Chapter 12
Economic Sustainability in Relation to Demographic Decline of Celtic Agglomerations in Central Europe: Multiple-Scenario Approach

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12.1 Introduction

On a transition from middle to late Iron Age period we encounter a transformation of the central European society which was represented especially by the new settlement forms—the oppida. They appeared as a part of a socio-economically advanced environment, together with a distinctive intensification of settlement patterns. When they emerged, being understood as "deliberate foundations rather than a gradual evolution" (Collis 2000), they represented complex systems with multiple functions. However, no issue is as variable at the same time as the oppida and range of their activities, functions and social hierarchies (for the discussion on some of them (Collis 2000)).

The central European oppida share the dynamics of their occupation: according to the archaeological record the population density increased from the beginning of the occupation (half of the 2nd century BC), peaked around the end of the 2nd century/beginning of the 1st century BC, and then, within two generations or so, it decreased again. This decrease seems to have been quite rapid and the final population might have been even five times smaller than during its highest density. This massive change in the first half of the 1st century BC was not restricted to the oppida only, but reflected also on settlements in the countryside even in wider European context (Haselgrove and Guichard 2013).

Causes for gradual trend of depopulation can be seen in several factors endogenous and exogenous. However, their greater exploration is obstructed by the

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overall lack of detailed archaeological data. In this situation we suggest to use agent-based models. Our aim is especially to ascertain the resilience of the food production system (i.e. carrying capacity) of the oppida under the dynamically changing (increasing/decreasing) population.

In next sections, after summarizing purpose of agent based-modelling and knowledge on economics and society in the Late Iron Age we introduce our models in NetLogo (Fig. 12.1). The first model of the population dynamics generates data on synthetic populations within alternative depopulation scenarios. The following food production and land use model is used for estimating the carrying capacity of the oppidum with respect to alternative agricultural scenarios. The last workforce model is used for studying labor input of agro-pastoral tasks during the harvest season under different weather conditions, overproduction and ratio of non-producers.

Notice here, that when thinking about modelling the Iron Age society and landscape, either we could start with the population data and explore the predicted site catchment or we could use the landscape data and estimate the likely population in the given area. Our approach was to develop the population dynamics model firstly, including alternative depopulation scenarios, and apply population data as input in subsequent models of land use and workforce allocation. Therefore the three models are designed to enable experimenting with alternative scenarios and strategies with the aim

- to test upper limits of self-subsistence (i.e. the highest possible population size, the largest manageable area of fields and maximum acceptable length of the harvest season with respect to available workforce) and
- to verify general theoretical hypotheses related to the functioning of the oppida within particular landscape environment and the ecological and economic rules that were shaping them.
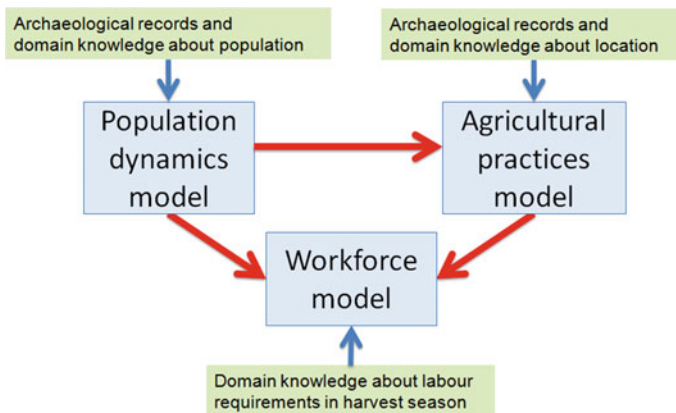

Fig. 12.1 Overview of models

12.2 Theoretical Background

12.2.1 Agent-Based Models in Archaeology

In the scope of archaeological research, agent-based models represent useful tool for testing of hypotheses and building theories through comparison of archaeological evidence with outputs of computational simulations. It is especially the dynamic aspect of models that makes them attractive for archaeologists: using models, it is possible to study spatial and temporal characteristics of development and adaptation of past societies.

Application of the agent-based modelling contributed significantly to the exploration and interpretation of key archaeological questions and topics such as subsistence strategies of hunters and gatherers (Lake 2000; del Castillo and Barceló 2013), spreading of neolitic agriculture to Europe (Conolly et al. 2008; Shennan 2007; van der Vaart et al. 2006), human impact on landscape and natural environment (Axtell et al. 2002; Wainwright 2008; Barton et al. 2010) and socio-economic factors influencing the development and/or collapse of complex societies. Iconic and frequently replicated project was Artificial Anasazi—model of disappearance of Anasazi culture in south-western America (Axtell et al. 2002; Janssen 2009). Other projects were focused e.g. on exploration of political and social structures in ancient Mesopotamia (Altaweel 2007, 2008), where different stress scenarios were applied (e.g. long term dry weather, economic crisis, demographic decline etc.) with the aim to test the resistance and sustainability of society with the given level of social complexity.

Quite often results that were achieved by social simulation and agent-based modelling can challenge traditional theories of economic production, labor input and sustainability of preindustrial society and offer new research directions and archaeological questions. Among these projects, we have to mention also Mesa Verde project which studies the development of population at American middle-west (Kohler and Varien 2012).

As well as in the area of social simulations in general, archaeological computational models are abstract: they work with the idea of past instead of the past itself, and generate data that optionally become source of new hypotheses. Therefore models can serve as behavioral laboratories for experimental ethno-archaeology (Premo 2010). By abstraction we mean the model often operates with artificial variables that have no real equivalents (e.g. attractiveness of the site, potential of the landscape, intensity of interactions) and that cannot be sufficiently and indisputably grounded in empirical data.

12.2.2 Small-Scale Agricultural Production in Late Iron Age

The agricultural economy could be explained partially as a response to environmental conditions and climate. The economic development then can be seen as an adaptive

system to the balance of the ecological factor. However, neither the economy nor society is determined solely by the limits of the environment (Erdkamp 2005); social and political factors also play an indispensable role. Therefore, an analysis of the subsistence strategies during the late Iron Age is as much a social and political study as it is an economic one. As such it can eventually help to understand the dynamics of the development in the second half of the 1st century BC.

The whole Iron Age world despite its technological innovations, specialization and economic contacts, or its level of complexity, was still principally a world of the common farmer. The organization of food production and its redistribution is an essential factor for understanding the complexity of the society and for determining its limits. Every type of society has a characteristic way of the flow of resources and commodities through it, and the organization of transforming these resources to products (Fuller and Stevens 2009). The major aspect in the food production is the significance of agriculture as the primary source of subsistence and organization of potential surplus production. For the socio-economic development, the key aspect is the principle of redistribution of surplus between the consumption and investment. In terms of the technological and economic progress, which contributes to social complexity, the surplus needs not be spent, but accumulated for further investment.

When a certain level of complexity within a society is achieved, and seasonal tasks somewhere allow engaging in non-agricultural activities and at the same time a regular supply of necessary foodstuffs from elsewhere is provided, regional differences (in terms of specialization) occur (Klir 2010). Such aspects and their mechanisms in the Iron Age are still being discussed. A traditional argument in these discussions concerning the level of complexity in the late Iron Age society is that the central places were set in their environments as so called "total consumers" (Salač 2006). That generally means that they were too specialized and hence engaged in other activities, so they were not capable of producing any foodstuffs. This fact should have eventually contributed decisively to the collapse of the Iron Age society in the 1st century BC. Some of these settlements surely had to overcome or accept some environmental constrains (imposed for example by higher altitude) or were forced to adapt their subsistence practices (e.g. develop an alternative approach to the exploitation of land). There are several proofs providing support to the notion that the food production was an inseparable part of the oppidum's life. The evidence is in fact abundant: numerous livestock, agricultural tools, storage facilities, botanical and pollen analyses etc.

In the models of social complexity population dynamics and exploitation of natural resources play an important role from which wide range of social phenomena have been explained (Bayliss-Smith 1978). According to historic sources, exceeding the appropriate carrying capacity was not a rare occasion in history (Schreg 2011) even in societies with developed market networks. Intensification of the production led to innovations in the agriculture on one hand but also to a more rapid depletion of the land resources especially where their extent was limited on the other. This prompted behavior, which could have led to more profound social change at the end of the Iron Age in central Europe. Our aim was to test these premises in the socio-cultural milieu of the central European oppida.

12.3   Models of the Staré Hradisko Oppidum

Our case study location is the oppidum of Staré Hradisko in Bohemia (Čižmář 2005). The core concept is the self-subsistence of the oppidum, i.e. the idea of 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 explore the dynamics of the food production and isolate possible crisis factors imposed either by environment or by un-sustainability of the economic strategies pursued. Main three questions are:

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

To answer these questions, we developed three models: the population dynamics model, subsequent food production and land use model and workforce allocation model.

12.3.1   Population Dynamics Model

12.3.1.1   Objective

This model generates data on synthetic population of the settlement (i.e. numbers of inhabitants with appropriate age/sex structure and related data on energetic requirements and available workforce), including optional population decline and structural changes. Synthetic population corresponds to assumptions based on archaeological evidence.

12.3.1.2   Theoretical Background and Scenarios

The population dynamics is defined by the initial population, its growth rate and death rate. In our case of the oppidum Staré Hradisko, the initial population is estimated to be between 600 and 800 individuals (depends on the spatial structure and the chronology of the site). Although details on structure and size of families are not known, archaeological evidence of settlement features indicates the probable existence of nuclear households of 4−6 members and communities of probably about 20−22 members residing within typical oppidum´s enclosed compounds. There is an archaeological evidence that the initial population grown quite rapidly. According the simplest Malthusian population model, the growth is exponential:

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

(P_0—initial population, r—growth rate, t—time)

For establishing the appropriate birth rates and life expectancy during the Iron Age the regional model life-tables created by Coale and Demeny for the ancient Roman population (Saller 1994) are the most relevant source of information. 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 was applied. The constraints to be satisfied are approximately constant ratios of male/female and ratio of age categories. The model outputs are time series of the synthetic population data for the period of 120 years, i.e. time series of numbers of individuals and the consumption of the population in calories representing:

- the energetic requirements of the population,
- the availability of the human workforce, i.e. actual number of people in productive age in particular age/sex categories.

Two main categories were distinguished: "strongforce" (males and young males who can perform heavier task such as ploughing, harvesting with scythes, forest clearance etc.) and "weakforce" (females, older children and elderly, who can pursue other tasks, such as sowing, hoeing, weeding, manuring, milking, various assistance tasks etc.). These categories are important for our later workforce model.

In order to reflect the population decline of the oppidum four (de)population scenarios are formulated:

1. Normal growth of the population (*baseline*) is defined. In this case the population grows by 2 % annual increment up to 2500−3000 individuals. This scenario corresponds to the stable situation without any adverse events.
2. Sudden proportional decline (*sudden depopulation*) is a massive one-time depopulation of 30−60 % of the inhabitants. It is naturally accompanied with the decline of workforce, livestock and food storage. It corresponds to the hypothesis of the emigration of the part of the population in the 1st half of the 1st century BC.
3. Continuous proportional decline (*gradual depopulation*) is less extensive but continuous depopulation of 3 % of the oppidum's inhabitants per year. It corresponds to the hypothesis of continuous emigration beginning in the 1st half of the 1st century BC.
4. Sudden non-proportional decline (*epidemic*) is a massive one-time depopulation of 30−60 % of inhabitants, more conspicuous in certain age groups (suckling, toddlers, children, and elderly). It causes significant workforce decline during the following decades.

Depopulation scenarios have consequences that are subject of our interest in the food production and land allocation model.

12.3.1.3 Model Design

Individuals are represented by agents with two parameters (age, gender). Simulation runs in 120 yearly time-steps. Each step consists of population update, i.e. increasing of agents' age according life tables and adding new agents, representing newborns. Optionally, in case of depopulation scenario, appropriate ratio of agents is removed. Model inputs are:

- initial population size,
- selection list of life tables,
- parameter Q which specifies the probability of woman-agent to give a birth.

Value of Q is applied in formula which was identified experimentally by optimization of two functions. The first function F1 expresses the percentual changes of final population X in relation to original population A.

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

The second function F2 defines average percent change in seven age groups (sucklings, toddlers, small children, older children, young adults, adults, elderly):

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

12.3.1.4 Outputs

This model is not used for experimenting in sense of exploration of spaces of parameters; it only generates population data for alternative depopulation scenarios (Fig. 12.2).

12.3.2 Food Production and Land Use Model

12.3.2.1 Objective

The purpose of the 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.
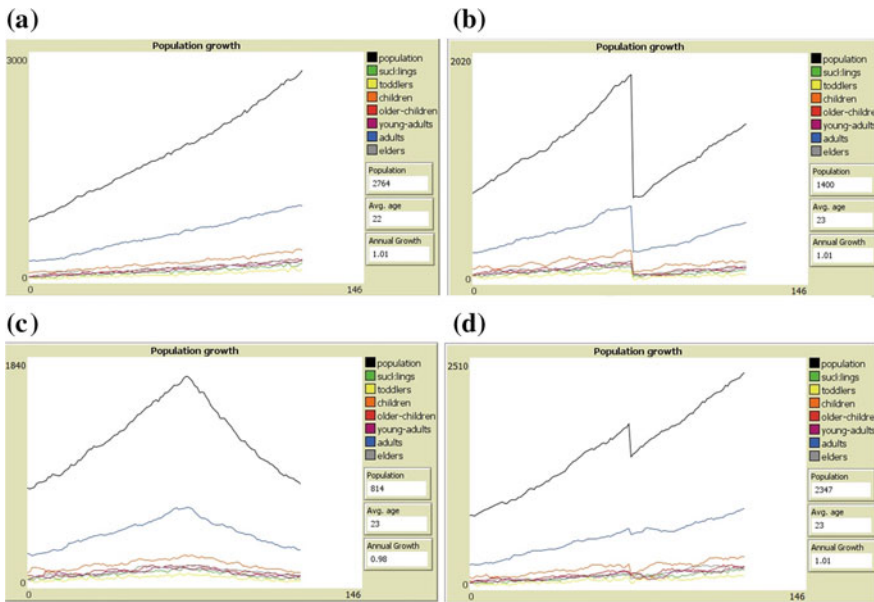
Fig. 12.2 Population dynamics: **a** baseline, **b** sudden decline, **c** gradual decline, **d** epidemics

12.3.2.2 Theoretical Background and Scenarios

The food production model captures the dynamics of agro-pastoral economy process (the oppidum's own agricultural production) in recurrent year-to-year cycles which is tested against subsistence, surplus production and carrying capacity factors. For each year, certain mixture of main land-use strategies (intensive agriculture, extensive agriculture, grazing livestock and deforestation) is applied. The abrupt or profound changes of the food storage make population to adapt to new conditions (to change the land-use strategy).

The food production model can apply population modelling outputs (i.e. time-series of synthetic population and its consumption that were calculated using caloric tables from population dynamics model, and potential workforce calculated from productive age and sex categories) together with authentic archaeological and environmental records of the region. The evidence of agricultural activities carried out by the oppidum inhabitants is indicated by particular artefacts (such as farming implements), archaeobotanical and archaeozoological assemblages, and settlement features (especially storage facilities).

The method of site catchment analysis (Jarman et al. 1972) can be used for the modelling of the oppidum's hinterland. Site catchment analysis approach is based on models of economics and ecological energy expenditure, and provides a framework within which the economic activities of particular site can be related to the resource potential of the surrounding area. We thus need 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 is modelled as cost distance according to walking speed from the centre—the oppidum. 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.

In order to refer more directly to the point of the community's subsistence, demography and organisation of labor in relation to its environment a concept of "ecosystem" (cf. Ebersbach 2002; Schreg 2011) was adopted. The ecosystem consists of all the basic productive aspects of the landscape (extent and quality of arable land, pastures, managed forests, unused resources and reserves) as well of the societal means which exploit them, such as labor, technology, subsistence strategies, land tenure, social and political structure and contacts (Schreg 2011). All these aspects form the spatial layout of the particular ecosystem.

The criteria for the prediction of fields are related to the environmental variables: topography, soils, and climate. The fields in the model have to be placed on fairly moderate slopes—less than 5°, 5−10° and 10−15° respectively. The pastures have to be on slopes less than 30 % and within an accessible distance from the water source. Together with the other variables "soils" (quality, depth, rockiness), "topography", and "wetness" (the topographical tendency of the particular grid cell to be more or less wet) it is put together through the multi-criteria evaluation analysis (Eastman 2006) by which different field suitability categories are created. The plots classified as unsuitable (too wet, too rocky or on slopes too steep) are excluded from the field and pasture suitability model. One of the crucial factors for the prediction of both fields and pastures is the accessibility from the settlement. Therefore most suitable areas are plotted as the most fertile zones located as close as possible to the settlement. A cost penalty was included for more distant fields (Chisholm 1979). This option applies especially for more intensive regimes of land-use; the cost impact is lower for the fields under the extensive practices. Fields within distance zones could have been subjected to different land-use and management—more intensive closer to the oppidum and more extensive further away in terms of infield and outfield management. The terrains which remained can be attributed to forest pastures, forest openings and woodland.

The default presumption for the model is that each household that cultivated the fields used animal traction. The actual area of fields, as well as the labor input per unit area, varies greatly according to the number of inhabitants and different arable farming strategies employed (Halstead 2014). 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. (Rothamsed research 2006; Kunzova and Hejcman 2009). Variable annual yields are also being regularly mentioned in the historic records (Erdkamp 2005; Campbell 2007). Therefore, using the 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

(Haltsead and O'Shea 1989). Therefore a general range between 500–3000 kg/ha (mean value 1500 kg/ha for the intensive and 1000 kg/ha for the extensive strategy respectively, can be considered as the 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" it is understood 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 essential hypothesis supposes the continuous growth of both the population and food production. The following agricultural strategies are assumed to have been possibly practised by the Iron Age population (cf. Halstead 1995):

- *Intensive farming* on small plots: fields were manured namely by stable dung and settlement waste; they were intensively tilled by hand, and weeded. Working animals could be used for ploughing; rotation of crops (cereals, pulses) was practiced. Intensive farming strategy represents the labor demanding option, which tends to be limited in scale or to cover only the subsistence and necessary surplus needs.
- *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, labor 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.

Both strategies could be combined in terms of infield and outfield land management in order to balance the work/land requirements. There are different consequences and constraints. Higher cereal consumption requires more intensive growing with ploughing and manuring; intensive manuring requires higher numbers of livestock; more animals require more working hours. Total manpower has to be allocated according to the appropriate sequences of agricultural activities and their timing during the year (seeding, harrowing, ploughing, harvesting or manuring).

Important issue is a livestock. Estimation of sizes of herds can be based on assumptions of sizes of households (Ebersbach 2002; Gregg 1988; Olsson 1991): when we take into account 8−10 cattle (2 ploughing oxen), 20–30 sheep/goats, 4–5 pigs and 1−2 horses per community of 4 families, total livestock can be calculated. The reproducibility of animals differs: for cattles, it is slow—0.5−0.8 calf/cow/year with mortality 20 %, therefore it takes 10−12 years (depends on the number of animals in herd) to double in size. Rates for horses are similar, with longer pregnancy and adolescence and subsequent lower herd growth; natality and mortality rates of sheep, goats and pigs are significantly higher. The culling/year sustainable for maintaining reproducibility is 10 % for horses, 15 % for cattle, 30 % for sheep/goats and 50 % for pigs. For the purpose of our model, there are three livestock scenarios (see also Fig. 12.3).
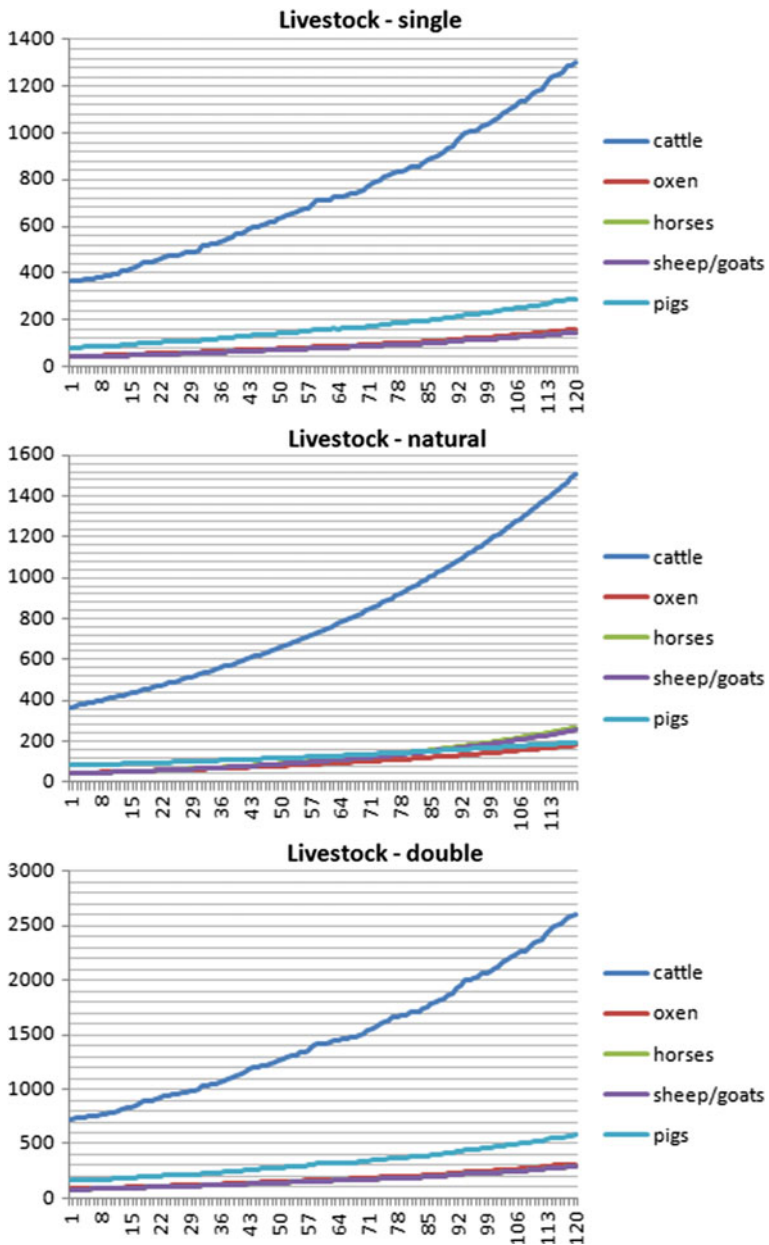
Fig. 12.3 Livestock scenarios for baseline population: single, natural and double numbers

Table 12.1 Minimum size of herds for populations of 800, 2000 and 2500 persons

	Herd per 1 community (20 persons)	800	2000	2500
Cattle	2−4 cows, 2−4 calves, 2 oxen	380−400	950−1000	1187.5−1250
Sheep/Goats	2−2.5	65−70	162.5−175	203.1−218.7
Pigs	4−5	170−180	425−450	531.2−562.5
Horses	1−2	40−50	100−125	125−156.2

- *Minimum numbers* with 0.5 cattle/person (Table. 12.1),
- *Double numbers* with (0.8−1 cattle/person) in case the initial and first-generations oppidum population had enough landscape resources to keep larger herds than originally proposed in the minimum option.
- *Natural numbers* with natural birth and mortality rates and probable slaughtering rates.

Typically, bigger populations have higher consumption requirements, benefit from higher manpower and manage larger areas. If additional land units were required for crop production or livestock grazing, appropriate part of the original woodland has to be cleared and thus changed into the arable land or pastures. The spreading and spatial organization of the site catchment is naturally shaped by accessibility (in model represented by friction surface modelled from local topography). If the limits are achieved, population adapts. Either part of the population leaves, or the food production and/or diet composition has to be changed.

Similarly to the population dynamics model, alternative scenarios were can be taken into account:

- *Sudden event: lost harvest*—the crop is damaged either by floods or droughts. The consumption requirements are not covered sufficiently, therefore the population is expected to adapt to the situation.
- *Sudden event: lost animals*—it can be caused by disease or theft. The meat and milk calories are not available and/or the ploughing oxen cannot be used, the arable land is affected and the agricultural strategy has to be modified.
- *Sudden event: fire*—the crop is destroyed including the storage (reserves from previous one or two years, seed for the next season), the populations is expected to adapt.
- *No event* (*baseline*)—no unexpected events happen, i.e. the food production is not affected by inauspicious weather, fire etc. If the population grows, the food productions grew correspondingly up to the spatial limits.

12.3.2.3   Model Design

The model environment represents Staré Hradisko oppidum (Fig. 12.4) located in a gridded landscape modelled using GIS. Total area is 70 km^2, one cell is 20 × 20 m (400 m^2). The individual cells are described by topographical land-use suitability
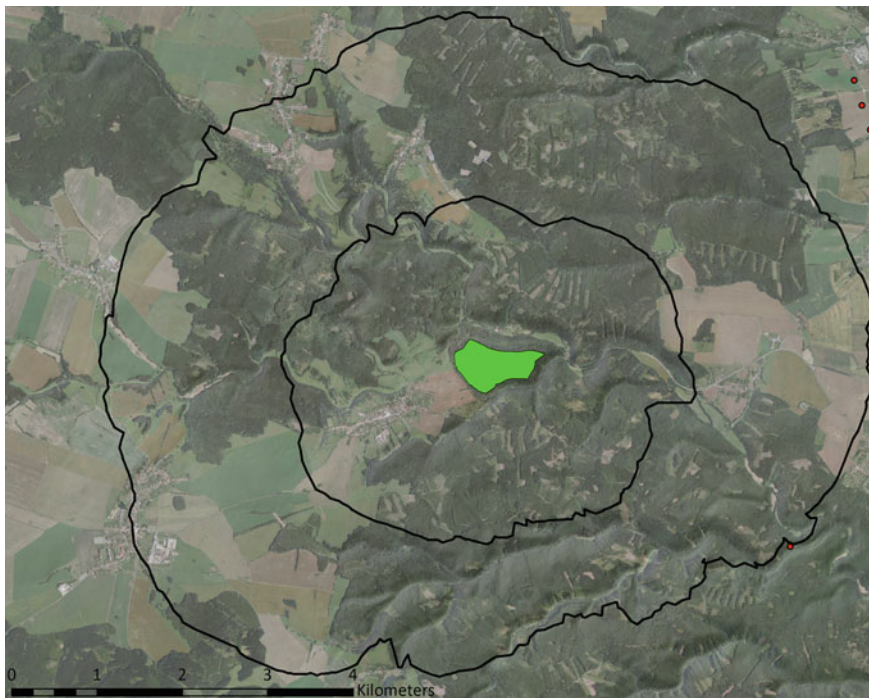
Fig. 12.4 Orthophotomap with the Staré Hradisko oppidum in centre and walking distances of 0.5 and 1 km

and economic variables that are encoded in map layers. Primary maps describe topography, hydrology, geology (soil quality) and potential land cover:

- *Slope* is initial variable for selection of areas to be used as fields and pastures, there are four levels of suitability,
- *Hydrology*: distances from water sources are calculated using gradient from the topography map and the map of fluvial sediments, topographical wetness index expresses tendency of the cell to be saturated by water in relation to values of gradient and surface outflow.
- *Original land cover* before deforesting and transformation into to the agricultural landscape is defined using botanic and pollen data from the oppidum (Neuhäuslová et al. 2001; Přichystal and Opravil 1992). Mixed forests are sources of wood.

Secondary maps define accessibility from the oppidum (*friction*) and suitability of each cell for agricultural activities. Basic walking distance is one hour, the corresponding formula is (Gorenflo and Gale 1990):

$$V = 6*e^{-3.5(S + 0.05)}$$

(S = slope in %)

Except the oppidum and water streams, there are following land use categories: fields and fallows, pastures and meadows, shrubs, managed forest and climax forest. In each of 120 time steps of the simulation, the grid of cells is updated, including transformation of one category into another (fields to fallows or meadows to shrubs). Model inputs are:

- population data,
- GIS data,
- diet specification (e.g. the ratio of cereal vs. proteins to be covered by the agricultural production),
- strategy and work allocation settings (e.g. intensive or extensive agricultural strategy, manpower per land unit and per task).

The food production models apply synthetic population data (i.e. time-series of number of inhabitants and their consumption requirements) together with authentic archaeological and environmental records with the region.

One simulation step corresponds to one agricultural year. The simulation starts with loading biophysical parameters of cells. Each cell updates its state according its current land-use category. At the beginning of the simulation run (year 1), part of the landscapes is already cultivated (initial livestock and fields areas are specified by input parameters). With update of the human population, also livestock populations are updated, including their caloric requirements.

For given parameters (current consumption, surplus, seed, loses) and general agricultural principles (fluctuation of the crop size) the size of field area is calculated. It is possible to simulate changes of areas (size, quality) in time (in single years).

The estimation of the necessary field area is based on the assumption that every year, if there were no unexpected events, the production covers needs of the population including safety margin (Müller-Herold—Sieferle 1997). The field area F is updated using formula:

$$F = \left(\frac{TC \times pCD}{exY \times 3440} \right) \times (1 + r) + \left(\frac{lA \times SR}{exY} \right)$$

(TC—total consumption, exY—expected yield from hectar (in calories), pCD—ratio of cereals in diet, r—reserves, lA—last current area of fields, SR—seed requirement)

The important sub-component of the model is the nitrogen cycle in soil which has impacts the crop production significantly. With the intensive strategy the nitrogen is applied with farmyard manure from animals stabled per nights and

during the winter months. Under the extensive strategy the nitrogen is applied by livestock grazing the fallows and biomass decomposition in the grassland pastures. Two strategies were applied in the model—either immediate or gradual releasing of nitrogen affecting the soil fertility for the following harvest.

The yearly production depends on overall tendency in field productivity and current external factors (sudden events, loses). The harvest size is expressed in calories and the amount of the harvest is divided into consumption, seed for the next season, and reserves which can be stored up to three years. From the comparison of reserves and consumption it is possible to estimate the general tendency. The share of cereals in the diet includes current harvest and reserves.

Each kind of domestic animal has its preference regarding pastures; basis is that some species can graze in the forest (cows, pigs) and other cannot (sheep/goats, horses). Overall deforested area is calculated according these preferences. Therefore, the grazed area PA (forest and grassland, including pastures and fallows) in each step is updated according to the formula:

$$\frac{(H \times 2 + S \times 0.1 + C \times 1.5) + (P \times 0.5 + (C - (PAS - H \times 2 + S \times 0.1)) \times 4)}{2 \pm 0.3}$$

(H—number of horses, S—number of sheep, C—number of cattle, P—number of pigs, PAS—pastures area)

Winter fodder consists of hay, leaf fodder, and surplus of grain production (especially for ploughing oxen) respectively. The area of hay meadows is calculated using formula:

$$MA = \frac{(C \times 5 + H \times 6 + S) \times 150 \pm 30}{3000 \pm 500}$$

(H—number of horses, S—number of sheep, C—number of cattle)

Leaf fodder area (LFA) is a forest area required to collect leaf fodder:

$$LFA = \frac{(C \times 6.5 + H \times 7.5 + S \times 1.5) \times 150 \pm 30}{2400}$$

(H—number of horses, S—number of sheep, C—number of cattle)

For each year and each land cell, the land category is optionally updated (transformation of fallows into fields after 3-year rotation, increasing the amount of biomass in meadows and forests or updating the nitrogen rate).

The bank of working hours is maintained, taking into account the current work disposition of the community which is calculated from the time needed for each activity.

12.3.2.4 Outputs

Firstly, we compared intensive and extensive strategy at the beginning (year 1) and at the end (year 120) within baseline population. The objective of the experiment was to estimate the maximum sustainable population and livestock inside the relevant part of the map, i.e. in the area that is manageable with respect to cost distance. In case of intensive strategy, there are two options related to livestock:

- grazing mainly in forests, with minimum areas of meadows for herding,
- maximum deforesting, with most of herds grazing in meadows.

See Fig. 12.5 for results. The initial setting was intensive strategy, mean crop size 1500 kg/ha, hay production 3000 kg/ha, leaf fodder 2400 kg/ha. In this case, the hinterland area is not exhausted and maximum population attacks final values for baseline scenario, i.e. over 3000 persons. With double livestock, which would require more space for grazing, the upper limit for human population is approx. 1500 persons.

In the second experiment, the long-term tendency in crop size, storage size and overall surplus/deficit was examined in relation to weather "events" (storms, rain, drought or frost) which impact on production significantly. The frequency of events was modelled on the basis of historic records from the same region (e.g. Brázdil et al. 2006). To ensure sufficient production to cover the energy consumption of the population of the settlement, including safety margin, the local population creates reserves—cultivating more land and stores surplus.

Our conclusion is that 10 % overproduction was not enough to face sudden events successfully, 50 % overproduction made population self-sufficient and with 100 % overproduction the available surplus (meaning shareable by feasting or market relations) appeared regularly. Version with baseline population scenario and
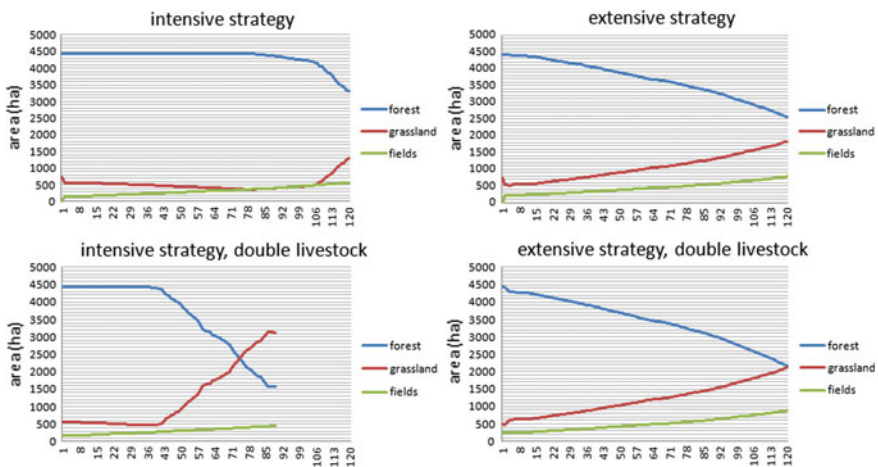

Fig. 12.5 Land use: comparison of intensive and extensive with natural and double livestock

sudden event "animal lost" (half of livestock is lost in year 75) shown that only double size of crop protects the population from deficit. Also, the baseline population scenario was compared with gradual decline scenario with "animal lost" event.

12.3.3 Workforce Model

12.3.3.1 Objective

Model enables experimenting with workforce allocation to parallel agricultural activities during the harvest season, which is the bottleneck of the agricultural year (cf. e.g. Halstead 2014). Key issues are the ratio of strong and weak workforce participating in harvest activities, the impact of weather and the ratio of targeted overproduction.

12.3.3.2 Theoretical Background and Scenarios

To achieve self-subsistence, the population has to allocate workforce effectively. For agricultural societies it means managing activities in given periods of the agricultural year and producing food not only to cover current caloric requirements, but also to create reserves, to cover probable loses and to prepare seed for the next season.

In relation to workforce capacities, there are several bottlenecks: spring and autumn periods of ploughing and seeding and especially the summer period of harvest which is relatively short (2−6 weeks) but extremely labor demanding (Halstead 2014). The harvest of cereals and pulses with their gradual ripening time has to be mastered in parallel with hay preparation (winter fodder for livestock) and moreover there are other daily activities such as herding and milking, domestic work or firing wood preparation.

Total working capacity depends on size of population. It is important to differentiate between "strongforce" (given by number adult men who are able to plough with oxen) and "weakforce" (given by the rest of workers). We assume certain ratio of non-working elite as well as some capacities permanently allocated to other than agricultural tasks (crafts, trade).

Labor input is variable during the agricultural year—lower in winter, higher is summer (Fig. 12.6) and differs for strongforce and weakforce (Table 12.2). Our model is focused on harvest season only during which the working capacities are allocated to:

- *standard, repetitive tasks* (housework, herding, milking and other care for livestock, preparing firing wood etc.),
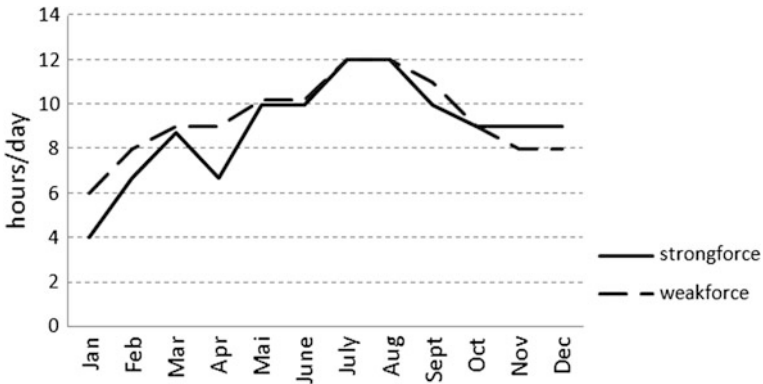
Fig. 12.6 Variable labour input during the year

- *seasonal activities* that form a logical sequence (harvesting and transport, threshing, winnowing and gathering of grain, concurrent hay harvest with drying, transport and storage).

The success of the harvest season depends on weather conditions, which accelerate (or delay) ripening of crops and shorten (or prolong) the period during which the quality of crops is the best (and the yield per hectare is the highest). As for the haymaking (after the rain the grass is wet and cannot be mowed), the number of rainy days represents constraint for the crop harvest process.

12.3.3.3   Model Design

Model runs in daily steps that represent the period from 1st July till the end of the harvest season, maximum length of the season 90 steps. We are interested especially in those settings of the model that would enable finishing the harvest process in three weeks or sooner, because models calculates with the option that after two or three weeks the quality of cereals decreases.

Model has got four input parameters:

- size of population,
- daily labour input of strongforce and weakforce (hours) and the ratio of non-working strongforce,
- average yield (kg/ha)
- probability of rainy weather (total number of rainy days).

Current size of population is used in initial static calculation of current size of livestock and land-use area to be maintained. Both human and animal populations have their caloric requirements that together define overall yearly consumption of cereals (including loses and seed). The main procedure is used to distribute working capacities to parallel tasks (crop harvest, hay harvest, herding and domestic work).

Activity	Strongforce	Weakforce
Harvest	90 h/1 ha	225 h/1 ha
Transport	20 h/1500 kg	40 h/1500 kg
Threshing	40 h/1500 kg	–
Winnowing	33 h/1500 kg	–
Gathering, storage	–	11 h/1500 kg

Table 12.2 Labour input during harvest process

Main output value is number of days that is necessary for completing the harvest process.

12.3.3.4 Outputs

Firstly, we explored the impact of bad weather on prolongation of the harvest process in case of the population of 1000 persons, 12 h long working day, 10 % of non-producers in population and average yield 1500 kg/ha. Under these circumstances and in case of relatively good weather (with probability of rainy weather under 30 %) the harvest process took less than 3 weeks.

Secondly, we assumed the probability of rainy weather between 10 and 30 % and the ratio of non-producers around 20 % and we examined the ability of the population to produce surplus for eventual trade activities. In case of good weather, the population of 1000 inhabitants could cover own needs even if the yield had been very low (around 800 kg/ha). In case of bad weather and very high yield (3200 kg/ha) it is possible to double the production.

Thirdly, we examined the ratio of non-producers (elite). Experimental results show that the maximum share of non-producers is 20 % in case of relatively good weather (probability of rainy weather up to 30 %, according the first experiment).

Depending on the either intensive or extensive strategy chosen, the landscape is covered by the mosaics of fields and pastures gradually verging into the managed forest. With the intensive strategy the livestock has to graze in the forest or, in case of work capacities allocated to forest clearance, on grassland pastures. With the extensive strategy the livestock is mostly left to graze the fallows. Baseline scenario shows clearly the limit of the predicted catchment: by the final years of the simulation the oppidum usually runs out of the area available for pastures. In this case the possible solutions include change of economic strategy, decreasing the number of animals, enlarging the catchment or emigration (Fig. 12.7).

12.4 Conclusion

Our models were created to analyze past socio-economic processes, determine possible crisis factors and understand ecological and cultural changes in Central Europe in late Iron Age. The immediate or gradual impact of the success rate in the
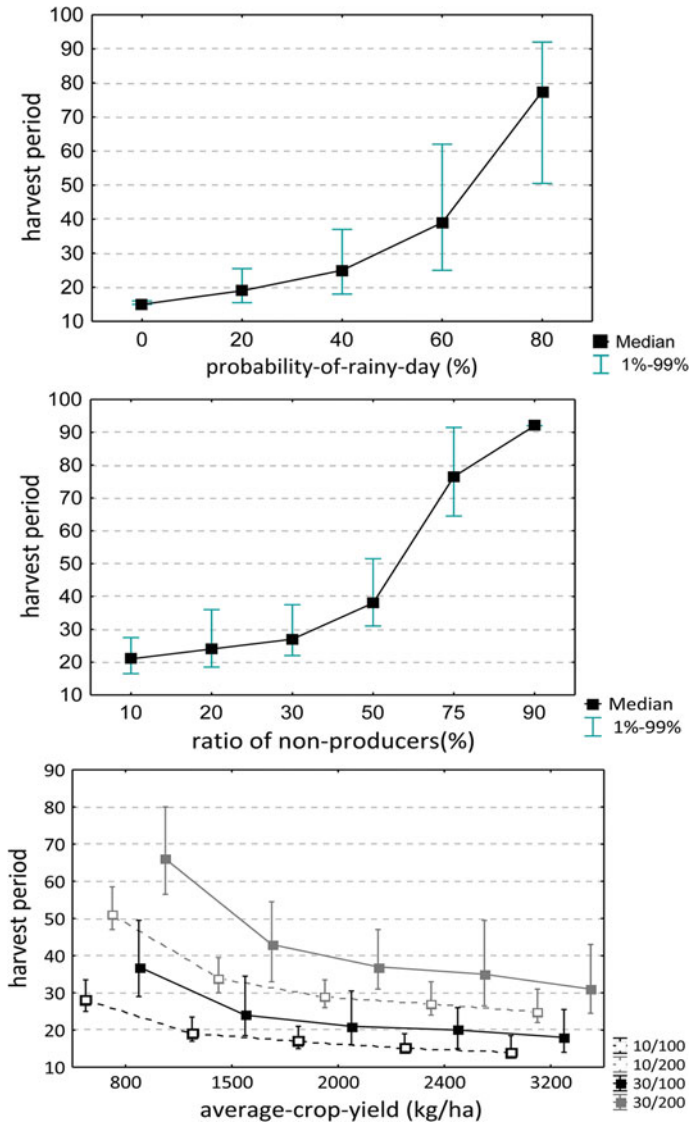
Fig. 12.7 Impact of bad weather, ratio of non-producers and average crop yield on the duration of the harvest process in days

food production and its potential influences on the economic and social processes were also addressed.

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 Iron Age in Central Europe increased over some time and then decreased again rapidly.

The population dynamics model provides realistic time series of energetic requirements, workforce availability and age distributions of population of the oppidum´s agglomeration. The modelling results showed different outcomes of the economic strategies performed by either growing or declining population.

The limits of the land-use strategies returned from the baseline scenario, when the population was expected to react by adjusting their economic strategies, started acting around the population density being around 3000 especially due to the depletion of available hinterland area (i.e. available field, forest and pasture plots) within the predicted catchment.

However, according to the archaeological record the population started decreasing after 70−80 years (sudden decline, gradual decline and epidemic scenarios). 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, accidents (fire, deceasing of the livestock), and other socio-economic (raids, theft) factors.

In our models it has been proven by experiments that not all of the oppidum population had to be engaged in the agricultural work. There is an archaeological evidence of elite members, which, expectably, were not involved in the agricultural production. Increasing and/or decreasing amount of free time represents in fact the level of society´s complexity and its changes reflect decline of this complexity connected to the loss of the production potential. The labor shortage may also point to the necessity of using the external supplies.

Our further research is focused on network analysis and network-based modelling of interactions between the oppidum and open village settlements and between individual settlements (i.e. food and raw resources circulation through social contacts). Network analysis (see e.g. Knappett 2013) is planned to be used for the interpretation of the archaeological data from the sites and for exploration of questions associated with cultural diffusion, settlement hierarchies and regional aspects.

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