# Chapter 9
# Understanding the Iron Age Economy: Sustainability of Agricultural Practices under Stable Population Growth

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## 9.1 Introduction

When searching for the explanation of subsistence strategies in different social groups of a complex society, the key factor is the relationship between its agricultural base and the social hierarchy of settlements. Due to the fragmented nature of data available such presumptions were mostly only theoretical and often failed to effectively capture the complexity of the system under consideration. As a consequence, we have only a limited picture of how societies may have functioned in past. In order to capture the whole complexity of subsistence, more sophisticated methods and tools are needed.

Recent studies show that, on top of a comprehensive collection of data, the building of explanatory models is a valid way of exploring the complexity of past societies (e.g. Kohler and van der Leeuw 2007). Models are valid scientific tools, which not only can help to understand human-landscape interactions and processes of change, but are also very powerful for suggesting directions for future research (Wainwright 2008), by challenging traditional ideas and exploring new issues (Wright 2007, p. 231). At the same time, models do not attempt to become exact reflections of the past reality; they just aim to provide more precise research questions, select appropriate attributes and factors to be further examined on an accurate spatial and temporal scale. This framework can be used to investigate socio-ecological interactions over a broad range of social, spatial and temporal

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scales, allowing for a wide range of past archaeological issues to be addressed. Agent-based models (ABM) provide an invaluable way to explore and test various theoretical hypotheses, including cases where detailed data is not available from the archaeological record.

This chapter deals with the subsistence strategies and the economic background of late Iron Age oppida in central Europe, the fortified agglomerations occupied in the last two centuries BC. Oppida settlements represent complex systems (societies) with multiple functions. They appeared as a part of an economically advanced environment, together with a distinctive intensification of settlement patterns. However, the oppida were mostly built in landscapes considered to have been marginal in regard to what appeared to be the common settlement strategy. Due to the specific location and the widespread evidence of late La Tène open lowland settlements (which were believed to supply the oppida with the necessary food resources) the agricultural potential of the oppida has usually been challenged (e.g. Salač 2000, 2006). According to the archaeological record, their settlement density in the late La Tène period increased over a short time span and then decreased again. This probably quite rapid depopulation and collapse of these agglomerations during the second half of first century BC was attributed, among all, to a supply crisis. In short: the oppida agglomerations were perceived as too "specialized" and therefore engaged in other activities than agriculture. Because of that, they were not capable of producing sufficient food. This fact should have eventually contributed decisively to the collapse of the La Tène social structure as a whole. Interestingly though, the archaeological record reveals clear signs of some engagement in agricultural production—by the evidence of crops cultivation, livestock breeding or traditional agricultural household units (cf. Küster 1993; Danielisová and Hajnalová in print). Therefore, the idea of the oppida acting as pure receivers of the agricultural products needs reconsideration. Causes for a gradual depopulation trend of the fortified settlements can be attributed to several factors both endogenous and exogenous. However, beside political (reaction to the military events), economic/commercial (difficulties on long distance commercial routes) and organizational (less people to perform necessary tasks), the ecological/subsistence problems are worth contemplation as well.

The relationship between population growth and the development of the society depends on the availability of basic resources from the environment; however, this relationship is in fact never constant. In the models of social complexity, which include and interconnect innovation, specialisation, political structure, market integration, but also migration, changes in settlement patterns and abandonment of settlements, population growth and over-exploitation of natural resources play an important role from which wide range of social phenomena have been explained (Bayliss-Smith 1978, p. 130). According to historical sources, exceeding the appropriate carrying capacity was not a rare occasion in history (cf. Schreg 2011, p. 312) even in societies with developed market networks. Intensification of production led to innovations in agriculture on the one hand, but also to a more rapid depletion of the land resources, especially where their extent was limited, on the other hand. This prompted behaviour which could have led to more profound social change at the end of the Iron Age in central Europe. Our main objective is to approach this issue by the modelling of population dynamics, and subsequently by the modelling of agricultural strategies and socio-economic interactions. This chapter presents the initial models focused at the moment on the oppidum's own agricultural production, i.e. a society pursuing agro-pastoral activities within the given temporal and spatial scale which is tested against subsistence, surplus production and carrying capacity factors. We aim to find the limit of the environment for the growing population at a certain point of time. Some of the fundamental questions being asked at that stage include:

1. Using what cultivation strategies can the population most effectively exploit natural resources in order to be self-sufficient?
2. What are the dynamics of production with constantly growing population (subsistence—surplus—success rate—diminishing returns)?
3. What is the maximum population that can be sustained in a given environment and when was this maximum reached?

In order to credibly recreate the economic life of an agglomeration in its specific environment, a coupled environmental and social modelling approach is employed. In more detail, we incorporate a GIS model representing the environmental conditions and an agent-based model addressing social issues (the population dynamics) and land-use patterns. As outcome, these models can provide substantial information about the limits of rural economy at a particular location and they may help to determine possible stress situations. As result we may be able to explain the reason for population decline, in case it was caused by reaching the limits of food production.

## 9.2 Methodological Approach

### *9.2.1 Theoretical Framework*

The relationship between population growth and development of the society depends on the availability of basic resources from a given unit of land, the ability of the population to exploit them as well as to socially organise this process. In this chapter, some models of interactions between the settlement and its natural environment are applied, including "settlement ecosystems" (the systems of land use based on the relationship between the landscape and human decision how to exploit it, cf. Ebersbach 2002), "population pressure" (the point in population growth when it is larger than the resource base, e.g. Bayliss-Smith 1978) and "carrying capacity" (the limit above which the population must either diminish or innovate their exploitation strategies, cf. Del Monte-Luna et al. 2004). All of these concepts will be tested against archaeological and environmental data. As precondition, we must define resource levels of the ecosystems (i.e. productivity of the land), productivity potential of the population exploiting these resources (i.e. labour input, technology and task management) and test if and under what conditions certain resources can become limiting factors, and what implications can be derived from that (e.g. adoption of new subsistence strategies, new technologies, commercial contacts, social transformations, settlement abandonment etc.).

By modelling subsistence strategies, we seek to explore the following questions:

- the size of the community and proportion of people engaged in agricultural work
- the organisation of the working process
- demands concerning land and labour
- the carrying capacity threshold
- the scale of sustainable agricultural production
- the stability of production (number of stress situations)

The theoretical framework for modelling the oppidum's own agricultural production encompasses the following tasks:

1. Modelling the population and its subsistence needs:
    a. Estimating the population size and its dynamics due to demographic processes.
    b. Estimating the available work force in relation to the population dynamics.
    c. Calculating the annual nutrient demands of the population.
2. Modelling crucial resources:
    a. Deliminating the maximum distance people would have been willing to go in order to cover their subsistence needs.
    b. Predicting the hinterland components (fields, fallows, pastures, woodlands etc.) according to the environmental conditions (a non-continuous pattern of arable land use zones).
    c. Organization of the working process in relation to the land-use patterns.
    d. Within the predicted hinterland, there should not be any competing sites (considered as contemporary), otherwise we would have to: (1) enlarge the settlements' catchment area, (2) consider a cooperative/competitive relationship between multiple sites.
3. Modelling resource exploitation and assessing its limits:
    a. Estimating the energy potential of key resources (yields of fields, pastures, fodder, woodlands . . .).
    b. Outlining possible exploitation and production strategies.
    c. Comparing the number of consumers and their needs in relation to the production.
    d. Relating the labour input to the production.
    e. Determining possible insufficient or lacking resources or productivity (labour input) and the impact of that factor.

4. Modelling the dynamics of the production:
   a. Including the fluctuations of the harvests according to different farming strategies.
   b. Measuring the actual levels of harvest, surplus and potential storage reserves.
   c. Determining the agricultural sustainability (number of stress situations).
   d. Detecting the limit threshold, estimating the carrying capacity of the hinterland in relation to the population pressure and the potential scarcity or depletion of resources.
   e. Count in the external factors, if there were any (climate variations, conflicts, socio-political decisions).

### *9.2.2 Modelling Tools*

In context of our agent-based modelling approach, agents may represent individuals, families and collectives, management agencies, and policy making bodies, all of whom are able to make decisions or take actions that affect development of the society and changes the environment. Because agent-based models are time-based, the development of the society can be studied for over 100 years in course of its evolution. Components of models include ecological, socio-economic and politico-cultural parameters addressing individual questions, which can be developed and implemented gradually by producing models that target individual questions separately.

Models are implemented in the agent-based modelling software package Netlogo (Wilensky 1999), its plug-ins and extensions:

- *BehaviorSpace* enables repeated run of simulations with different settings of parameters. Output data can be stored and further processed using statistical toolkits.
- *BehaviorSearch* (Stonedahl 2011) is a tool which allows automated search for (near) optimal values of parameters of models with respect to objective function. The search process is performed with evolution computation techniques, which are widely used for optimization problems. The nature of the algorithm does not guarantee that the calculation always converges to the global optimum, but on the other side, it is general enough to be able to solve wide scale of problems. For demonstration of BehaviorSearch, see the replication of the "Artificial Anasazi" Project (Stonedahl and Wilensky 2010).
- *Fuzzy-plug-in* (Machálek et al. 2013) provides fuzzy-related functionality. It is based on a FuzzyLogic library by Cingolani and Alcalá-Fdez (2012). The plug-in was implemented for the purpose of our research.

The advantage of the simulation process lies in a relatively fast transcription of parameters into the programming language. Many different scenarios can be created by alteration, adaptation and combination of the input data. Therefore, we can aspire to simulate quite complex phenomena (such as the "agricultural year"). A more difficult task is the definition of relevant research questions, isolation of valid parameters and the actual definition, execution, evaluation and recurrent adaptation of the created models (also see Chap. 4). Outputs can be compared to a broad framework of data established by combining the results from archaeological excavations, archaeological surveys and regional-scale environmental studies.

## 9.3 Data Resources and Modelling Inputs

The models are based on the region around the oppidum of Staré Hradisko (Czech Republic). It offers quite complex archaeological and environmental data and analyses carried out upon the material collected during the long-term excavations (cf. Čižmář 2005; Meduna 1961, 1970a,b; Danielisová 2006; Danielisová and Hajnalová in print). Sections 9.3.1–9.3.4 summarise the sources of the environmental input variables and agricultural production processes used in our study.

### *9.3.1 Environmental Data and Ecology*

Given all the required input parameters for the modelling of the landscape exploitation, the most relevant data that reflected the oppidum's setting needed to be obtained (cf. Table 9.1). Because detailed LIDAR scans were not available for this location, a digital elevation model (DEM) of the relief was computed using local

**Table 9.1** Environmental input variables

| Environmental variables | Source |
|---|---|
| Relief (digital elevation model—DEM) | Modelled in GIS from 1:5,000 topographical maps (ArcGIS, resolution 5 × 5 m) |
| Landforms, topographical features, topographic wetness index | Modelled in GIS from DEM (ArcGIS, IDRISI, Whitebox, Landserf) |
| Hydrology | Modelled in GIS from DEM and complemented by fluvial sediments in geological maps and historic mapping (ArcGIS, manual correction) |
| Geology and soils | Digitised from geological and soil maps 1:50,000 |
| Soil quality | BPEJ soil evaluation |
| Potential vegetation | From Neuhäuslová (2001) |
| Climate | Macrophysical Climate Model (MCM) created from local meteorological data, cf. Bryson and DeWall (2007), Danielisová and Hajnalová (in print) |
| Weather | Recorded historic frequency of the "events" (hailstorms, late frosts, heavy rains . . .), from Brázdil et al. (2006) |

contour maps. The DEM data were used to form secondary variables such as the terrain settings, the location of landforms (slope gradient, aspect, local elevation difference), and the topographical features. The hydrologic settings were derived from DEM and completed by the geologic and historic mapping in order to recreate (as closely as possible) the original stream network irretrievably altered by current agronomic practices (e.g. melioration). Location of streams can help to predict the location of settlements and the activities requiring the proximity of water source (e.g. pastures). Hydrologic modelling was used as well to the computation of the topographic wetness index. This variable describes the propensity for a land plot to be saturated by the runoff water, given its flow accumulation area and local slope characteristics (Lindsay 2012). It is used to locate the areas (from the topographical point of view classified simply as flat) with tendency to be wet or dry. Soil coverage, geology and the potential vegetation should also contribute, as input data, to addressing the agricultural potential of an area.

It should be noted that these variables are interconnected. Since one is often derived from the other, their impact can multiply in GIS modelling. Geology was therefore used to delimit the individual structures (alluvial plains, rocks etc.) and potential vegetation served as secondary evidence to the soil data. Suitability of the soils for farming is measured by the soil type (light Cambisols, Gleys or Pseudogleys, colluvial deposits and fluvial deposits in the floodplains), the amount of humus, their depth and rockiness, accessible through the so-called BPEJ evaluation of the farmland. Modelled local MCM (Macrophysical Climate Model) mean annual temperatures and annual precipitation for the oppidum of Staré Hradisko showed warmer and to a certain extent also wetter conditions during the occupation of the oppidum in comparison to modern times (Danielisová and Hajnalová in print). This model also addresses the potential evapotranspiration, calculated from the annual temperature and precipitation. It reflects the general tendency of the climate to be “more wet” (colder, wetter) or “more dry” (warmer, less precipitation) which can influence the location of the farming plots (e.g. avoiding the wet plains etc.).

### *9.3.2 Socio-Economic Variables*

The occupational span of the oppidum is around 150 BC to 50–30 BC, i.e. ca. 100–120 years of existence. According to the chronologically significant material (cf. Table 9.2), the population density was increasing during the initial 2–3 generations (50–80 years), until it reached the point when it started to decrease again (ca. 80–70 BC). This decline seems to have been quite rapid (1–2 generations); the final population might have been even five times smaller than during its highest density. Concerning exact numbers, unfortunately, only approximate data is available, but given the archaeological evidence (number of households, chronologically significant artefacts) the initial population density should have certainly comprised several hundreds of people.

**Table 9.2** Input variables and information on the anthropogenic aspects of the models (for the definition of "strongforce" and "weakforce" see Sect. 9.4.1)

| *Population and economical structures* | |
|---|---|
| Social/economic variable | Source |
| Population density | Settlement structure vs. chronology of occupation (personal items—e.g. brooches, frequency of coins, amounts of refuse in settlement stratigraphy, number of households) |
| Cultivated crops | Archaeobotanical collection (Hajnalová 2003) |
| Storage devices | Settlement structure (Danielisová 2006) |
| Stock keeping | Archaeozoological collection (Peške, unpublished data) |
| Agricultural tools (ploughshares, hoes, harrows, scythes, leaf foddering knives, rotary querns) | Material collections (Meduna 1961, 1970a,b; Čižmář 2005; Danielisová and Hajnalová in print) |
| Distance costs and hinterland area | Walking distance from the settlement (Chisholm 1979), algorithm (Gorenflo and Gale 1990) |
| Settlement ecosystems | Agricultural strategy in relation to the environment and the production goals (Ebersbach 2002; Schreg 2011) |
| *Agricultural practices* | |
| Activity, practice | Source |
| Intensity of land-use (agricultural strategies) | Intensive-extensive-mixed (Bakels 2009; Halstead 1995; Danielisová and Hajnalová in print) |
| Field plot sizes | 0.235–0.94 ha/person including seed corn and losses (Halstead 1987, 1995; Dreslerová 1995) |
| Fallowing | Fields: fallows = 1:3 (Fischer et al. 2010; Halstead and Jones 1989) |
| Crop yields | 700–3,000 kg/ha (Bogaard 2004; Hejcman and Kunzová 2010; Kunzová and Hejcman 2009; Rothamstead Research 2006) |
| Ploughing rates | 0.21–0.42 "strongforce"*/ha (Halstead 1995; Russell 1988) |
| Hoeing, harrowing, weeding rates | 0.85–1.27 "weakforce"*/ha (Halstead 1995; Russell 1988) |
| Manuring | (Minimum) N = 46 kg/ha (Hejcman and Kunzová 2010; Kunzová and Hejcman 2009; Bogaard et al. 2006; Fischer et al. 2010) |
| Harvest and crop processing rates | 0.42 "strongforce" + 0.85 "weakforce"/ha (Halstead 1995; Halstead and Jones 1989; Russell 1988) |

The increasing population trend should be reflected in models of food and fodder production (i.e. the spatial change in the field, pasture, and forest area) as well as in the numbers of livestock.[1] Data derived from the archaeological record are used to create anthropogenic aspects of the models and form model inputs. Ethnographic data can clarify agricultural strategies and processes as well as add new details. Table 9.2 shows an overview of the input variables and their sources.

[1] Livestock-woodland models (currently under development) are not presented in this chapter.

Potential evidence of agricultural activities carried out by the oppidum inhabitants can be indicated by particular material groups, archaeobotanical and archaeozoological assemblages, and settlement features (especially storage facilities), (cf. Danielisová 2006; Danielisová and Hajnalová in print). From the cultivated plants, the majority in the archaeobotanical assemblages is represented by glume species (barley—54 %, and spelt—24 %) and to a lesser extent by free-threshing wheat (13 %). Pulses have also been attested. Enclosed farmsteads at the oppidum revealed clear evidence of surface storage devices (granaries). There is neither the evidence of sunken silos, which would enable long-term storage of cereals, nor communal storage facilities, which would indicate bulk supplying of the whole community. Concerning the provisioning for the individual households, it can be said that they were likely in charge themselves.

### *9.3.3 The Agricultural Hinterland*

All societies in the past aimed at obtaining their necessary natural resources from the immediate vicinity. The method of Site Catchment Analysis (Higgs and Vita-Finzi 1972) was used for modelling the oppidum's hinterland (Fig. 9.1). This approach is based on models of economics and ecological energy expenditure, and provides a framework within which the economic activities of a particular site can be related to the resource potential of the surrounding area. We thus needed to delimit the "easily accessible" area in the site's surroundings, which would have encompassed fields/fallows, pastures, meadows and managed forests. Considering the locational rules of the "least effort models" and the variable topography, the area was modelled as cost distance according to walking speed from the centre (Fig. 9.1a). A formula of travelling velocity $V$ across terrain suggested by Gorenflo and Gale (1990, p. 244) was used to delimit one hour of walking distance:

$$V = 6 \cdot e^{-3.5([\mathit{slope\ in}\ \%]+0.05)}$$

This roughly corresponds to a distance of 4–5 km generally considered as a threshold for the travelling on a daily or semi-daily return (cf. Chisholm 1979, p. 64).

The criteria for the prediction of fields were related to the environmental variables: topography, soils, and climate (cf. Table 9.1 and Sect. 9.3.1). The fields had to be placed on fairly moderate slopes—less than 5°, 5°–10° and 10°–15°[2] respectively. Together with the other variables "aspect", "soils" (quality, depth,

[2]Opinions on how steep slopes are still cultivable quite differ. In the agricultural models it was believed that slopes beyond 7°–10° were not tillable, though this applies especially for the machinery not the manual cultivation (cf. Fischer et al. 2010). These (indeed arbitrary) categories deliberately represent more benevolent option suited for hand tools (<15°) and ploughing animals (<10°).

rockiness), "topography", and "wetness"[3] it was put together through the Multi-Criteria Evaluation analysis (Eastman 2006, pp. 126–134) by which different field suitability categories were created (Fig. 9.1b). The plots classified as unsuitable (too wet, too rocky or on slopes too steep) were excluded from the field model. One of the crucial factors for the prediction of fields was the accessibility from the settlement. Therefore most suitable areas were plotted as the most fertile zones located as close as possible to the settlement. A cost penalty was included in the agricultural model for fields exceeding the distance of 2 km (cf. Chisholm 1979, p. 61). This option applies especially for more intensive regimes of land-use; the cost impact was lower for fields where extensive practices were carried out. Fields within distant zones could have been subjected to different land-use and management types—more intensive closer to the oppidum and more extensive further away (cf. Sect. 9.3.4). The remaining terrain can be attributed to open and forest pastures, forest openings and woodlands.

### *9.3.4 Production Processes*

Labour rates and resources required for each of the agricultural tasks listed in Table 9.2 have been studied (Russell 1988; Halstead 1995; Halstead and Jones 1989 etc.) and can be used for modelling of farming practices. The default presumption for the model is that households used animal traction for cultivating their fields. The actual area of fields, as well as the labour input per unit area, varies greatly according to the number of inhabitants and different arable farming strategies employed. With higher yields during an increasing intensity of cultivation, the area of fields could have decreased and vice versa. High annual harvest fluctuations are apparent in modern agricultural experiments (e.g. Rothamsted Research 2006; Hejcman and Kunzová 2010; Kunzová and Hejcman 2009). Variable annual yields are also being regularly mentioned in the historic records (cf. Campbell 2007; Erdkamp 2005). Therefore, using mean yield estimation in archaeological modelling would provide only a static indication of production. A relative structure of inter-annual fluctuations in the ancient crop yields from a particular area may be established by extrapolating from modern or historical data, preferably from the same region and without estimating any absolute mean value (Halstead and O'Shea 1989, p. 6; Hejcman and Kunzová 2010). A general range between 500 and 3,000 kg/ha (Danielisová and Hajnalová in print) can be considered

[3]The categorization (with decreasing "suitability") of the variables was the following: Aspect: slopes exposed to the cardinal points (from the South to the North); soil quality: Cambisols, Cambisols with Gley, Gleys and Pseudogleys, fluvial deposits in the floodplains; soil depth and rockiness: low, moderate, high (according to the BPEJ land evaluation); topographic wetness index: delimited the areas which were "too wet" (especially in the floodplains; more detailed categorization of this variable will be useful especially for the modeling of the pastures); topography: excluded slopes too steep ($>15°$) or areas too rocky etc.

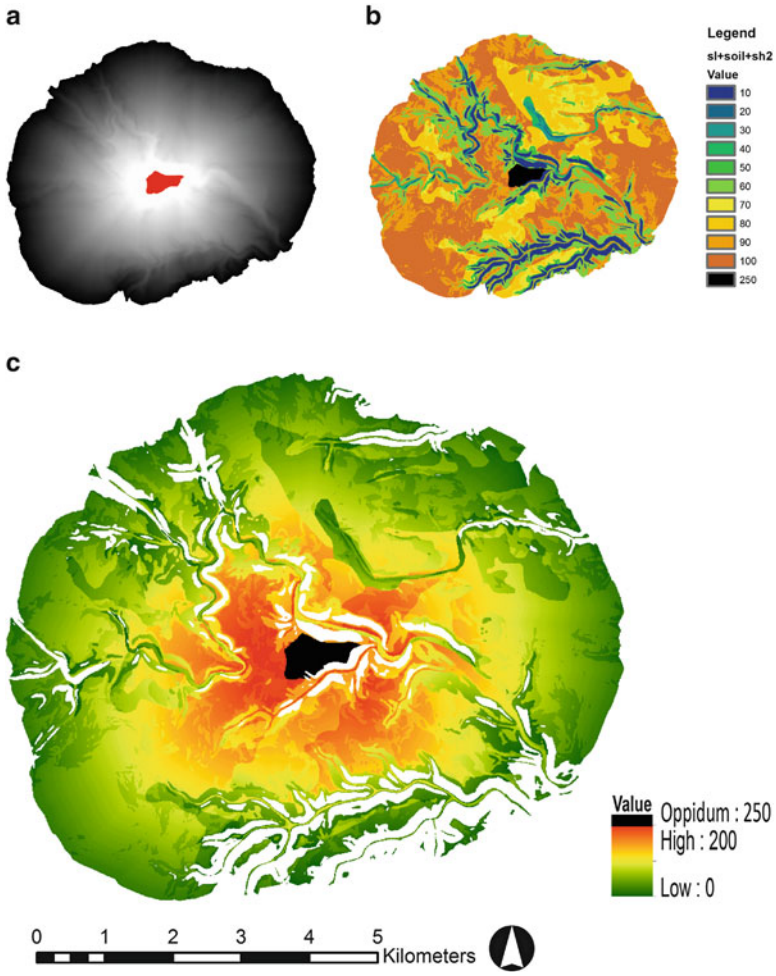


**Fig. 9.1** Quantitative GIS model of the oppidum's hinterland area within its predicted catchment: (**a**) cost distance from the settlement, (**b**) evaluation of land suitability for the cultivation of crops, (**c**) resulting model of the hinterland's suitability for agricultural tasks. The "utility index" ranges from 0 to 250 (0–200 represents increasing suitability, 250 is the oppidum)

a suitable variance of general yield variability, derived from the information on local environmental and climate conditions, the reconstructed scale and intensity of farming (by "intensity", we understand the amount of labour input required to process one unit area of land) and production targets (from small subsistence needs to surplus production requirements). The following three agricultural strategies are assumed to have been possibly practised by the Iron Age population (also see Table 9.2 for a reference regarding input values):

1. Intensive farming on small plots: fields were manured by grazing and stable dung; they were intensively tilled by hand, and weeded. Working animals could be used for maintaining higher yields; also, rotation of crops (cereals, pulses) was practised. An intensive farming strategy represents the most labour-demanding option, which tends to be limited in scale or covers only the subsistence needs. Larger production (in the meaning of surplus production) would require higher labour input at the expense of the other activities (like stock farming).
2. Extensive farming on large plots: fields included fallows and were managed less intensively. They were manured especially by grazing animals. The plots could be usually under continuous cropping (i.e. no crops rotation) as the periods of fallow allowed for the sufficient regeneration. An extensive strategy could have been employed especially when the available land was abundant, population pressure low, labour was engaged elsewhere, or it was more preferred than the intensive production. With this strategy the potential for surplus production was higher, but could fluctuate heavily.
3. Mixed strategy: this comprised a combined approach of land managed more intensively within the infields (closer to the settlement) and more extensively in the outfields (further from the settlement). Both were ploughed by working animals. Infields would be fertilised by the farmyard manure, could be weeded or hand tilled. Crop there was rotated as under the intensive strategy. For the fields further away, fallows were included (management of which was less intensive).

The extensive strategy, as well as the mixed one, required quite large areas to be available without any competing sites around. When population growth caused pressure on resources, extensively managed fields further away could be turned into more intensively managed ones. If the increasing intensity of land cultivation could not be matched by either adequate labour input or numbers of animals (to secure necessary manuring), a stress situation would develop.

## 9.4 Models

In the models of social complexity, population growth plays an important role. Population pressure and over-exploitation of resources are very important concepts from which a wide range of social phenomena can be explained (Bayliss-Smith 1978, p. 130). Our primary objective int that context was to find a stable and reliable model of the population growth, with matching initial and final age distributions. The simulation of the population dynamics (Sect. 9.4.1) provided input data for further modelling and investigation of the oppidum's production potential and carrying capacity threshold of the hinterland (Sects. 9.4.2 and 9.4.3). Agricultural production around the oppidum is perceived as having developed from the beginning of land cultivation, relative to the beginning of the occupation of the oppidum, and having lasted for about 100–120 years.

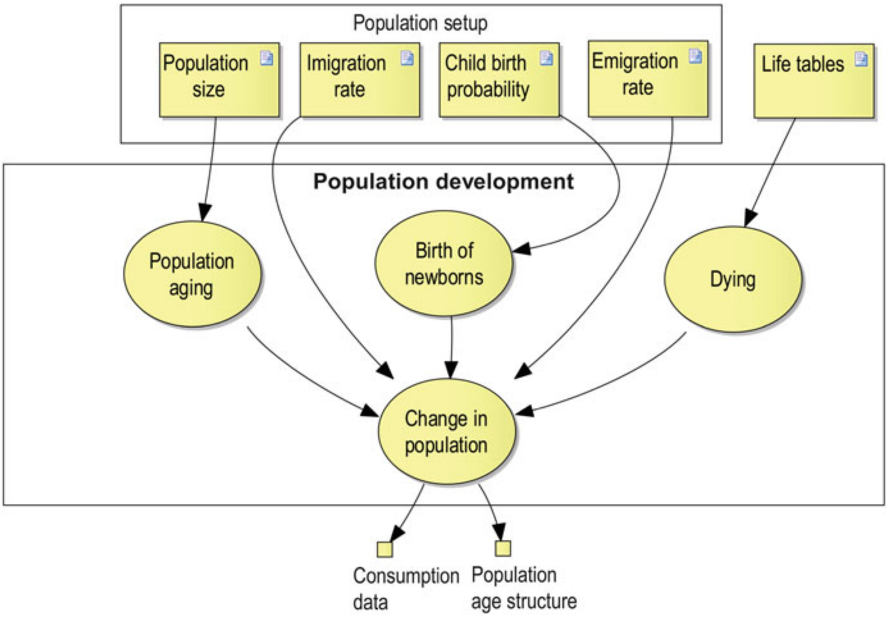


**Fig. 9.2** Population model

### *9.4.1 Population Dynamics Model*

Population growth is defined as the change in number of individuals over time (Fig. 9.2). It is assumed that all populations grow (or decline) exponentially (or logarithmically), unless affected by other forces. The simplest Malthusian growth model assumes the exponential growth is

$$P(t) = P_0 e^{rt}$$

where $P_0$ is the initial population, $r$ is the growth rate and $t$ is time. In our case, the initial number of inhabitants is said to be between 500 and 800, the maximum number of inhabitants after 100–120 years is between 2,000 and 5,000. The rapid annual growth can in suitable circumstances reach 2 % (cf. Turchin 2009, p. 12).

Our model has one type of agent representing inhabitants. Each such "inhabitant-agent" is characterized by gender (male, female), age (discrete value), and age-category (suckling, toddler, child, older child, young adult, adult or elder). Auxiliary variables were added for monitoring characteristics of the whole population: percent-of-suckling, percent-of-toddlers, percent-of-children, percent-of-older-children, percent-of-young-adults, percent-of-adults, percent-of-elders. Summarizing variables num-of-inhabitants, actual-workforce and actual-consumption inform about the structure the population.

The model has the following input parameters:

**Table 9.3** Proportional distributions of the age groups

| Age group | % in population |
|---|---|
| Suckling (0–1) | 11.43 |
| Toddlers (1–3) | 5.71 |
| Small children (3–10) | 14.29 |
| Older children (10–14) | 11.43 |
| Young adults (15–19) | 8.57 |
| Adults (19–48) | 37.14 |
| Elderly (48–) | 11.43 |

**Table 9.4** Daily caloric requirement for different sex and age groups (after Gregg 1988, Table 1, modified)

| Age group | kcal/day |
|---|---|
| Suckling (0–1) | 0 |
| Toddlers (1–3) | 1,360 |
| Small children (3–10) | 2,000 |
| Older children (10–14) | 2,300–2,500 |
| Young adults (15–19) | 2,500–3,000 |
| Female adults (19–48) | 2,600 |
| Male adults (19–48) | 3,000 |
| Elderly (over 49) | 2,000 |

- initial population size between 500 and 800 individuals,
- initial population age structure,
- abridged life tables interpolated to a full variant,
- probability $Q$ of a woman having a child in a specific year.

The initial population consist of seven age-groups (suckling, toddlers, children, older children, young adults, adults and elderly), the proportional distribution of each age-group was defined experimentally (see Table 9.3) (Olševičová et al. 2012).

Depending on each sex/age category, one person should yearly consume his/her *required amount of cereals* × *their caloric value* (1 kg of wheat = ca. 3440 kcal).[4] The cereals are assumed to cover 70–75 % of daily energy intake; the rest was supplemented by proteins and other nutrients (cf. Table 9.4).

During the initialization of the model, a population of the supplied size is created. Each inhabitant-agent is assigned an age and gender; globally, counters regarding the number of inhabitant-agents in each age and gender group are updated. The main procedure simulates 120 time steps (see Listing 9.1). At each time step, each inhabitant-agent applies its *get-older* procedure. The procedure operates with abridged life-tables, adopted from the regional model life-tables created by Coale and Demeny for the ancient Roman population (Saller 1994). We used the Model Life Tables Level 3 a 6 West. To complete missing values in the tables (as they were in 5-year intervals), the Elandt-Johnson estimation method (Baili et al. 2005) was

[4]For example in case a male adult agent requires 3,000 kcal daily, this means 1,095,000 kcal yearly, which equals 322.05 kg of cereals/year (if only cereals are consumed).

applied. The inhabitant-agent, representing women between 15 and 49 years, also executes the *birth-rate* procedure (avg. 5.1 children per woman) that operates with probability $Q$.

The model ignores more detailed aspects like partner selection and proportions of various families' formation (nuclear-extended), as those are the variables which would have to be set arbitrarily, without sufficient supporting data. While population size, life tables and population structure were available to us, it was very complicated to estimate the probability $Q$ without relevant statistical data. It should be noted that the probability $Q$ is in fact composed of multiple components, some of them depending on others. Biological fertility of both partners can be estimated (in general, it is decreasing with age), but such a parameter itself cannot explain the whole $Q$, as there are many socio-economic and other biological factors. As a consequence, NetLogo's BehaviorSearch tool was used to identify parameters of $Q$ experimentally, using genetic algorithms.

**Listing 9.1** Population model pseudocode

```
model-setup
  load life tables
  create initial population of N inhabitant-agents
    for each inhabitant-agent
      set initial age
      set gender (male or female)
  set global variables
    count number of suckling
    count number of toddlers
    count number of children
    count number of older children
    count number of young adults
    count number of adults
    count number of elders
  update plots and monitors
end

model-go
  repeat for 120 steps
    set global variables
      count number of weak workforce
      count number of strong workforce
      count total consumption
    for each inhabitant-agent
      get-older
    for each female-inhabitant-agent
      birth-rate
    set global variables
      count number of suckling
      count number of toddlers
      count number of children
      count number of older children
      count number of young adults
      count number of adults
      count number of elders
```

```
    update plots and monitors
  export population data
  export consumption data
  export workforce data
end
```

The probability $Q$ is a function of a woman's age, with the additional limitation that it is defined to be non-zero only in the interval 15 to 49 years.

Based on empirical findings (fertility rate around 5.1; more than two children rarely survived infancy), we have decided to discretize the function $Q$ using intervals of 5 years. This means that probability $q_i$ applies for ages $i, \ldots, i+4$. Taking into account the fact that the time step of the model is one year and that the interval where $Q$ is non-zero from age 15 to age 49, we actually look at a vector of size 7. Individual probabilities are discretized, too—we consider only integer values {0,1,2,...,100}. Based on that, we can define following parameter vector:

$$Q = (q_{15}, q_{20}, q_{25}, \ldots, q_{45}),\ q_i \epsilon \{0, 1, 2, \ldots, 100\} \tag{9.1}$$

To be able to use BehaviorSearch, an objective function must be also defined. Our objective was to optimize parameters such that a defined population size was achievable; as constraint, the population structure should be as close as possible to the original one. Hence, each of these two aspects were modelled as an own objective function. Function $F_1$ given in Eq. (9.2) is the first one, giving the percentage of change in final population $x$ considering an initial population $A$.

$$F_1 = \frac{|x - A|}{A} \tag{9.2}$$

The second aspect is covered in function $F_1$ (Eq. (9.3)), which represents the average percentage change in seven population's age intervals (suckling, toddlers, children, older children, young adults, adults, elders). More specifically, the change in percentage within the individual age and sex groups was compared to the initial population structure.

$$F_2 = \frac{1}{7} \sum_{i=1}^{7} \frac{|x_i - x_i'|}{x_i'} \tag{9.3}$$

However, BehaviorSearch cannot optimize multi-objective functions; therefore the problem must be converted into a single-objective optimization. We have used simple Euclidean distance:

$$F = \sqrt{F_1^2 + F_2^2} \tag{9.4}$$

In the overall objective function $F$ (Eq. (9.4)), both contained objective functions have the same weight. It should be also noted that the function $F$ can no longer be interpreted as a percentage, as opposed to functions $F_1$ and $F_2$.

The model has the two following outputs:

- necessary energy input (caloric input value extrapolated from the actual oppidum population in all sex/age groups) for each year of simulation (Fig. 9.3a).
- available workforce (actual number of people in productive age in particular age/sex categories) for each year of the simulation (Fig. 9.3b). Two main categories were distinguished: "*strongforce*" (males and young males who can perform heavier task such as ploughing, harvesting with scythe, trees cutting etc.) and "*weakforce*" (other age/sex categories, except very small children, who can pursue other tasks, such as sowing, hoeing, weeding, manuring, milking, various assistance tasks etc.).

Multiple configurations of the model have been tested. As results show, it turned out that there was no single exclusive function meeting initial requirements, and hence, multiple directions had to be explored (as described in the next sections).

### *9.4.2 Crop Production Model*

The purpose of this model is to compare agricultural strategies likely to be employed by the oppidum's population in relation to the necessary land-use area and ratio of the population engaged in agricultural work, in order to find out (1) whether the hinterland of the site itself had capacity to sustain constantly growing population of the oppidum and (2) if the oppidum's society could support food non-producers (craft specialists or elite). Following model inputs were defined (see Fig. 9.4):

- two time series from the population growth model (giving the values of the caloric requirements and available workforce for each year of simulation, cf. Sect. 9.4.1),
- the map of arable land around the settlement (modelled in GIS, cf. Sect. 9.3.3),
- the type of the agricultural strategy (cf. Sect. 9.3.4).

Three different land cultivation strategies (intensive–extensive–mixed) were implemented. While intensive farming provides higher yields on smaller area than extensive farming, it also requires significantly higher labour input. The production of cereals should be at least equal to the total consumption (plus seed corn—from every harvest 200 kg of grain/ha must be secured for the next-year's sowing) and should be achieved with the available workforce. Yields above the actual consumption represent a surplus and are stored. Around 10–15 % is accounted for losses. Keeping part of the surplus grain in storage until the next harvest can substantially diminish the impact of attested harvest fluctuations. Currently, these are driven randomly with the addition of sudden "events" (such as hailstorms, frosts or flash-floods). Each year there is a probability of some such event which can reduce the total harvest. Due to the absence of sunken silos, the maximum storage period was set to three years. After that time, the crop storage from the first year must have been consumed (surplus grain could be for example fed to

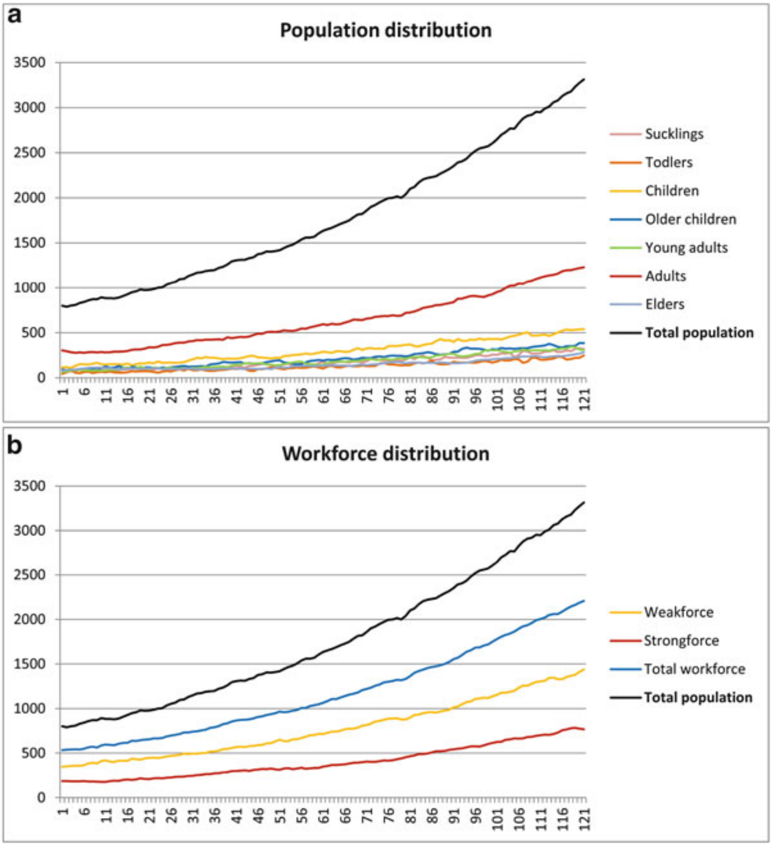


**Fig. 9.3** Population Model outputs. (**a**) Growth of population—age groups, for initial number of 800 inhabitants. (**b**) Growth of strong, weak and total workforce, for initial number of 800 inhabitants

animals) or disposed of.[5] In case of a harvest failure, the oppidum's population should compensate using their reserves. This way, the years of bad harvests are counted as "bad-years" when the consummation level is higher than the production level and as "critical-years" when there are three bad years in a row. If the stored reserves are depleted as well, the model returns "years-with-no-food" which means that the population faces a crisis with acute food shortage.

The map of land suitability was imported to NetLogo, to be used as the background for visualization (Fig. 9.5). The possibilities are either to use a generalised raster map (as .png file) or to import an ascii text file. We used second option,

[5]This issue can be further examined for example also in relation to the feasting events when the surplus grain is consumed (cf. Van der Veen and Jones 2006).

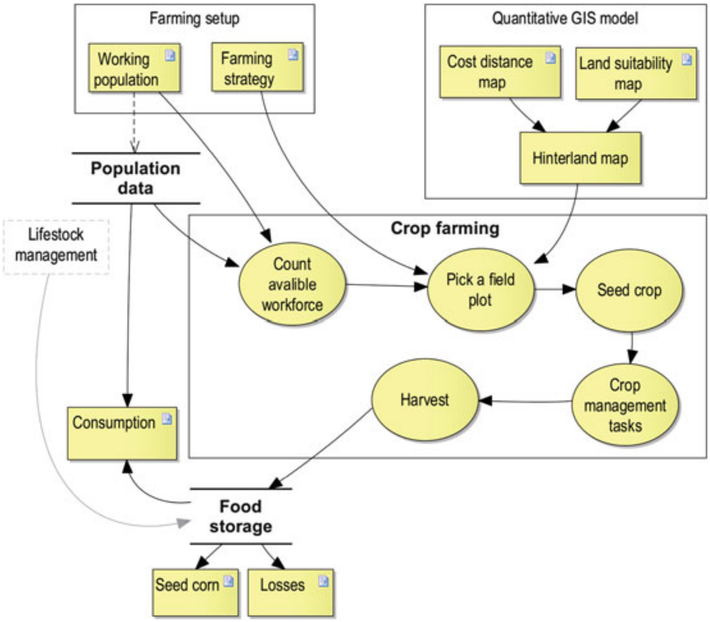


**Fig. 9.4** Crop production model

because it preserved original coding of layers and realistic spatial proportions. The oppidum is situated in the middle of the map and the area around was classified according to the "utility index" of the suitability for cultivation (cf. Fig. 9.1).

The following model inputs are defined:

- the average crop and its standard deviation in case of intensive and extensive management (between 700–3,000 and 500–2,000 kg/ha respectively),
- the ratio ("strongforce", "weakforce) of working population (between 0 and 1),
- the ratio of cereal consumption (between 0 and 1),
- the number of workers per hectare for each strategy,
- seed corn for the following year and losses.

**Listing 9.2** Crop production model pseudocode

```
model-setup
  load map
  update visualization
    recolor patches according to attractiveness, distance and
     ↪ current state of  cultivation
  load population data
  load consumption data
  load workforce data
  initiate animal-agents
end
```

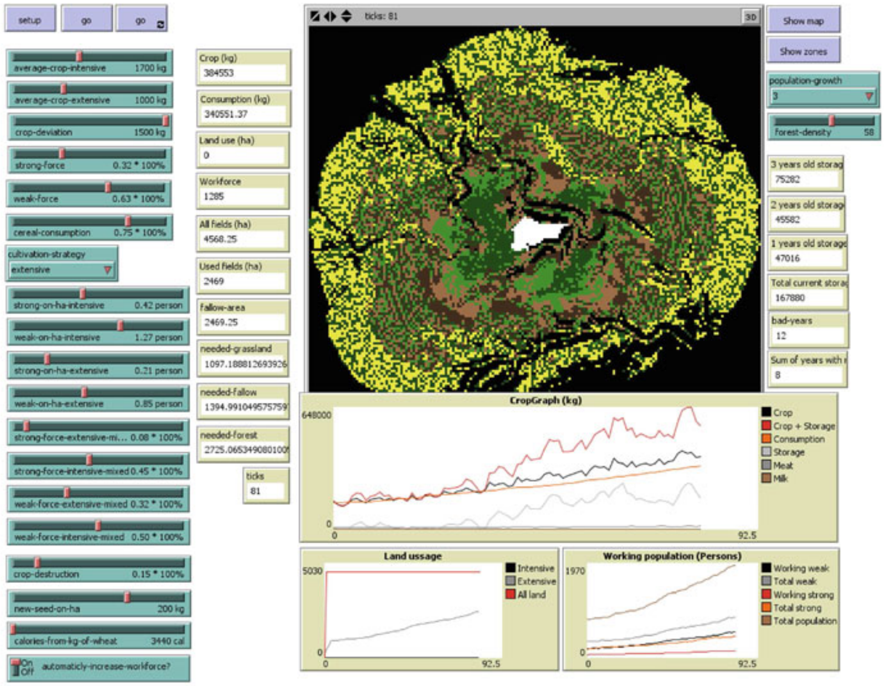


**Fig. 9.5** Crop Production Model interface: sliders for setting initial values of parameters (*left*), visualization of the land-use in case of extensive strategy (*right*)

```
model-go
  repeat for 120 steps
      set global variables
        count number of animals
        count cereals requirement
      update fields allocation according strategy
      update crop
        count crop
        count storage
        count destroyed storage
      update animal data
        slaughter-animals
        milking
      update plots and monitors
      update visualization
        recolor patches according attractiveness, distance and
         ↪ current state of cultivation
end
```

The initialization of the model (refer to Listing 9.2) consists of loading and visualization of input data, especially loading text files with the time series of population, workforce and consumption. In the main procedure, the cycle repeats

120 times to simulate 120 years. In each simulated year, global variables are updated, characteristics of each patch of the land are updated according to current agricultural strategy and related crop data are processed and visualized.

We compared three agricultural strategies experimentally, with the aim to identify the appropriate labour input and carrying capacity of the hinterland. Frequencies of bad and critical years as well as years without food were examined, in order to ascertain under which model setups stress situations occur. The frequent appearance (i.e. several consecutive years) of bad, critical or even years-with-no-food means the particular agricultural strategy was not applicable.

With the outputs from the Population Model (cf. Sect. 9.4.1) the labour input under all strategies required between 25–40 % of the male and young male adults ("strong-force") and 40–55 % of the rest of the population ("weak-force") (see Fig. 9.6). That means that not all of the oppidum's population had to be engaged in the agricultural (meaning cereal production) work.

Other set of experiments was focused on the sustainability of the land-use in relation to strategies employed. In the case of an intensive strategy being employed, a population experienced several bad-years between the years 18 and 38 plus one period of critical-years (years 36–38) caused most likely by the labour shortage (returned from the Population Model). After that the production was stable to the ninth decade (year 93) of the oppidum's occupation, where the farming had to be carried out in more distant field plots with decreased net returns (Figs. 9.6a and 9.7a) because of the applied cost penalty. Then, the intensive strategy could not be efficiently practiced, because more labour input had to be invested into the necessary subsistence tasks. In total, a population of ca. 2,500 persons could sustain the agricultural production until the end of the oppidum's existence, but struggled considerably from the ninth decade.

In case of an extensive strategy being used, the simulated population did not experience problems with the labour shortage in the third decade, but from the year 92 onward, the population of ca. 2,000 people would encounter problems with availability of the arable land (see Figs. 9.6b and 9.7b). Due to extensive fallowing, the cultivated area would be much larger than with the intensive strategy. The cost penalty (though with moderate impact compare to the intensive strategy) also influenced the net returns from the fields. The population would increase for another 10–15 years, living on storage reserves, but after that period, the land-use approach must have changed, the crops must have been supplied externally, or the population density must have declined. The process of adaptation to the new conditions may have included the intensification of the agricultural practices, in order to reduce the cultivated area.

A combination of intensive and extensive cultivation practices appeared as a suitable compromise between land and labour shortages under constantly growing population density, though during the third decade the population experienced similar situation as when practising the intensive strategy (Fig. 9.6c). The experimental results showed that the population can maintain a more or less constant level of surplus (turned into storage), and must therefore have experienced a minimum of crisis situations due to harvest failures. In our experiments, the ratio of the

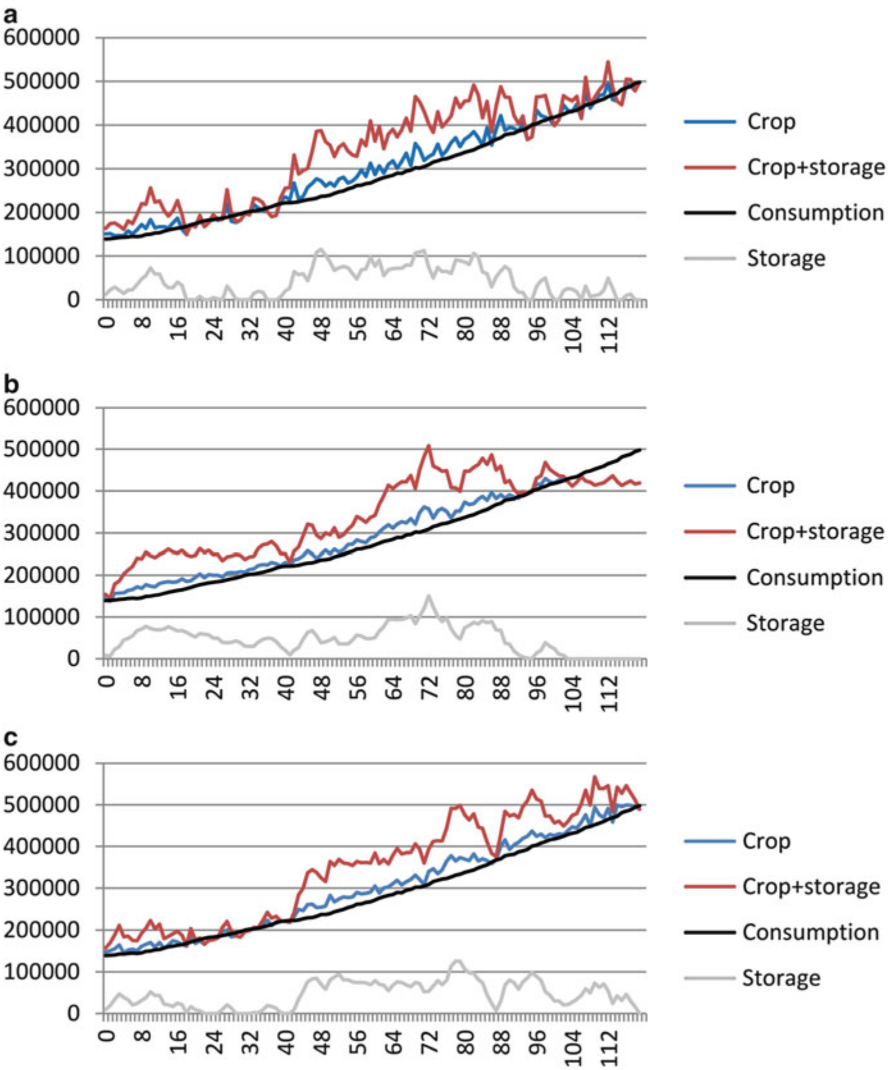


**Fig. 9.6** Sustainability of production under different agricultural practices. (**a**) Intensive strategy: strongforce 34 %, weakforce = 55 %, average crop 1,500 kg/ha, standard deviation 1,000. (**b**) Extensive strategy: strongforce 25 %, weakforce = 40 %, average crop 1,000 kg/ha, standard deviation 500. (**c**) Mixed strategy: strongforce 29 %, weakforce = 50 %, average crop 1,000–1,500 kg/ha, standard deviation 700

intensive and extensive cultivation practices within the mixed method was set to 1/3:2/3 (intensive:extensive). However, choosing between the two strategies or their combination depends on the decisions of the farmers who are affected by many other factors (quality and accessibility of land, availability of the workforce, preference of

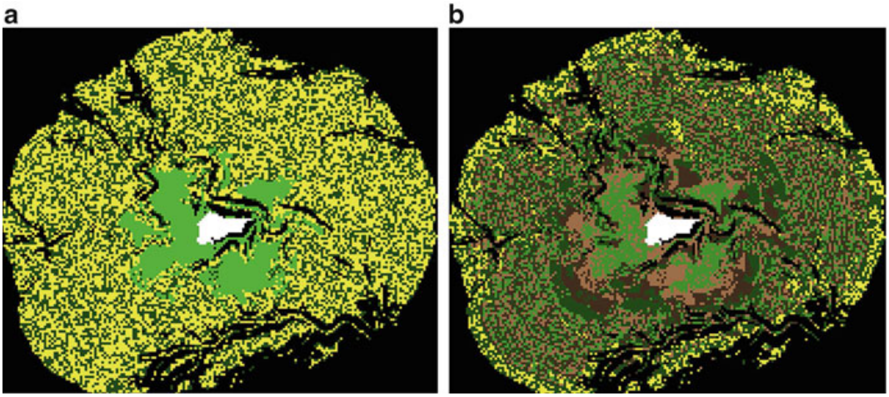


**Fig. 9.7** Total field areas. (**a**) Intensive strategy: average crop 1,500 kg/ha with standard deviation 1,500, strong force 0.42 person/ha, weak force 1.27 person/ha. (**b**) Extensive strategy: average crop 900 kg/ha with standard deviation 1,000, strong force 0.21 person/ha, weak force 0.85 person/ha

other subsistence strategies like stock farming, climate changes, bad harvests etc.). Such a process is presented in the Field Allocation Model, using fuzzy methods as technical basis.

### *9.4.3 Field Allocation Model*

While the typical process of human-driven research concerning the land-use is usually performed using GIS tools with multi-criteria decision analysis (Eastman 2006, pp. 126–134), our model provides an alternative approach with possible extensions in terms of household/people interactions with the landscape (cf. Olševičová et al. 2012; Machálek et al. 2013). In order to model the farmers' decision processes concerning spatial structure of their fields, we created fuzzy system helping to provide initial hypotheses in terms of crop field layouts.

Fuzzy rule-based systems build on top of the theory of fuzzy sets and fuzzy logic introduced by L. Zadeh in 1965. With classical sets, we assign each object either an "is-member" or an "is-not-member" property. On the contrary, in case of fuzzy sets, a *membership degree function* in the interval [0; 1] is used (see e.g. Babuška 2001; Ross 2010). This leads to a different (but still consistent with our understanding of Boolean logic) concept of set operations and related logical operations. Fuzzy rule-based systems provide a way to encode domain specific knowledge and control behaviour of a system or entity in conformity with this knowledge. The rules have following general form: IF *antecedent proposition* THEN *consequent proposition*.

Fuzzy propositions are statements like: "x is big", where "big" is a linguistic label, defined by a fuzzy set on the universe of discourse (Babuška 2001). Linguistic labels are also referred to as fuzzy constants, fuzzy terms or fuzzy notions.

A linguistic variable is a quintuple (Klir and Yuan 1995)

$$L = (x, A, X, g, m) \tag{9.5}$$

where $x$ is the base variable (it also represents the name of the linguistic variable), $A = A_1, A_2, \ldots, An$is the set of linguistic terms, $X$ is the domain (universe of discourse) of $x$, $g$ is a syntactic rule for generating linguistic terms and $m$ is a semantic rule that assigns to each linguistic term its meaning (a fuzzy set in $X$).

Attempting to encode the knowledge of Iron Age farmers in terms of land suitability and accepting their limited analytical capabilities we see a fuzzy rule-based system containing a set of if-then rules as a natural tool to express their decision processes (i.e. subjective, approximate, using terms like "near", "far", "weak", "strong", "fair"; cf. Ross 2010).

This model simulates the farmers' decision-making process regarding suitability of individual land patches for crop (or animal) husbandry and also about correction of predefined percentages of intensive farming according to the difference between actual harvest and annual nutritional requirements of the community. In addition, the total harvest can be modified by a long term trend function to simulate progressively decreasing or increasing carrying capacity of the area.[6] Taking into account existing land suitability evaluation (cf. Sect. 9.3.1) we have split the problem into two levels:

- The first level represents an evaluation of land based only on the terrain's invariant properties (such as distance, slope, etc.). The problem how individual land characteristics influence suitability has already been addressed in human-landscape occupational rules as well as in the field of agricultural practices (cf. Jarosław and Hildebrandt-Radke 2009; Reshmidevi et al. 2009).
- The second level introduces a dynamic factor (e.g. the harvest from the previous season). An evaluation process from the first level can be understood here as an initial step (time "zero") where inhabitants have not yet influenced the environment in any way. But in the next season, their knowledge becomes broader, because they can evaluate the results of their previous assumptions on what part of the land is more or less suitable to be farmed with a specific cultivation strategy.

A single type of agent—a household which represents one or more families living in a settlement (house or a group of houses) with the arable land around, is defined. We assume that the "hinterland" is based on exploring accessible areas around the settlement, which lies in the centre.

Our proposed fuzzy inference requires four linguistic variables as input:

1. the distance of individual land patches from the household,

[6]This model forms a part of the main group of Agricultural Models. Its trial runs are presented on the smaller site (four households)—the lowland open settlement of Ptení, where the landscape settings are similar to the oppidum of Staré Hradisko.

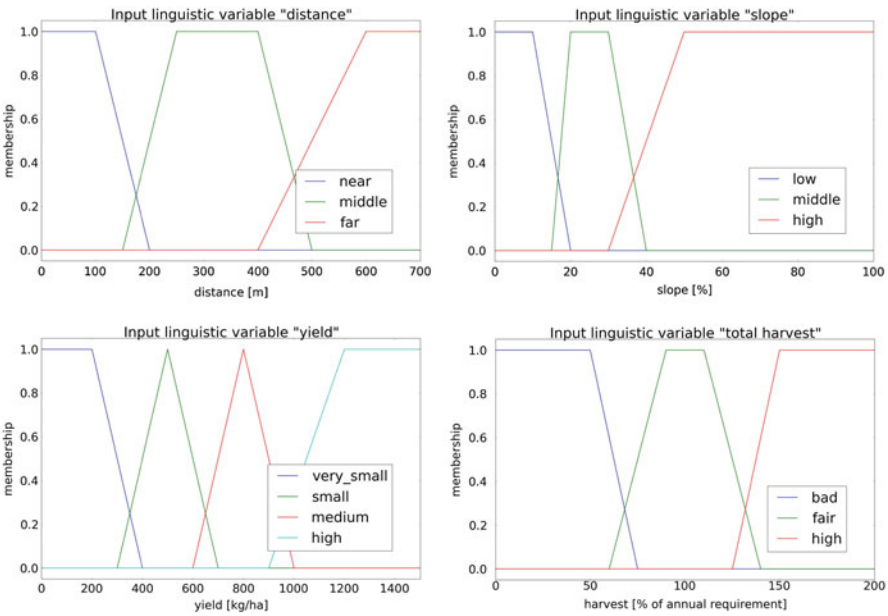


**Fig. 9.8** Input variables of the fuzzy inference system

2. a slope gradient,
3. suitability of individual land patches,
4. the total harvest (as a percentage of inhabitants' annual nutrition requirements).

The concrete form of the membership functions related to these variables is the result of the previous GIS analysis (for the parameters see Sects. 9.3.1 and 9.3.3) and also of empirical testing (Fig. 9.8). A key parameter influencing both total and patch-level yields is the suitability of soil. The model works with 5 "soil categories": unfarmed soil of the settlement, alluvial soil and three additional qualitative categories for arable land.

The stochastic nature of crop yields required selecting a proper random distribution. While there exist objections against normally distributed crop yields (e.g. Ramirez et al. 2001), modelling yields by normal distribution still cannot be refused in general (e.g. Upadhyay and Smith 2005). We have applied it also in our model, due to the lack of detailed evidence. Coming to details, the mean of the distribution separates aforesaid yield ranges into equal halves and standard deviation is defined so that the maximum and minimum values are at $\pm 3\sigma$. The estimated distributions $N(\mu; \sigma^2)$ were calculated as:

$$\mu = \frac{(Y_{min} + Y_{max})}{2} \tag{9.6}$$

$$\sigma = \frac{(Y_{max} - Y_{min})}{6} \tag{9.7}$$

As an output of the fuzzy inference system, two linguistic variables have been defined:

1. suitability—this variable quantifies suitability of a single land patch in terms of its usability for growing crops. Patches with suitability near a value of 100 can be understood as very suitable (near the household, flat and with good yield potential). Patches near 0 are considered to be inappropriate (far lying, sloping, low yield potential).
2. intensity—although the model operates with a parameter, which specifies the percentage of household's arable land, it also provides auto-correction of this value according to the difference between required and actual harvest. The real proportion of cultivated land is calculated as a product of farming and intensity. The variable intensity is expected to be approximately 1 if the total harvest is about equal to the requested value (parameter required-annual-yield).

**Listing 9.3** Fuzzy-rules pseudocode for The Field Allocation model

```
RULE 1: IF yield IS very_small THEN suitability IS low;
RULE 2: IF slope IS high THEN suitability IS low;
RULE 3: IF distance IS near AND (slope IS low OR slope IS middle)
 ↪  AND (yield IS high OR yield IS medium) THEN suitability IS
 ↪ high;
RULE 4: IF distance IS near AND (slope IS high) AND (yield IS
 ↪ high) THEN suitability IS middle;
RULE 5: IF distance IS middle AND slope IS low AND (yield IS NOT
 ↪ very_small) THEN suitability IS high;
RULE 6: IF distance IS middle AND slope IS middle AND yield IS
 ↪ high THEN suitability IS high;
RULE 7: IF distance IS far AND (slope IS low) AND (yield IS
 ↪ medium OR yield IS high) THEN suitability IS middle;
RULE 8: IF distance IS far AND (slope IS middle) AND (yield IS
 ↪ NOT very_small) THEN suitability IS low;
RULE 9: IF distance IS near AND slope IS low AND yield IS NOT
 ↪ very_small THEN suitability IS high;
RULE 10: IF distance IS middle AND slope IS low AND (yield IS
 ↪ small OR yield IS very_small) THEN suitability IS low;
RULE 11: IF harvest IS fair THEN intensity IS normal;
RULE 12: IF harvest IS bad THEN intensity IS high;
RULE 13: IF harvest IS high THEN intensity IS low;
```

To calculate yield $y_p$ of a specific patch we have defined the following function:

$$y_p = \frac{25 \cdot h \cdot y}{10000} \cdot T \cdot r$$

where $\frac{25}{10000}$ recalculates per-unit yield to model's patch size, $h$ is a yield per hectare, $y$ is normal random variable with properties so that $h \,.\, y$ has properties of the distribution defined in Eqs. (9.6) and (9.7). $T$ is a coefficient expressing an influence of a farming type (it has value of 1 for intensive farming and 0.3 for extensive farming) and $r$ is an optional coefficient to apply long-term trends (i.e. climate change). For the fuzzy inference system, 13 rules have been defined; these can be found in Listing 9.3.

As always in fuzzy logic, the operator AND is defined using the $min$ function, while OR is defined using $max$function. For rule activation, the $min$ function was used. For rule accumulation, a bounded sum method (i.e. $min(1, \mu_A + \mu_B)$) was used. Fuzzy implication in based on Mamdani's inferencing scheme.

Figure 9.9 presents an example of land evaluation. Land area in the model is represented by a grid of discrete patches of the same size. Stochastic properties of the model cause that even several neighbouring patches may sometimes differ significantly in terms of calculated suitability. Such result is hard to interpret directly, because we cannot expect that a real farmer was mixing crop husbandry practices (including the "no-use" one) every few meters. To resolve this problem, we have at the moment proposed to post-process the resulting "suitability map" using linear filtering:

$$g(i, j) = \sum_{k,l} f(i + k, j + l)h(k, l) \tag{9.8}$$

Here, $f$ represents the input signal, $h$ is called linear convolution kernel. We have been using the following bilinear kernel:

$$h(k, l) = \frac{1}{16}\begin{pmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{pmatrix} \tag{9.9}$$

The suitability map can be understood as a spatial signal in which a proper linear convolution kernel serves as a low-pass filter which attenuates higher frequencies from the signal (Szeliski 2010).

While treating the suitability as a continuous variable is convenient in terms of described calculations, it is more complicated to apply such a variable directly in practice (i.e. what should farmer do exactly if the suitability is x?). Because of that we defined a mapping from continuous suitability variable to an ordinal set of suggested farming types (see Fig. 9.9).

Figure 9.10 shows a comparison between discussed fuzzy model and multi-criteria based solution which considers only distance and soil type. Given a required target yield, we can see that the fuzzy model is capable of producing results with comparable accuracy, the only exception being low intensity farming: the model evolves from a defined starting property size and is unable to reach the required area within the running time limit (it evaluates too many patches as unsuitable).

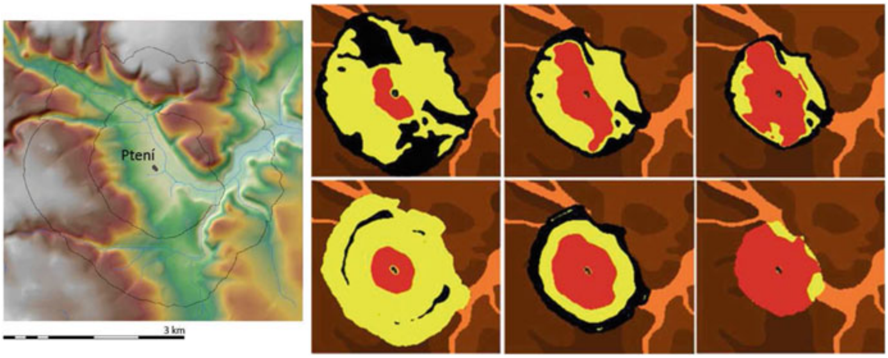


**Fig. 9.9** The open settlement of Ptení: fuzzy (*first row*) and multi-criteria based (*second row*) model, required annual yield = 9,000 kg, required ratios for intensive farming = 10 % (*left*), 50 % (*centre*) and 90 % (*right*), *red area* = best suitability for intensive farming, *yellow area* = best suitability for extensive farming or pastures, *black area* = evaluated land of lower suitability

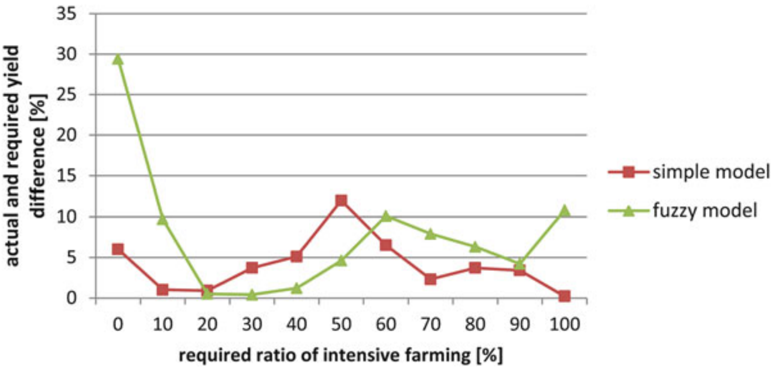


**Fig. 9.10** Fuzzy (including linear filtering) and alternative model—target yield accuracy

## 9.5 Discussion

Results achieved can be discussed in the light of the framework of available data: according to the archaeological record, the settlement density in the late La Tène period having increased over some time and then decreased again rapidly. The goal of our modelling effort was to ascertain whether "crossing the carrying capacity" situation was a main factor in the process of the abandonment of settlements. Setting the proper values was a difficult undertaking. We have only limited data concerning the initial and final populations at Staré Hradisko. Rather, we have information on the occupational development. Despite that, the Population dynamics model provides realistic time series of consumption, workforce and age distributions of population of the oppidum's agglomeration. It is essential to note, however, that its development did not take into account a sudden decline in the occupation observed in the archaeological record. This is because our goal was to explore the cause of this decline. To be able to address that issue, we first needed an invariable model of the population growth. Therefore, the modelling results showed a constantly growing population from the beginning until the end of the occupation (i.e. the “Baseline”). Maximum supposed “real” population density of the oppidum, reached only by natality, could then be seen around the years 80–90 of the simulation. With such a demographic profile, the oppidum’s community could in fact practice all land-use strategies without any substantial problems apart from those imposed by natural harvest fluctuations due to weather and other (e.g. socio-economic) factors.

Using our models, we have proven by experiments that not all of the oppidum’s population had to be engaged in the agricultural work. When other labour tasks are implemented (such as animal production and forest management), further experiments will be able to answer the question of sustainability of the non-producers at the oppidum. Since there is an archaeological evidence of elite members, which, presumably, were not involved in the agricultural production, the labour shortage may point to the necessity of using the external supplies.

The limits of the land-use strategies returned from the Crop Production Model, when the population was expected to react by adjusting their economic strategies, started acting around the population density being over 2,500 (under the intensive strategy—cost distance factors) and around 2,000 (under the extensive strategy—depleting of hinterland area). If the population growth would have reached this maximum value after first 80–90 years (due to massive immigration for example), that could be the realistic interpretation of the occupation’s decline.

According to historical sources, exceeding the appropriate carrying capacity was not a rare occasion in history (cf. Schreg 2011, p. 312). Intensification led to innovations in the agriculture on the one hand, but also to a more rapid depletion of the land resources where their extent was limited on the other. When experiencing population growth, the households had to work harder in order to keep their life standards, due to the law of diminishing returns (Turchin and Nefedov 2009, p. 1). This concept refers to the fact that while the population increases exponentially, the growth of subsistence resources is only linear and generally slower. As the population approaches the carrying capacity, the production level gradually declines. This means that when reaching the carrying capacity threshold, the surplus becomes zero, and upon further population growth it becomes negative. At this point, the population faces a lack of resources for its reproduction and its density must decline (Turchin and Nefedov 2009, pp. 8, 10, Fig. 1.1a) or their subsistence strategies must be adapted to the new situation. Such adaptability processes may include changing the extensive cultivation practices into more intensive land use regimes (i.e. cultivating land with higher labour input on smaller area) or a change in economic preferences to stock farming or craft industries. The results of the mixed land-use model showed that the optimal strategy would have been to combine different agricultural practices. This inspired the Agricultural model II, which focuses on the decision process of farmers in choosing the optimum farming strategy in order to balance potential problems, with space and labour availability.

The results show that, since the adequate oppidum population (living from their own resources) was able to exploit environmental resources around the oppidum without simultaneously exhausting them, a rapidly growing number of inhabitants could—at some point—cross the limits of the sustainable agricultural production and experience several stress situations. Especially for the labour intensive scenario, the model resulted in diminishing returns from the cultivated land as the cost of farming more distant field increased. Around the population peak, the gradual depletion of stored reserves resulted in a supply crisis, which must have provoked a strong social response. This evolution can be a typical development towards societal decline following the distinctive upsweep accompanied by rapid population growth especially in the environment where the market economy was weak (Chase-Dunn et al. 2007; Turchin and Nefedov 2009). This hypothesis is a main subject for testing in further research.

## 9.6 Conclusion

This chapter has attempted to discuss the applicability of agent-based social simulation as a tool for the exploration of the late Iron Age oppida agglomerations, especially from the point of view of the population growth and related sustainability of production. By presentation of three consecutive NetLogo models—the model of population dynamics and two agricultural models—we intended to demonstrate the ability to move from a static data set (archaeological and environmental records) to dynamic modelling that incorporates feedback mechanisms, system integration, and nonlinear responses to a wide range of input data.

Even in case when detailed data is limited, these models could point to the constraints of the particular agricultural strategy and population density in relation to the specific environment (Schreg 2011, p. 307). In our case, evolution of computational techniques such as genetic algorithms (available through BehaviorSearch) or fuzzy rules (implemented in our jFuzzy plug-in) helped us to identify missing values of parameters and to optimize model settings. This approach can help to analyse past socio-economic processes, determine possible crisis factors and understand ecological and cultural changes.

Future studies will build upon the presented models. The applied approach can be adapted for other regions, and other economic strategies can be explored. Our next objectives are to investigate further the population structure of the oppidum, by incorporating different types of households and related attributes of the individuals. The agricultural models are planned to be enhanced by more detailed weather data, analyses of the animal production and related labour input resulting into a more complex image of the social structure. The models of interaction within the region will focus on the possibility of the food and raw resources circulation through social contacts. Also, elaboration of the decision process of Iron Age farmers promises an encouraging way where to direct our further research. At the moment, our models end with the limits of the given agricultural practice, when reaching a certain population density. By including the social variables representing farmers' independent decisions to change from one economic strategy into another (or to adopt new ones) in order to cope with worsening conditions of the sustainable agricultural practice, our model can approach the past social complexity studies on a new level.

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## References

Babuška R (2001) Fuzzy and Neural Control Disc. Course Lecture Notes, Delft University of Technology

Baili P, Micheli A, Montanari A, Capocaccia R (2005) Comparison of four methods for estimating complete life tables from abridged life tables using mortality data supplied to EUROCARE-3. Math Popul Stud 12:183–198

Bakels C (2009) The Western European Loess Belt: Agrarian History, 5300 BC – AD 1000. Springer, Leiden

Bayliss-Smith T (1978) Maximum Populations and Standard Populations: The Carrying Capacity Question. In: Green D, Haselgrove C, Spriggs M (eds) Social Organisation and Settlement: Contributions from Anthropology, Archaeology, No. 47(i) in BAR International Series (Supplementary), Oxford, pp 129–151

Brázdil R, Valášek H, Chromá K (2006) Documentary evidence of an economic character as a source for the study of meteorological and hydrological extremes and their impacts on human activities. Geogr Ann A 88(2):79–86

Bryson RA, DeWall K (eds) (2007) A Paleoclimatology Workbook: High Resolution, Site-Specific, Macrophysical Climate Modeling. Mammoth Site of Hot Springs, Hot Springs

Campbell BMS (2007) Three Centuries of English Crops Yields, 1211–1491. Medieval Crop Yields Database, The School of Geography, Archaeology, and Palaeoecology, The Queen's University of Belfast. http://www.cropyields.ac.uk

Chase-Dunn C, Niemeyer R, Alvarez A, Inoue H, Sheikh-Mohamed H, Chazan E (2007) Cycles of Rise and Fall, Upsweeps and Collapses: Changes in the Scale of Settlements and Polities Since the Bronze Age. In: Conference on Power Transitions, University of Indiana, Bloomington. http://irows.ucr.edu/papers/irows34/irows34.htm

Chisholm M (1979) Rural Settlement and Land Use. An Essay in Location. Hutchinson, London

Cingolani P, Alcalá-Fdez J (2012) jFuzzyLogic: A Robust and Flexible Fuzzy-Logic Inference System Language Implementation. In: Proceedings of the IEEE World Congress on Computational Intelligence 2012

Čižmář M (2005) Keltské oppidum Staré Hradisko. No. 4 in Archeologické památky střední Moravy, Vlastivědné Muzeum v Olomouci, Olomouc

Danielisová A (2006) To the Architecture of Oppida: Reconstruction of One Part of Settlement Pattern Behind the Ramparts. In: Architektura i budownictwo epoki brązu i wczesnych okresów epoki żelaza: Problemy rekonstrukcji. Muzeum Archeologiczne, Biskupin, pp 269–302

Danielisová A, Hajnalová M (in print) Oppida and Agricultural Production - State of the Art and Prospects: Case Study from the Staré Hradisko Oppidum (Czech Republic). In: Produktion – Distribution – Ökonomie. Siedlungs- und Wirtschaftsmuster der Latènezeit. Kolloquium Otzenhausen 2011, Universitätsforschungen zur Prähistorischen Archäologie, S. Hornung

Del Monte-Luna P, Brook BW, Zetina-Rejón MJ, Cruz-Escalona VH (2004) The carrying capacity of ecosystems. Glob Ecol Biogeogr 13:485–495

Dreslerová D (1995) A Settlement - Economic Model for a Prehistoric Microregion. Settlement Activities in the Vinoř-Stream Basin During the Hallstatt Period. In: Kuna M, Venclová N (eds) Whiter Archaeology? Papers in Honor of Evžen Neústupný, Institute of Archaeology, Prague and Academy of Sciences of the Czech Republic, pp 145–160

Eastman JR (2006) IDRISI Andes: Guide to GIS and Image Processing. Clark University, Worcester. http://clarklabs.org/terms-of-use.cfm

Ebersbach R (2002) Von Bauern und Rindern: Eine Ökosystemanalyse zur Bedeutung der Rinderhaltung in bäuerlichen Gesellschaften als Grundlage zur Modellbildung im Neolithikum. No. 15 in Basler Beiträge zur Archäologie, Schwabe, Basel

Erdkamp P (2005) The Grain Market in the Roman Empire: A Social, Political and Economic Study. Cambridge University Press, Cambridge

Fischer E, Rösch M, Sillmann M, Ehrmann O, Liese-Kleiber H, Voigt R, Stobbe A, Kalis AJ, Stephan E, Schatz K, Posluschny A (2010) Landnutzung im Umkreis der Zentralorte Hohenasperg, Heuneburg und Ipf: Archäobotanische und archäologische Untersuchungen und Modellberechnungen zum Ertragspotential von Ackerbau und Viehhaltung. In: Krausse D (ed) "Fürstensitze" und Zentralorte der frühen Kelten, Band 2, no. 120 in Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Württemberg, Theiss, Stuttgart, pp 195–265

Gorenflo LJ, Gale N (1990) Mapping regional settlement in information space. J Anthropol Archaeol 9:240–274

Gregg SA (1988) Foragers and Farmers. Population Interaction and Agricultural Expansion in Prehistoric Europe. University of Chicago Press, Chicago

Hajnalová M (2003) Rastlinné makrozvyšky zo Starého Hradiska. Technical Report, Výskumná správa archeobotanická

Halstead P (1987) Traditional and ancient rural economy in Mediterranean Europe: plus ça change? J Hell Stud 107:77–87

Halstead P (1995) Plough and power: the economic and social significance of cultivation with the ox-drawn ard in the Mediterranean. Bull Summerian Agric 8:11–21

Halstead P, Jones G (1989) Agrarian ecology in the Greek islands: time stress, scale and risk. J Hell Stud 109:41–55

Halstead P, O'Shea J (eds) (1989) Bad year economics. Cambridge University Press, Cambridge

Hejcman M, Kunzová E (2010) Sustainability of winter wheat production on sandy-loamy Cambisol in the Czech Republic: results from a long-term fertilizer and crop rotation experiment. Field Crops Res 115:191–199

Higgs ES, Vita-Finzi C (1972) Prehistoric Economies: A Territorial Approach. In: Higgs E (ed) Papers in Economic Prehistory. Studies by Members and Associates of the British Academy Major Research Project in the Early History of Agriculture. Cambridge University Press, Cambridge

Jarosław J, Hildebrandt-Radke I (2009) Using multivariate statistics and fuzzy logic system to analyse settlement preferences in lowland areas of the temperate zone: an example from the polish lowlands. J Archaeol Sci 36:2096–2107

Klir G, Yuan B (1995) Fuzzy Sets and Fuzzy Logic: Theory and Applications. Prentice-Hall, Englewood Cliffs

Kohler TA, van der Leeuw SE (eds) (2007) The Model-Based Archaeology of Socionatural Systems. School for Advanced Research Resident Scholar Book, Santa Fe

Kunzová E, Hejcman M (2009) Yield development of winter wheat over 50 years of FYM, N, P and K fertilizer application on black earth soil in the Czech Republic. Field Crops Res 111:226–234

Küster H (1993) The Carbonized Plant Remains. In: Wells P (ed) Settlement, Economy and Cultural Change at the End of the European Iron Age. Excavations at Kelheim in Bavaria, 1987–1991, International Monographs in Prehistory, Archaeological Series, vol 6, Ann Arbor, pp 57–60
Lindsay J (2012) Whitebox Geospatial Analysis Tools. Manual. http://www.uoguelph.ca/~hydrogeo/Whitebox/Help/MainHelp.html
Machálek T, Cimler R, Olševičová K, Danielisová A (2013) Fuzzy Methods in Land Use Modeling for Archaeology. In: Proceedings of Mathematical Methods in Economics 2013
Meduna J (1961) Staré Hradisko. Katalog nálezůložených v muzeu města Boskovic. FAM II. Brno. Museum Catalogue
Meduna J (1970a) Das keltische oppidum Staré Hradisko in Mähren. Germania 48:34–59
Meduna J (1970b) Star'e Hradisko, ii. Katalog der Funde aus den Museen in Brno (Brünn), Praha (Prag), Olomouc, Plumlov und Prostějov. FAM V. Brno. Museum Catalogue
Neuhäuslová Z (2001) Potential Natural Vegetation of the Czech Republic, Braun-Blanquetia: recueil de travaux de géobotanique, vol 30. Dipartimento di Botanica ed Ecologia dell'Università di Camerino, Camerino, map
Olševičová K, Cimler R, Machálek T (2012) Agent-Based Model of Celtic Population Growth: NetLogo and Python. In: Nguyen N, Trawiński B, Katarzyniak R, Jo GS (eds) Advanced Methods for Computational Collective Intelligence. Studies in Computational Intelligence, vol 457. Springer, Berlin
Ramirez O, Mishra O, Field J (2001) Are Crop Yields Normally Distributed? Paper Presented at the Annual Meeting of the American Agricultural Economics Association, Chicago
Reshmidevi T, Eldho T, Jana R (2009) A GIS-integrated fuzzy rule-based inference system for land suitability evaluation in agricultural watersheds. Agric Syst 101(1–2):101–109
Ross T (2010) Fuzzy Logic with Engineering Applications, 3rd edn. Wiley, Chichester
Rothamsted Research (2006) Guide to the Classical and Other Long-Term Experiments, Datasets and Sample Archive. Lawes Agricultural Trust, Bury St. Edmund
Russell K (1988) After Eden. The Behavioral Ecology of Early Food Production in the Near East and North Africa, BAR International Series, vol 391. British Archaeological Reports, Oxford
Salač V (2000) The Oppida in Bohemia: A Wrong Step in the Urbanization of the Country? In: Guichard V, Urban SSO (eds) Les Processus d'urbanisation à l'âge du Fer, Collection Bibracte 4, Archaeological Centre Bibracte, Glux en Glenne, pp 151–156
Salač V (2006) Die keltischen Oppida und ihre Macht. In: Krenn-Leeb A (ed) Wirtschaft, Macht und Strategie – Höhensiedlungen und ihre Funktionen in der Ur- und Frühgeschichte, Archäologie Österreichs Spezial, vol 1, Österreichische Gesellschaft für Ur- und Frühgeschichte, pp 233–245
Saller R (1994) Patriarchy, Property and Death in the Roman Family. Cambridge Studies in Population, Economy and Society in Past Time. Cambridge University Press, Cambridge
Schreg R (2011) Feeding the Village - Reflections on the Ecology and Resilience of the Medieval Rural Economy. In: Klápště J, Sommer P (eds) Processing, Storage, Distribution of Food. Food in the Medieval Rural Environment (Ruralia VIII), Ruralia, vol VIII. Brepols, Turnhout, pp 301–320
Stonedahl F (2011) Genetic Algorithms for the Exploration of Parameter Spaces in Agent Based Models. Ph.D. thesis, Northwestern University, Evanston. http://forrest.stonedahl.com/thesis/forrest_stonedahl_thesis.pdf
Stonedahl F, Wilensky U (2010) Evolutionary Robustness Checking in the Artificial Anasazi Model. In: Proceedings of the 2010 AAAI Fall Symposium on Complex Adaptive Systems
Szeliski R (2010) Computer Vision: Algorithms and Applications. Springer, Berlin. http://szeliski.org/Book/
Turchin P (2009) Long-term population cycles in human societies. Ann N Y Acad Sci 1162:1–17
Turchin P, Nefedov SA (2009) Secular Cycles. Princeton University Press, Princeton
Upadhyay B, Smith E (2005) Modeling Crop Yield Distributions from Small Samples. In: Canadian Agricultural Economics Society Annual Meeting, San Francisco. http://purl.umn.edu/34161

Van der Veen M, Jones G (2006) A re-analysis of agricultural production and consumption: implications for understanding the British Iron Age. Veg Hist Archaeobot 15:217–228

Wainwright J (2008) Can modelling enable us to understand the rôle of humans in landscape evolution? Geoforum 39:659–674

Wilensky U (1999) NetLogo. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston. http://ccl.northwestern.edu/netlogo/

Wright HT (2007) Progress in Cultural Modeling. In: Kohler T, van der Leeuw SE (eds) The Model-Based Archaeology of Socionatural Systems. SAR Press, Santa Fe, pp 229–232