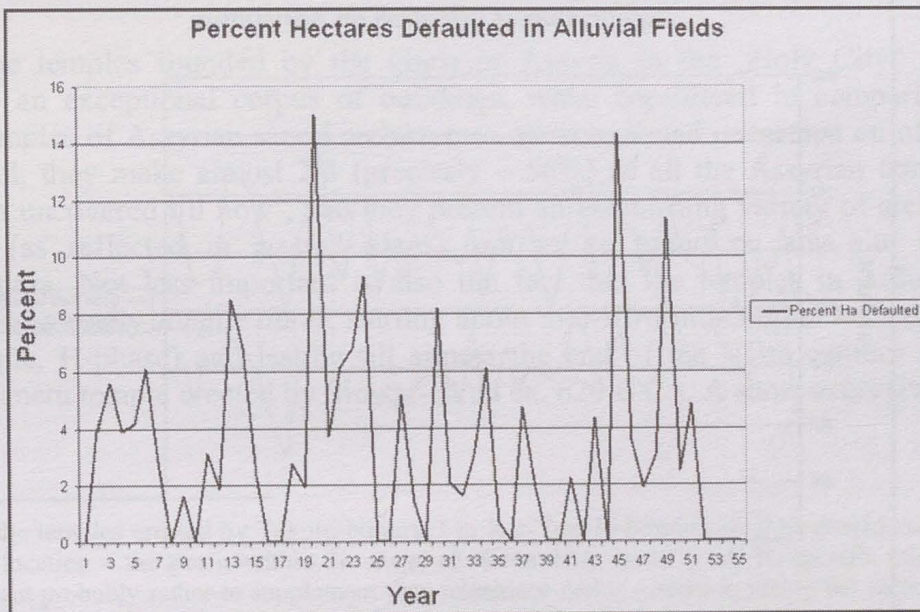


Fig. 8. Graph showing percent of agricultural hectares defaulted in the alluvial zone

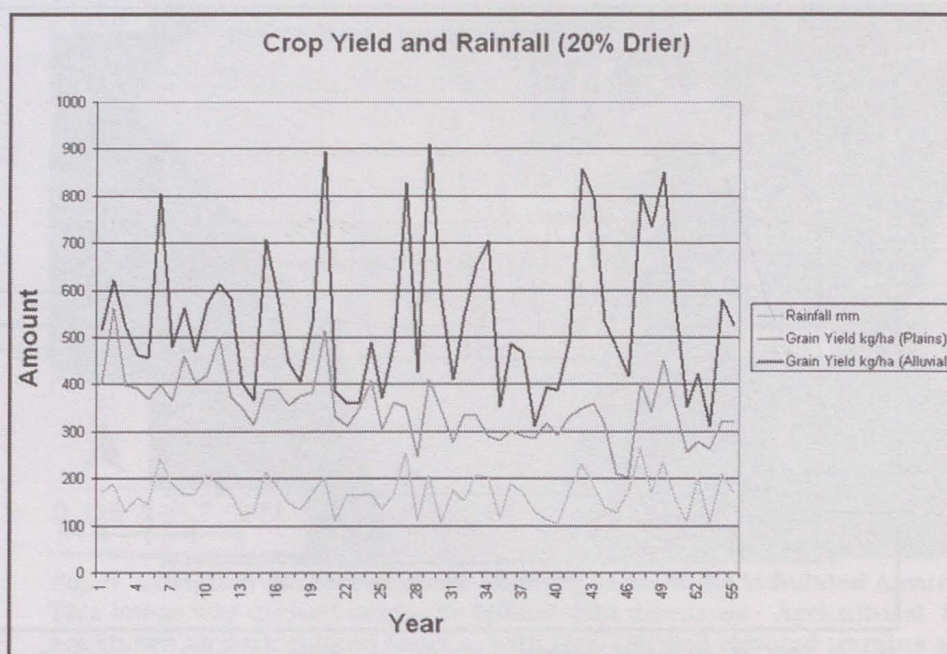


Fig. 9. Graph showing barley yield results based on a 20 % reduction in rainfall amounts from the baseline scenario

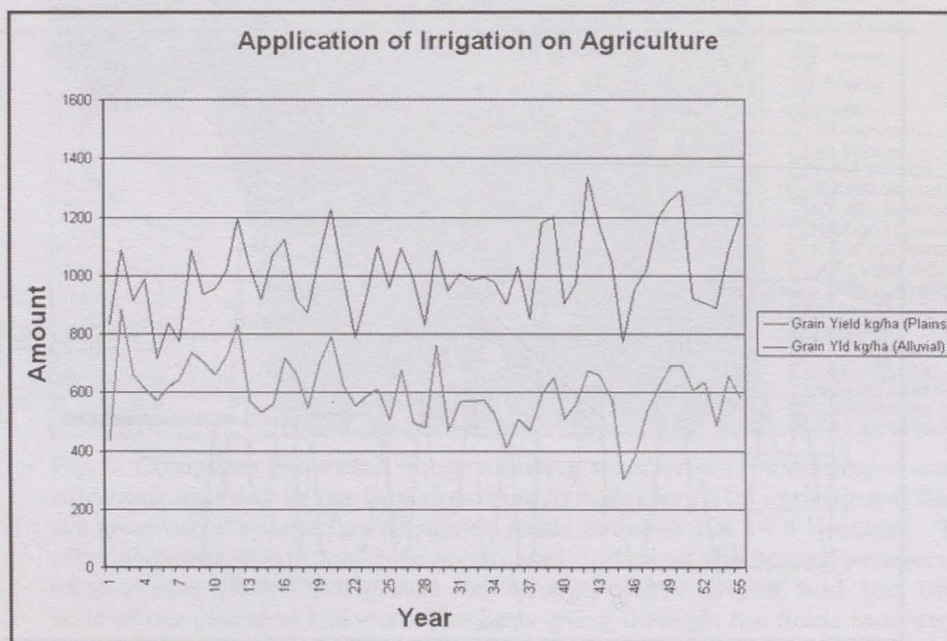


Fig.10. Graph showing the results of agricultural yield after applying 240 mm of irrigation per year