CHAPTER 11

OUTPUT FROM THE AGENT-BASED MODELING PROGRAM

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INTRODUCTION

Having presented an overview of settlement and aspects of the socio-economic framework of greater Mesopotamia in earlier chapters, we now turn to some of the 'outputs' resulting from the MASS project. These are not presented in detail, as parts have been published before (Wilkinson *et al*. 2007a & 2007b; Christiansen & Altaweel 2006a & 2006b; Altaweel & Paulette this volume Chapter 12; see also Altaweel 2008; Altaweel & Watanabe 2012). However, because the implications of these models have more far-reaching repercussions than originally appreciated, we present here the core results together with some implications. These results from the agent-based models are followed by a range of alternative models (Chapters 12, 13 & 14) together with a broader synthesis and discussion resulting from the entire project (Chapter 15). Readers will note the contrast between the models presented in Chapters 11 and 12, which can be classed as 'high dimensional' models, and the 'low dimensional' models of Chapters 13 and 14. This distinction will be further evaluated in Chapter 15. We also point out that the models which follow in this chapter are able to draw upon the SWAT model within the ENKIMDI simulation framework.

Before discussing some results, we present two forms of output which enable the rather indigestible data formats (which include huge spreadsheets) to be visualized. These comprise first, the field mosaics as indicators of cropping patterns and cycles, and second, the household diaries (see also Chapter 10). In many sections that follow, we state at the beginning of the section the main reference from the MASS Project previously published on this topic.

VISUALISATION OF RESULTS

Field Mosaics

To recap (from Chapter 10), the model site for the simulation is assumed to have an initial population of around 500, supported by a surrounding cultivation territory of over 300 crop field patches, each ca. 3ha, extending roughly two kilometres from the site centre (Fig. 10.2). Although loosely based upon the site and region of Tell Beydar (Chapter 4), the site and field mosaics used in the simulation are meant to be representative of a range of agricultural environments in the Upper Khabur basin of Syria. Specifically, the simulation area offers not only deep cultivable soils within the main valley, but also extensive areas of thin soils on a basalt plateau to the west, which today are used as extensive pastures and probably would have had a similar function in the Early Bronze Age (Wilkinson 2000).

The baseline simulations, which were usually run for 100 years of simulation time, showed social activities and environmental process dynamics run at very fine spatial and temporal scales. Animations provided snapshot views of particular states of the surrounding lands showing the state of fields and vegetation at various times. These simulations are updated daily together with minute-by-minute activities of all household work crews at various locations (Christiansen & Altaweel 2006a: 21-22).

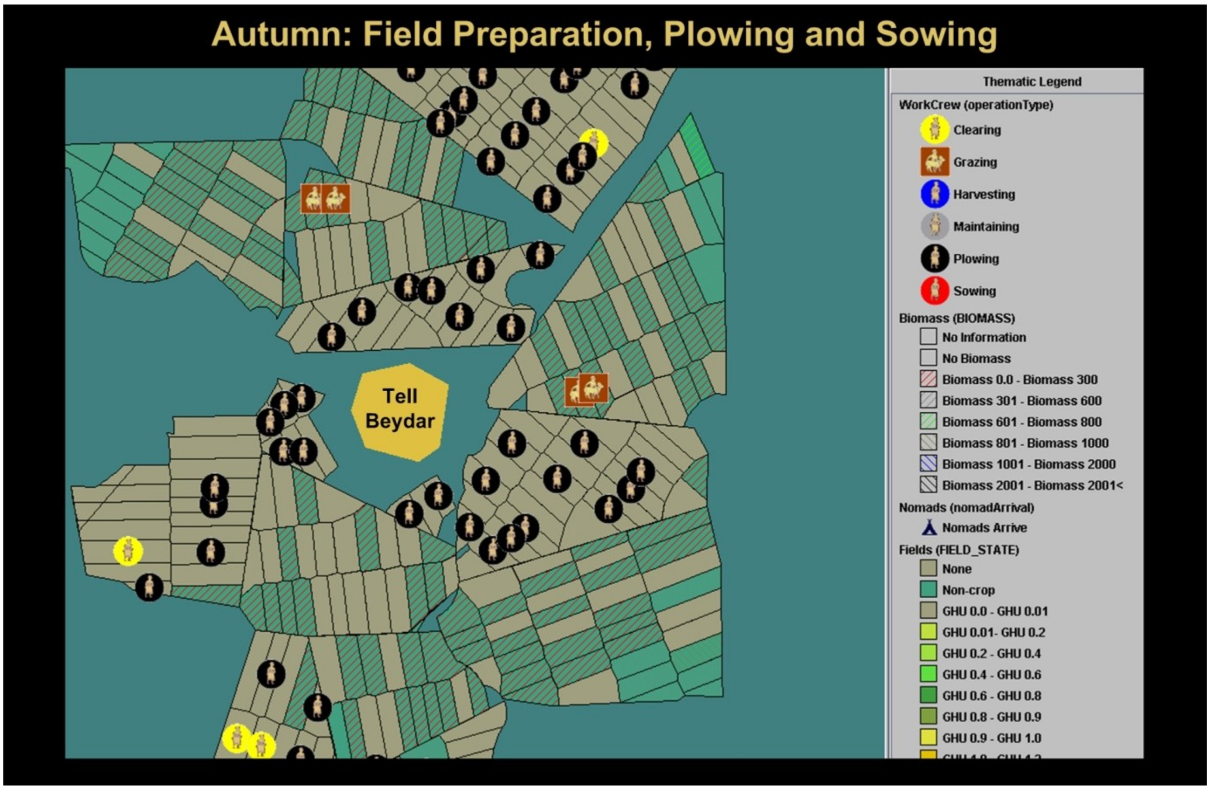

Fig. 11.1 Field mosaics for autumn; that is during field preparation, plowing and sowing.

Thus, in Figure 11.1 (representing the situation in the autumn), the phenological state and standing biomass density of field vegetation are encoded using background colour and coloured diagonal lines respectively. In this case the four cooperatively-tended herds from the local settlement are shown foraging in the fallow fields chosen by their respective herding groups (Fig. 11.1): those fields which are nearest to the settlement and which have sufficient biomass to sustain that day's grazing and browsing are then used, although the following day the chosen fields may be different. In the figures (11.1-11.4) activities of the work crews are indicated by colour-coded icons. For example, on the autumn day depicted, all crews except for those of the herding groups were either clearing fields or had finished clearing and were engaged in plowing. Significantly, those households that appear to be behind in their work – in other words, those that are clearing their fields of weeds and brush and are not yet plowing – are working in fields that are more remote from the settlement. For this simulation, and others that follow, the model settlement is assumed to be nucleated, with all houses concentrated at the centre of the crop field mosaic. This follows the pattern inferred for most tell-communities in the northern Fertile Crescent (Chapter 4). Because of this nucleation, the crews working the more distant fields must walk further to and from their tasks, with the result that they have less time each day to devote to their actual field tasks (Chisholm 1962); this puts their households under somewhat greater food stress, thereby reducing their sustainability. Because of the contextual richness of the fine-scale social and environmental settings in the simulations, such subtleties appear quite frequently in the model runs. Moreover, following the chain of subsequent events, they can, in some cases, have impacts on sustainability that are far greater than might be expected.

Overall, figures 11.1-11.4 illustrate the seasonal round, from sowing (11.1) in the autumn through weeding in the early spring (Fig. 11.2), harvesting in the late spring (11.3), to a phase of limited light grazing in the late summer (11.4). Because of differences in timing, distance to fields and access, these seasonal events do not take place at the same time. Significantly, access is perceived differently by the nomads (seen on Fig. 11.4) who use the more accessible fields first, namely those nearest to the territorial boundary and away from the village.

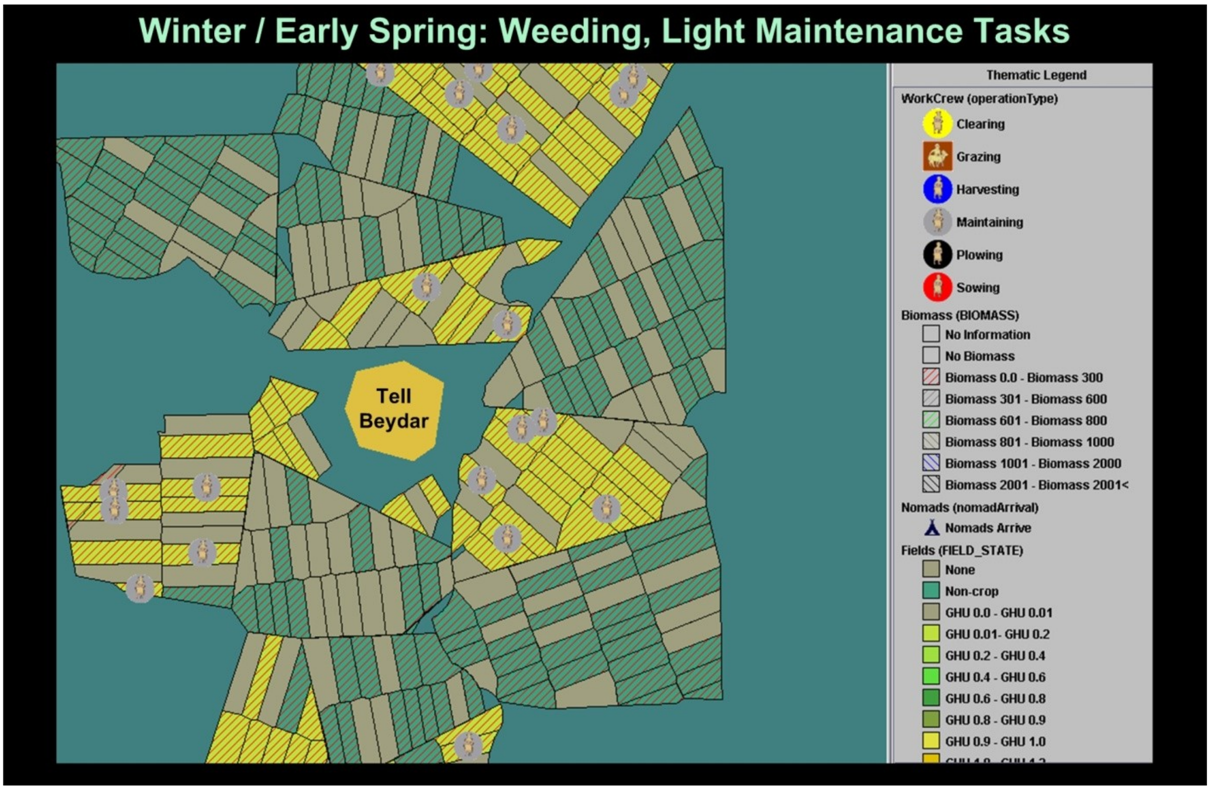

Fig. 11.2 Field mosaics for winter / early spring; that is during light maintenance tasks including weeding.

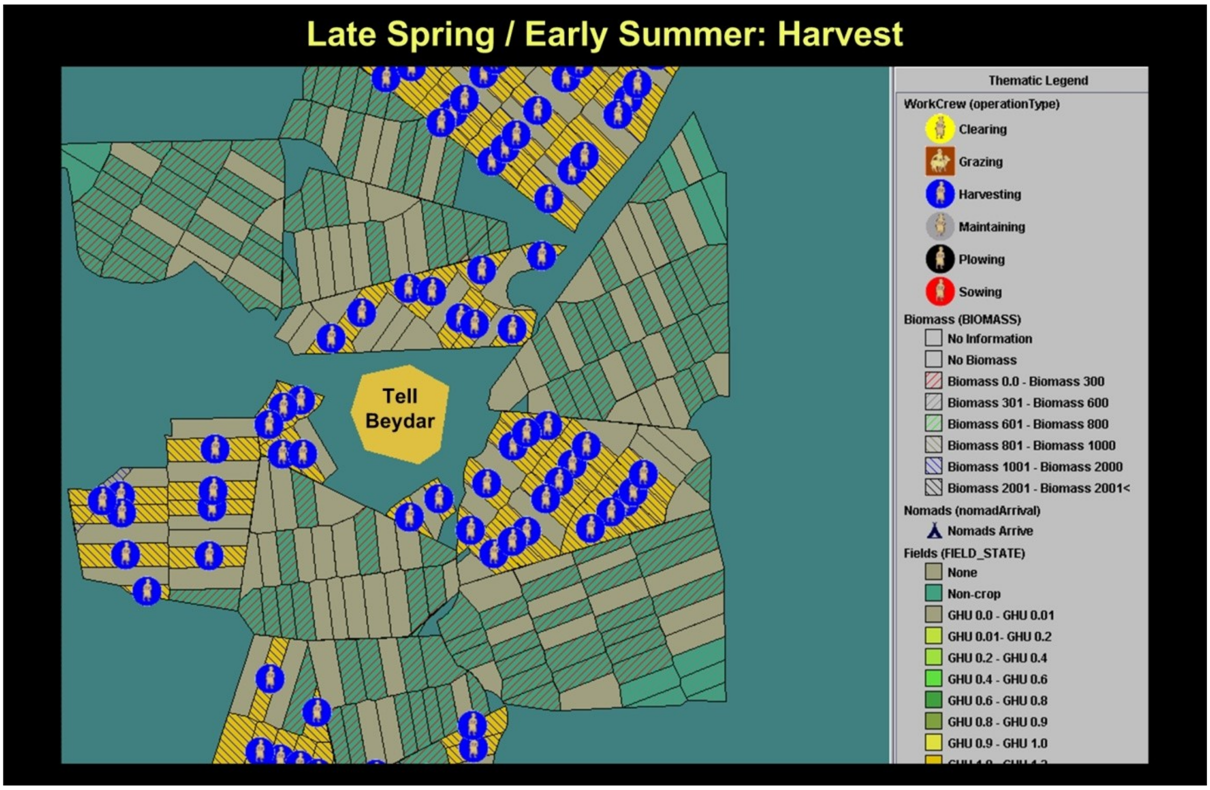

Fig. 11.3 Field mosaics for late spring/ early summer harvest.

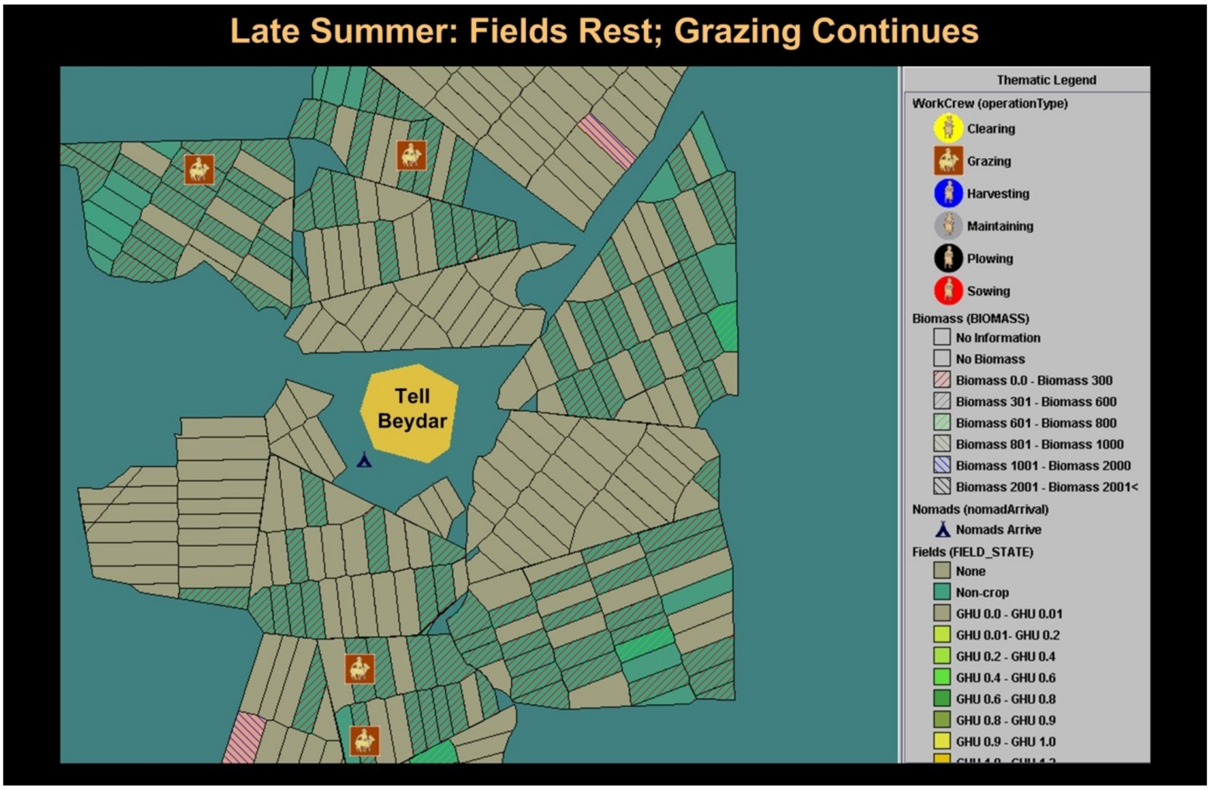

Fig. 11.4 *Field mosaics for late summer when fields are at rest; note the encroachment of grazing in the more distant fields.*

Household Diaries
(Christiansen & Altaweel 2006b: 25-29)[1]

The 'household diaries', which provide details about household members such as their behaviors and possessions over time, were a crucial part of the model output. In addition, the diaries record all significant demographic events (birth, deaths, marriages, etc.), as well as existing resources such as reciprocal exchanges, gifts, and loans in a given year. Figure 11.5 provides a sample which shows how the diaries provide basic information on the households and can be used to interpret major events in the household life cycle.

By way of example, we begin in year 8 of a baseline scenario as published by Christiansen and Altaweel (2006b; Fig. 11.6). Here Household 72 consists of six members in a multiple-family household, a type common in the ancient Near East (Bagnall & Frier 1994; see Chapter 7). Two births occurred in year 8, with one member of the household marrying and moving to the household of her new husband. Such moves are to be expected in past Near Eastern societies (Schloen 2001). According to the household grain reserves, the household members had little problem obtaining sufficient food, and the household was even able to provide a small grain loan to another household in the community. In addition, Household 72 had 15 sheep and goats that could have been used to relieve food stress.[2]

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[1] This, and subsequent references of this type, represents the main MASS paper referred to in the section that follows.

[2] They could either have been eaten or exchanged for much-needed grain.

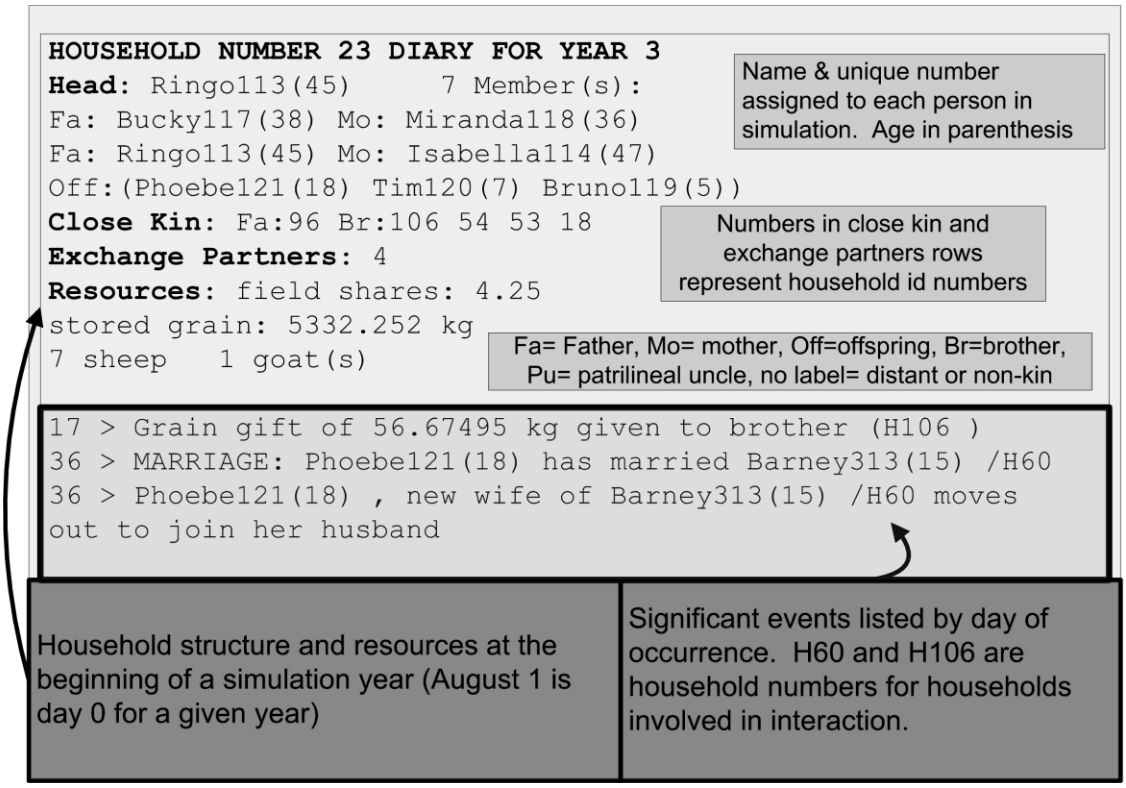
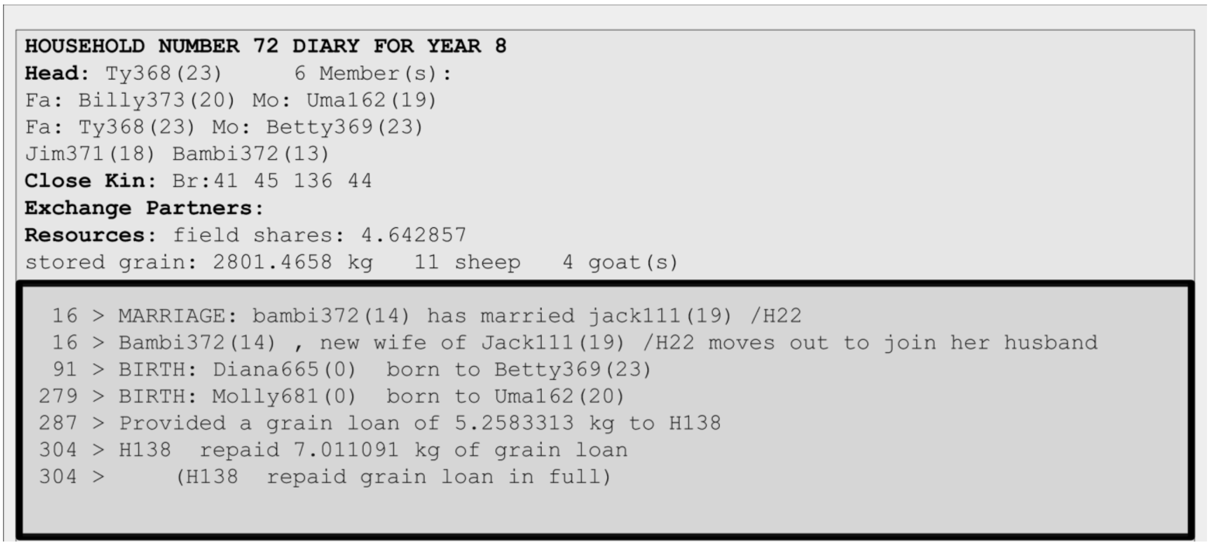


Fig. 11.5 Example of a household diary for Household 23, year 3.



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HOUSEHOLD NUMBER 72 DIARY FOR YEAR 8
Head: Ty368(23)     6 Member(s):
Fa: Billy373(20) Mo: Uma162(19)
Fa: Ty368(23) Mo: Betty369(23)
Jim371(18) Bambi372(13)
Close Kin: Br:41 45 136 44
Exchange Partners:
Resources: field shares: 4.642857
stored grain: 2801.4658 kg   11 sheep   4 goat(s)

 16 > MARRIAGE: bambi372(14) has married jack111(19) /H22
 16 > Bambi372(14) , new wife of Jack111(19) /H22 moves out to join her husband
 91 > BIRTH: Diana665(0)  born to Betty369(23)
279 > BIRTH: Molly681(0)  born to Uma162(20)
287 > Provided a grain loan of 5.2583313 kg to H138
304 > H138  repaid 7.011091 kg of grain loan
304 >     (H138  repaid grain loan in full)
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Fig. 11.6 Household diary for Household 72, in year 8.

By the next year (year 9), Billy373, his wife, and child had departed Household 72 to form a new nuclear family household (Household 141; Figure 11.7). In this particular scenario, large households can be highly productive by having more available members to perform labor tasks. Nevertheless, households comprising several families can also fissure due to higher social stresses between the members, as is evident from this example. By creating a new household which was without access to many of the resources that belonged to their previous household, in a relatively short period the family of Billy373 faced significant food stress. This stress was not necessarily disastrous, however, because the household was able to depend on kinship bonds for one-way gift transfers. Nevertheless, by day 235, the household was forced to seek a grain loan from a non-kin household (Household 143), an option that was much less favourable for Household 141. Despite the attempts of Household 141 to request grain gifts from its kin members, at the time of the food request none of the kin members could provide such assistance, forcing the household to seek a grain loan from other members of the community. Nevertheless, this loan was not too burdensome for the household, and it was therefore able to repay this grain loan with interest by day 306, that is, shortly after the harvest.

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HOUSEHOLD NUMBER 141 DIARY FOR YEAR 9
Head: Billy373(21)     3 Member(s):
Fa: Billy373(21) Mo: Uma162(20)  Off:(Molly681(0) )
Close Kin: Fa:57 PU:33
Resources: field shares: 1.0  stored grain: 247.43134 kg

 48 > *** HOUSEHOLD ESTABLISHED: H141
180 > Grain gift of 64.54647 kg received from p uncle ( H33 )
206 > Grain gift of 55.100643 kg received from p uncle ( H33 )
235 > Obtained a grain loan of 53.52634 kg from H143
291 > Grain gift of 48.80343 kg received from p uncle ( H33 )
306 > Repaid 71.36828 kg of grain loan to H143
306 >     (Repaid grain loan in full to H143 )
306 > Grain gift of 92.88394 kg received from p uncle ( H33 )
364 > Grain gift of 59.823555 kg received from father ( H57 )
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Fig. 11.7 Household diary for Household 141, year 9.

The pattern of borrowing grain that began in year 9 then continued into the following year (Figure 11.8), with the result that at the beginning of year 10, the household was in worse shape than it had been in the beginning of year 9 (see grain reserves). This was partly because the household gave a portion of the harvest away to pay the previous year's grain loan. Thanks to the existence of its kin members, however, the household still had the potential to be sustainable, first by receiving labor assistance in farming tasks (a behavioral option enabled in this simulation), and second by grain gifts. However, most disastrous was the death of Billy373. Ultimately, the loss of an important labor resource reduced the ability of the household to produce sufficient crop yields, at least without assistance in the form of labor from other households. Not only can such labor assistance be costly (in terms of exchange goods or future obligations), but also difficult to obtain in certain years. As a result, Uma162, the young widow of Billy373, and her child were in a dire situation. Faced with few options for household sustainability, Uma162's situation propelled her to choose to marry into another household, taking her child with her and thereby ending the history of Household 141.

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HOUSEHOLD NUMBER 141 DIARY FOR YEAR 10
Head: Billy373(22)     3 Member(s):
Fa: Billy373(22) Mo: Uma162(21)  Off:(Molly681(1) )
Close Kin: Fa:57 PU:33
Exchange Partners: 143
Resources: field shares: 1.0  stored grain:
92.12256 kg

 26 > Obtained a grain loan of 58.954517 kg from H142
 73 > DEATH: Billy373(23)
103 > MARRIAGE: Uma162(22) has married Homer16(19) /H2
103 > Uma162(22) , new wife of Homer16(19) /H2 moves out to join her husband
103 >     along with her dependents: Molly681(1)
103 > HOUSEHOLD DISSOLVED
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Fig. 11.8 Household diary for Household 141, Year 10.

Although these summary results are based on a virtual community operating within a simulation, the processes determining the results were built using data from the ancient Near East. In other words, the household and individual behaviors, together with the demographic circumstances, derive from historical examples from the Bronze Age and later periods. These are intended to reflect the realities past societies faced under conditions of food stress (Christiansen & Altaweel 2006a; Wilkinson *et al.* 2007a: 61-62). The cognitive attributes allocated to the agents allowed them to evaluate different behavioral options before choosing what they believed to be their best course of action, such as seeking a one-way gift exchange from a kin member rather than borrowing grain from unrelated agents. This demonstrates that the simulation framework is capable of allowing agents to perceive and respond to their simulated social and natural surroundings from their own perspectives.

How agents make cognitive choices in past and present social systems is, of course, debatable, especially as such choices can vary depending both upon the agents' motivations as well as upon social factors and rational, emotional, intuitive or unconscious choices (Kennedy 2012: 170-72). Not surprisingly, even computer scientists have varying approaches to the recreation of systems that simulate human cognition and agency (Kauffman 1994; Plotkin 1993; Carley, Prietula & Lin 1998). For example, in the case presented above, Billy373 made a choice to break away from the oft-cited Mesopotamian practice of staying in multiple-family households. In this case, human agency is not constrained by a given social structure common to a particular society. As a result, Billy373 did not behave as an automaton; rather, he was able to make a choice that enabled non-normative results to occur, despite the fact that some of his other behaviors conformed to common Mesopotamian practices. Within the context of this simulation, no particular socio-behavioural theory is strenuously followed. Rather, the examples simply provide a way of showing that different theoretical perspectives can be incorporated into a simulation in a way that allows archaeologists and anthropologists to test a wide range of ideas and beliefs. The end results of such testing can contribute insights into a particular theoretical framework through observation of how that framework operates within a virtual society.

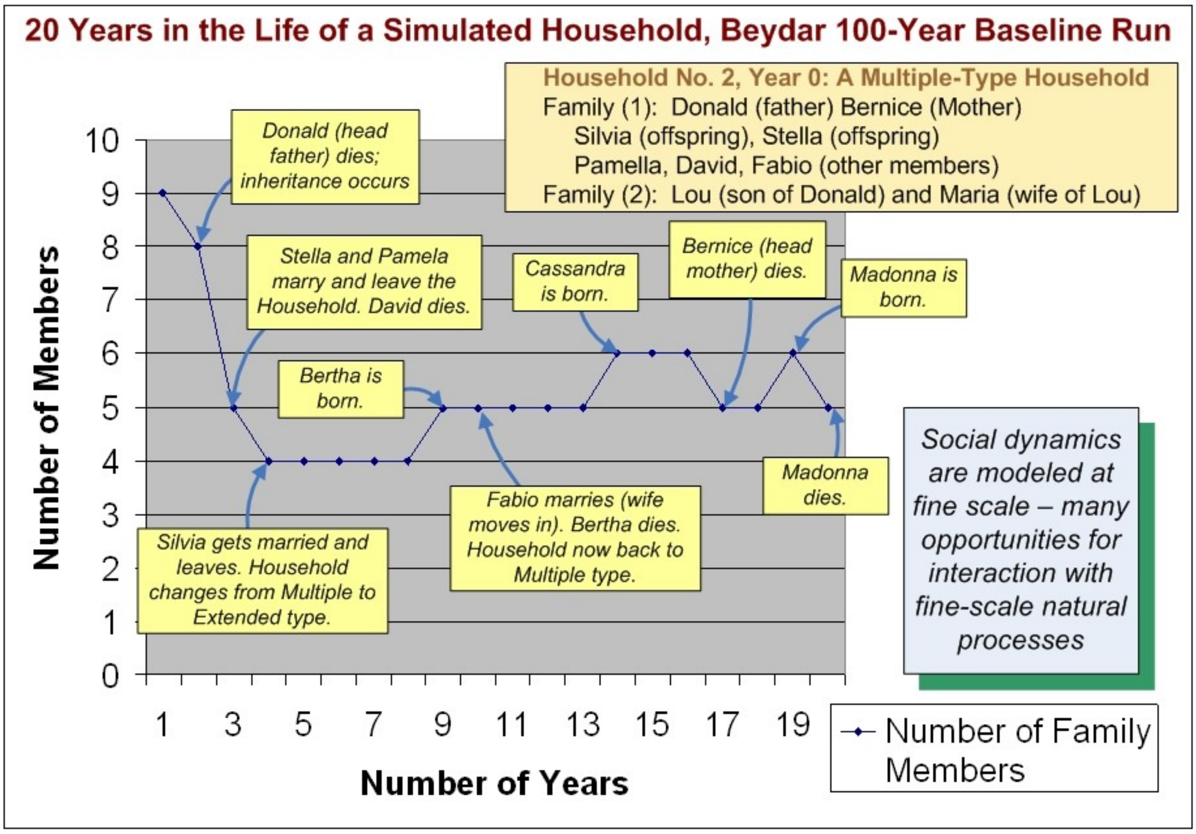


Fig. 11.9 Household cycle: Household 2 for first twenty years.

At a more general level we can construct household life cycles, as indicated in Figure 11.9 (see also Gallant 1991). This represents a twenty-year episode in the existence of a single household (Household 2) drawn directly from a 100-year pilot run of the ENKIMDU system for the Beydar-like modeled village mentioned earlier. In Figure 11.9, the incidents that drive household evolution are captioned in the simulation years in which they occurred. Clearly the life history of this household was quite turbulent and, given the prevailing death rates, this cycle might be expected to be closer to the norm than to the exception.

SELECTED OUTPUTS

Environment

As outlined in Chapter 2, the environment should not be seen as a static framework, but rather as a variable range of dynamic factors that influence the daily practices of its inhabitants, but which also provide a range of constraints on daily life and economic activity. These factors also mutually reinforce and influence each other so that the environment can be seen to influence everyday human activities and, equally, human activities influence the environment. However, because environmental effects are not always predictable, there are a number of unforeseen consequences that emerge from the modeling – these are not minor effects, but rather feed into the entire way that life is conducted in these Near Eastern communities, as well as opening up new opportunities. The various scenarios discussed below enable us to look beyond the obvious, logical or 'common sense' interpretations. We begin with a seemingly foundational relationship, that between rainfall and crop yield.

Soil moisture and crop yield

Fallow versus annual cropping

Traditional practices of crop husbandry in the Fertile Crescent incorporate fallow into the agricultural cycle, so that any one field is cultivated and sown for wheat or barley in one year and then remains under fallow the next. This practice goes back to at least the Neo-Assyrian period (Johns 1901), or even, at Nuzi, to the fifteenth century BC (Zaccagnini 1975: 219-20), if not longer. The advantage of fallowing is that, in a summer-dry climate, rain that falls on the un-cropped land remains in the soil as moisture which benefits the subsequent year's crop. Although the resultant bonus of 10-25% of the previous year's rainfall may seem rather insignificant, it can make all the difference to moisture-stressed cereals, and by acting as an insurance can ensure more stable crop yields. As an example, in the American Great Plains failed crops (defined there as < 400kg/ha) occurred in 10 years out of 27 under continuous wheat planting, but in no cases after fallowing was carried out (Loomis 1983: 360; for general discussion Wilkinson *et al.* 2004: 47-51).

One of the earliest simulations of the MASS Project examined the differences between fallowed and annual cropping for soils and climate equivalent to that of the Tell al-Hawa area in northwest Iraq.[3] Figures 11.10 a & b show the distribution of rainfall (squares) over a 100-year simulation, with the yields of annual and biennial barley superimposed (diamonds).

The overall differences in production between the annual and biennial strategies are more clearly evident on Figure 11.11, which shows biennial production gyrating from zero (in fallow years) to moderately high yields (in cropped years), together with fluctuating yields (diamonds) representing annual production.

[3] These simulations, undertaken in 1999, were part of a prototype project with the same Argonne National Laboratory team who formed the main part of the NSF-funded Project. Unlike the later models, these simulations comprised a relatively simple range of physical inputs rather than the wide range of social practices and physical conditions of the later ENKIMDU case studies.

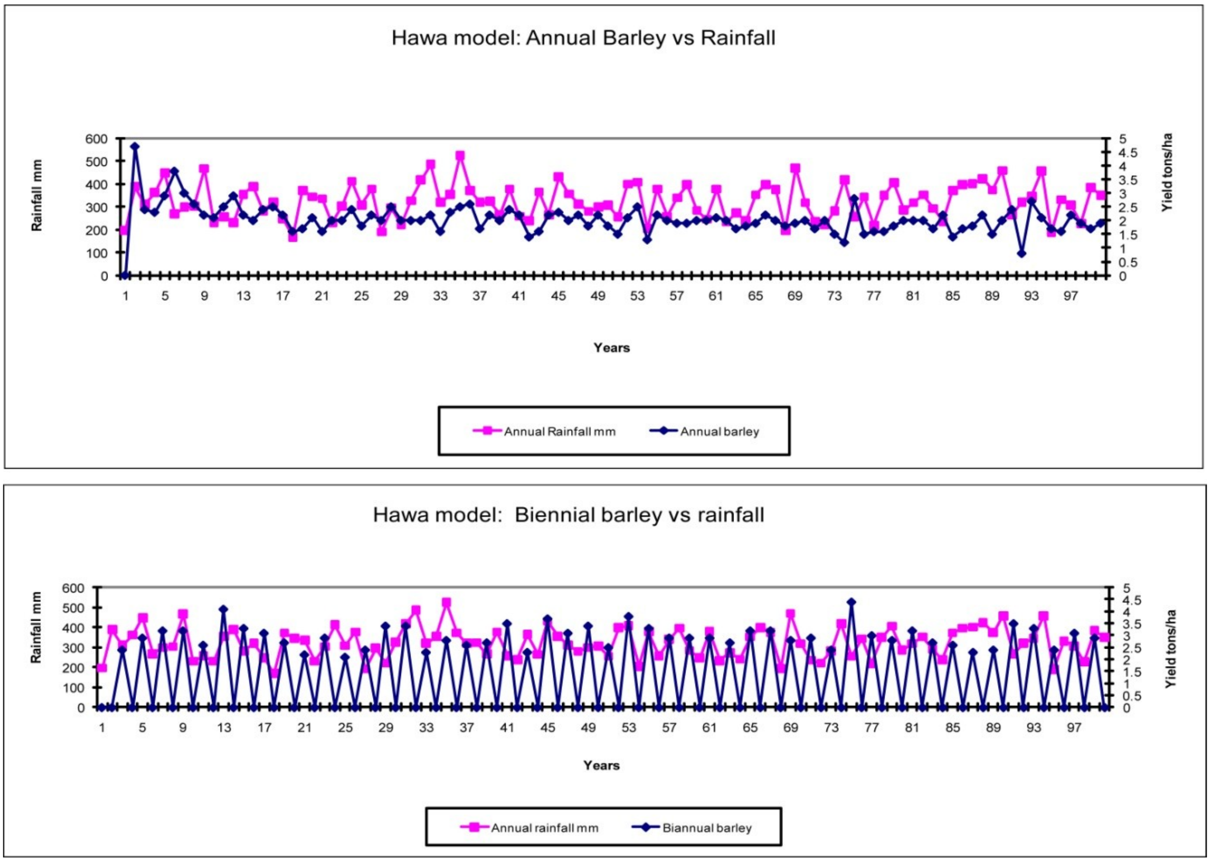


Fig. 11.10a) Hawa model showing annual yield compared with mean annual rainfall for 100 year simulation. b) Hawa model showing biennial yield compared with mean annual rainfall for 100 year simulation. Note that yield drops to zero during fallow years.

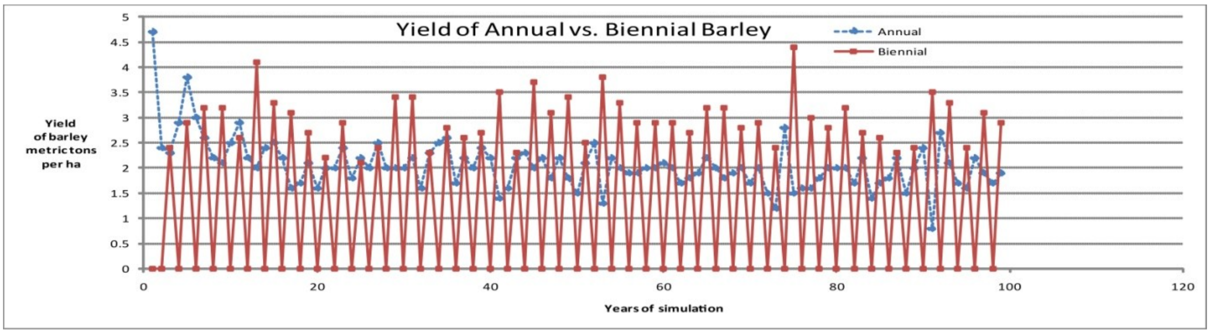
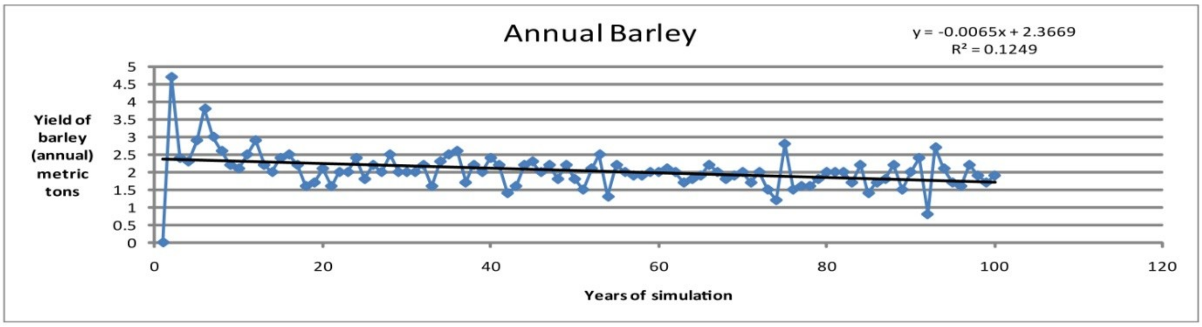


Fig. 11.11 Hawa model showing annual and biennial yields on same axes for comparison.

The differences between the two strategies become even more evident in Figs 11.12 a & b, which demonstrate a clear decline in crop yield for annual production, compared with the relatively stable yields of biennial cropping (see linear trend lines on Fig. 11.12). Expressed quantitatively, the annual strategy represented a decline from around 2.3-2.4 tons/ha to ca. 1.8 tons/ha, which indicates a decrease of some 23% over 100 years. This compares with stable or perhaps even slightly increasing yields when employing biennial production.[4]

[4] However, this slight increase appears to be simply because the random weather generator has created rainfall figures which show a slight increase through the simulation.



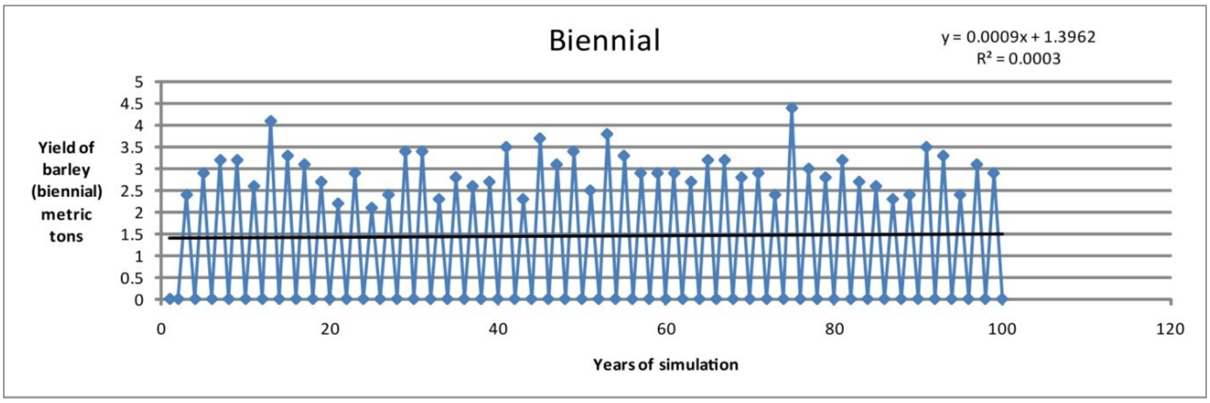


Fig. 11.12 a) Hawa model showing decline in crop yield under annual cropping. b) Hawa model showing stable yields under biennial fallow.

The above simulations support the argument that biennial cultivation with fallow years provides more stable crop yields, in contrast to annual cropping, which is associated with a progressive yield decline (as was also demonstrated for rain-fed cultivation in the Assur case study: Altaweel 2008 and below). However, to Chalcolithic and Bronze Age communities the attraction of annual cropping would have been that the relatively modest yields, when totalled, still exceed by a significant amount total production under biennial crops (Table 11.1).[5] On the other hand, because the biennial yields include crop yields of zero every second year, they appear artificially low. Hence, when only the cropped years are averaged (i.e., excluding the zero years) crop yields are significantly higher (Table 11.1).

Table 11.1. Mean and total yields (biennial and annual crops) for the Hawa case study.

	Biennial crops	**Annual crops**
Total yield over 100-year period	144.4	203.8
Mean yield for 100-year period	1.44	2.04
Mean yield for biennial strategy (cropped years only)	2.95	Not applicable

[5] The choice between biennial and annual cropping will, of course, also depend on the relative availability of cultivable land, labor and plow animals.

Overall, it follows that the traditional fallowing regime, although providing a low *total* production, does provide higher yields in those fields that are cropped, and that yields are more sustainable in the long term.[6] The significance of these results will be elaborated in Chapter 15; additional examples of yield decline are provided in this chapter below.

Severe Five-Year Drought (Baseline Scenario Variant 3)
(Wilkinson, *et al.* 2007a).

In this scenario we chose to examine the adaptive response of the simulated settlement to a severe environmental shock, namely a prolonged drought. We imposed a dramatic reduction of rainfall through years 8 to 12 of the simulation: rainfall levels fell from the mean annual figure of 300mm to the perilously low level of around 100mm per year (Fig. 11.13).

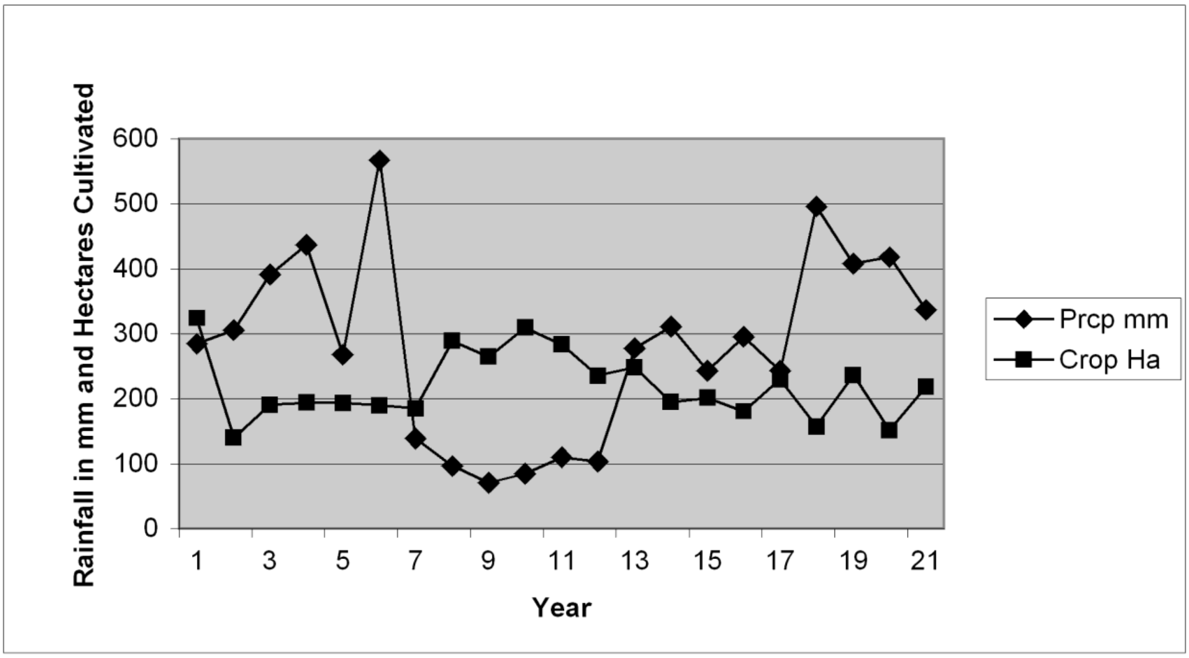


Fig. 11.13 The imposed drought between years 8 & 12 of the simulation and the associated increase in the cultivated area (Wilkinson et al. 2007a fig. 13).

The climatic shock imposed during the simulation prompted several types of adaptive responses by the agents. First, the number of hectares cultivated in the year following the drought increased substantially. This response was triggered by agents attempting to crop as many fields as possible to compensate for a decline in yields per hectare. This expedient proved at least partially successful, not only because of this compensation effect but also because by expanding the area cultivated, there were probably more opportunities to leave certain fields under fallow, a tactic which encourages the accumulation of moisture within the soil over the fallow season (as noted above). Such water-conserving practices were followed by all simulated households. Conversely, after normal rainfall amounts resumed, the number of hectares cultivated decreased as crop yields per hectare returned to normal and there was a reduced need to cultivate more fields. The significance of this adaptive strategy is elaborated below.

[6] However, biennial fallow is associated with other problems, such as soil degradation and the depletion of soil organic matter (summarized in Wilkinson *et al.* 2004: 51-52). Again, these relationships depend upon the availability of land, labor and plow animals. Because the labor productivity would be higher under biennial fallow, thanks to the higher yields when the fields are cropped, biennial regimes would be more efficient. The potential for future modeling scenarios is clearly evident here.

In order to combat the stress caused by the low rainfall and reduced yields, households made greater use of their kin networks to share or exchange food resources. Thus, Figure 11.14 demonstrates a somewhat chaotic increase in gift exchanges during the drought. Other transactions between households also increased during the drought years, which again underscores the significance of kin and social networks. However, the number of transactions for the other stress-reducing options (namely loans and livestock sold) was less than that of kin members sharing food resources with each other. It is more difficult to explain why the number of transactions decreased after the first year of the drought, and this may be explained by reference to the previous figure; perhaps households had become adjusted to a new quasi-equilibrium during the drought by consistently planting a greater area of fields in grain until the drought relaxed its grip.

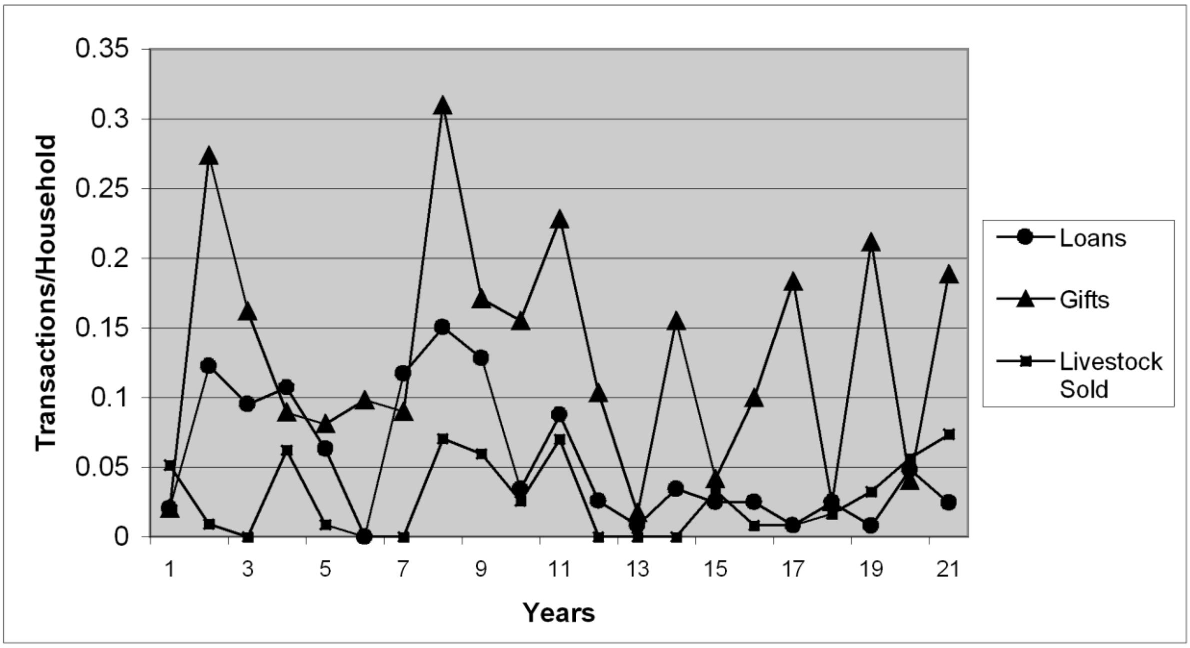


Fig. 11.14 Volume of household grain gifts, livestock sales, and grain loans for the specified 5-year drought.

Overall, by introducing a suite of coping mechanisms the community appears to have absorbed the environmental shock of the five-year drought rather well. This is despite grain yields declining by 46% on average during the drought period (that is, from 697kg/ha down to 376kg/ha). Although the total population of the settlement did level off for the duration of the drought, growth was resumed at roughly the pre-drought rate once the drought ended. In this scenario, the demographic shift was due to temporarily increased emigration rates rather than declining birth rates. The rate of increase in the number of households appeared to be essentially unaffected by the drought.

However, this scenario also provides a warning, because some of the coping methods may not be elastic. For example, in some parts of Northern (Upper) Mesopotamia the populations were cultivating their fields to the full capacity and may have even violated fallow by cropping cereals every year. In such cases, for example in the regions of Tell al-Hawa and Hamoukar, there may have been no additional space to allow for the expansion of cultivated areas, especially because rulers in primary cities were probably extracting tax and thereby forcing local communities to increase or intensify cultivation. Moreover, the exchange networks were not infinitely elastic, and eventually a stage would have been reached when there was no more food within the communal coffers to be exchanged or loaned out to other members of the kin group or extended community. Again, availability of labor is significant, for example, medieval Syriac manuscripts demonstrate that when population and labor were severely reduced, many fields would go uncultivated (Widell 2007: 56).

In addition to simulation runs over durations of 60 to 100 years, we employed 'sensitivity studies' in the form of exploratory runs to test the sensitivity of the simulated landscape and settlement system to perturbations in various parameters (Christiansen & Altaweel 2006b: 223). For example, we tested to determine the response that would result from a 10% reduction in precipitation. When the 100 year baseline run was repeated with mean annual rainfall reduced from 328mm per year to 296mm, the average barley yield was reduced by 1.7% – that is, from 553kg/ha to 544kg/ha – and the average harvest sufficiency (i.e. yield divided by need) was reduced from 1.105 to 1.084, a 1.9% drop. In other words, a 10% reduction in rainfall (to 296mm/yr) did not appear to stress barley unduly, from which we can tentatively deduce that the community may be sustainable (at least with respect to cereal production) even at lower mean rainfall levels. Such a reduction in mean annual rainfall, which is likely to occur quite frequently where communities are situated in climatically marginal areas (such as the zone of uncertainty in Syria), would therefore appear to be within the bounds of normal experience in such communities and implies a certain resilience. However, it is clear that it would affect the long-term storage of grain, which could weaken the overall sustainability of the community (see below).

Comments and Interpretations

The five-year drought scenario demonstrates that a number of coping mechanisms kicked in as a response to the drought. As long as the coping mechanisms and the social ties and networks were in existence, the agent communities were capable of dealing with at least moderate shocks. At rather lower reductions in rainfall (10%, as in the sensitivity study) the community, at least in the short term, was quite resilient. However, if for example the scale and complexity of the social networks was reduced, the communities and households became less resilient and suffered significant losses. This scenario illustrates how an environmental impact can be translated into an economic impact, being mediated and perhaps absorbed through the social networks.

These results immediately raise the question: how do these results correspond to reality? At a general level the tension between the exchange of grain and livestock parallels that from the recent ethnographic past in West Africa, where during the famines and droughts of the 1970s there was a tendency for livestock sales to peak during crises (Fig. 11.15). In West Africa, peasant farmers sold their cattle to buy increasingly scarce and expensive grain (Mortimore 1989), with the result that there was a glut of cattle and a sharp drop in their value alongside a massive increase in the value or price of grain (see below for further discussion). Although the role of markets in the late prehistoric and proto-historic economies continues to be debated, the operation of factors such as those that prevailed during the West African drought would result in economic imbalances, with those members of the community with more resources and ample food in store becoming enriched with animals at the expense of the progressively impoverished peasants. Ultimately, this could result in the households of the elites (or affluent) becoming major holders of livestock. This would not simply have provided the classic 'wealth on the hoof': aside from the large quantity of meat, the resultant wool would have contributed to the growing textile industry, which cuneiform sources indicate was a major industry during the third millennium BC (McCorriston 1997). The implications of this are elaborated below. In addition, the progressive increase in livestock holdings by a segment of the community could result in members of such households taking to the steppe to seek more pastureland, becoming part- or even full-time nomadic pastoralists, while perhaps retaining a foothold in the parent community. Such processes could affect urban population as well as creating demographic increases in nomadic pastoral groups. Again, such processes appear to correspond well to what we see in the archaeological and historical records (Wilkinson *et al.* 2012).

The extensification of land use acted as an adaptive strategy during periods of extended drought. In a 2007 article in *American Anthropologist*, this was recognized as follows:

> 'Therefore the situation of a run of dry years during a phase of maximum urbanisation and land use intensification might therefore be much more significant than a run of dry years where land was freely available. In other words, the increasing urbanization that occurred during the later third millennium BCE in the face of a drying climate might have resulted in severe crop failures, famine and societal collapse.

However, this would have varied spatially depending upon local climate, population density, trade and wealth.'
(Wilkinson *et al.* 2007a: 66)

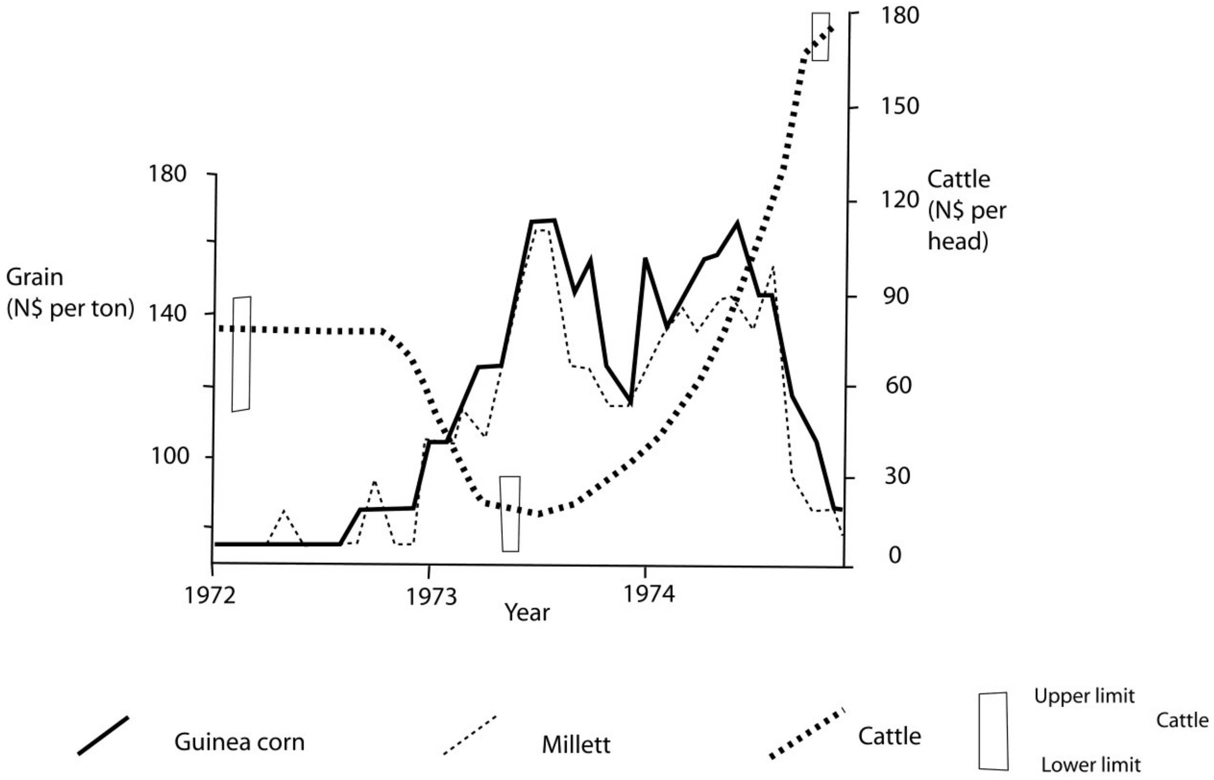


Fig. 11.15 Example from West Africa showing the fall in the price of cattle at approximately the same time as grain (Guinea corn) increases in price during a famine (re-drafted from Mortimore 1989, fig. 3.5).

This observation is significant because more recent investigations in northern Syria demonstrate, rather counter-intuitively, that there was a phase of rapid 'urban' expansion within the zone of uncertainty (rainfall from 300-180mm per annum) during the second half of the third millennium BC, a time of variable and drying climate. Some of these settlements fall into the class of 'citadel cities' as first defined by Oppenheim (1964); they were large, between 30ha and 100ha in area, and would not normally be expected to be supportable under such marginal climates. Some of these sites appear to have developed under the very specific circumstances of the prevailing agro-pastoral economy in which large flocks of sheep were pastured within the steppe lands of the zone of uncertainty. Unlike the circumstances occurring during the preceding fifth and fourth millennia BC, when most settlement occurred in the moister part of Northern Mesopotamia (rainfall > 350mm per annum), the later third millennium BC appears to have been a time of expansion into the zone of uncertainty, perhaps in order to engage in so-called 'opportunistic stocking' which, although carrying high rewards, also entailed significant risks (Wilkinson *et al.* 2012 and references therein). The resultant wool from the expansive sheep flocks would then have contributed to the burgeoning textile industry well known from both southern and northern Mesopotamia (Gelb 1986; Biga 2010).

However, because these large sites were situated in a sparsely populated landscape with few constraints on cropping, they would have been ideally situated to engage in extensification of cropping. This would have entailed enlarging their field areas during years of low rainfall. For example, in one model scenario, the range of crop yields was 400-1000kg/ha and the available land ranged from at least 60-180ha. In this case, the cropping system would have been sufficiently elastic for a low-yield year (if cropped over the maximum area of 180ha) to have yielded some 72,000kg of grain, whereas a high-yield year cropped under a conservative 60ha would yield only 60,000kg. Moreover, years of crop 'failure' within an agro-pastoral regime would have resulted in a huge area of green barley as fodder. This situation was evident in the dry springs of 2008, when the failed crop around Jerablus provided a bonanza for the flocks of the local population or visiting nomads (see Chapter 2). However, during very harsh springs when crop failure was total, the crop would have been so minimal that it would have been impossible to sustain the sheep (Mike Charles pers. comm.). In other words, the adaptive strategies of intensification, together with failed barley used for grazing, could only be feasible during periods of moderate drought; extreme drought would have initiated major crises.

Of course, the insurance represented by extensification does not come without penalty, and in order to cultivated the larger area of fields it would have been necessary to sow more seed, use more labor and marshal more plow teams.[7] Such strategies would probably have been beyond the capabilities of most subsistence agriculturalists, but would potentially have been within the capabilities of urban elites or the royal household. It would also be necessary for the farmer to ascertain whether a given year would be particularly dry or not. This is a tricky task, because although there is a relationship between autumn rainfall and total annual rainfall, the correlation is low (Wilkinson in Jas 2000: 19 & fig. 12). However, because the autumn rainfall is important for the initiation of rooting, then it is possible that the farmer would farm a greater area if the autumn (i.e., September to November) rainfall was low.[8]

Soil Exhaustion

(Altaweel 2008).[9]

Soil exhaustion resulting from a loss of nutrients, or related deterioration in soil quality or structure, is an often-cited environmental factor affecting long-term agricultural productivity. Because the underlying crop models incorporate a range of soil factors (Chapter 10), it is therefore possible to infer how crop yields relate to indices of soil quality.

Altaweel's agricultural sustainability paper employed existing environmental models because they have been validated in a wide range of environmental settings (Altaweel 2008). The simulation was set within part of northern Iraq (near the Assyrian capital of Assur) with a mean annual rainfall of roughly 200mm; in other words, this was a marginal climate where crop failure was frequent and irrigation would be beneficial. The specific modeling tool employed is the Soil and Water Assessment Tool (SWAT) which addresses crop growth (Arnold & Allen, 1992; Arnold *et al.* 1998; Neitsch *et al.* 2002) as well as the following significant environmental processes:

- soil evolution
- vertical and horizontal hydrology
- evapotranspiration
- plant phenology
- daily weather.

[7] The extensification scenario became the focus of a specific discussion at a workshop in Chicago in 2013. Here we emphasize that the complexities of agricultural decision making in a traditional society must have been such that the extensification option may not always have been possible. Alternatively, it can be argued that the citadel cities were not constrained in the same ways as modern villages; therefore, the extensification option may have been taken up under appropriate circumstance. The key point here is that only complex computer simulations are really capable of tackling such questions.

[8] Note that in one Scenario (032104A_100yaPTFof0(1).25) crop yield shows a significant decline over 100 years, whereas precipitation rose slightly, as did the total area cropped. In other words, there seems to have been an adaptive response of the community to expand cropped hectares in order to compensate for *declining* yields.

[9] The paper under discussion, published in the *Journal of Archaeological Science* in 2008, although not part of the original MASS Project, was undertaken by Mark Altaweel who had been a team member. Only those aspects of this paper that relate to climate change and manuring are discussed here.

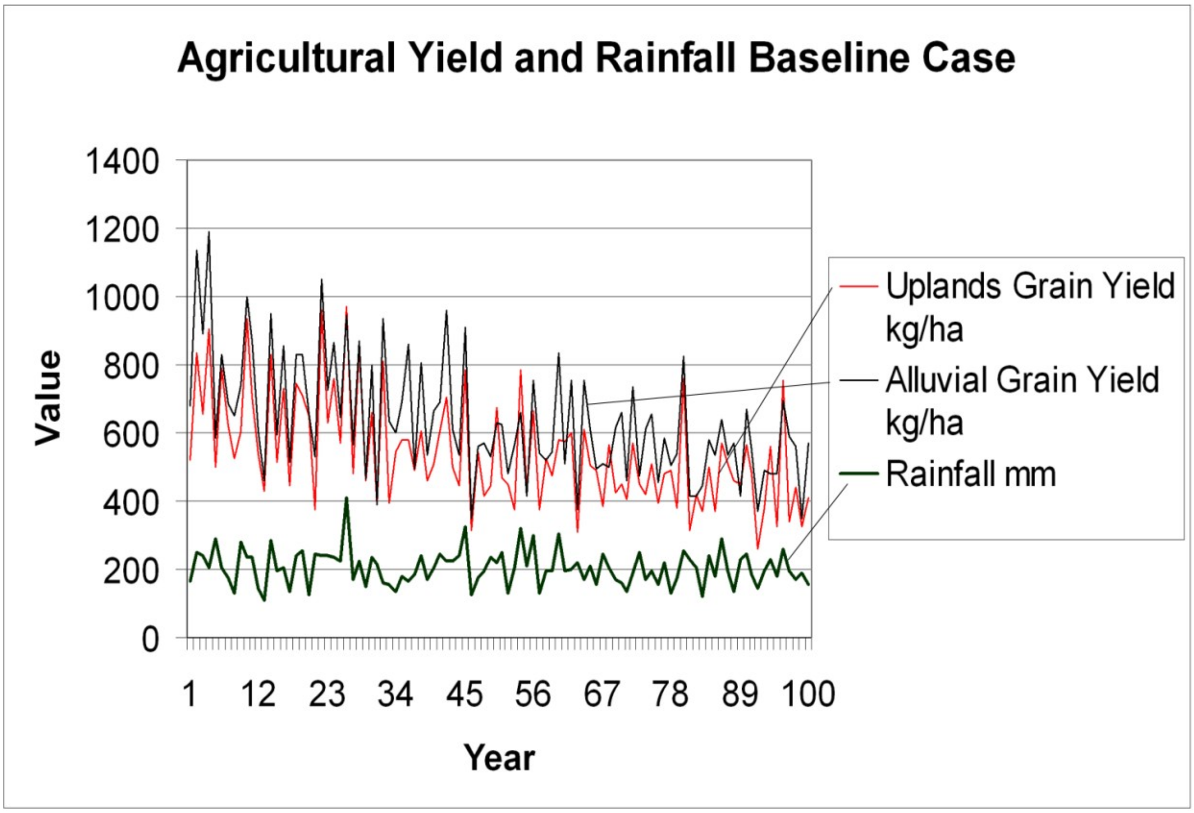


Fig. 11.16 Chart showing agricultural yields in the upland plains and alluvial zones in the region of Assur (Iraq) as well as rainfall amounts during a baseline simulation. (Figure 5 from Altaweel 2008, with permission).

In this simulation nitrogen (N) stress was employed as an indication of stress on crop yield (Altaweel 2008: 826-7). In the original simulation, Altaweel also used potassium (K) but N is emphasized here because of its key role in crop nutrition. In this case, when N stress is 0 it is regarded as having a minimal affect on crop yield, whereas rising values are indicative of an increasing stress on crop growth: when it increases to 1, no crop growth is possible due to a high level of N stress. This simulation, under conditions of biennial fallow and with rainfall fluctuating around 200mm per annum, suggests that over time crop yields declined from 623 and 731kg/ha down to 474 and 555kg/ha after 100 years (Fig. 11.16: upland and lowland respectively; Altaweel 2008: fig. 5).[10] This decline appears to be due to rising N stress, which increased to around 0.6, together with the loss of associated nutrients, after 100 years. This appears to be only slightly less than the amplitude of fluctuations in rainfall experienced during Early Bronze Age climate fluctuations in the Levant. For example, at Soreq Cave, extreme $\delta^{18}O$ readings between 6.5 and 4.6 correspond to rainfall figures of perhaps 725 and 350mm per annum, but with a rather lower range for the smoothed values corresponding to between 620 and 520mm per annum (Bar-Matthews & Ayalon 2011:167)[11]. Because of the uncertainties involved in both the models and the Soreq data it would be unwise to force the conclusions too far, but it seems that overall loss of soil nutrients and associated soil fertility contribute an additional uncertainty to agricultural production.

[10] Note that in this case biennial fallow did not appear to stabilize yields as was the case for the Hawa model. This may be because that under the conditions of the Assur case study, the loss of N and crop nutrients may have resulted in a greater decline in crop yield, and soil moisture was not the critical factor.

[11] Because Soreq Cave is so distant from Assur, we are only employing it as an example of an order of magnitude range of values, not for specific temporal trends.

Comments and Interpretations

Significantly, in the Assur case, yields did not decline continuously; rather, during the last ten years of the simulation the curve flattened to near 390kg/ha in the uplands and 450kg/ha in the alluvial areas (Altaweel 2008: 826-27). This levelling-off of yield decline is similar to that observed in long-term crop trials, in which un-manured and un-fertilized soils show a crop yield decline through time. In some cases these showed stability, albeit at low yields, after some 50 years (Edmeades 2003). Such indications of crop-yield or nutrient decline are not restricted to formal trials. For example, interviews of local inhabitants from the village of Halula (within areas of rain-fed cereal cultivation in the Middle Euphrates valley of Syria) indicate that significant crop yield has declined within living memory: the leader of one household mentions that normal yields of 20 bags of barley (from 1ha) had decreased to 10 bags today (i.e., in approximately 2006), whereas a second household experienced a decline from 15 to 10 bags over some 20 years (Arab 2007). Similarly, nitrogen status (measured as $\delta^{15}N$) from carbonized cereals from archaeological sites in the same region showed a significant decline from the Neolithic to recent times (Ferrio *et al.* 2007: 50-51).

Moreover, the simulations indicated that manuring, under rain-fed cropping, resulted in increased yields, a point which underscores the need to fertilize soils to maintain yields (Altaweel 2008: 828). This need to supply manure to maintain long-term fertility and to increase crop yields is supported by fieldwork which suggests that the application of manures was a common practice in the third millennium BC (Wilkinson 1989). However, because the field results cited relate to the application of household wastes to fields, it is important to appreciate that different types of manure will have different results. This is especially because one of the key nutrients in manure (nitrogen) is volatile and can be burnt off in household hearths before dung becomes household refuse which can be applied to the soil. Although this is not the case with the direct application of animal manures (which were specifically selected for in the Altaweel model), a range of other complexities arise. Consequently, although the application of manures is a valuable additive for the enhancement of crop yields and sustainability, local circumstances of manure application, climate and other factors are also crucial (Fraser *et al.* 2011).

If the scale of the settlement system is increased, then the scale of nutrient loss might also be expected to increase also. For example, McNeil reminds us that in the case of urban settlement hierarchies, more nutrients would be lost because they were exported from fields to the cities and were usually not returned unless they were specifically returned as night-soil (McNeill 2010: 363). Although such cases of the return of night-soil as compost to outlying agricultural areas is well known, for example around post-medieval London, the distribution patterns of fertilizers, composts and manures are not well known for the Bronze Age Near East. Although field evidence for manuring with household waste has produced extensive field scatters around major centres such as Tell al-Hawa and Hamoukar, as well as their satellites (Wilkinson 1990; Ur 2010), it is not clear whether the outlying settlements, which presumably exported some of their grain as tax to the central city, ever received ash, compost or night-soil in return from the central city as compensation for lost nutrients. Here an increase in scale of the model to incorporate a full hierarchy of settlements would provide a more realistic reconstruction of nutrient flows.

DEMOGRAPHY & FOOD SUPPLY

Stability and change
(Wilkinson *et al.* 2007a)

One immediate outcome of the ENKIMDU modeling is that the population of the model settlement (or its equivalent expressed as the number of households) can appear rather stable with only low-amplitude fluctuations, whereas the inputs (such as mean annual rainfall, crop yield etc) can exhibit a high amplitude (Fig. 11.17).

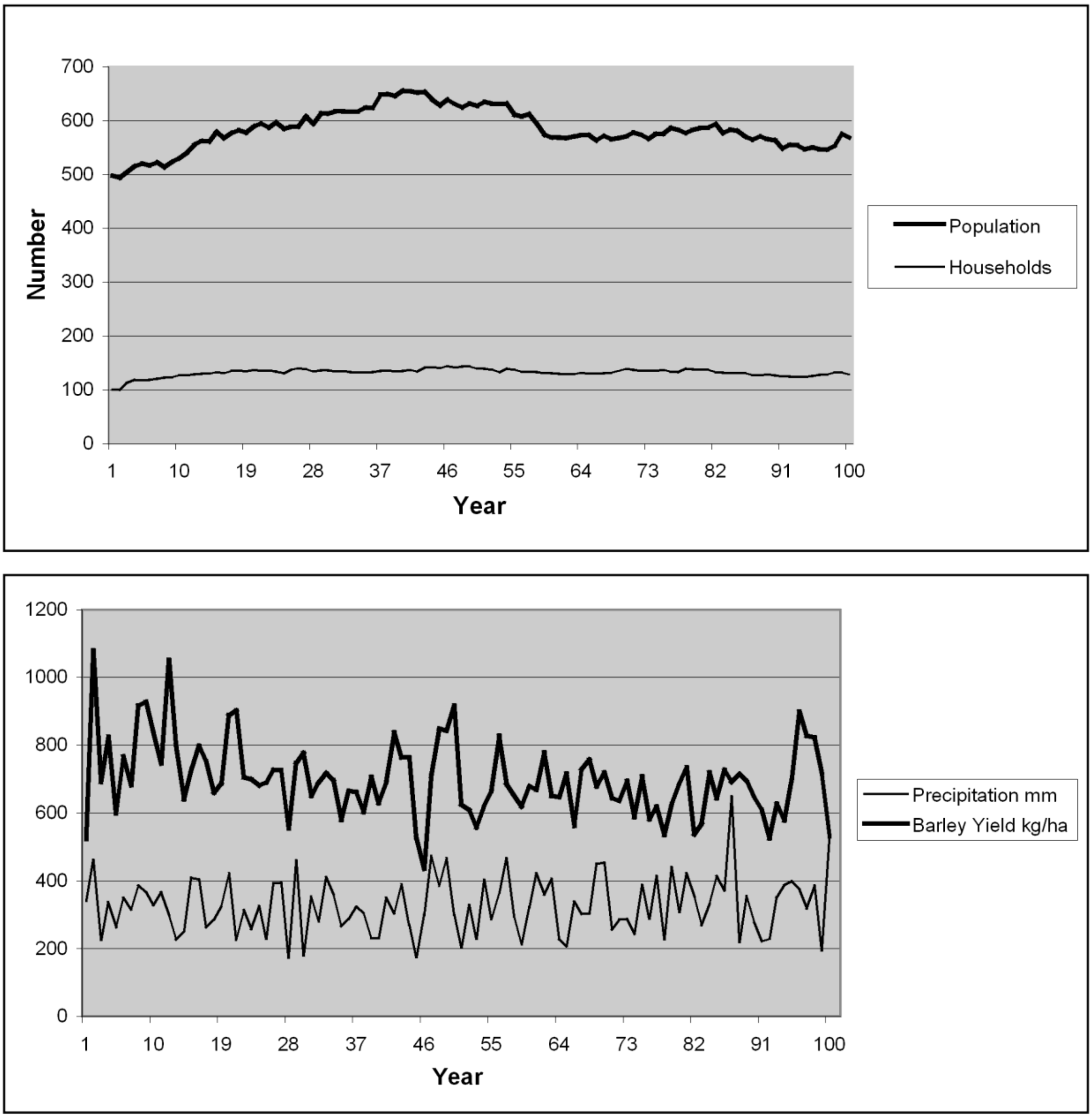


Fig. 11.17 a) 100 year baseline run: total population and number of households. b) Barley yield and precipitation. Note how the inputs (i.e. precipitation and barley yield) show a high range of variation whereas the population and number of households are rather stable.

This basic demographic outcome of the modeling is shown by the 100-Year Baseline Results (Fig. 11.17a). In this scenario, total population rose about 14%, from 501 initially to 569 at the end of 100 years, after peaking at 639 people, 38 years into the run. This amounts to an increase of around 0.73% per annum, a high rate for a prehistoric or early historic community. However, because numbers rise and then fall, attaining 569 at the end of the simulation, the 100-year growth rate is rather less at 0.136% per annum. Over the same period, the number of households increased 30% from 99 to 129, with a peak of 144 households occurring in year 46. In other words, the number of households increased at a higher rate than the actual population rate, and was apparently rather more stable.

Total settlement births and deaths over the 100-year time span were 3,250 and 2,683 respectively (Wilkinson *et al*. 2007a: 63). If the settlement had been a completely closed system, population could have doubled in that time, assuming that the agricultural capacity of the settlement catchment could support that number. However, the modeled system is not closed; over the course of the run, about 5 per year (499 people) 'emigrated' from the settlement, leaving the simulation completely. Because there is no flow of persons into the settlement from other settlements for this baseline scenario, the growth of net population is more modest.

Comments and Interpretations
It is important to note that emigrations are not necessarily an indication of a sustainability failure of the settlement as a whole. Rather, our perception is that it is a reflection of the inability of a household to command the resources to sustain itself, even after we factor in the aid of gifts from close kin, exchanges with non-kin, or loans of grain. Model results indicate that such occurrences of individuals or household failures are common, even when the settlement as a whole appears to be thriving. In such cases it appears that there is no single mode of growth; rather, some households are able to grow while others fail, in part perhaps because of unfortunate decisions or circumstances. Therefore the simulation shows evidence of some degree of realism, wherein the local circumstances of individual households and their networks really does matter.

Because we are only dealing with an individual community, rather than a network of settlements, it is significant that the population of the simulated settlement remains rather stable in the medium term (most simulations did not exceed 100 years). This appears to compare with the development of tells which, in general, show relative stability over long periods of time. For example, in the region of the Middle Euphrates in Syria, not only is the small tell the commonest class of settlement in the region, it is also the type of settlement that persists for the longest period of time (Wilkinson *et al.* 2012). In the case of the small tell, however, it is important to appreciate that these play a range of functions in the landscape, including indicators of land ownership, small fortifications, religious places and so on. Nevertheless, it is significant that small settlements do show evidence of long-term 'sustainability', a result that supports earlier simulations by Zubrow and Robinson (1999; also Chapter 15).

Stress Scenario: Acute Labour Shortage at Harvest
(Wilkinson *et al.* 2007b: 202-205)

Ancient populations are dynamic, not only as a result of community members leaving to go elsewhere or bringing wives from other communities, but also as a result of arbitrary events such as if some community members left to fight wars or to supply corvée labor. By creating acute labour shortages such events can provide major stresses. For example, in one scenario (Figure 11.18), 90% of the adult male population of the settlement was withdrawn from the simulation, without warning, 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 11.18). After this, all of the males returned to the settlement. This hypothetical episode, which more likely reflects a demand for corvée labor by a local political power rather than a war, required the simulated community to bring in its grain harvest with a drastically reduced labor force.[12] In this instance much of the harvest was lost, and those households unable to obtain grain gifts were compelled to seek food using alternative coping strategies such as selling livestock and borrowing grain to sustain themselves. Not only does Figure 11.18 show how the volume of grain gifts and grain loans both peaked temporarily during and immediately after the labor crisis, the most noticeable change was a much higher level of livestock trading activity that began with the corvée episode but persisted to the end of the scenario. Such an intense and chronic adaptation might be an indication that the crisis had either destabilized the settlement or initiated a long term adaptation.

In general, the settlement appears to have weathered the crisis, and 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 through 20. Although 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.

[12] See comments on the crucial role of the availability of labor, above.

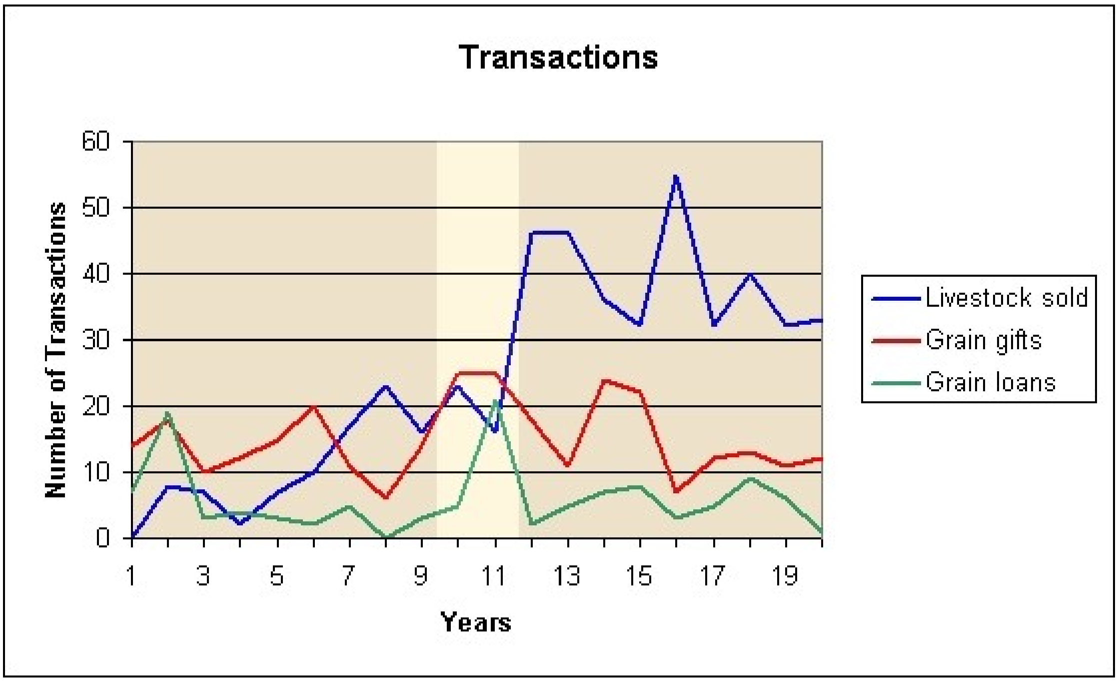


Fig. 11.18 The number of exchanges in terms of livestock sold (top), grain gifts (centre) and grain loans (bottom). Wilkinson et al. 2007b: fig. 9.14).

In such cases the household diaries provide deeper insights into the effects of the 'corvée episode' on the sustainability of the model settlement. Figure 11.19 (15) illustrates the format of the Household Diary output for two representative and roughly comparable agent households, Household 1 and Household 21, for year 6 of the acute harvest / labor crisis simulation. Household 1 is a five-member nuclear family, whereas Household 21 contains a five-member nuclear family plus one relative, the surprisingly durable Gigi100, who at age 67 is a statistical anomaly given the rather brutal death rates built into the model's population demographics.

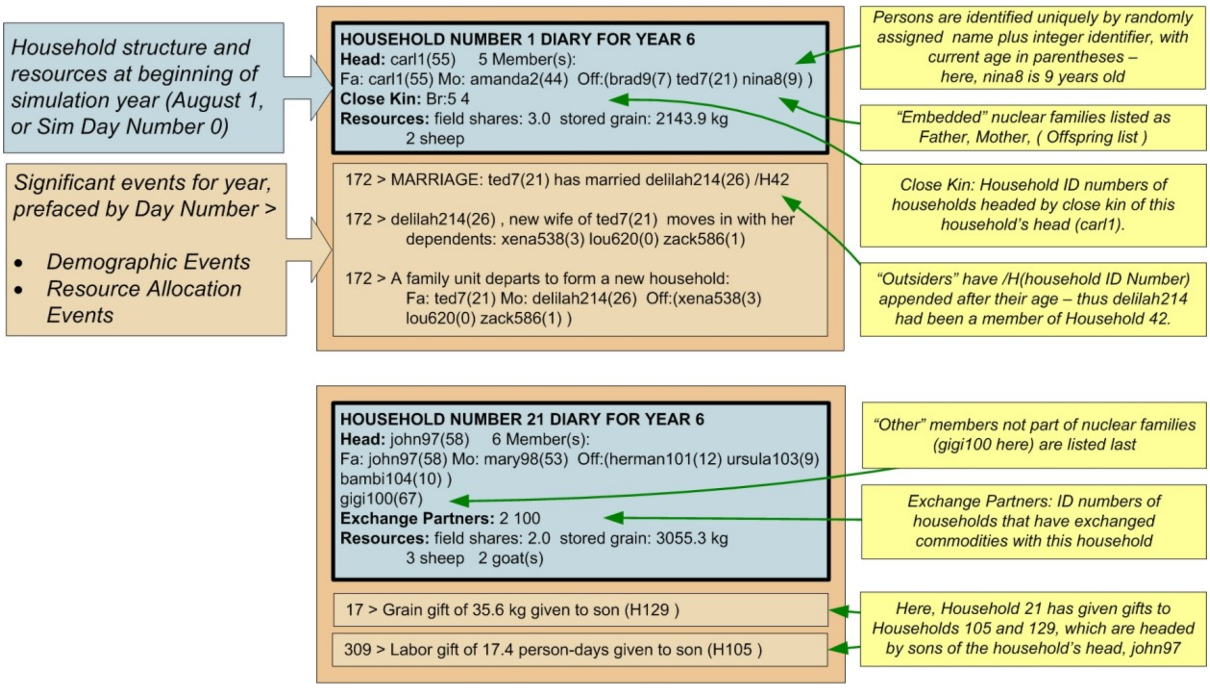


Fig. 11.19 Sample Household Diaries for Households 1 and 21 for the scenario of the corvée episode: Year 6.

Both Households 1 and 21 began year 6 with field shares, livestock, and a substantial grain reserve. The only apparent advantage of Household 1 was that it was able to request aid from two close-kin households, Households 4 and 5, each of which was headed by a brother of Carl1, the head of Household 1. In year 6, Household 1 celebrated the wedding of the eldest son of the house and witnessed his departure to form a new household with his bride and her prior dependent children, whereas Household 21 was sufficiently well-off to be able to provide gifts of food and labour to other close-kin households.

Unfortunately, for simulation years 10 and 11 (Figure 11.20), the years of the labor crisis, the household diaries tell a different story. Household 1 enters this critical interval with a more substantial grain reserve than Household 21. In year 10, both households appeared stable, and both were able to provide gifts to other households. However, although Household 21 could afford to buy a goat to slaughter for Ursula103's wedding feast, shortly thereafter they were compelled to begin selling off livestock to obtain much needed grain.

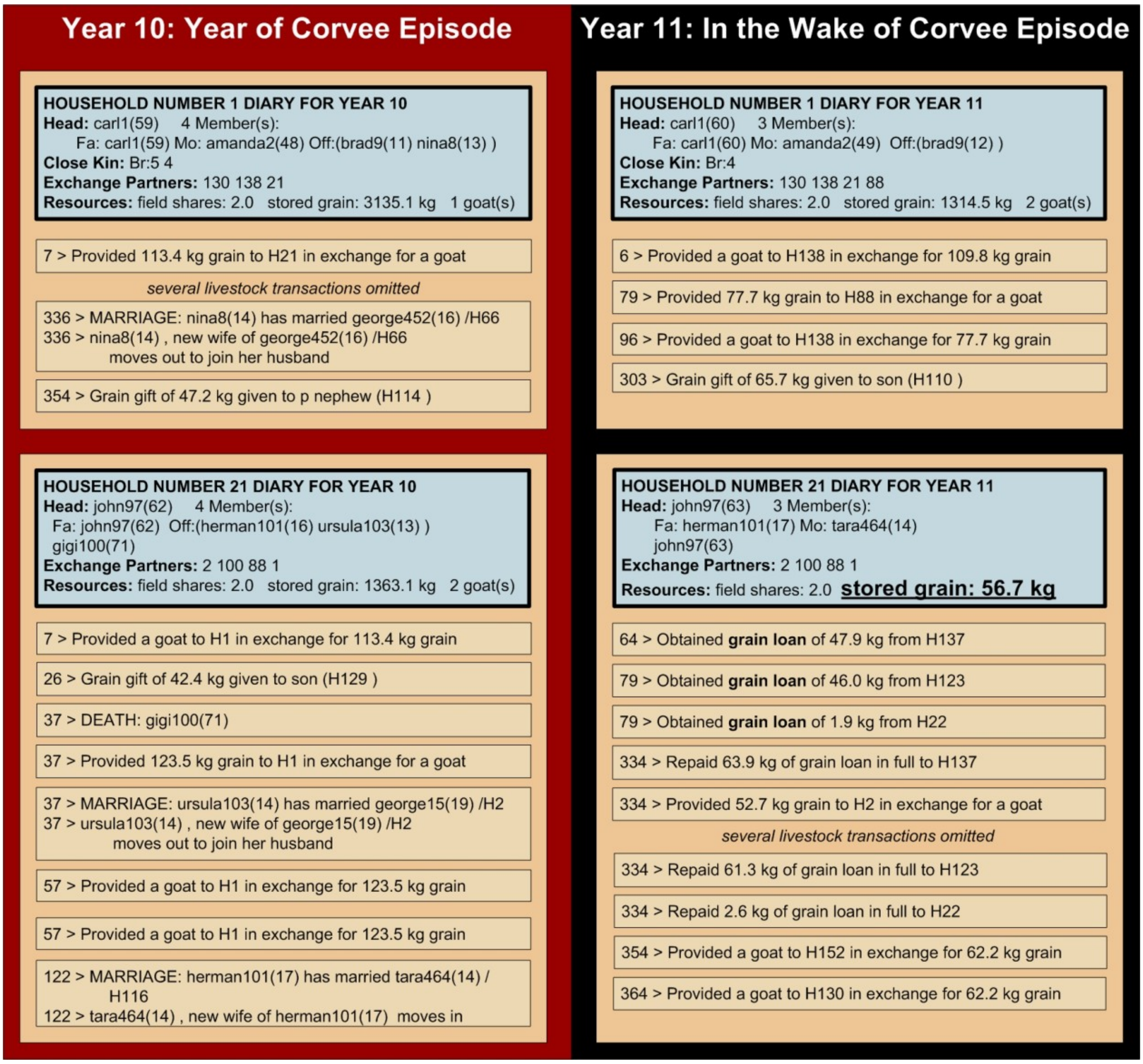


Fig. 11.20 Sample Household Diaries for Households 1 and 21 for the scenario of the corvée episode: crisis years.

Overall, the temporary removal of nearly all adult males at harvest time in year 10 led to serious grain losses for both Households 1 and 21 due to insufficient harvest labor. As indicated on Figure 11.20, the grain reserves of both households at the start of year 11 were well below the previous year's starting levels. Household 21 began that year with virtually no grain, and consequently started to obtain grain loans. Although the household was able to repay these loans, it had to sell all of its livestock, indicative of the level of food stress it was experiencing. At this point grain loans became Household 21's main option for obtaining food until the next harvest had been gathered in. Unfortunately, this option became less viable as the household defaulted or struggled to repay its loans, a situation compounded by other households denying its loan requests.

In year 14, Household 21 gave up the struggle and emigrated – in other words left the simulation (Figure 11.21). When the household was most in need of support from its kin, the lack of close kin capable of providing assistance in the form of grain gifts, with minimal conditions, sealed its fate. On the other hand, Household 1 survived the crisis quite well because its connections to other members of its kin-group, as well as connections to other households in the settlement, enabled it to sustain itself.

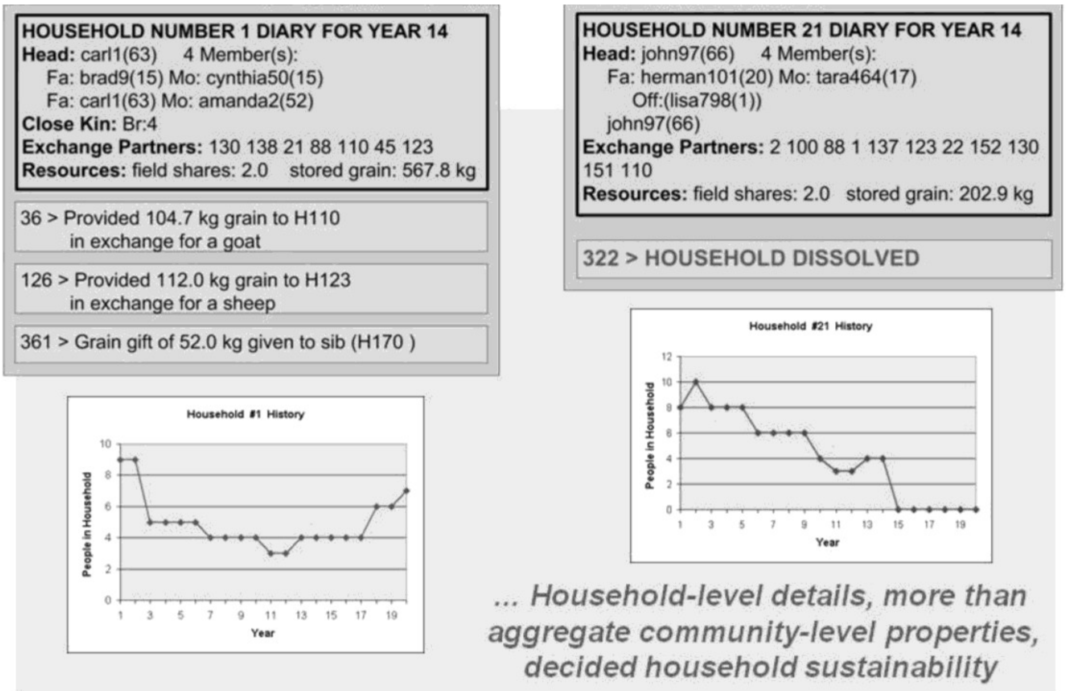


Fig. 11.21 Sample Household Diaries for Households 1 and 21 for the scenario of the corvée episode: Year 14 (i.e. after the crisis years).

Comments and Interpretation

These household-level examples demonstrate that the fine-scale details really do matter. This is because the specific circumstances in which each household finds itself can have a greater influence on the sustainability of the household than the aggregate properties of the overall community. This scenario underlines the benefits of analyzing communities at the levels of the agent household and its individual household members, and highlights some of the diverse social behaviors and natural factors represented in the simulation framework that are key to understanding household dynamics. Of particular significance is that, in many of these scenarios, we can see that simple decisions can lead to complex behaviors and results. That said, of course, the underlying decisions can be rather elementary: namely, to buy or not to buy, to loan or not to loan, to sow or not to sow. Nevertheless, the incorporation of such decisions into the scenario demonstrates that individual agency can potentially have a significant affect on the outcome of model communities.

Chronic Shortage of Plow Teams
(Wilkinson, *et al.* 2007b)

Discussions of societal change and collapse rarely focus on humdrum topics such as the simple plow. However, as discussed in earlier chapters, the process of plowing and the availability of the appropriate animal traction was crucial to the successful functioning of ancient communities. The following scenario was intended to test the resilience of the simulated settlement to variations in the access of households to plow teams. This scenario was developed based upon Tell Beydar's ancient textual sources that record the number of livestock available for plow teams for the settlement and the surrounding area (Widell 2004). 10-year simulations were run for three variants that differed from the first 10 years of the baseline case only in the settlement's overall number of plow teams per household. The base case value was 0.5, namely half as many plow teams as households (in other words two households were sharing one plow team). We also examined cases in which the plow team ratio was 0.25, 0.1875, and 0.125 (i.e. one per four households, one per 5.3 and one per eight households). It was assumed for these variant cases (as well as in the baseline case) that the plow teams were considered to be community resources for which households would have to queue up for access.

Simulation results (Figure 11.22) illustrate a pattern not infrequently seen in complex systems: they show an abrupt change in aggregated system behavior as a hidden resource threshold is reached. The population traces in Figure 11.22 indicate that the 0.25 and 0.1875 plow teams 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, in the 0.125 case (one plow team for every eight households) the simulated community experienced an aggregate system catastrophe, resulting in a precipitous decline in settlement population over ten years.

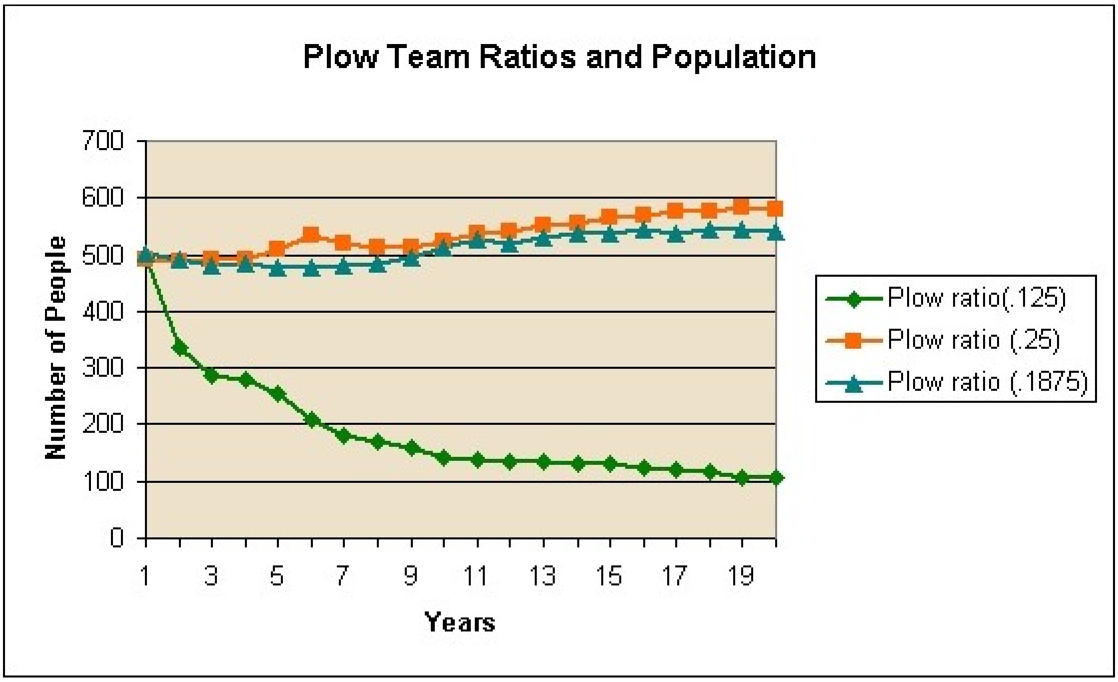


Fig. 11.22 The effects of plough team availability on settlement population.

Our complex, multilayered simulations provide numerous reasons, natural and/or societal, for crop failure. However, in our controlled scenarios we have isolated the inability of some households to obtain access to plow teams as a critical factor. Specifically, certain scenarios tested what events would result when there was insufficient time to get fields plowed and crops planted before the winter rains set in. Because we made the simplifying assumption of a constant plow team ratio, the number of plow teams dropped along with the settlement population, so that 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 11.22 had unfolded in full. Nevertheless, the constraint of the 'hidden' plow teams appears genuine, and constitutes a serious potential vulnerability to the settlement community.

Interpretations and Comments

The plow team scenario suggests that there is a significant degree of flexibility in a rural community, so that up to (perhaps) five or six households can share a plow team. This echoes medieval documentation on rural husbandry in Britain. For example:

> 'In the north [of East Anglia] the hamlet remained the principal unit of residence, and the ideal arrangement, according to a fifteenth-century document, was a settlement of nine houses, all sharing one plow team, with one kiln, one churn, one cat, one cock and one herdsman.'
> (F. Pryor 2010: 361 (citing Wade-Martins 1995: 42).)

Although this quote suggests a rather higher threshold than was observed in the MASS simulation, both indicate not only the degree of flexibility that exists, but also, implicitly, the presence of a threshold. This means that a settlement of a given population (e.g., six households with each household consisting of six members = population of 36), depending upon its resources, could continue to exist by sharing plow teams according to various combinations. For example: six households with one plow team per household, six households with two households sharing one plow team, up to perhaps the threshold of six households sharing one plow team. However, if for any reason the number of plow teams available fell below the critical threshold of around five or six households per plow team, severe malfunctions would result.

By way of illustration, although dating to a later period than considered in the MASS Project, the annals of the Neo-Assyrian kings of the tenth and ninth centuries BC often record 'tribute' being extracted from the subject states of Assyria. For example, in the ninth century BC, amongst other items, Ashurnasirpal demanded 1,000 oxen as tribute from Lubarna, the ruler of Patin (in the Amuq or Hatay region of southern Turkey).[13] This could have had a huge impact on the production of grain crops by shifting the capacity to plow the fields towards the critical threshold of or near six households per plow team. Such a situation could either lead to conflict within the community over the allocation of plow teams, or a major decline in cereal cultivation.

Baseline Scenario 1: Chronic Harvest Blight
(Wilkinson *et al.* 2007a)

In the severe harvest blight scenario, the modeled blight has a probability of occurrence of 50% per year, in which case it affects roughly 50% of the ripening grain fields. We have assumed that the blight occurs in circular patches with radii of 1.0km; affected areas are not spatially correlated from year to year. Those fields affected lose between 80-90% of their grain yield in the month or so before harvest. Therefore the total spatially and temporally averaged effect of the blight is to reduce grain yields by roughly 0.5 x 0.5 x 0.8, or about 20%. This presents a major problem for the settlement community because the blight impacts are *not* felt uniformly, but instead have a disproportionate impact upon a subset of settlement households.

In the 50-year scenario, the blight had a significant impact on the simulated settlement. Table 11.2 compares the frequency with which households resorted to exchange-related coping mechanisms in the 50-year blight case compared to the first 50 years of the baseline case. Because of the chaotically varying crop yields experienced in the blight case, households had to resort to a significantly higher volume of grain loans (up 90%) and exchanges of livestock for grain (up 45%). On the other hand, grain gifts from kin maintained a consistent level in both runs.

[13] Discussed in Bryce (2012: 214), with further details on the historical context.

Table 11.2. Comparison of household rate of access to exchange-related food stress coping mechanisms in harvest blight and baseline scenarios (per year and per household)

	Livestock sold	Grain gifts	Grain loans	Exchanges
Baseline Case Mean	0.0318	0.1305	0.0307	0.0630
Blight Case Mean	0.0461	0.1351	0.0584	0.1043
Blight/Baseline	1.450	1.035	1.902	1.656

Ultimately, those households that could not sustain themselves by applying the coping mechanisms available were forced to emigrate, or perhaps to become indentured to larger households. Fifty years into the simulation, the settlement population in the blight case was 452, down from the initial population of 501 and far below that of the baseline run, which was 628 at the 50-year mark.

Again, this scenario suggests that some form of stress stimulates exchange mechanisms, and although it would be overly simplistic to suggest that economic transactions are a product of stress and hardship, in this case it would appear that there is some form of relationship between adverse conditions and exchanges.

Population and disease

Stress Scenario: Diphtheria Epidemic
(Wilkinson *et al.* 2007b)

Not only were contagious diseases a significant factor for ancient populations to contend with, but also were probably specially problematic in urban settlements, where population densities were large and absolute numbers could attain several thousand people. The following scenario entails the imposition of an acute stress on our model settlement in the form of a severe epidemic. In this case we have chosen an outbreak of diphtheria, which is very contagious and in this case specifically targeted the children of the settlement.[14] Diphtheria can cause rapid and widespread death among populations (particularly the young); for many years the disease has been a leading cause of death for children under fourteen years of age (Hardy 1998). Although it is well known that disease can have devastating impacts on human populations, 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.

In this scenario the modeled epidemic occurred in year 20 of the simulation and caused the deaths of approximately 80% of children and infants under age twelve. This is, of course, a rather severe death rate, but it is used for illustrative purposes only. Much lower – e.g., 20% – death rates for a total population have been recorded for outbreaks in the last century (Kleinman 1992). This epidemic was employed as a purely demographic event and there was no attempt to undertake a physiological simulation of the onset and progression of diphtheria.

In the resultant population outputs (Figure 11.23), after a rapid plunge, the settlement population growth rate recovered in the first few years after of the epidemic to attain a figure of a little over 500 people. However, population subsequently declined, and in the long term, the settlement population decreased as the age cohort struck by the disease was not available for reproduction under the social rules of marriage stipulated in the simulation. Initially, the high attrition of that age cohort did not negatively affect household sustainability.

[14] Diphtheria is a respiratory illness, specifically of children. A disease resembling diphtheria has been described from Greece and the surrounding areas in the late centuries BC/early centuries AD, as well as from the same area in the sixteenth century AD (Carmichael 1993: 680-83). Furthermore, J.D. Cherry (1993: 656) notes that a croup-like illness (diphtheria is a croup-like illness) was possibly known as early as the second century AD, and reported by Areteaus of Cappacocia (Turkey) among others. The disease appears to have been common in Syria and Egypt at that time.

Rather, it was a moderately positive factor, because young children are a drain on household resources specifically in terms of the amount of food they produce as a result of their labor.

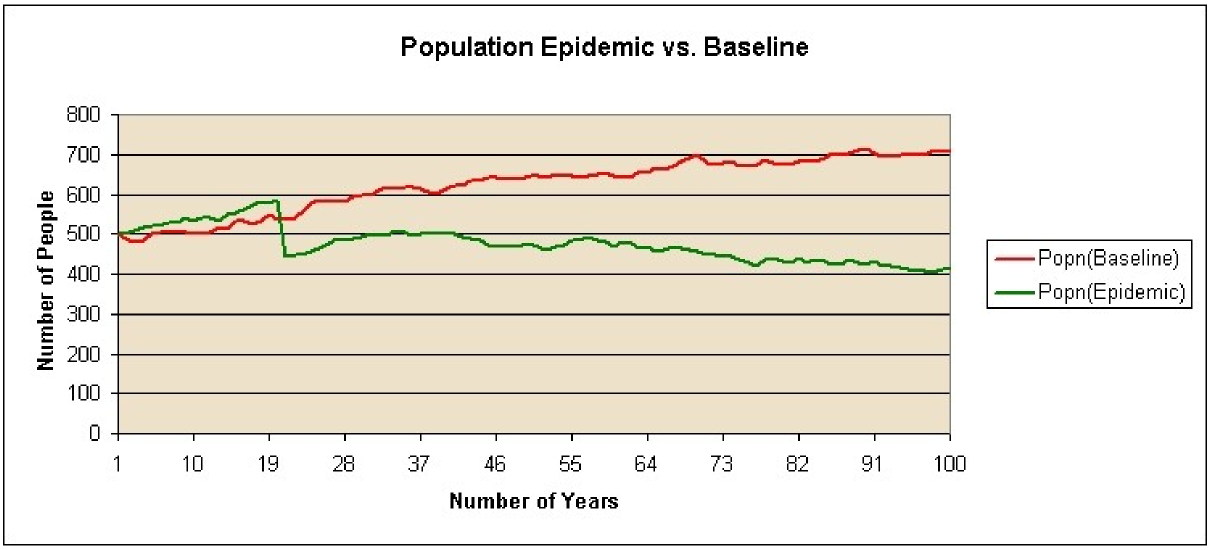


Fig. 11.23 Settlement population trends in the epidemic case (below) and the baseline case (above).

Within fifteen years of the epidemic – that is, at about the age when most of the young victims would have grown into productive adults – the losses for that age group began to exert a more severe effect on the settlement. This would have resulted in labor shortages and an 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) which substantially compromised some households' resilience to stress. As a result of the greater food stresses caused by declining labour resources, the overall volume of economic exchanges among households increased, particularly in the last 35 years of the simulation (Figure 11.24).

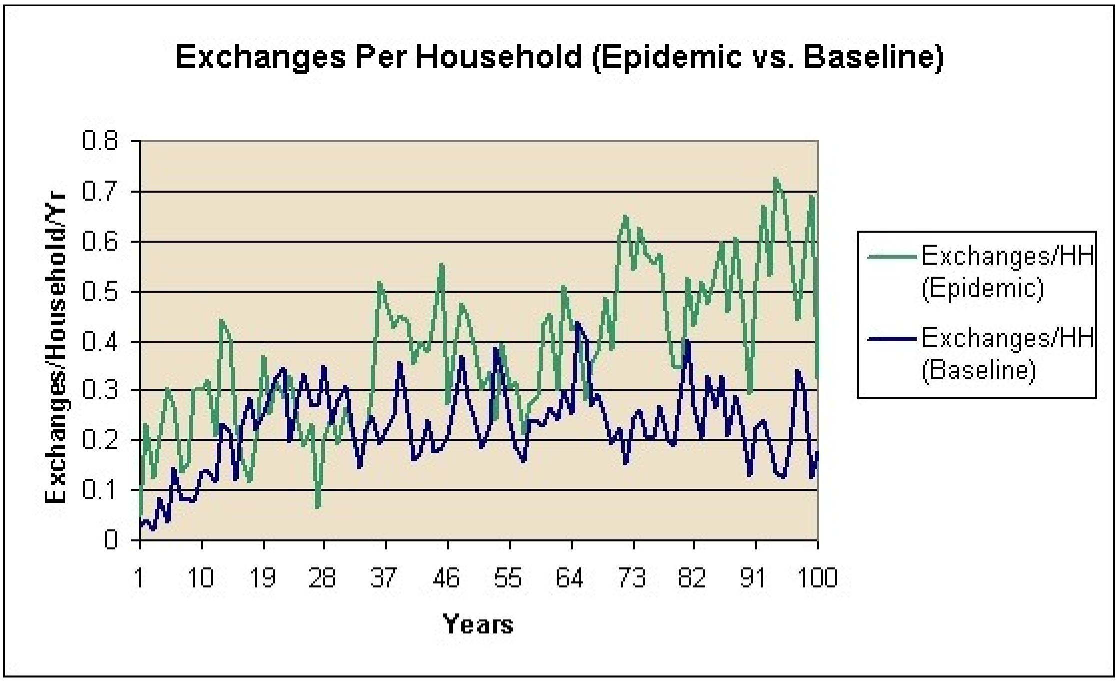


Fig. 11.24 Number of exchanges for the epidemic case (top line) and baseline case (lower line). Note that the modeled epidemic occurred in year 20 of the simulation.

One impact of the disease was that the missing children left gaps in the continuity of families across generations. This reduced the average number of close kin households that a household could call upon for non-reciprocal assistance by about 20% when compared to pre-epidemic levels. Consequently, by year 95 no household had more than four kin-household connections, whereas in the same period for the baseline case some households had seven kin-related households. In other words, the emigration of many households due to failure to cope with food stress significantly eroded the inter-household kinship network.

The diphtheria scenario clearly demonstrates how short-term population shocks can have significant impacts on long-term population trends. Of course, cultural behaviors could have changed this dynamic, specifically if immigration was able to help replenish the population. However, the main point of this example is that population trends cannot be easily predicted without looking at concurrent interactions of social and natural systems. It is also crucial to note that short term shocks can have rather long term impacts on population trends.

Interpretations and commentary

Although diphtheria may not be the ideal disease to use in this simulation, because it is a soft tissue disease and is not therefore recognized in skeletal remains,[15] other contagious diseases could have a similar impact. In fact, as argued by Barnes *et al.* , 'infectious disease loads became an increasingly important cause of human mortality after the advent of urbanization, highlighting the importance of population density in determining human health and the genetic structure of human populations'(2010: 1). Moreover, because the disease reduced kinship networks, the exchange networks also appear to have been reduced and so that the ability of the community to survive shocks was similarly reduced. In fact, the demographic transition associated with urbanism may have had several components, among them being the immigration of people to fuel urban growth, and a secondary counteracting process resulting from infectious diseases which reduced populations significantly. As a result of such diseases, immigration of population (or increased birth rates) would have been essential to sustain urban growth: it can therefore be inferred that if these processes stopped, then population would eventually decline. The simulation results for diphtheria therefore represent only a part of the demographic processes influencing urban growth.

Kin networks and sustainability of communities
(Christiansen & Altaweel 2006b)

In addition to basic sustenance, the MASS simulations were constructed to incorporate kin networks and links between household agents as much as possible (see Household Diaries, above). Such networks, which enabled household agents to freely exchange products at will, specifically operated when a household experienced food stress. Not only did this provide a buffer for households, but also allowed them to continue to function when the household budget was showing a deficit. In extreme cases, such stresses manifest themselves in the use of alternative 'famine foods', as is frequently demonstrated in the ethnographic literature (Mortimore 1998: 112).

The operation of social and kinship networks can be illustrated by the overall community-level food stress. This is measured as the net deficit in terms of food requirements for members of the settlement (Christiansen & Altaweel 2005: 23-24). This measure records food shortfalls for households that fail to obtain sufficient food reserves at any point in a given year. In other words, *all* food available for a household is converted into equivalent kilograms of grain, and then the kilograms needed are subtracted from the kilograms available. This conversion is necessary because food can be obtained not only from agricultural production of cereals and lentils, but also from livestock, hunting, fishing, dairy production, and the collection of wild plants, etc. By converting all food quantities to the equivalent in terms of kilograms of grain it is possible to provide a standardized overall measurement. For example, if a household slaughtered a sheep, the meat produced would then be converted into equivalent kilograms of barley grain.

[15] Charlotte Roberts pers. comm. 27th Feb. 2013

The outcome of one 100-year simulation is shown on the deficit grain graph (Fig. 11.25). Here, although food deficits for some households increased after the beginning of the simulation, this deficit did not increase steadily, as might be expected for a population that had greater emigration rates during the second 50 years of the simulation. Instead, a major factor that caused households and people to emigrate was the loss of links in their network of kinship connections over time. This is indicated by the overall number of kinship connections within the community: for year 35 the number of connections was 349 (that is, 2.4 close kin-households per household), whereas by year 95 there were only 206 connections (i.e., 1.5 close kin-households per household). With fewer kinship connections, any given household that was in deficit would have diminished opportunities for obtaining loans or exchanging products, with the result that even a small food crisis could cause individuals to 'emigrate' out of the simulation, since there would be fewer bilateral kin members on hand to help struggling individuals (Christiansen & Altaweel 2006b: 24).

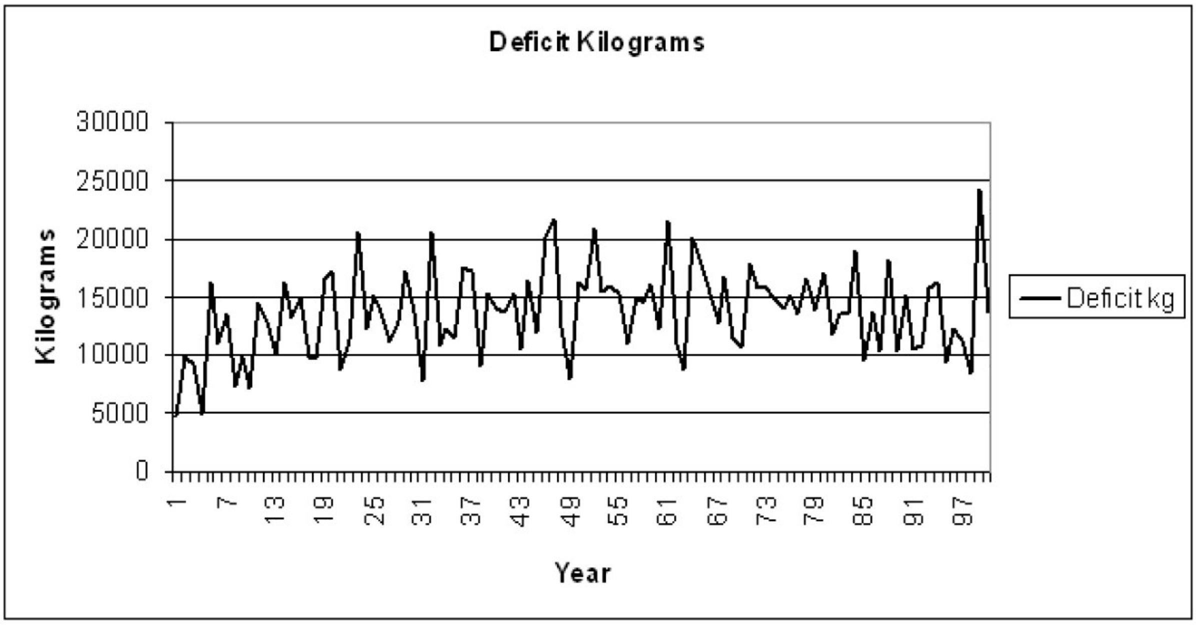


Fig. 11.25 Graph showing deficit kilograms of grain (or food converted into grain kilograms) for the overall simulated settlement.

Comments and Interpretations

It appears from this scenario that a food deficit alone (or greater overall community food stress) is not necessarily the sole cause of higher emigration rates and lower community sustainability. The diminished capacity of the social networks plays a crucial role by reducing the capacity of the community, in general, to redistribute products between households in times of crisis.

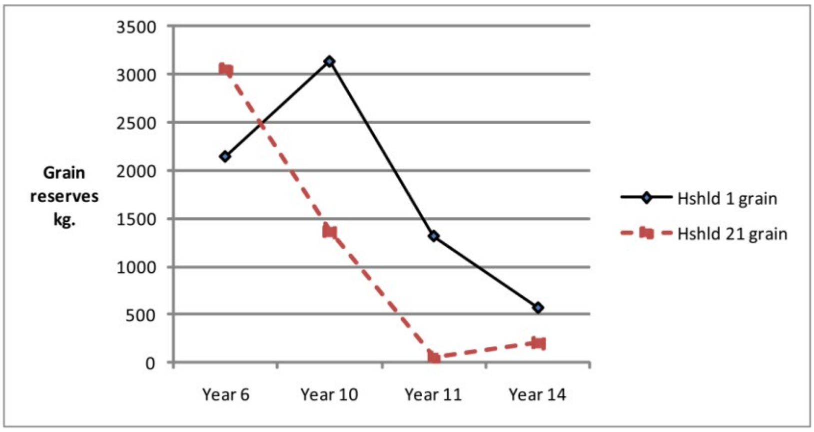
Other simulations demonstrate the importance of social and kin-based networks in the household economy. For example, the *Village Ecodynamics Project* demonstrates that those simulations which include a built-in kinship social network were able to support larger populations than was the case where no resources could be exchanged among kin (Kobti 2012).

Of course, it is possible to dismiss the uses of social networks presented here as overly functionalist and economic. Although to some degree this critique may be valid, it must be emphasized that the social and kin-based networks embedded in the ENKIMDU model represent only the first step in the development of such networks. The existing networks within the model readily provide the foundations for more sophisticated networks of information flow, in which the information stored via the network can be seen as a form of social or collective memory. Moreover, those individuals occupying the hubs of such networks or key positions within the network of collective memory can then develop their roles as brokers and facilitators (Webb & Bodin 2008: 109). Such relationships must surely provide the foundations for social and political power which, when scaled up, provide the core of emergent political hierarchies.

ECONOMIC & SOCIAL FACTORS

Rich-get-richer affects
(Wilkinson *et al.* 2007b; Chapter 12)

One scenario tested by the agent-based models was one in which the more affluent households would become richer and gain more resources than those that started with fewer resources (the so-called 'Matthew Effect'; see Adams 2001: 354). Although this effect is evident in some simulations, small details in individual family case histories can make a significant difference to the outcome. For example, in the above-mentioned discussion of two households during the corvée case, Household 1 – which before the withdrawal of labour had fewer resources – was in a better position to sustain itself when the crisis started in year 10 (Fig. 11.26). Significantly, it also had a larger kin-network to draw upon when required, which provided an essential buffer during the crisis. On the other hand, the seemingly more affluent Household 21, which held more livestock and grain reserves in year 6, was badly situated when the corvée episode hit, and this together with its limited kinship network hastened its ultimate demise (Fig. 11.21).



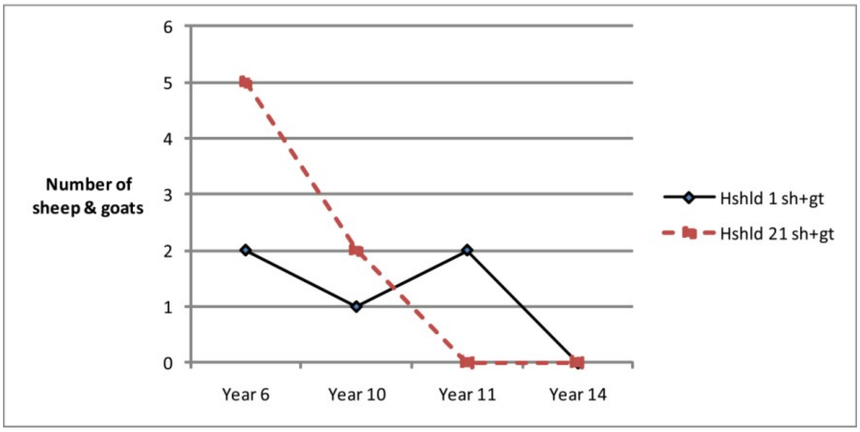


Fig. 11.26 a) Grain reserves of Households 1 and 21 during the corvée crisis, b) Total household sheep and goats for the same two households.

This is an informative guide to the uncertain outcomes of agent-based models. First, in this case, the better provisioned household (21) ultimately failed, in part because of its weaker kin-network, and by so doing although it dropped out of the simulation, it would under appropriate circumstances perhaps have become a member of a larger institution which would then have become richer as a result of the increased labour. Household 21 may therefore have been reduced to the status of those semi-free households (*guruš/geme2*) which became reduced by debt or poverty to the point that they became indentured to one of the great institutions (Gelb 1965; Stein 2005: 133).

One of the key questions asked of the models is: under what circumstances did the households increase their holdings of sheep and goat (especially the former), which were capable of supplying large quantities of wool? Probably the best example of increasing returns from sheep came from the nomad-sedentary model (Chapter 12) where there was a selective accumulation of silver and livestock within a small number of sedentary households – in this case, those households which started off with more resources. However, the significance of this exchange varied seasonally.

The results from the modeling has shown that during a drought there is increased exchange transactions between households, with those households with larger grain reserves being in a better position to exchange spare grain for livestock at favorable terms of exchange (see the above drought scenario). Comparable mechanisms have been recognized during the west African droughts of the 1970s (Mortimore 1989: 55-62) where some households became enriched with livestock, as discussed above. As long as these animals could be fed, they increased in value after the drought. In such cases select families gained more livestock resources. During droughts, the loss of animals would often be differential, with larger stock-holding families retaining or perhaps increasing their livestock, whereas other families, often the poorer ones, would lose their animals entirely (Mortimore 1989: 62). Ultimately, this mechanisms may have contributed to the development of a poor underclass who lacked any household herds or flocks.

Although in some scenarios the numbers of sheep did actually increase, this was because problems in the simulation resulted in crop yields crashing, so that the only outcome for the agent community was to shift their economy to sheep rearing. Such outcomes, although they instruct us about what might eventuate under extreme conditions, can hardly be regarded as realistic.

Commentary
The transfer of wealth within the community as a result of the differential effect of stresses is also evident within the modern world, where rapid increases in the economic gap between the rich and the poor are becoming increasingly evident (Wilkinson & Pickett 2010). Although this process is hardly surprising, it is significant how rapidly such effects appear.

CONCLUSIONS

The above case studies illustrate the types of outcomes that can result from simulations of a single sedentary community. As stated, social networks are crucial to the operation of such settlements, and the associated interactions would have been even richer if it had been possible to undertake simulations for a whole system of interlinked communities (as laid out in Figure 10.3). Unfortunately this was not possible. However, thanks to the work of Altaweel and Paulette, it was possible to effect a series of simulations which examined the interactions between a sedentary community and visiting pastoral nomads, as is discussed in the following chapter (Chapter 12).

REFERENCES

Adams, R. McC. (2001). Complexity in Archaic States. *Journal of Anthropological Archaeology* 20: 345-360.

Altaweel, M. (2008). Investigating agricultural sustainability and strategies in northern Mesopotamia: Results produced using a socio-ecological modeling approach. *Journal of Archaeological Science* 35(4): 821-835.

Altaweel, M., & Watanabe, C. (2012). Assessing the resilience of irrigation agriculture: applying a social-ecological model for understanding the mitigation of salinization. *Journal of Archaeological Science.* 39(4): 1160-1171.

Arab, G., (2007). Socio-economics of Halula region (Middle Euphrates, Syria). In R.B. Capdevilla & M. Molist Montaña (eds.), *MENMED: From the Adoption of Agriculture to the Current Landscape: Long-term interaction between Men and Environment in the East Mediterranean Basin*, pp. 107-140. Barcelona: Monografies 9, Museu d'Arqueologia de Catalunya .

Arnold, J.G., & Allen, P.M. (1992). A comprehensive surface-groundwater flow model. *Journal of Hydrology* 142: 47-69.

Arnold, J.G., Srinivasin, R., Muttiah, R.S., & Williams, J.R. (1998). Large area hydrologic modeling and assessment. Part I: Model development. *Journal of the American Water Resources Association* 34(1):73-89.

Bagnall, R.S. & Frier, B.W. (1994). *The Demography of Roman Egypt*. Cambridge: Cambridge University Press.

Bar-Matthews, M. & Ayalon, A. (2011). Mid-Holocene climate variations revealed by high-resolution speleothem records from Soreq Cave, Israel and their correlation with cultural changes. *Holocene* 21(2): 163-172.

Barnes, I., Duda,A., Pybus,O.G., & Thomas, M.G. (2010). Ancient urbanization predicts genetic resistance to tuberculosis. *Evolution:* 1-7.

Biga, M. G. (2010). Textiles in the administrative texts of the royal archives of Ebla (Syria, 24th Century BC) with particular emphasis on coloured textiles. In C. Michel & M.-L. Nosch (eds.), *Textile Terminologies in the Ancient Near East and Mediterranean from the Third to the First Millennia BC*, pp. 146-72 Oxford: Oxbow.

Bryce, T. (2012). *The World of the Neo-Hittite Kingdoms. A Political and Military History.* Oxford: Oxford University Press.

Carley, K.M., Prietula, M..J, & Lin, Z. 1998. Design versus cognition: the interaction of agent cognition and organizational design on organizational performance. *Journal of Artificial Societies and Social Simulation*. 1(3).

Carmichael, A.G. (1993). Dipheria. In K. F. Kiple (ed.) *The Cambridge World History of Human Disease*, pp. 680-683. Cambridge: Cambridge University Press.

Cherry, J.D. (1993). Croup. In K. F. Kiple (ed.) *The Cambridge World History of Human Disease*, p.656. Cambridge: Cambridge University Press.

Chisholm, M. (1962). *Rural Settlement and Land Use*. London: Hutchinson.

Christiansen, J. H. & Altaweel, M. R. (2006a). Understanding ancient societies: A new approach using agent-based holistic modeling. *Structure and Dynamics: eJournal of Anthropological and Related Sciences 1(2), article 7. http://repositories.cdlib.org/imbs/socdyn/sdeas/vol1/iss2/art7/.*

Christiansen, J.H. & Altaweel, M. (2006b). Simulation of natural and social process interactions: An example from Bronze Age Mesopotamia. *Social Science Computer Review 24(2): 1-17.*

Edmeades, D.C. (2003). The long-term effects of manures and fertilisers on soil productivity and quality: a review *Nutrient Cycling in Agroecosystems* 66: 165–180.

Ferrio, J.P., Voltas, J., & Araus, J.L. (2007). Reconstruction of agronomic conditions: the results of Carbon isotope composition ($\delta^{13}C$) in charred crop grains. In R.B. Capdevilla & M. Molist Montaña (eds.), *MENMED: From the Adoption of Agriculture to the Current Landscape: Long-term interaction between Men and Environment in the East Mediterranean Basin*, pp. 49-51. Barcelona: Monografies 9, Museu d'Arqueologia de Catalunya.

Fraser, R., Bogaard, A., Heaton, T., Charles, M., Jones, G., Christiansen, B.T., Halstead P., Merbach, I., Poulton, P.R., Sparkes, D. & Styring. A. (2011). Manuring and stable nitrogen isotope ratios in cereals and pulses: towards a new archaeological approach to the inference of land use and dietary practices. *Journal of Archaeological Science* 38 (10): 2790-2804.

Gallant, F. (1992). *Risk and Survival in Ancient Greece: Reconstructing the Rural Domestic Economy*. Stanford CA: Stanford University Press.

Gelb, I. (1965). The Mesopotamian ration systems. *Journal of Near Eastern Studies* 24(3): 230-43.

Gelb, I. J. (1986). Ebla and Lagash: Environmental Contrast. In H. Weiss (ed.) *The Origins of Cities in Dry-farming Mesopotamia in the Third Millennium B.C,* PP. 157-67. Guilford, CT: Four Quarters Publications.

Hardy, I.R.B. (1998). Diphtheria. In A.S. Evans & P. S. Brachman (eds.) *Bacterial Infections of Humans: Epidemiology and Control*, pp. 253-268. Portland: Plenum Press.

Johns, C.H.W. (1901). *An Assyrian Domesday Book, or Liber Censualis of the District Round Harran in the Seventh Century BC*. Assyriologische Bibliothek 17. Leipzig: J.C. Hinrichs.

Kauffman, S.A. (1993). *The Origins of Order*: *Self Organization and Selection in Evolution*. Oxford: Oxford University Press.

Kennedy, W.G. (2012). Modelling Human Behaviour in Agent-Based Models. In A.J. Heppenstall, A.T. Crooks & L.M. See (eds.), *Agent-Based Models of Geographical Systems,*pp. 167-179. Dordrecht: Springer.

Kobti, Z. (2012). Simulating household exchange with cultural algorithms. In Kohler, T.A. & M.D. Varien (eds.) Emergence and Collapse of early Villages: Models of Central Mesa Verde Archaeology, pp. 165-174. Berkeley: University of California Press.

Kleinman, L.C. (1992). To end an epidemic. Lessons from the history of Diphtheria. *New England Journal of Medicine* 326: 773-777.

Loomis, R.S. (1983). Crop manipulations for efficient use of water: an overview. In H.M. Taylor, W.R. Jordan & T.R. Sinclair (eds.) *Limitations to Efficient Water Use in Crop Production,* pp. 345-74. Madison WI: American Society of Agronomy.

McNeill, J.R. (2010). Sustainable survival. In P.A.McAnany & N. Yoffee (eds.) *Questioning Collapse: Human Resilience, Ecological Vulnerability, and the Aftermath of Empire*, pp. 355-366. Cambridge: Cambridge University Press.

Mortimore, M. (1989). *Adapting to Drought: Farmers, Famines and Desertification in West Africa*. Cambridge: Cambridge University Press.

Mortimore, M. (1998). *Roots in the African Dust. Sustaining the Drylands*. Cambridge: Cambridge University Press.

Neitsch, S.L. Arnyold, J.G., Kiniry, J.R., Williams, J.R., & King, K.W. (2002). S*oil and Water Assessment Tool Theoretical Documentation, Version 2000*. Temple, TX: Blackland Research Center.

Oppenheim, A.L. (1964). *Ancient Mesopotamia: Portrait of a Dead Civilization*. Chicago: University of Chicago Press.

Plotkin, H., (1994). *The Nature of Knowledge*: *Concerning Adaptations, Instinct and the Evolution of Intelligence*. London: Penguin Press.

Schloen, D. (2001). *The House of the Father as Fact and Symbol: Patrimonialism in Ugarit and the Ancient Near East*. Winona Lake, IN: Eisenbrauns.

Stein, G. (2005). 'Invisible' social sectors in Early Mesopotamian State Societies. In V.L. Scarborough (ed.*)* *Catalyst for Ideas: Anthropological Archaeology and the Legacy of Douglas W. Schwartz*, pp. 121-48. Santa Fe, NM: School of American Research Press.

Ur, J.A. (2010). Cycles of Civilization in northern Mesopotamia, 4400-2000 BC. *Journal of Archaeological Research* 18: 387-431.

Wade-Martins, S. (1995). *Farms and Fields.* London: Batsford.

Webb, C. & Bodin, Ö. (2010). A network perspective on modularity and control of flow in robust systems. In J. Norberg, J. & G.S. Cumming (eds.) *Complexity Theory for a Sustainable Future*, pp. 85-118. New York: Columbia University Press.

Widell, M. (2004). Some Observations on the Administration, Agriculture and Animal Management of Tell Beydar. *Ugarit-Forschungen* 35:717-733.

Widell, M. (2007). Historical Evidence for Climate Instability and Environmental Catastrophes in Northern Syria and the Jazira: The Chronicle of Michael the Syrian. *Environment and History* 13: 47–70.

Wilkinson, T.J. (1989). Extensive sherd scatters and land-use intensity: some recent results. *Journal of Field Archaeology* 16(1): 31-46.

Wilkinson, T.J. (1990). *Town and Country in SE Anatolia vol.1: Settlement and Land Use at Kurban Höyük and Other Sites in the Lower Karababa Basin*. Chicago: Oriental Institute Publications 109.

Wilkinson, T.J. (2000). Settlement and Land Use in the Zone of Uncertainty in Upper Mesopotamia. In R. Jas (ed.), *Rainfall and Agriculture in Northern Mesopotamia*, pp. 3-35. Leiden: Nederlands Historisch-Archaeologisch Instituut.

Wilkinson, T.J., Miller, N.F., Reichel, C.D. & Whitcomb, D. (2004). *On the Margin of the Euphrates: Settlement and land use at Tell es-Sweyhat and in the Upper Lake Tabqa Area, Syria.* Oriental Institute Publications 124. Chicago: University of Chicago.

Wilkinson, T.J., Christiansen, J. H., Ur, J. A., Widell, M. & Altaweel, M. (2007a). Urbanization within a Dynamic Environment: Modeling Bronze Age Communities in Upper Mesopotamia. *American Anthropologist*. 109 (1): 52-68.

Wilkinson, T.J., Gibson, M., Christiansen, J.H., Widell, M., Schloen, D., Kouchoukos, N., Woods, C., Sanders, J., Simunich, K.-L., Altaweel, M., Ur, J.A., Hritz, C., Lauinger, J., Paulette, T. & Tenney, J. (2007b). Modeling settlement systems in a dynamic environment: case studies from Mesopotamia. In T. A. Kohler & S. E. van der Leeuw (eds.) *The Model-Based Archaeology of Socio-Natural Systems*, pp. 175-208. Santa Fe, NM: School for Advanced Research Press.

Wilkinson,T.J., Galiatsatos, N., Lawrence, D., Ricci, A., Dunford, R., & Philip, G. (2012). Landscapes of settlement and mobility in the Middle Euphrates of Turkey and Syria during the Late Chalcolithic and Early Bronze Age: a re-assessment. *Levant* 44 (2): 139-85.

Wilkinson, R., & Pickett, K. (2010). *The Spirit Level: Why Equality is Better for Everyone*. London: Penguin Books.

Zubrow, E., & Robinson, J. (1999). Chance and the human population: population growth in the Mediterranean. In J. Bintliff & K. Sbonias (eds.) *Reconstructing Past Population Trends in Mediterranean Europe*, pp. 133-44. The Archaeology of the Mediterranean Landscape 1. Oxford: Oxbow.