

# **The Model-Based Archaeology of Socionatural Systems**

**Edited by Timothy A. Kohler and Sander E. van der Leeuw**



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# **Modeling Settlement Systems in a Dynamic Environment**

## *Case Studies from Mesopotamia*

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The development of early states and civilizations continues to occupy the attention of archaeologists and anthropologists. Despite the use of words like *complexity*, few have made real progress in dealing with the full range of variables involved in the development of complex societies. One trend recently observed is a shift away from the testing of explanatory models of the early state and towards an emphasis on “state dynamics,” in other words, how these states actually functioned (Stein 2001:355). If early state societies were truly complex, then it is necessary to tackle the full range of complexity that exists. To do this with any degree of analytical rigor, we must build up large, complex models that incorporate a wide array of data sources and incorporate a range of interacting processes: social, economic, environmental, and political. Here we outline the early results of a program employing techniques of agent-based modeling to model the early stages of state-level society in the Near East.

Fundamental questions being addressed include (1) how and why did third- and fourth-millennium-BC cities of southern Mesopotamia grow to a greater size and complexity than those in the rain-fed north? (2) what was the dynamic trajectory of such

settlements through time? and (3) how did the resultant cities respond to a capricious natural environment, and were they able to grow, survive, or decline under a range of social, environmental, and economic stresses?

In an article published in 2001, Guillermo Algaze argued that “the primacy of southern Mesopotamia was in part due to the fact that southern societies had several important material advantages over polities in neighboring areas.” The factors contributing to this so-called Mesopotamian Advantage were a denser and more varied concentration of exploitable subsistence resources, higher and more reliable agricultural yields, and a more efficient distribution system based on water transport. Algaze (2001:200) suggested that “these advantages promoted the creation of inherently asymmetrical exchange patterns among independent polities in the Mesopotamian alluvium and between those polities and societies in neighboring regions which, over time, produced important organizational asymmetries between southern societies and contemporary polities.”

An underlying assumption of our modeling approach is that the urban centers in northern and southern Mesopotamia were, in part, emergent phenomena resulting from positive feedback processes that promoted growth, nucleation, and population concentration and negative feedback processes that constrained such growth to within certain limits. In the northern Mesopotamian cities, which attained a size of little more than 130 ha (Stein 2004:66–7; Wilkinson 1994), the negative feedback processes—provided by, for example, the frictional effect of overland transport of staple products—constrained growth to populations of little more than ten to twenty thousand people. In contrast, for cities in the south, the higher agricultural yields, as well as the existence of an efficient system of channels for transporting staple crops products, lifted the constraining effects of negative feedback processes, thereby allowing settlements to grow to 400 ha or more in area.

Nevertheless, it would be overly simplistic to pretend that urban growth resulted simply from the operation of so-called bottom-up factors. The cuneiform literature is replete with examples of kings exerting their power by razing cities to the ground, founding new ones, and shifting river channels. Also, the contribution of the deliberate and self-conscious establishment of archaeological sites is important to understand. Possibly, the tension between bottom-up and top-down processes resulted in the pattern of urbanization we see in the archaeological record of the Bronze Age. Here we focus on the bottom-up processes that resulted in the growth of early settlements and their ultimate transformation into hierarchical systems of settlement.

Factors such as interregional exchange and networks of information flow must also have contributed to the differential patterns of growth between the south and the north. We feel, however, that by starting with the basic subsistence economy instead of the fully developed political economy, agent-based models can successfully capture the development of the latter, as well as show patterns of interregional exchange as emergent properties of the settlement systems.

At the present state of modeling, our settlements are still at the transition between

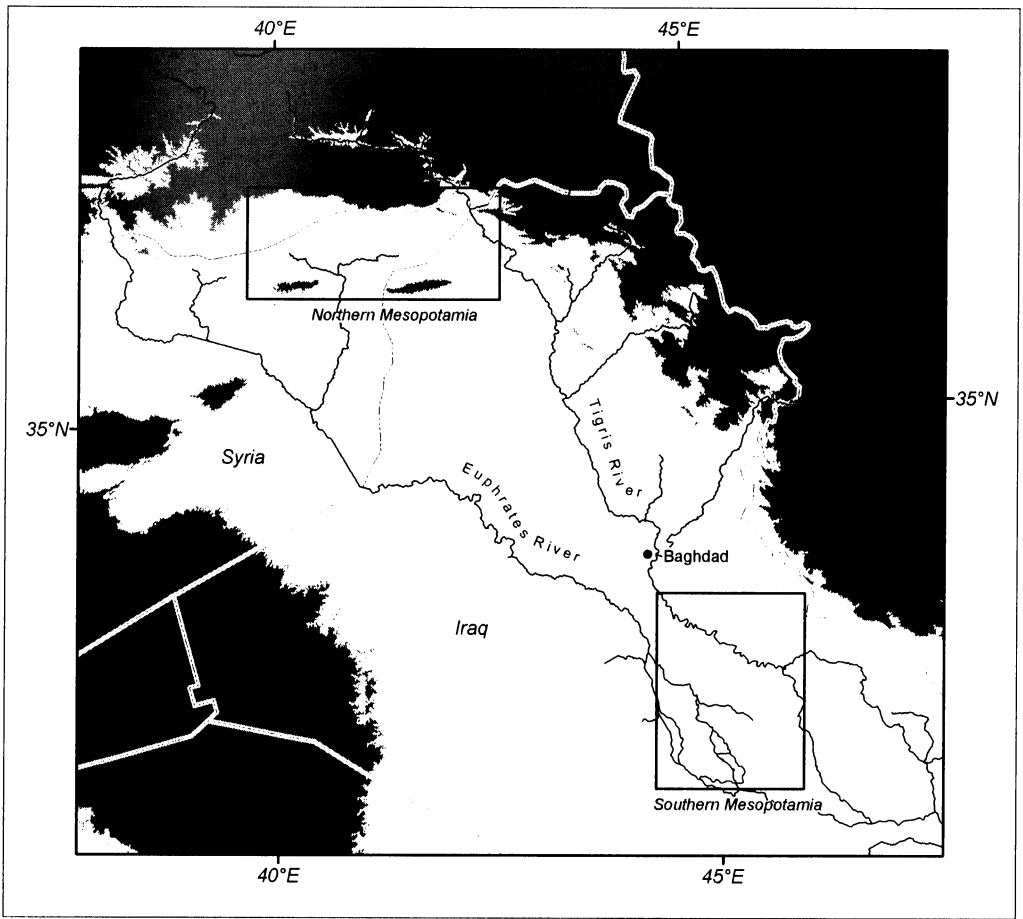


Figure 9.1. The location of main study areas in northern and southern Mesopotamia.

a subsistence economy and a political economy, but the examples discussed demonstrate how such models can supply rich insights into the development of early states.

Owing to the vast scale of the Mesopotamian region, no modeling program can successfully capture the fine granularity of the landscape, broad patterns of agricultural production and interregional exchange systems, and movements of pastoral nomads. Nevertheless, remote sensing and new technologies of 3D mapping enable archaeologists to deal with the spatial scales necessary to build up models of expansive settlement systems. Recent use of remote sensing and Digital Terrain Elevation Data (DTED) can now demonstrate the remarkable contrast between the transport networks of northern and southern Mesopotamia. For rain-fed northern Mesopotamia, Corona satellite imagery provides a sensitive rendering of the route systems (hollow ways) within part of the third-millennium polity of Nagar (Tell Brak) (figures 9.1 and 9.2). These have been mapped in a “window of landscape preservation” in the upper Khabur Valley (Ur 2003) to show a dramatic series of radial route systems around Early Bronze Age sites; the phases of occupation date from approximately the fourth millennium to

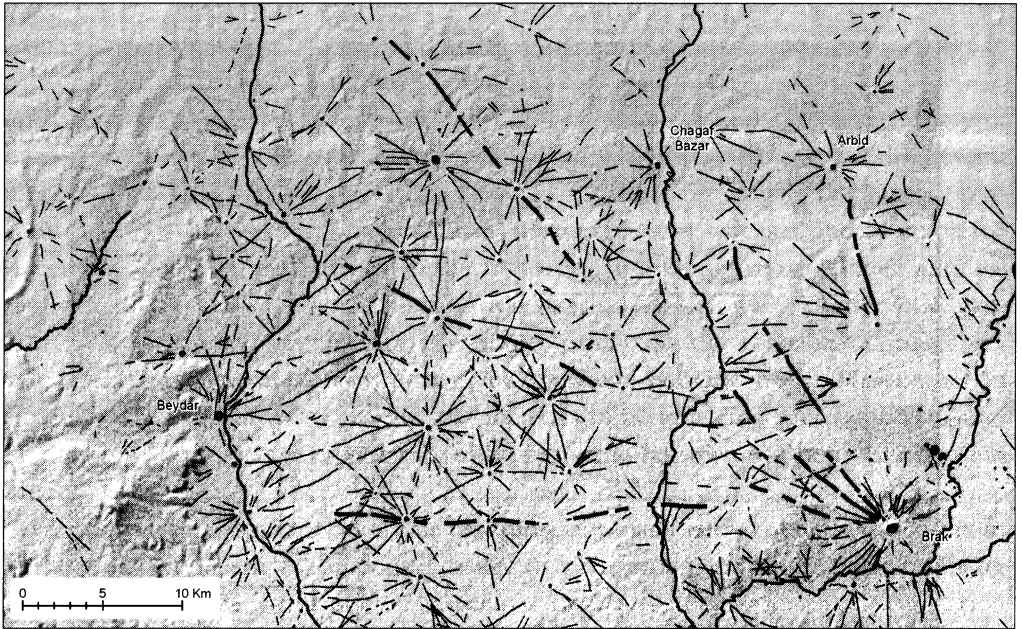
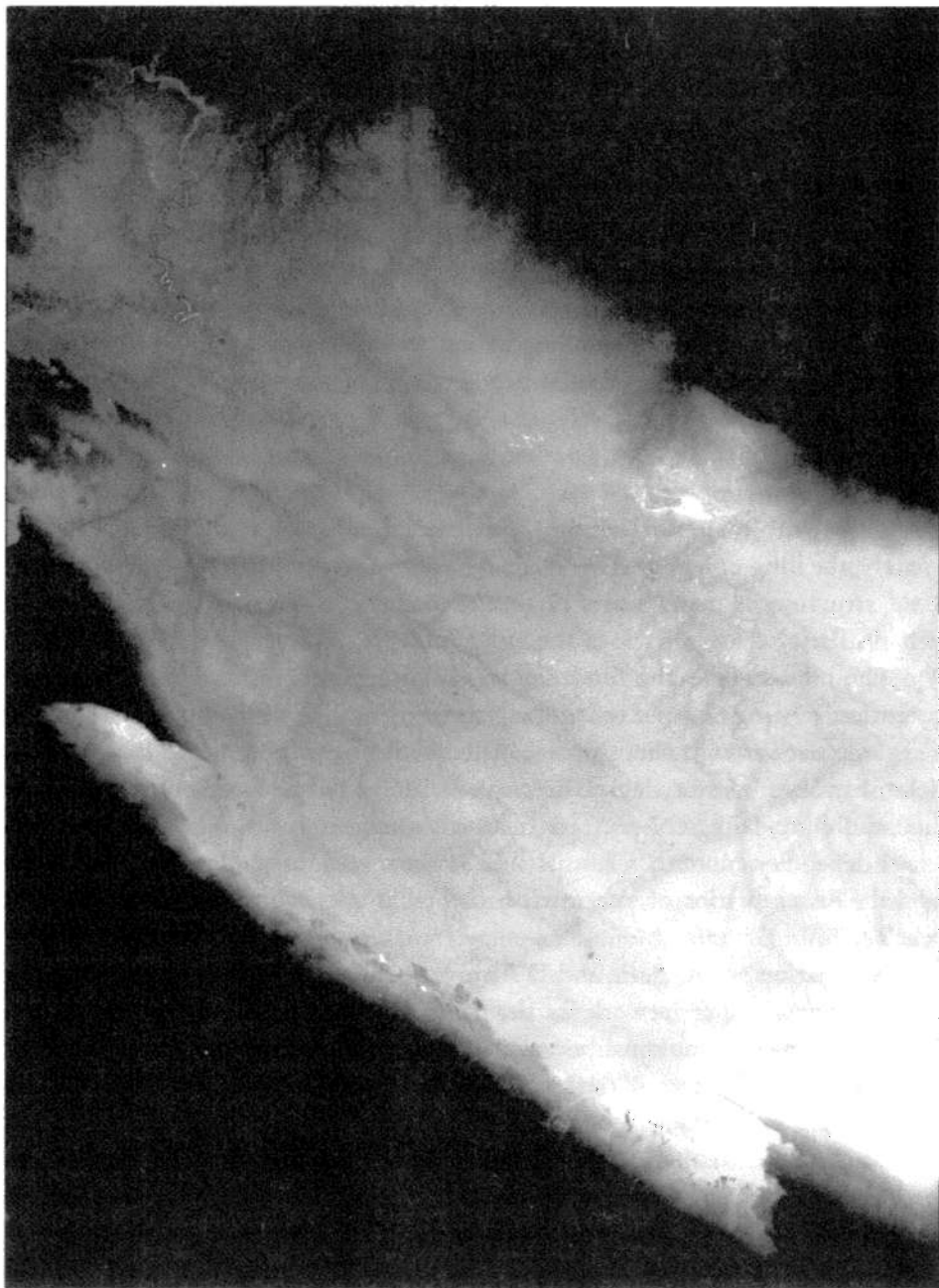


Figure 9.2. The network of communications represented by hollow way systems in the Khabur Basin, Syria.

the late third or second millennium BC. In addition to radial routes around local centers, a number of interregional routes provided evidence for the existence of cross-country networks. Viewed subjectively, it would appear that most transport was effectively local in nature and focused on the movement of people and produce from settlement to fields or the pastures just beyond (Wilkinson 1993). Nevertheless, cross-country routes were also in operation and may represent the well-known itineraries of the cuneiform sources.

In contrast, recently released Shuttle Radar Topography Mission (SRTM) (digital terrain) imagery provides a remarkable picture of the anastomosing channel patterns that provided the basic transport network of southern Mesopotamia (figure 9.3). As yet, only certain elements of this complex palimpsest of low topographic levees can be dated (although see Cole and Gasche 1998), and the pattern illustrated must be regarded as being of a multiperiod date. Nevertheless, this data is sufficient to demonstrate that the network of channels, forming “low friction” anastomosing rivers, their branches, and excavated canals, supplied a well-integrated transportation system network ideal for shifting bulk materials from place to place, thereby making up for regional disparities of production or supply. Although the existence of such a network has been known since the early days of Mesopotamian archaeology (Adams 1981; Jacobsen 1960), the new technology renders this in all its remarkable complexity.

In addition to transport systems that served either to constrain or to expedite the movement of staple products, environmental fluctuations must be incorporated into models of regional economy. High floods in the Zagros Mountains would contribute



0 20 40 80 120 160 Kilometers

Figure 9.3. The pattern of levee systems in southern Mesopotamia, as recorded by SRTM imagery (courtesy of US Geological Survey).

to overbank flooding in the main Tigris and Euphrates rivers, thereby promoting avulsion (Gibson 1973). Runs of dry years would constrain production in the dry farming north, perhaps contributing to production failure and demographic collapse (Weiss et al. 1993), or result in stresses that would impact pastoral nomads throughout the region.

## ***Approaches to Modeling***

The basic “agent” employed in the present model is the individual as a member of a patriarchal household. This type of household is well attested as the fundamental social and economic unit in the ancient Near East (Schloen 2001). Textual evidence shows that many kinds of common action and shared interests on the part of supra-household groups were symbolized in terms of membership in the same patriarchal household. It is possible to scale up this concept to encompass various political, economic, and religious groups, because larger social groups (including entire kingdoms and empires) were perceived as consisting of many hierarchically nested households subsumed within an overarching “household” headed by a “master” or “father” (ultimately, the king or a god). This recursive pattern, replicating the same familiar household structure at many scales of measurement, conforms to the notion of “fractal” self-similarity characteristic of the global order of complex adaptive systems.

The household is the fundamental social group being modeled, so considerable attention is being devoted to studying the provisioning of the household, as well as its development through time. Because the subsistence economy is ultimately based on relatively simple, everyday nutritional demands and agricultural production of the household, modeling this sector is relatively straightforward. However, Mesopotamian cities depend on more than subsistence, so the model must allow for trade or exchange and the dissemination of information, as well as the accumulation and distribution of wealth.

A variation on the Earle and D’Altroy model of staple and wealth economies provides a conceptual framework for the development of economies in the ancient Near East (Earle 2002). One must be wary, though, of projecting such models back in time uncritically (see Schloen 2001:199–200). In Upper Mesopotamia, three basic components of the economy can be recognized: The staple economy (1) is easy to model because it is rooted close to the site and a significant part of production is dependent on rainfall. The flow of wealth (2) and the pastoral economy (3) are more difficult because they entail increasing the modeling framework to cover much larger areas. This is particularly acute in trade and exchange: if the modeling framework is to be expanded, then scaling up the entire model to encompass innumerable additional settlement systems becomes a potential necessity. Similar problems of increasing system scale arise when dealing with pastoral economies that range over large areas of desert or steppe. In both cases, though, adopting certain simplifying mechanisms can sidestep the problems.



The increased flow of information through time is also significant because the “urban revolution” straddles the invention or introduction of writing. Although the genesis of many settlements (in both the north and south) takes place before writing was developed, urbanization itself logically was a process that co-evolved with the development of writing. Not only did writing permit the expansion of bureaucratic processes (Gibson and Biggs 1991), but also the growth of writing and bureaucracy probably allowed the further expansion of urban institutions and cities themselves. Because of their sheer scale and complexity, the modeling of the later stages of such complex entities is not dealt with in this chapter. At present, we are still wrestling with the problem of bridging the conceptual gap between subsistence or relatively simple political economies and the complex state bureaucracies that grew up, especially in southern Mesopotamia.

Although the complexities of later Mesopotamian civilizations have yet to be incorporated, by introducing the individual as agent we can deal with more slippery concepts, such as rhetorical skill, physical strength, and charisma, all factors that can underpin political authority (Schloen 2001:200) and without which urbanization could not take place.

### ***Input Data and the Data Manual***

Constructing a computer model of an ancient community from the “ground up” requires a wide range of input data relating specifically to the basic processes of everyday life and to the behaviors of the individual agents. Factors such as the size range of the households and component families, the agricultural calendar that regulated much of everyday life, additional requirements for feast days, weddings, and the like, the components of the pastoral economy, sources of fuel, and so on all need to be represented, ideally in a quantitative way. This information must come from a wide range of sources such as archaeological excavations, ethnoarchaeology, and technical consultants’ reports, as well as cuneiform texts and other historical documents.

Because most of these types of sources are common to other modeling projects, they can be summarized in tabular form (table 9.1; see also Hunt 1991). The Middle East provides a wide range of data sources because of the extensive ethnographies (for example, Russell 1988; Sweet 1974) and the rich source of consultants’ reports produced for various development projects. Limited demographic data are available for the site of Kish in modern Iraq, as well as Dinka Tepe, and Hasanlu in Iran (Rathbun 1982, 1984). More extensive mortality data from the Roman period have enabled life tables to be constructed (Saller 1991), thereby providing a crucial source for the demographic profile of the community.

The Mesopotamian cuneiform record provides a unique source of evidence for the model and has played an extremely important role in the formulation of our agent-based and household-based model on a general theoretical level (see Schloen 2001). Moreover, the texts contribute in many important ways to our empirically based

**Table 9.1 Source and Class of Input Data to the Model**

Class	Subclass	Source				
		Cuneiform Texts	Other Historical Texts	Ethnographic Data	Consultants' Reports	Environmental and Landscape Data
Consumption	Cereals	-	-	-	-	-
	Caloric needs	-	-	-	-	-
	Feasts	-	-	-	-	-
	Building materials (chaff, wood)	-	-	-	-	-
	Fuel needs	-	-	-	-	-
	Demography					
	Mortality	-	-	-	-	-
	Family size	-	-	-	-	-
	Marriage and inheritance	-	-	-	-	-
	Crops grown	-	-	-	-	-
Agricultural production	Agricultural area	-	-	-	-	-
	Fallow	-	-	-	-	-
	Plough animals	-	-	-	-	-
	Seeding rates	-	-	-	-	-
	Agricultural calendar	-	-	-	-	-
	Field shape and size	-	-	-	-	-
	Land ownership	-	-	-	-	-
	Labor input	-	-	-	-	-
	Soils data	-	-	-	-	-
	Flock size	-	-	-	-	-
Pastoral economy	Livestock density	-	-	-	-	-
	Fodder needs	-	-	-	-	-
	Pastoral lands	-	-	-	-	-
	Trade exchange, tribute	-	-	-	-	-
Secondary products	Pestilence, locusts	-	-	-	-	-
	Climate data	-	-	-	-	-
	Droughts	-	-	-	-	-
External factors	Droughts	-	-	-	-	-
	Crop yields	-	-	-	-	-
Control						

modeling of Mesopotamian society and provide a wide range of specific ancient data that would be difficult to obtain with an equivalent level of detail and/or reliability through studies of solely archaeological or ethnographic material. Ideally, such sources should derive specifically from the site and area being modeled. Although we are fortunate to have some valuable texts from the site of Tell Beydar (see below), in order to extract the maximum utility from the available sources, it is necessary to extrapolate from a wider geographical region, as well as from a broader time range than the third millennium BC.

A significant part of the Mesopotamian economy was based on agriculture, and the textual evidence provides detailed information on practically every aspect of agricultural production. Whereas the late third millennium BC in southern Mesopotamia has produced a substantial corpus of textual data on agriculture, the contemporary textual evidence from Upper Mesopotamia and the dry-farming regions of the Near East remains scarce. Nevertheless, private and royal archives exist for the city of Nuzi of the kingdom of Arraphe near modern Kirkuk; these archives can be dated to the middle of the second millennium BC (Pedersén 1998:15–29). The approximately five thousand tablets offer an exceptional wealth of information concerning real estate, fields, and agricultural matters for a concise period of nearly eighty-five years. In addition, a small, earlier archive of some two hundred tablets from the Akkadian period (ca. 2350–2150 BC) has been found at the same site (Gasur).

The farmers in Nuzi appear to have relied only on broadcast sowing and the regular plow *majāru* without the seeding funnel (Widell 2005). Consequently, we have to assume that seeding rates were significantly higher than in the south (see below). In the Akkadian period, the standard seeding rate is recorded to have been 60 northern SILA barley per IKU of field, or approximately 87 kg per hectare (Zaccagnini 1979a: 854–855).<sup>1</sup> This rate is roughly twice as high as that for irrigated fields in southern Mesopotamia during the Ur III period, and Zaccagnini has argued that the Akkadian IKU in Gasur, in all likelihood, was significantly larger than the IKU in southern Mesopotamia (1979a:856). However, all other data on seeding rates come from fields where the seeder plow was employed. If we assume that the region of Gasur received similar annual rainfall in the Akkadian period as it does today (ca. 400 mm), then 87 kg per hectare appears realistic for broadcast sowing. A single text from Gasur lists the unitary barley yields from different fields (see Zaccagnini 1979a:855) as ranging from 592 to 666 kg per hectare, indicating a seed:yield ratio of 1:6.8–7.7. The system of measuring surface areas used in later texts from Nuzi is less clear (Zaccagnini 1979a), and any absolute numbers of seed rates and/or yields remain uncertain. Nevertheless, the relative proportions between seeding rates and the yields recorded in Nuzi, ranging from 1:8 to 1:1, with the majority of the attestations in the order of 1:5–7 (Zaccagnini 1975), seem to fit the ratio recorded in Gasur.

Some fields in the texts from Nuzi also were irrigated (*šaqû*), but it is generally accepted that 80 to 90 percent of the fields relied exclusively on rainfall (Zaccagnini 1979b:107–13). The shapes and sizes of the fields in Nuzi are uncertain, but the

majority of them were significantly smaller than the fields in the province of Lagash in southern Mesopotamia (Zaccagnini 1979b:77). Moreover, some 98 percent of the Ur III Lagash fields were devoted to barley (Maekawa 1974:41), but only 80 percent of the Nuzi fields were used for this cereal, the remaining fields being used for emmer and wheat (Zaccagnini 1975:192–93, 217).

For southern Mesopotamia, the most comprehensive description of agricultural procedures from ancient Mesopotamia is the “Farmer’s Instructions” (Civil 1994). The 111-line text, tentatively dated to the eighteenth century BC or slightly earlier, can be seen as a manual of the fundamental rules of cereal cultivation for an entire year. It has provided an overall framework for our modeling of agricultural tasks, specifically irrigation, plowing, harrowing, sowing, harvesting, threshing, and winnowing. This outline for our model of the agricultural calendar has been complemented and revised using other textual sources. In particular, the tens of thousands of published administrative and economic tablets from the second half of the third millennium provide detailed information on specific issues crucial for our modeling work. When these economic texts, which predominantly concern agricultural matters, are studied together in homogeneous series, they offer details on most aspects of ancient Mesopotamian agriculture.

As an example of such a homogeneous series, a group of about seventy cadastral texts from the province of Lagash in southern Mesopotamia, dated to the Ur III period (ca. 2112–2004 BC), provide evidence on land measurements and boundaries (Liverani 1990:155).<sup>2</sup> These so-called round tablets describe the agricultural landscape of the alluvial plain and provide the orientation, size, and shape of the individual fields cultivated in the province (Liverani 1990, 1996; Maekawa 1992). Moreover, many of the round tablets also provide significant data on the expected yields of the fields in question. According to Maekawa (1974:26), the average yield in the Ur III king Amar-Suen’s seventh year was 31 GUR and 244 SILA barley per BÜR land (932 kg/ha) and 25 GUR and 11 SILA per BÜR (733 kg/ha) in the following year, Amar-Suen 8.<sup>3</sup> Such high yields compare with the average barley yields of 1,396 kg ± 67.5 per hectare on irrigated fields cultivated with primarily primitive agricultural technologies in the Diyala region in the 1950s (Adams 1965:17). Depending on the seeding rates, the Ur III yield rates would equal an average productivity of some fifteen to twenty times the seed volume used on the fields (Liverani 1990–91:365; Maekawa 1974:27). Such impressive productivity rates are easier to accept if we take into account that the farmers in southern Mesopotamia were drilling seeds into the furrows with a so-called seeder plow (APIN) pulled by oxen, a technique that reduces the amount of seed grain by half, compared with broadcast sowing (Halstead 1995:14). Naturally, this technique left its mark on the agricultural landscape of the south. The fields in the round tablets were very large; the majority were in the range of 100 to 125 IKU, or around 35 to 44 ha (Liverani 1996:figure 2). The standard seemingly was 6 BÜR (108 IKU), which would equal roughly 38 ha (Maekawa 1992:408). These fields, which were organized in a regular pattern of extremely narrow, elongated strips, constitute a clear

indication of the institutional character of the cereal production in southern Mesopotamia (Liverani 1996:8–10; Maekawa 1992:407).<sup>4</sup> Long and narrow fields are more suitable for plowing with oxen and the seeder plow, because elongated fields would reduce the number of turns for the plowing teams (Liverani 1990:171). The main reason, however, for the shape and size of these fields can be found in the specific irrigation system (so-called furrow irrigation) that prevailed in the extremely flat alluvial plain of southern Mesopotamia. Farther to the north but well within the zone of irrigated agriculture, the fields of Mesopotamia take a more irregular and less elongated form (see Liverani 1996, 1997).

Overall, data from cuneiform texts, although skewed towards the official economy rather than everyday, village-based agricultural production, provide a valuable source of information that enables a sensitive and often quantitative comparison between the irrigated south and the rain-fed north. However, not all of these data can be harnessed as input for the model; some, instead, must act as a control for model output. The copious records of crop yields can be employed as a cross-check on the output generated from the US Department of Agriculture's Soil and Water Assessment Tool (SWAT) model (see below), thereby enabling us to determine the realism of the modeling.

## ***The Construction of a Landscape Framework***

Here we summarize the main features of the landscapes of northern and southern Mesopotamia that provide a framework for the simulations. Further details of the northern Mesopotamian landscape are found in the section on Tell Beydar.

### ***Rain-Fed Northern Mesopotamia***

Today the rain-fed lands of northern Mesopotamia are a breadbasket for agricultural production, with a history extending back to the origins of agriculture in the prepottery Neolithic (ninth millennium BC). As a result of this extended history, the landscape is peppered with multiperiod occupation mounds (tells), which occur every few kilometers along temporary and permanent watercourses and form a network of relict settlements across the landscape. The hierarchy of Early Bronze Age (third millennium BC) tells ranges in size from small, usually fortified settlements of 1–5 ha, up to towns of 100 ha or a little more. Overall, the extensive areas of cultivable land available for northern communities enabled such polities to grow because these large areas compensated for the relatively modest yields (Weiss 1986). In addition, a significant amount of land was under intensive cultivation, as is indicated by the presence of low-density scatters of ceramics across the ground surface around major settlements. Such “field scatters” are inferred to be a by-product of the spreading of household waste (including ash and burned dung from hearths and kilns) on fields as fertilizer to counteract nutrient loss and allow for increased intensity of cropping (Wilkinson 1982).

## *The Irrigated South*

Agriculture in southern Mesopotamia is wholly reliant on irrigation systems that derive their water from a complex network of natural and dug channels developed over some seven thousand or more years. Not only did such channels allow the distribution of water, but also (perhaps more important) they enabled staple products to be transported from place to place more efficiently than was the case with the overland transport systems of the rain-fed north.

Many soils of the alluvial lowlands have decreased agricultural potential because of high salt levels, a problem that is traditionally ameliorated by the practice of fallowing (Gibson 1974). When viewed as a whole, the complex alluvial landscape of the Mesopotamian plain suggests that modeling land use patterns and settlement in southern Mesopotamia will require a different emphasis and structure than that of the rain-fed north.

The channel systems and their deposits, which crisscross the expanse of the alluvium, result in a mosaic of landscapes of different time periods. The scant archaeological and textual evidence suggests that early agriculturalists took advantage of the network of anastomosing branches of the Euphrates River, using simple techniques such as levee breaks or sluices to control the water flow to fields or settlements. A gradual shift from the reliance on natural anastomosing branches to increasingly artificially created and manipulated channels appears to have fully developed by the late third or second millennium BC. This shift from the natural branches, which constrained settlement and agriculture to narrow bands of cultivation along the main branch, to feeder channels farther away from the main branch meant that settlement could then extend along the newly created channels.

Natural processes include the abrupt splitting of river channels (avulsions), which can result in catastrophic channel shifts and the abandonment of channels and their associated settlements (Gibson 1973). Alternatively, if a new channel developed but both channels continued to flow to form a partial avulsion (Stouthamer and Berendsen 2000), the resultant increase in channel length within an otherwise desertic area would have increased the opportunity for settlement and therefore settlement system growth.

Similarly, the excavation of canals may have contributed to demographic growth. Because indigenous communities may have been fully occupied maintaining existing canals and undertaking routine agricultural tasks, the excavation of new canals would require additional labor, perhaps in the form of *corvée*. The introduction of massive labor forces, along with their camp followers, would necessarily increase food demand and would entail additional increases in the food production systems, further increasing the scale and complexity of irrigation systems (Wilkinson 2003:87–99). Overall, both the natural process of channel splitting and the deliberate act of cutting large canals could have fueled positive feedback processes and the consequent growth of population and urban settlements.

Key datasets used for this preliminary model are Corona images from the late 1960s, Spot images of the 1990s, and ASTER images from 2001 (used to create a

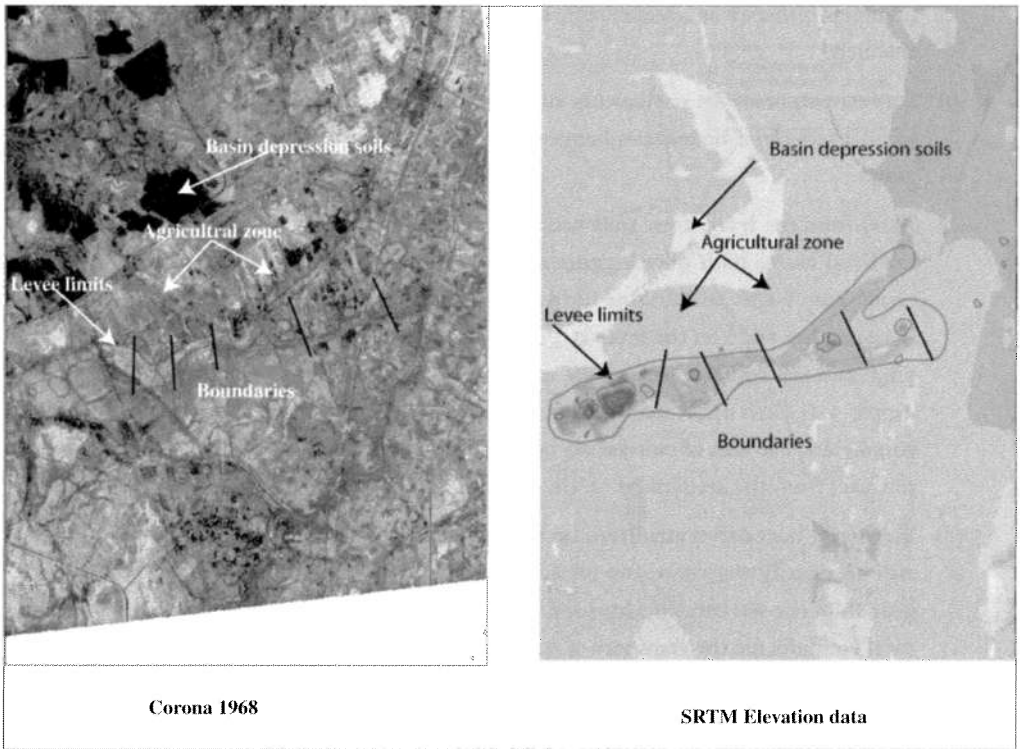


Figure 9.4. Settlements distributed along the line of a levee system near Borsippa, southern Iraq.

Digital Elevation Model [DEM]), as well as archaeological ground survey information and ground soil data. Integration of these datasets into a GIS format allows us to determine the basic layout of settlements of a known date and their relationship to irrigation canals.

The basic settlement module that forms the core of the present model can be distinguished on satellite images and DTED models as a series of settlement mounds recognizable at regular intervals along low, sinuous levees (figure 9.4). The populations of these settlements would be supported by the products of palm gardens along the levee crest and cultivated fields on the slope that led down to flood basins beyond (Postgate 1992). Such flood basins, evident on images and terrain models as enclosed hollows, provided sumps for excess irrigation water, as well as seasonal pastureland. Beyond the agricultural land, desert steppe, often saline, supplied intermittent pasture for larger flocks of sheep and goats, as well as refuges for wild animals. Marshlands were also important (Cole 1994), and the procurement of marshland and riverine resources must have formed a significant component of the local economy, especially in the far south of the plains (Pournelle 2003).

A basic model of settlement and agricultural territory uses the module described above and makes a limited number of assumptions (figure 9.5):

- (a) Channels bifurcate and settlements are arranged at intervals along the component channels.
- (b) For contemporaneous settlements aligned along the crest of a channel levee, the mutual territorial boundaries between settlements are estimated using Thiessen polygons.
- (c) Away from the levee, crest soils become more clay-rich and fine grained, and towards the flood basins both waterlogging and the likelihood of salinization increase. As a result, crop yields will decline until it becomes counterproductive to grow crops. Because crop yield on the levee slope will be a function of soil properties, waterlogging, and salt content, this can be modeled by means of our crop model (SWAT) to supply a de facto distal land-use boundary. In addition to being a function of the soil parameters, the area of cultivation may be constrained by the amount of time it takes to travel from the settlement on the levee crest.
- (d) Territorial boundaries estimated between settlements and parallel to the levee crest will necessarily constrain crop production, which, in turn, could limit the overall growth of the settlement. However, because the riverine channels or canals provide ideal conduits for the transport of staple goods, any shortfalls in production can be alleviated by importing grain by boat, that is, as long as areas upstream or downstream are providing a sufficient surplus.

Overall, if social or economic conditions in any given settlement are propitious for growth, there are fewer reasons for such growth to be constrained in southern Mesopotamia than in the north. Because irrigation systems produce both higher and more reliable yields than rain-fed farming areas, we anticipate that shortfalls in supply from any one center could be counteracted by imports from elsewhere, provided that the political and social conditions are appropriate. In fact, conditions of production constraint may encourage and even suck surplus production from other areas along the same channel system. The irrigated landscape therefore differs significantly from landscape in the rain-fed farming zone, where the efficient import of bulk products from reliable surplus products along the channel cannot override the constraints arising from the limited size of cultivated territories.

### ***Modeling a Northern Settlement Enclave in the Tell Beydar Area***

The current model focuses on a single settlement system localized around Tell Beydar in the Khabur Basin of northern Syria. Rainfall there, at approximately 300 mm per year, is just sufficient for rain-fed cultivation. Surveyed by a team from the Oriental Institute in 1997 and 1998, in collaboration with the Syrian-Belgian team based at Tell Beydar (Lebeau and Suleiman 1997), this area has yielded the remains of some eighty-two sites (Wilkinson 2000). The twenty Bronze Age sites, which are aligned



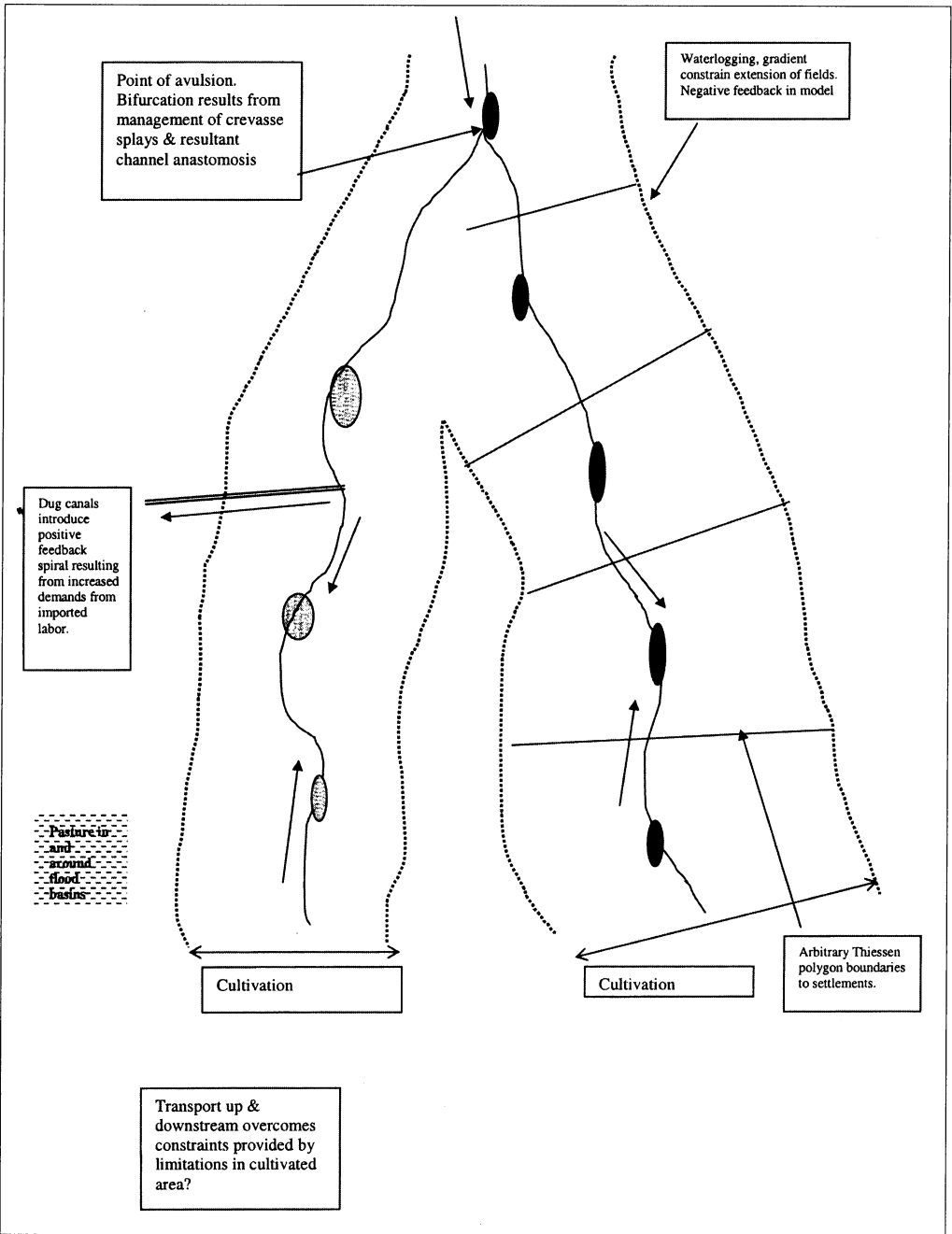


Figure 9.5. A model illustrating structural features and constraints operating along a typical levee system in southern Mesopotamia.

mainly along the seasonal watercourses (wadis) or natural route systems, form a hierarchical distribution, with Tell Beydar (at 17–22 ha) at the apex (table 9.2). An extensive basalt plateau extending to the west of Tell Beydar and the main Wadi Awaidj

*Table 9.2 Settlement Hierarchy in the Vicinity of Tell Beydar*

<i>Rank in Settlement Hierarchy</i>	<i>Number of Sites</i>
Provincial capital (Tell Beydar) ca. 22.5 ha (17 ha)	1
“Towns” (7–9 ha)	3
Village (2.5–4.0 ha)	5
Small village (<2 ha)	8

shows only sporadic evidence for settlement, of which a negligible amount dates to the Bronze Age (van Berg et al. 2003). The basalt plateau provided a long-term pastoral resource for the inhabitants of the nearby communities. To the east, this must have been supplemented by more limited areas of open space that extended between the reconstructed cultivation zones (figure 9.6).

The spatial layout of the subsistence economy can be reconstructed (1) from the estimation of site-sustaining areas derived from site areas, (2) from the area of cultivated land inferred from the fade-out point of hollow ways, and (3) by the evidence for plow teams derived from cuneiform texts (Widell 2004; Wilkinson et al. in press). The site areas provide a coarse estimate of site population, assuming that on-site population falls within a specified range, conventionally one to two hundred persons per hectare (Adams 1981; Stein and Wattenmaker 1990). The so-called fade-out points of the radial hollow ways, by providing estimates of long-term cultivation (see figure 9.6), indicate how much land was available to support the population of the contained settlement. Beyond this cultivation territory, areas of nonfarmed land can be inferred. By default, these presumably comprised pasture, fuel-gathering areas, or waste that extended to the next settlement land-use module.

Because cuneiform texts from Tell Beydar provide evidence for the number of plow teams in use for a specified season, the landscape evidence for cultivated areas can be cross-checked. The cuneiform texts, written in a form of Old Akkadian (Ismail et al. 1996), specify the number of plow animals used around Tell Beydar, as well as around six neighboring satellite communities. Assuming that each team was capable of plowing .3–.4 ha per day (.2–.3 for asses; Palmer and Russell 1993) and allowing for biennial fallow and an appropriate amount of waste (25 percent; Van Driel 1999/2000:85 n. 30), we can estimate the total area of cultivated land for Beydar and its neighbors (table 9.3).

The landscape approach coupled with the textual data provides estimates of settlement populations, as well as the capacity of the agricultural area to support that population. Although coarse, these estimates suggest that Beydar’s population exceeded the agricultural production of its fields and that surplus product was required and indeed produced from its neighbors. In a similar manner, discrepancies between the

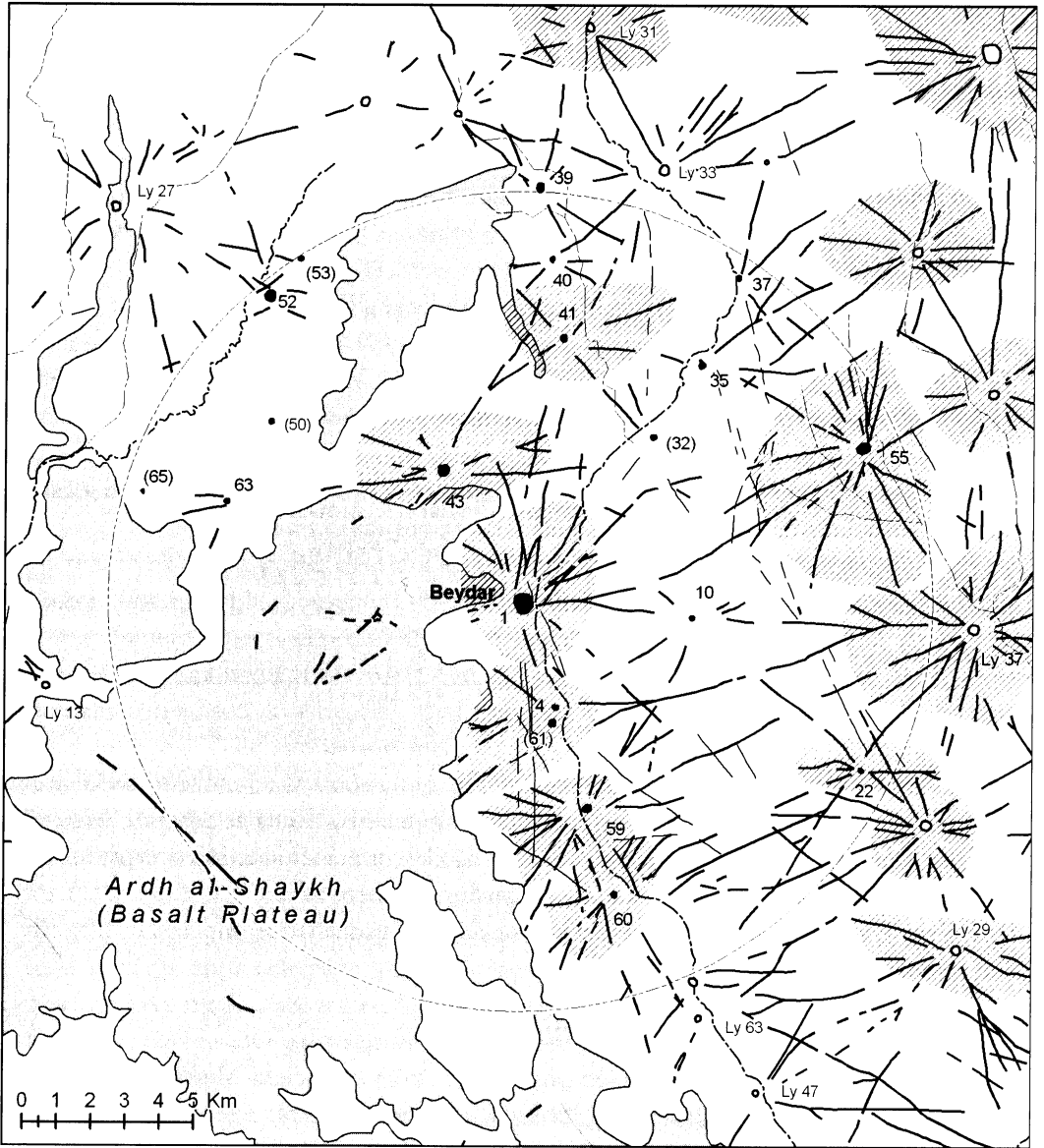


Figure 9.6. Reconstructed land use zones of the Tell Beydar area (Syria), with the basalt plateau in gray and areas of cultivated land estimated from the fade-out point of hollow ways in diagonal hatching.

estimated cultivation catchment and the on-site population demonstrate that, for a more extensive area encompassing Tell Brak (Nagar, the regional capital), the larger settlements were net importers of food whereas the smaller tells were net exporters (Wilkinson et al. in press). Although necessarily coarse, such techniques enable us to perceive the rough structure of the political economy.

**Table 9.3 Estimated Cultivated Areas for Tell Beydar and Its Satellite Sites**

*Beydar with Satellites*

	Area Required to Sustain the Estimated Site Population (100–150 persons/ha)	Area Estimated from All Plow Animals Administrated by Beydar
Total land allocated (demand?)	2,267–3,400 ha	1,683–3,132 ha

*Beydar Only*

	Area Estimated from Hollow Way Catchment around Beydar	Area Estimated from Plow Animals Working Beydar Fields
Arable land around Beydar (supply?)	1,503 ha	1,131–2,097 ha

## **The Simulation Framework**

The model of landscape outlined for northern Mesopotamia provides a “static” view of settlement and land use. Here agent-based models are introduced to capture the dynamics of population change as it occurs within a system of land use and settlement that experiences a series of stress situations or alternative scenarios imposed during the simulations.

### *Overview of the Simulation Engine*

To provide insights into the complex process dynamics of ancient Mesopotamian settlement systems, we have developed “Enkimdu,” a new, holistic, agent-based simulation engine. This simulator is a multidisciplinary, dynamic software object model of the social and natural world of ancient Mesopotamia, capable of representing diverse natural and social processes and their interactions at variable scales and scopes.

Enkimdu differs from most agent-based simulation systems that have been used in archaeological/anthropological modeling investigations: its explicit, fine-scale representation of the dynamics of key natural processes operates concurrently with the dynamics of the social processes carried out by the social agents. This approach has made it possible to model important fine-scale interactions and feedbacks between social and natural processes.

The simulations for the Tell Beydar pilot studies described below address natural processes (weather, crop growth, hydrology, soil evolution, population dynamics) and

societal processes (farming and herding practices, kinship-driven behaviors, trade) interacting daily across simulation runs that span decades to centuries. Software objects representing the key components of the simulation domain are resolved and modeled at the level of individual persons and households, individual agricultural fields, and individual herd animals. Each of the decision-making “agents” in the simulation domain—each person, each household or other organization—governs its own behavior in the simulations, based on its own local rules and in response to its own perceptions, preferences, capabilities, and goals.

Close coupling of heterogeneous dynamic processes can be represented by taking advantage of some of the advanced simulation technologies developed over the past decade at Argonne National Laboratory. One of these technologies is the Dynamic Information Architecture System (DIAS) (Christiansen 2000a), a generic, object-based computer simulation framework. The DIAS infrastructure has made it feasible to build and manipulate complex simulation scenarios in which many thousands of objects can interact via simulation models that represent dozens to hundreds of concurrent dynamic processes. In the DIAS object-based modeling paradigm, the domain objects (for example, household objects and field crop objects) drive the simulation. These domain objects express their own dynamic behaviors by invoking simulation models that can address specific aspects of these objects’ behaviors. Essentially every domain object, social or natural, that possesses dynamic behaviors can act as its own software agent. The simulation models, which can include proven, existing models and new, purpose-built codes, are not embedded directly in the software objects. Instead, they are selected for execution by their “owner” objects as they are needed, as a function of simulation context. Each such model converses with the simulation in the language of the relevant domain object attributes; models interact with the objects that their owner objects “know,” but models never need to interact directly with other models. This approach pays major dividends in simulation scalability as more and more process models are added to a simulation framework: there is no need to maintain an exponentially growing set of model-to-model linkages and data protocols as models are added.

In developing Enkimdu, we are also making extensive use of Argonne’s Framework for Addressing Cooperative Extended Transactions (FACET) (Christiansen 2000b), a facility for constructing flexible and expressive agent-based object models of social behavior patterns. By using FACET models to implement social behaviors of individuals and organizations within the context of larger DIAS-based natural systems simulations, it has become possible for us to conveniently address a broad range of issues involving interaction and feedback among natural and social processes.

### *Dynamic Software Object Representation of the Simulation Domain*

A simplified schematic representation of many of the classes of software object that make up our ancient Mesopotamian simulation domain appears in figure 9.7. The major classes of domain entity (Field, Household, and the like) are shown as the large

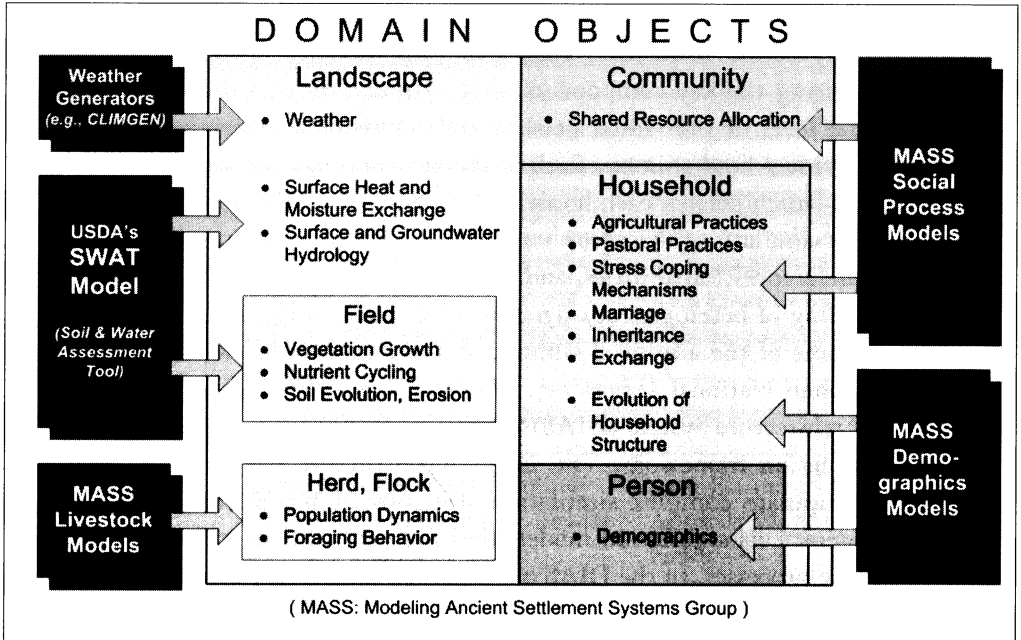


Figure 9.7. Simulation entities and dynamic behavior models.

blocks occupying the center of the figure. The bulleted lists within each entity block call out modeled dynamic behaviors of these simulation entities. The entity behaviors are implemented by the ensemble of simulation models depicted as shadowed blocks at the left and right margins of the figure.

The simulation software includes both custom-built models created by the MASS team and existing, off-the-shelf models well suited to represent some of the key behaviors needed to support our model settlement system dynamics. One such off-the-shelf model is the US Department of Agriculture's SWAT simulator (Arnold et al. 1998; Arnold and Allen 1992). The list of processes addressed by the SWAT system includes hydrology at individual field to watershed scale, daily agricultural weather, soil evolution and erosion, nutrient cycling dynamics, vegetation growth, grazing and browsing by livestock, and various effects of human intervention, such as tillage (plowing, planting, harvesting) and irrigation.

At present, we use the ClimGen Markov chain weather generator (Stöckle, Cambell, and Nelson 1999), as well as the SWAT model's internal weather generator, to synthesize representative daily agricultural weather, based on climatological summaries. As we expand our modeling scenarios to encompass whole regions, we intend to use mesoscale numerical weather models, such as the National Center for Atmospheric Research's mesoscale model MM5 (Anthes and Warner 1978), with initial and boundary conditions drawn from long-run paleoclimate global circulation model simulations, to provide a spatially varying regional weather signal for our simulations. Regional-scale hydrological processes that are beyond the scope of applicabil-

ity of the SWAT model's hydrological submodels will be addressed by the US Geological Survey's coupled ground- and surface-water model (MODBRANCH; Swain and Wexler 1993) or other comparable modeling codes.

### *Modeling Representation of Social Agents*

Thus far, the principal categories of social-agent behavior pattern addressed within the Enkimdu framework are demographic and kinship-based behaviors, subsistence-based behaviors, and simple reciprocal exchanges of labor and commodities. The model incorporates a population generator that can produce initial populations of simulated persons, grouped into households. These are demographically sound, with appropriate proportions of each type of household structure represented, and have a plausible initial density of cross-household kinship ties. The reference demographic model is Coale and Demeny's (1966) Model West Level 2 (for males) and Level 4 (for females). Distribution of household types is based on census data for Roman Egypt (Bagnall and Frier 1994). Modeled demographic and kinship-based social agent behaviors, driven by these data sources and by results derived from investigation of ancient textual sources and ethnographic evidence, include

- (a) Reproductive rates, and death probabilities by age and gender
- (b) Age- and gender-dependent person role changes
- (c) Marriage
- (d) Inheritance
- (e) Household restructuring and evolution (for example, fission and aggregation)
- (f) Kin gifts of food and labor

Modeled subsistence behaviors are mainly related to agriculture or pastoralism. Modeled households with the capacity to plant a grain crop will generally do so because producing a grain harvest represents the principal means of coping with long-term food stress problems. Agricultural behavior patterns are among the elements of social agent behavior that have been incorporated into Enkimdu with the aid of the FACET modeling framework, using FACET's extensive built-in facilities for modeling and tracking resource management and conflict resolution dynamics. Examples of the layout of some of the FACET models for households' agricultural behavior patterns are shown in figure 9.8.

Each step in these FACET-based models is a submodel, with a required (though often variable) cast of participants who must provide the appropriate resources (labor, use of equipment, supplies) necessary to perform the task. The flow from step to step is generally deterministic yet can be mutable, with action sequences diverted or preempted by outside events. Work crew requirements are generally different for each step, tailored to the needs of the task.

Pastoralism was important to many ancient Near Eastern economies and was significant in Bronze Age Tell Beydar (van Lerberghe 1996). Our representation of the

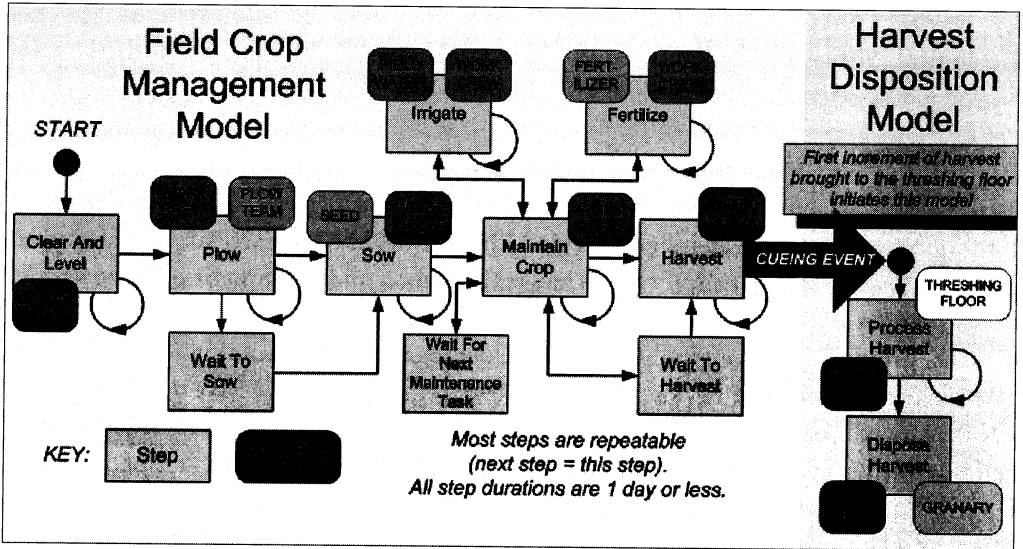


Figure 9.8. Examples of FACET models for agricultural practices.

pastoral component includes custom-built models of sheep and goat physiology and population dynamics (Blaxter 1967; Redding 1981) and new FACET-based models of the societal behavior patterns, at household and community levels, that relate to pastoral activities.

Among the main driving forces behind our present modeling representation of adaptive societal processes at the household level are social and environmental stresses and other stimuli perceived by agents representing individual households. The most prominent relate to food stress, which would have been a constant problem in the Mediterranean region (Gallant 1991). To combat food stress, household agents can choose from a spectrum of coping behaviors (figure 9.9).

Households must evaluate their stresses with respect to several time horizons because the coping mechanisms appropriate to each time frame are not generally the same. For example, if a household perceives a potential food shortage two years ahead, an appropriate response might be a plan to plant a barley crop. If the shortage is projected for two days ahead, however, then the barley crop response is not sufficiently timely; a better adaptation might be to seek a grain loan from a close kin household or to sell off some livestock for grain. The household's food stress assessments take into account resources on hand (for example, stored grain) and perceived effects of planned and ongoing household initiatives, both positive (such as anticipated future dairy products from a household's livestock holdings) and negative (such as repayment of a grain loan). Household agents periodically recheck their food stress at intervals that depend on their current, perceived stress levels (checking more frequently at higher stress). They also recheck stress levels after any occurrence that could change the household sustainability balance, such as a new bride moving into a household and a crop being harvested. As figure 9.9 indicates, for any given time horizon a household



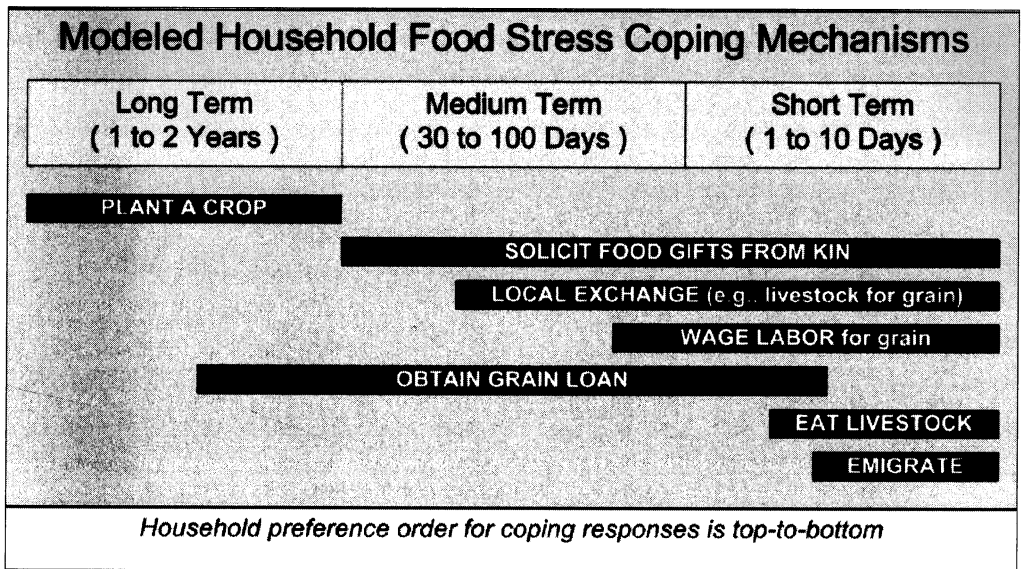


Figure 9.9. A household agent's food-stress coping mechanisms.

will attempt to apply coping adaptations in preference order, choosing the least disruptive means to mitigate its stress. An acutely stressed household always attempts first to utilize its kinship networks to solicit nonreciprocal gifts of food or labor. If kin households are unable to assist (because they themselves are too stressed) or the household simply has no close kin households to ask, then it tries to utilize its network of established, non-kin, trading-partner households for reciprocal exchange. Failing that, it seeks beneficial reciprocal exchanges with any other household in the community.

Another form of household stress is deficiency of labor for agricultural production. This form of stress, like food stress, can be alleviated through the use of kin networks. However, if kin are unavailable for assistance and households cannot find sufficient non-kin workforces for food production activities, this labor stress can exacerbate the food stress. Labor shortages for agricultural activity may not be a near-term problem for households, but household agents seek to address such deficiencies in the long term, before the onset of acute food stress.

### *Simulated Process Interactions and Feedbacks*

Figure 9.10 illustrates the tempo and “temporal texture” of dynamic process model execution in a simulation. The triggering of models representing the dynamic processes for each class of domain entity shown in the figure are identified in a stylized way by vertical tick marks on a one-year time line that runs from left to right for each process. The tightest spacing of tick marks depicts *daily* process updates, though updates for some processes may occur more frequently. As figure 9.10 indicates, the characteristic time scale varies substantially by process type. Enkimdu operates as a discrete event simulation, rather than on a fixed time step basis, so modeled processes

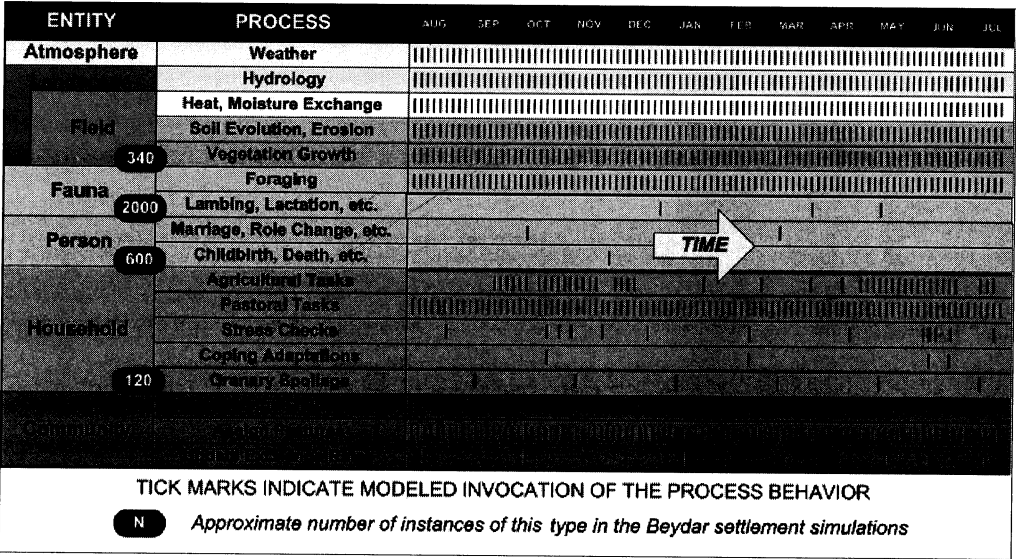


Figure 9.10. The temporal texture of modeled concurrent social and natural processes.

can be triggered to start and end at whatever times and intervals are appropriate for them. The models implementing the dynamic processes active in each Enkimdu domain object acquire the context needed as input for each increment of their execution by sampling this continually changing, natural and societal environment. Process interaction and potential feedback occur whenever one process requires a domain object attribute that may have been modified by a different process. Fine-scale, cross-discipline process interaction is a natural consequence of the way the simulation framework is structured.

The numbers in ovals in the leftmost (ENTITY) column of figure 9.10 denote the approximate number of individual objects of each type that are actively performing their specified processes in the Tell Beydar modeling scenarios discussed below. For example, in the model scenarios roughly 120 Household objects are independently performing subsistence tasks, rechecking their sustainability (via “stress checks,” as discussed above) and formulating and applying adaptations to cope with stress when needed.

### Simulations for Tell Beydar

The layout for the Tell Beydar simulation is depicted in figure 9.11. In developing the Tell Beydar simulation scenarios, we have used ancient textual information and modern survey data specific to the site, reinforced by substantial additional information from a wide range of applicable ancient and modern sources throughout the Near Eastern and Mediterranean world, as discussed above. Our modeling representation can best be considered as roughly representative of Bronze Age settlements like Tell Beydar, but it is also applicable to a broader range of pre-industrial, agropastoral settlement systems.

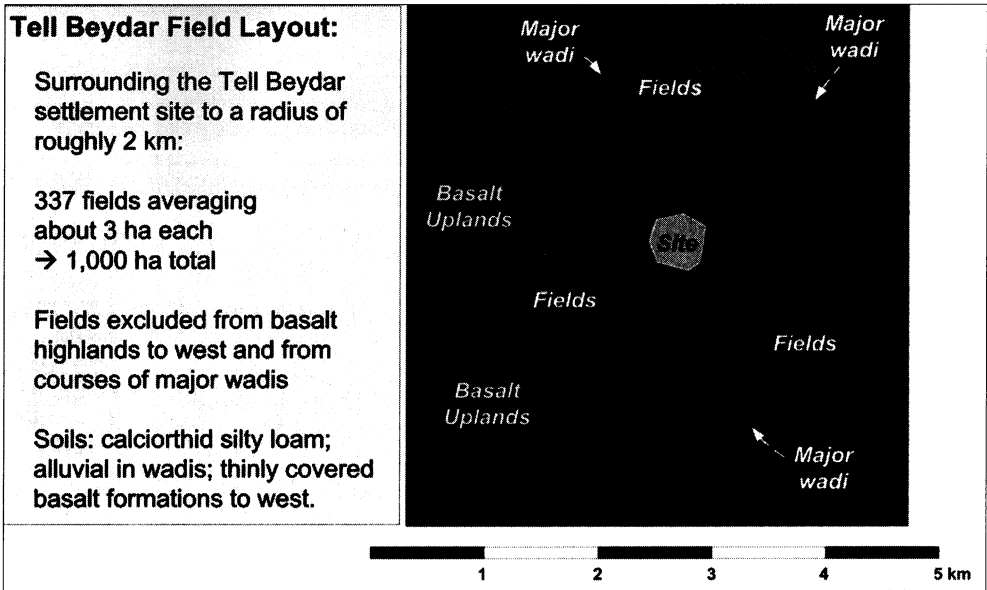


Figure 9.11. The study area and initial conditions for the Tell Beydar simulation.

### Baseline One-Hundred-Year Simulation

The initial baseline case begins with a small settlement of 501 individuals in 105 households occupying the Beydar site. Initially, each household was given twelve live-stock (eight sheep and four goats) and one inheritable field share for each male in a communally shared, agricultural-field redistribution system. All households attempted to engage in agriculture, growing an archaic strain of barley using Bronze Age farm implements and techniques and strictly observing biennial fallowing. Daily weather data were derived based on monthly climatological summaries of observations from Mosul, Iraq, using a Markov process weather generator. We did not impose any major climate trends significantly deviating from the mean value. The precipitation amounts averaged 328 mm per year but ranged from 173 to 649 mm per year over the one-hundred-year run because of normal climate variability. For the baseline run, we did not impose any external stresses on the model settlement. Such special stress cases are dealt with in separate, variant simulation scenarios.

During the span of the baseline simulation, the total settlement population rose about 41 percent, from 501 initially to 708 at the end of one hundred years. Over that same period, the number of households increased 46 percent, from 105 to 154, with a peak of 158 households in Year 89. The settlement's one-hundred-year total numbers of births and deaths were 3,521 and 2,951, respectively. The modeled population was also affected by episodes of emigration, a last-ditch option available to households that proved unable to sustain themselves. A total of 363 individuals emigrated during the entire run, or about 12 percent of the population losses due to deaths. Immigration into the settlement from the outside was not represented.

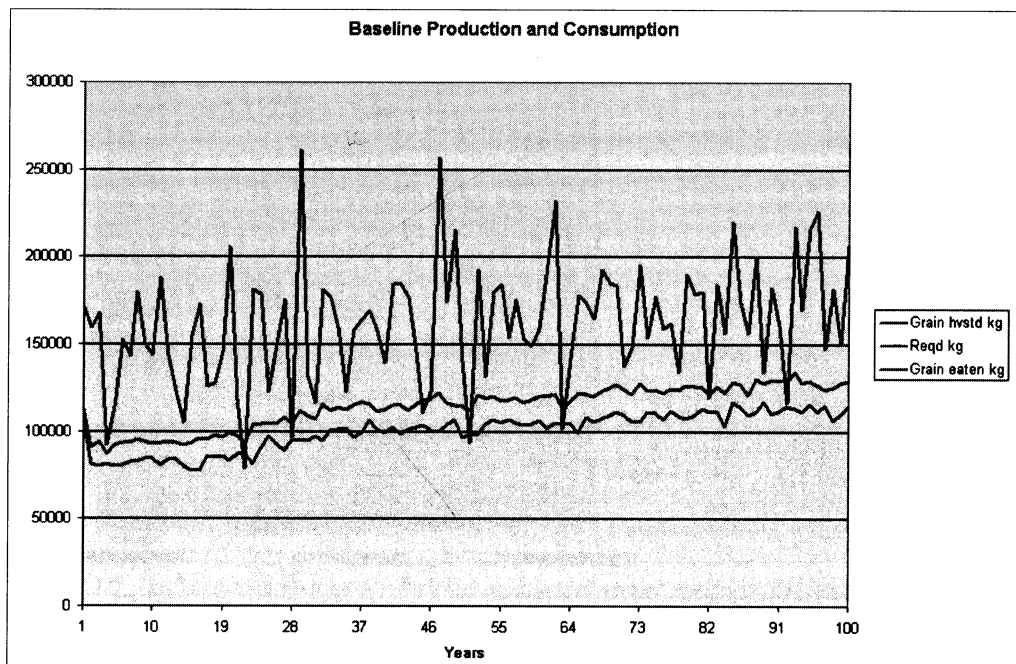


Figure 9.12. The one-hundred-year baseline simulation: food production and consumption.

It should be noted that emigrations do not necessarily indicate sustainability failure of the model settlement as a whole. Rather, they reflect specific, individual households that had become nonviable because of their inability to cope with food stress or, in some cases, social stress. An example of the latter case is a household that experiences the death of a member and is then left with no adults to manage its affairs. That household will dissolve, and members who cannot find a household willing and able to take them in are forced to emigrate.

Figure 9.12, showing the production and consumption of Tell Beydar throughout the one-hundred-year baseline period, indicates that in most years the settlement had more than a sufficient supply of food. Not only does this figure show how much grain was consumed by individuals, but also the required kilograms line indicates how much food had to be supplied by other items, such as dairy products, wild plants and game, and garden vegetables. From the figure, it is apparent that in most years the settlement had a more than adequate supply of grain to be sustainable.

In the baseline run, the settlement was not subjected to any external environmental or social stresses beyond the normal run of climate variability, soil variability, and demographic mischance. This “paradise scenario” was unlikely to prevail over long intervals. We therefore executed a series of variant scenarios to see how the model Tell Beydar settlement responds to various forms of unusual stress. We have begun to investigate the impacts of *environmental* stress factors, such as prolonged droughts and chronic crop blights (see Wilkinson et al. in press). In contrast, the results for the three

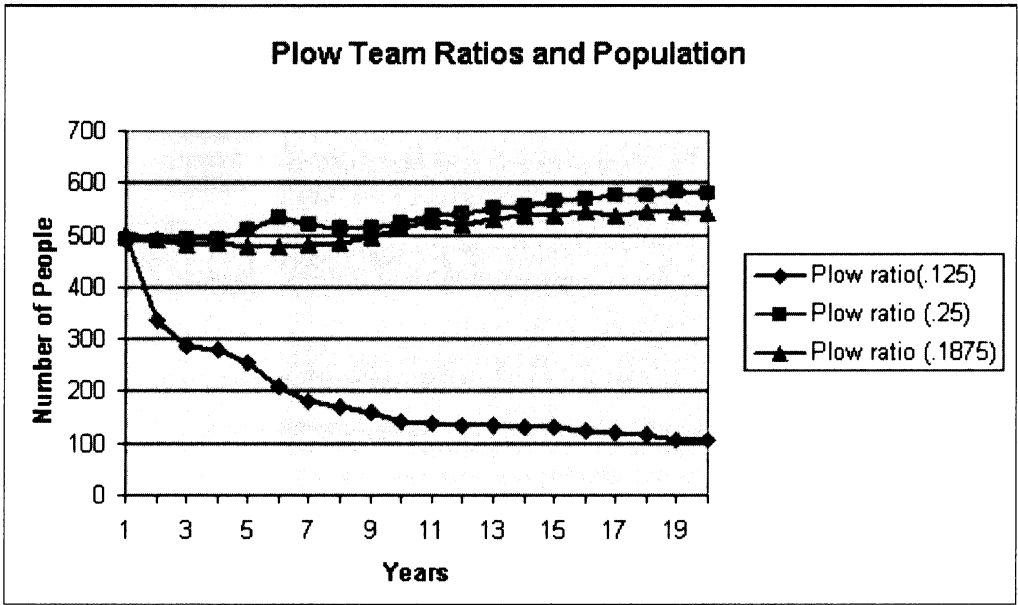


Figure 9.13. The effects of plow team availability on settlement population.

simulation scenario variants described below explore some of the effects of acute and chronic *societal* stresses.

### *Stress Scenario: Chronic Shortage of Plow Teams*

Variations in a major component in the agricultural process—households’ access to plow teams—tested the resiliency of the simulated settlement. The idea for this scenario was drawn from Tell Beydar’s ancient textual sources that record the number of plow teams available for the settlement and surrounding area (Widell 2004). Ten-year simulations were run for three variants that differed from the first ten years of the baseline case only in the settlement’s overall number of plow teams per household. The base case value was .5 (half as many plow teams as households). We also examined cases in which the plow team ratio was .25, .1875, and .125. For these variant cases (as well as in the baseline case), the plow teams were assumed to be community resources for which households would have to queue up for access.

Simulation results (figure 9.13) illustrate a behavior not infrequently seen in complex systems: an abrupt and vivid change in aggregated system behavior as a hidden resource threshold is reached. The population traces in figure 9.13 indicate that the .25 and .1875 plow-team-per-household ratio cases appear to be sustainable, differing little from the base case. This implies that plow team availability is not a serious constraint to successful agriculture at those resource levels. However, the simulated community in the .125 case (one plow team for every eight households) experienced an aggregate system catastrophe, with a precipitous decline in settlement population over ten years.

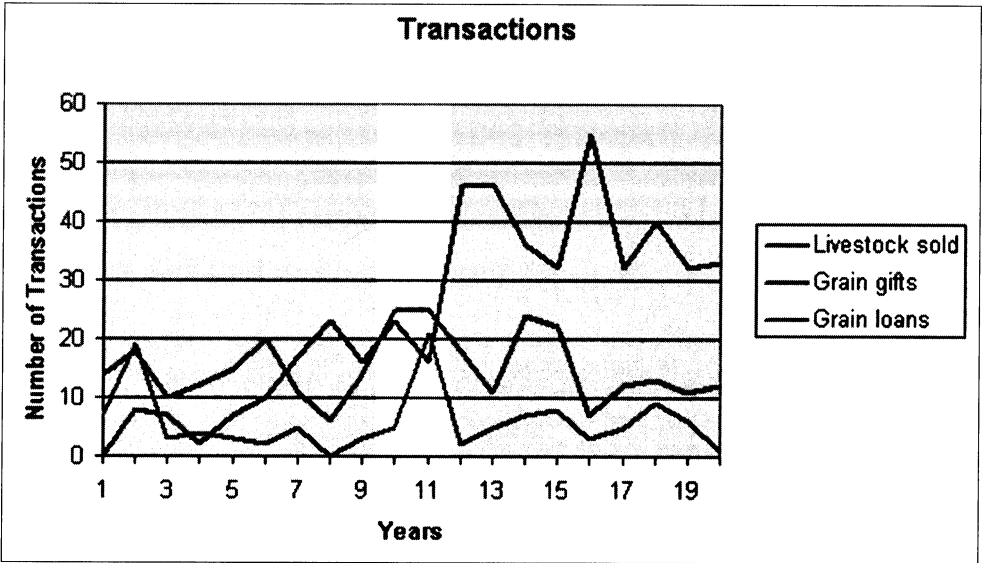


Figure 9.14. The volume of exchanges for the *corvée* episode scenario.

In our highly complex, multilayered simulations, a great number of possible reasons, natural and/or societal, can account for crop failure. However, in these controlled scenarios we have isolated as a critical factor the inability of some households to obtain access to a key resource—plow teams—in sufficient time to get fields plowed and crops planted before the winter rains begin. Because we made the simplifying assumption of a constant plow-team ratio, the number of plow teams dropped along with the settlement population, so the situation did not stabilize as the settlement began to empty of people. Presumably, adaptive farming households would have learned to adjust the number of plow teams to the need well before the crisis depicted in figure 9.13 had unfolded in full. Nevertheless, the “hidden” plow team constraint is genuine and constitutes a serious potential vulnerability.

### *Stress Scenario: Acute Labor Shortage at Harvest*

Without prior warning, 90 percent of the settlement’s adult male population was withdrawn for a six-month period, from March to September, in the tenth year of a twenty-year simulation (highlighted for Year 10 and Year 11; figure 9.14). Afterward, they returned to the settlement. This hypothetical episode required that the simulated community bring in its grain harvest with a drastically reduced labor force, perhaps reflecting a demand for *corvée* labor by a local political power. Much of the harvest could not be saved, and households unable to obtain grain gifts were compelled to seek food through alternative coping strategies such as selling livestock and borrowing grain. Figure 9.14 shows how the volume of grain gifts and grain loans peaked temporarily during and immediately after the labor crisis. However, the most noticeable change is a much higher level of livestock trading activity that began with the *corvée*

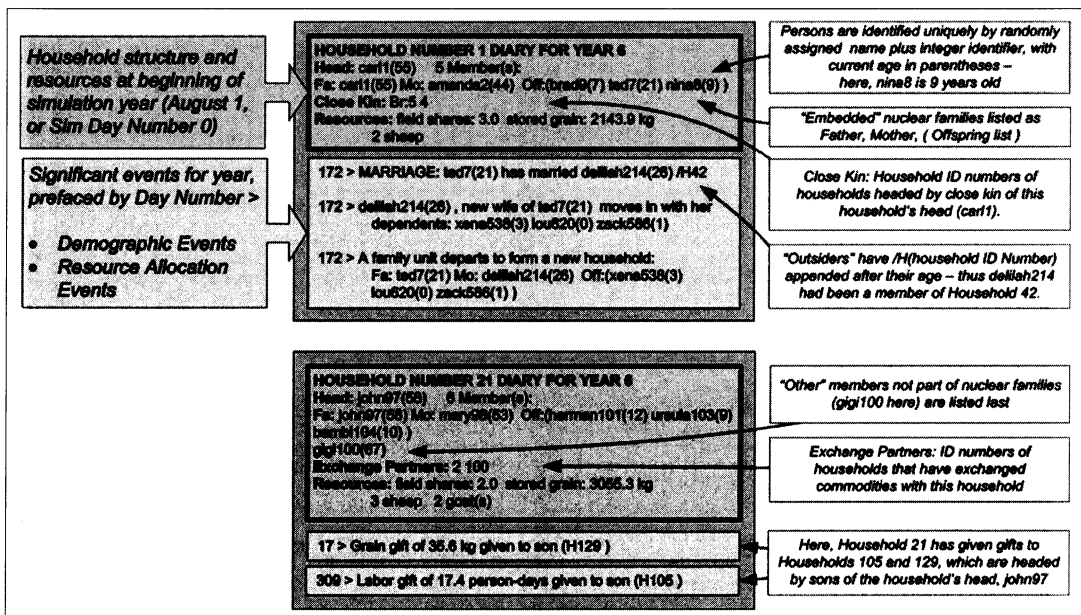


Figure 9.15. Sample Household Diaries for the corvée episode scenario: Year 6.

episode but persisted to the end of the scenario. This more energetic adaptation effort might be an indication that the crisis had destabilized the settlement to some degree.

The settlement appears to have weathered the crisis well. Except for a small net population loss due to emigration in Year 11 (twelve emigrants), the settlement population trajectory is comparable to the baseline case for Years 12–20. Though annual population losses due to emigration remained low, they were systematically higher after the crisis, increasing to roughly four persons per year from a pre-crisis average of 1.7 persons per year.

For deeper insights into the effects of the corvée episode on the model settlement’s sustainability, it is useful to look at the scenario from the standpoint of the individual household agents, rather than at the aggregate properties of the settlement. To accomplish this, we can examine the “Household Diary” output stream from the simulations. Household Diaries record all significant demographic events (birth, deaths, marriages) and resource-related events (gifts and loans, reciprocal exchanges) for each household for each year in a simulation.

Figure 9.15 illustrates the format of the Household Diary output for two representative and comparable agent households, Household 1 and Household 21, for Year 6 of the acute harvest labor crisis scenario simulation. Household 1 consists of a five-member nuclear family. Household 21 contains a five-member nuclear family and another relative, the surprisingly durable gigi100, who at age sixty-seven is a statistical anomaly, given the brutal death rates built into the model population demographics. Both households begin Year 6 with field shares, livestock, and a substantial grain reserve. Household 1’s only apparent advantage is that it can call for aid on two close-kin

Year 10: Year of Corvee Episode

Year 11: In the Wake of Corvee Episode

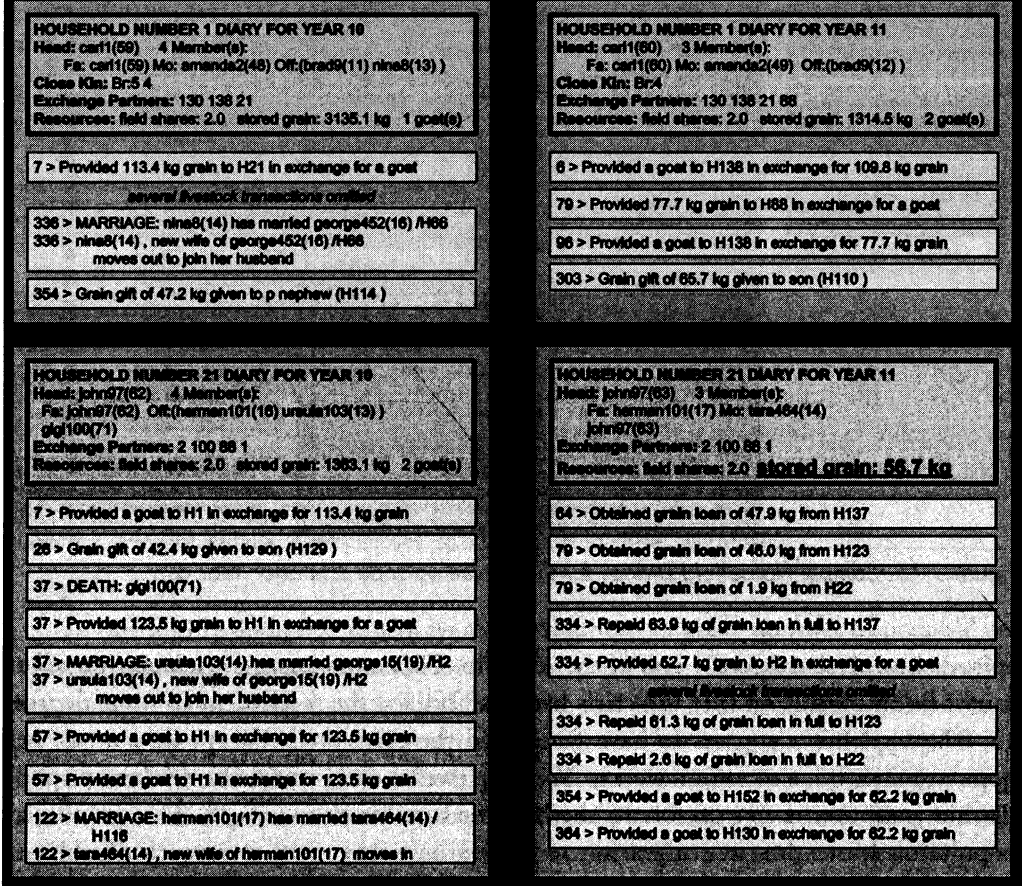


Figure 9.16. Sample Household Diaries for the corvée episode scenario: crisis years.

households, Households 4 and 5, each of which is headed up by a brother of carl1, the head of Household 1. The diaries for Year 6 also indicate that Household 1 celebrated the wedding of the eldest son of the house and saw his departure to form a new household with his new bride and her prior dependent children; Household 21 was sufficiently well-off to be able to provide gifts of food and labor to other close-kin households.

The Household Diaries for simulation Years 10 and 11 (figure 9.16), the years of the labor crisis, tell a different story. Household 1 enters this critical interval with a substantially deeper grain reserve than Household 21. In Year 10, both households still appear stable and capable of providing gifts to other households. However, even though Household 21 could afford to buy a goat to slaughter for ursula103’s wedding feast, shortly thereafter it had to begin selling off livestock to obtain needed grain.

The temporary removal of nearly all the adult males at harvesttime in Year 10 led to serious grain losses due to insufficient harvest labor. As figure 9.16 shows, both



households' grain reserves at the start of Year 11 were well below the preceding year's starting levels. Household 21 began that year with virtually no grain and consequently began to obtain grain loans. It was able to repay these loans but had to sell all its livestock, indicating that it was experiencing considerable food stress. At this point, grain loans became Household 21's primary option for obtaining food until the next harvest was in. This option, however, became less viable as the household defaulted or struggled to repay its loans and other households began denying its loan requests.

In Year 14, Household 21 gave up the fight and emigrated. When it needed kin support the most, the lack of close kin who can provide frictionless assistance (that is, grain gifts) sealed its fate. Household 1 continued to thrive. Its kinship connections to other households in the settlement improved its ability to sustain itself.

These household-level examples demonstrate that the fine-scale details do matter: the specific circumstances in which each household finds itself can have a greater influence on the household's sustainability than do the aggregate properties of the community. This scenario example underlines the desirability of analyzing communities at agent household and person levels and highlights some of the diverse social behavior and natural factors represented in the Enkimdu framework that are key in understanding household dynamics.

### *Stress Scenario: Diphtheria Epidemic*

We imposed an acute stress on the Tell Beydar model settlement in the form of a severe epidemic, perhaps an outbreak of diphtheria, that specifically targeted the children. Diphtheria can cause rapid and widespread death among populations, particularly among very young individuals. For years, in fact, diphtheria was a leading cause of death for children under fourteen years of age in many countries, with death often occurring within one week of contraction (Hardy 1998). It is well known that disease can have devastating impacts on human populations; however, it can be difficult to determine how acute fatal diseases such as diphtheria affect long-term population dynamics under given cultural norms of marriage and household structure.

The modeled epidemic occurred in Year 20 and caused the deaths of approximately 80 percent of children and infants under age twelve. We selected a severe death rate for illustrative purposes; 20 percent death rates for a total population have been recorded for outbreaks in the past century (Kleinman 1992). The epidemic was modeled as a purely demographic event; we did not attempt physiological simulation of the onset and progression of diphtheria.

In the scenario population results (figure 9.17), the settlement population growth rate recovered in the first few years after the epidemic. However, the settlement population declined in the long term because the age cohort struck by the disease was not available for reproduction under our given social rules of marriage. Initially, the high attrition of that age cohort did not negatively affect household sustainability. In fact, it was a moderate positive factor because young children are a drain on households in terms of their resource utilization relative to the amount of food they help to produce.

Within fifteen years of the epidemic, at about the age most of the young victims would have been productive adults, the losses for that age group began to exert a more severe effect on the settlement. Labor shortages and overall decline in births relative to deaths (from a ratio of 1.2 births to deaths in the baseline case, to 1.1 in the diphtheria case) substantially compromised some households' resilience to stress. With greater food stress caused by declining labor resources, the overall volume of economic exchanges among households increased, as can be seen in figure 9.18.

The missing children left gaps in family continuity across generations, reducing the average number of close-kin households that a household could call upon for non-reciprocal assistance by about 20 percent with respect to the pre-epidemic levels. By Year 95 in the diphtheria case, no household had more than four kin household connections; in the same period for the baseline case, some households had seven kin-related households. The emigration of many households due to failure to cope with food stress further eroded the interhousehold kinship network.

What the diphtheria scenario shows is that short-term population shocks can have significant impacts on long-term population trends. Certainly, cultural behaviors could have changed this dynamic, specifically if immigration was an option to help replenish the population. The point this example makes is that we cannot easily predict population trends without looking at concurrent interactions of social and natural systems.

## **Discussion**

The Tell Beydar reconstructions show that the more traditional landscape model (summarized previously) provides a plausible model in which the various data sources, in general, converge on a similar outcome. However, it results in a static equilibrium model that relates to a situation in which agricultural production had seemingly stabilized at its maximum extent. In contrast, the simulations capture more dynamics of the community, so one can discern detailed, agent-level social evolutionary trends. The example of the two households in the labor shortage scenario effectively shows the different forms of evolutionary trends that households can follow. Throughout the interval, simulated fine-scale dynamics of social and natural processes profoundly affected both households' abilities to function and survive. The fine-scale outcome of the *corvée* episode was particularly instructive because one household collapsed while a very similar household was able to sustain itself. In addition, by looking at the aggregate behaviors of the agent households, we can discern how our "Tell Beydar-like" settlement evolves through time. This makes Enkimdu a valuable tool for studying long-term socioevolutionary trends at both the individual/household and settlement levels.

Certain households also show signs of accumulating more pastoral animals as a result of favorable conditions of exchange. In contrast, other households lose resources and in certain cases become impoverished, thereby leaving the simulation. Such processes hint that, over time scales in excess of the present century-long simulation runs, we may discern the development of elites and impoverished clients. Overall, such

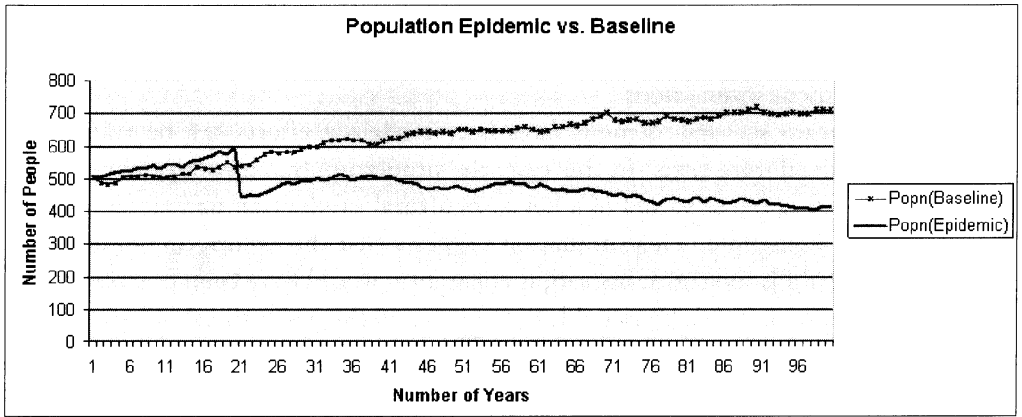


Figure 9.17. Settlement population trends in the epidemic case and the baseline case.

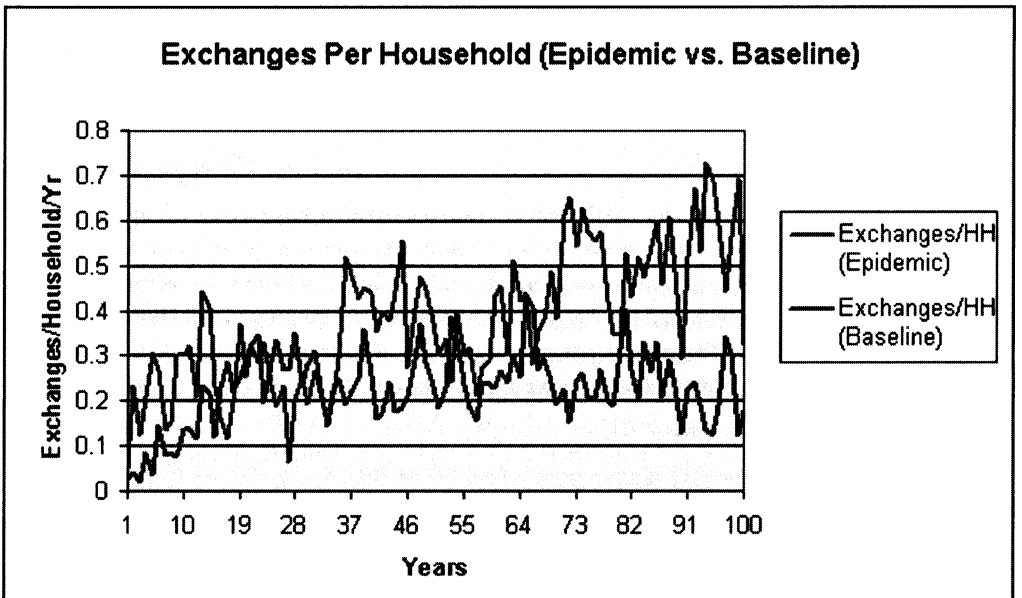


Figure 9.18. The volume of exchanges for the epidemic case and the baseline case.

dynamics will change not simply the consumption patterns but also, in theory, the social dynamics of the entire community. In the near future, as the simulation incorporates additional social dynamics and simulation functionality, we can expand this engine to look at regional dynamics and interactions among multiple settlements and nonsettled populations.

When we compare input data (such as trends in annual rainfall) with “output” in the form of number of households or community population, it becomes apparent, for the parameters we have chosen to model, that high amplitude and variable inputs result in low amplitude outputs (Wilkinson et al. in press). This may suggest that system complexity and the number of opportunities offered for exchange or modifying

production may suppress the fluctuation of what appears to be a key driving variable in the form of climate. This has significant implications for the understanding of human-environment interactions.

The plow team scenario demonstrates how modeling efforts can be valuable in testing data derived from texts. In this case, the simulation framework provided a test for a text-derived range of values of a key agricultural production parameter, namely, plow teams per household. This simulation suggests that the assumption of one plow team per household is too rigid. Instead, it apparently would have been feasible to allocate plows to more than one household, but only up to the given threshold after which the community suffered critical losses of agricultural production.

The overall outcome of the simulations, although preliminary, shows how complex datasets can be analyzed to produce plausible, nonlinear, and frequently unexpected results. Our understanding of Mesopotamian social mechanisms is far from complete, but the ability to test our hypotheses makes the simulation effort valuable in answering questions concerning socioecological dynamics. Ultimately, we aim to run multiple scenarios in order to produce sensitivity studies, as well as sets of trajectories for each community or set of communities.

### **Acknowledgments**

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### **Notes**

1. Note that this measurement corresponded to .842 liters in northern Mesopotamia.
2. Most of the tablets can be dated to the seventh and eighth years of King Amar-Suen’s reign.
3. All calculations assume that 1 IKU (1/18 BÜR) equals 3,528 sq m, 1 SILA in southern Mesopotamia (1/300 GUR) equals 1 liter, and 1 liter barley equals .62 kg.
4. Obviously, the round tablets were drawn up within the “public sector” of the society, so it is not surprising that the fields in these texts belonged to the same public or official part of the economy. The organization of private fields—if they existed—remains uncertain.