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ORIGINAL ARTICLE

Models of wetland settlement and associated land use in South-West Germany during the fourth millennium B.C.

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Abstract A GIS-based modelling approach is presented that interprets existing data on subsistence strategies of pile-dwelling people of the Lake Constance area in South-Western Germany and North-Eastern Switzerland. This is conducted using the examples of the settlement sites at Hornstaad-Hörnle 1, Sipplingen-Osthafen and Degersee 1. Soil distribution and the geomorphologic features of a landscape are used as the basis for illustrating various scenarios of land use depicting hypotheses of economic strategies and aspects of the human-environment-system. In particular the implications of the crop system and the discussion about Shifting Cultivation or Intensive Garden Cultivation are used as different modelling inputs, alongside the spatial demand for cattle herding and for the extraction of timber. The Carrying Capacity of the landscape around the three settlement sites is calculated with respect to the agricultural system applied.

Keywords GIS · Carrying Capacity · Wetland archaeology · Landscape archaeology · Archaeological modeling · Neolithic land use

Introduction

Remains of settlements that were constructed in peat bogs or at lake shores during the fourth millennium B.C. can be found in pre-alpine lowlands of all countries surrounding the European Alps (Schlichtherle and Suter 2009). Due to well-established research strategies integrating archaeology, biology and the geosciences, the subsistence strategies of the related people and their corresponding land use system can be reconstructed in high resolution (e.g. Billamboz et al. 2010; Jacomet 2008, 2009; Jeraj et al. 2009; Maier et al. 2001). This encompasses proof for shifting preferences for certain crop species (Jacomet 2004) or the substitution of certain nutritional elements by others due to environmental influence (Schibler 2006; Jacomet and Schibler 2010a). While on the micro-scale a large amount of knowledge has been gained from the lake- and peat bog sediments, the interpretation of the data in terms of the corresponding macro-scale is not as clear. For instance, the influence of deteriorating climatic conditions is discussed controversially (Bleicher 2013; Magny 2013), as is the question of the cropping system (e.g. Bogaard 2004; Schier 2009). These and similar questions relate to the settlement system in the landscape as a whole; the reasons for the high degree of dynamics and instability in wetland sites (Ebersbach 2010) is not known, neither is it clear whether the common image of widely unsettled hinterlands holds true, or if it is distorted due to different edaphic conditions under water and on dry land (Ebersbach 2012). In order to address these questions, it seems promising to integrate the existing data into scenarios. The present article introduces and discusses an approach that is based on geographical information systems (GIS) and facilitates the generation of maps that illustrate various scenarios of land use around the settlements in question. The value of combining spatial analyses derived from GIS with palaeoenvironmental data of (pre-) historic settlements has already been demonstrated in many projects. Zhang et al. (2010) have used this strategy to explore possible relationships between local arable ecology, crop-processing strategies and the natural

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environment in pre-historic China. Ullah (2011) developed a GIS-based method to reconstruct site-catchments as a basis for simulation modelling of late Neolithic settlements in Jordan. Caseldine et al. (2008) discuss landscape reconstructions based on pollen analysis and archaeology applying GIS. In this investigation, which is based on a unpublished diploma thesis (Baum 2010), three basic questions are addressed:

(1) What major elements and processes constitute the land-use system of the inhabitants of pile dwellings and peat bog settlements of South-Western Germany and Switzerland in the fourth millennium B.C.?
(2) Is it possible to specify an average "Carrying Capacity" of the landscape surrounding the settlements with respect to the supposed subsistence strategies of the pile-dwelling people?
(3) How can the spatial implications of different land use systems be illustrated and related to the patterns observed in archaeology?

These questions are investigated using well-known sites in three study areas: Hornstaad-Hörnle 1 (Ho 1 in this paper) and Sipplingen-Osthafen (Si) are located on the South-Western and North-Western shores of Lake Constance, respectively, the site Degersee 1 (De 1) is situated on the shores of Lake Degersee, a small lake to the North-East of Lake Constance as shown in Fig. 1. The scenarios presented explicitly do not represent an assumed single reality. Instead, they are a compromise between the known and the plausible, mediating between different interpretations of the data collected so far given by various disciplines (e.g. Bogaard 2004; Schier 2009). This is used as the starting point for future modeling purposes, which will consequently be enhanced, integrating more data and adding more sophisticated sub-models. The ultimate goal is to generate simulation models which best reproduce the spatial pattern observed in archaeology, integrate all relevant data and go along with the least discrepancies between them. Similar successful simulation projects demonstrate the value of the approach (e.g. Axtell et al. 2002). In this article, I describe the background in environmental and economic archaeology and present first results obtained using a simple GIS-based model. An important output of the model will be an understanding of the importance of different parameters and the range of changes occurring due to varying inputs of one single aspect.

The sites and their environment

The regional setting and the location of the sites Ho 1, Si, and De 1 is shown in Fig. 1. All sites lie in the Northern alpine foreland of South-Western Germany and were covered by ice shields during the last glaciation (Krayss and Keller 1983). Geomorphologic features of the landscape such as drumlin-fields, glacial and kettle-hole lakes and extensive moraine areas testify to these processes (Liedtke et al. 1995, p. 612). Soils are most often derived from glacial sediments with the exception of areas subjected to strong erosion or sedimentation during the Holocene (Stahr and Peyer 1997). Figure 2 shows the local conditions within a radius of 2 km around the three settlement sites.

The site Ho 1 (47.964° N 9.005° E) is located at the tip of the Höri peninsula near the outlet of Lake Constance into the river Rhine at 395 m a.s.l. While it is surrounded

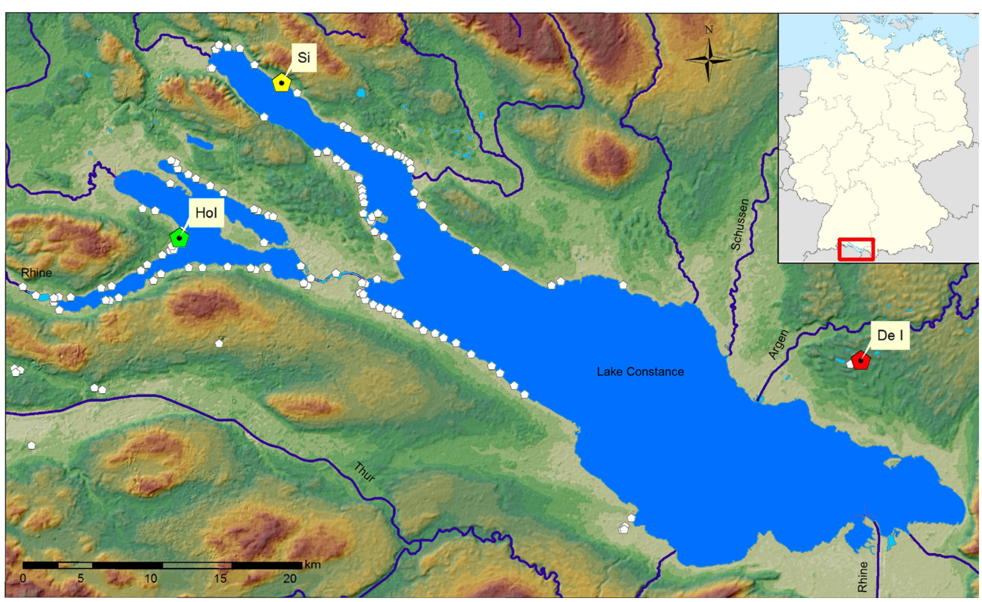


Fig. 1 Distribution of pile-dwellings and peat bog sites near Lake Constance in SW-Germany and NE-Switzerland (not complete). Ho I: Hornstaad-Hörnle 1. Si: Sipplingen-Osthafen. De I: Degersee 1. © LGL Baden-Württemberg (www.lgl-bw.de)

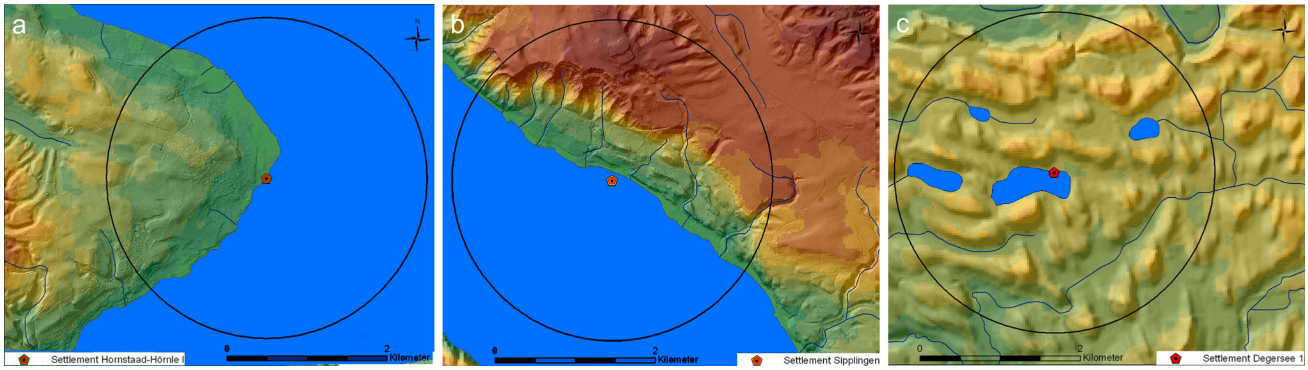


Fig. 2 **a**, **b**, **c** The landscape in a 2-km-radius around the sites Hornstaad-Hörnle 1, Sipplingen-Osthafen and Degersee 1 © LGL Baden-Württemberg (www.lgl-bw.de)

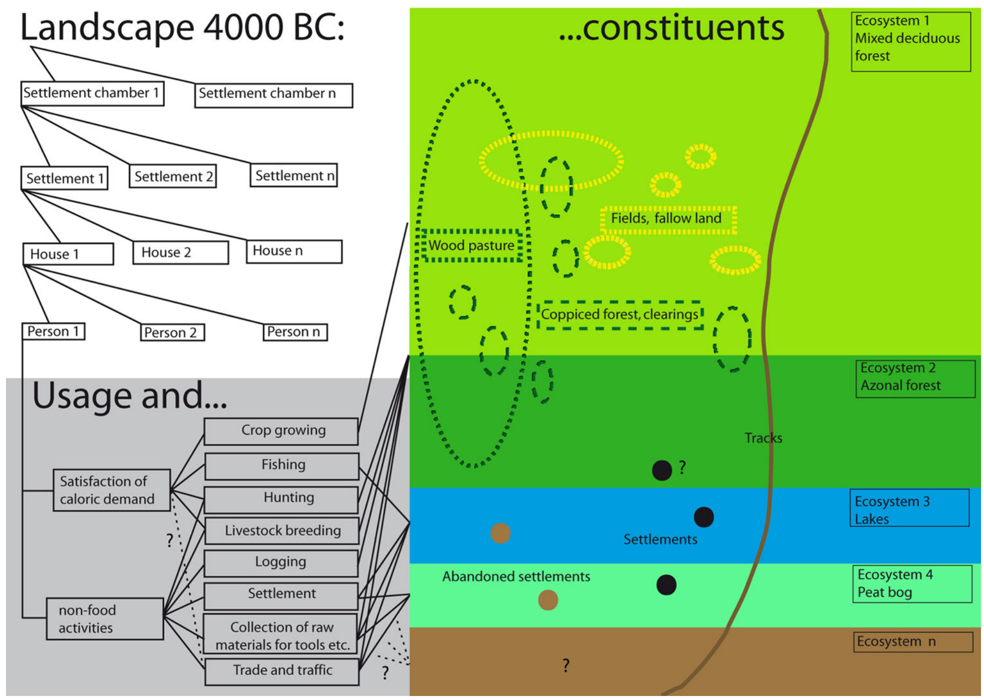
by water on three sides, to the West lie the gently rising slopes of the Schiener Berg. The areas near the water level are characterized by high groundwater tables and clayey soils, part of which are composed of large amounts of lake marl (Seekreide), while in the hinterland, luvisols are dominant (Vogt 2001). With a mean annual temperature of 9–10 °C and only 80–90 frost days annually, it is warmer than the other sites, and has an annual rainfall of 800–900 mm (all climate data from Leibundgut 2001). The settlement site at the Bay of Sipplingen (47.793° N 9.102° E) is unique because of its steep slopes rising up from Lake Constance at 395 up to 750 m a.s.l. at the Sipplinger Berg. While the higher upland parts are characterized by gently inclined areas, near the lake the landscape drops dramatically. At the bottom of the bay, which has an area of about 1.7 km^2, a pronounced hilly area in the South-Eastern and central part is replaced by more level areas in the North-Western part. This pronounced relief of tectonic origin (Schreiner 1958) is the reason for a relatively high percentage of rendzic leptosols and colluvisols (Billamboz et al. 2010), while the flat areas are covered mostly by luvisols or, to a smaller extent in the upland, gleysols (LGRB 2013). Near the lake, the buffering capacity of the large water body results in a mean annual temperature of 8–9 °C and 80–90 frost days a year, while in the higher areas, the temperature reaches only 7–8 °C and there are up to 120 frost days a year. The precipitation reaches 800–900 mm in the lower parts and up to 1,100 mm annually in the upland. Lake Degersee (47.612° N 9.654° E) is located to the North-East of Lake Constance in an undulating landscape composed of drumlin hills, small lakes, valleys and peat bogs (Mainberger and Mainberger 2010). Luvisols on slopes and hilltops and colluvisols on slope toes are replaced with the rising water content in the valleys by gleysols and histosols (Weiss 2009). Climatic conditions at Lake Degersee are influenced by the proximity of Lake Constance, which lies 4 km to the South, and by the increasing altitudes of the Westallgäu Mountains reaching 1,000 m a.s.l. only 12 km to the east. This results in a moderate annual temperature of 8–9 °C with an average of 100 frost days a year, and relatively high annual rainfall exceeding 1,300 mm. For Ho 1, many years of scientific research have brought forth a large quantity of data and detailed knowledge of many aspects of settlement-related processes (e.g. Dieckmann et al. 2006; Maier et al. 2001). In this study, I refer to the settlement termed Ho1A, the first houses of which were constructed in 3917 B.C. In 3911 B.C., the inhabitants of the “Hornstaader Gruppe” can be assumed to have numbered 250 persons, if all 50 houses within this time frame were inhabited by 5 persons. Probably in the autumn of 3910 B.C., most houses were destroyed by fire; after this event, only a few new houses were built and around 3906 B.C. construction came to an end. Similarly, many aspects of the settlements in the Bay of Sipplingen are well-known due to many years of intensive research (e.g. Billamboz et al. 2010; Kolb 2003). Many strata of various extents represent discontinuous lakeside dwelling here from 3919 B.C. until 2415 B.C. with repeated gaps of several centuries. In this text, I refer to the settlement termed S3 of the older Pfyn Culture around 3857–3817 B.C. In contrast, the settlements in Lake Degersee were only discovered in 2002. Archaeological and palaeoecological research was carried out during the years 2009–2011, but the full publication of the results will take some time; preliminary reports can be found e.g. in Maier et al. (2010) and Mainberger and Schlichtherle (2009). In this project, the Settlement De 1A, probably inhabited for only a few years during the first quarter of the fourth millennium B.C., is discussed.

Landscape and subsistence strategies in the fourth millennium B.C.

A landscape serves as a screen displaying the consequences of all interacting processes performed and evoked by its biotic and abiotic elements. Also it is the framework and the economic basis for all human actions that take place. The starting point of the modelling project presented here is therefore the analysis of the ecosystem against the background of the archaeological pattern that we are concerned with. In the Lake Constance area, the main geomorphic features of the natural landscape were formed during the Pleistocene or earlier (Eberle and Eitel 2010, p. 110), so in the fourth millennium B.C. the relief showed no major differences from what we know today. The most influential soil-formation factors are climate, animals and plants, relief, parent material, human influence and time (Scheffer and Schachtschabel 2010). Thus it is most probable that in the fourth millennium B.C., the soils derived from glacial sediments—which are the dominant parent material in the study area (Stahr and Peyer 1997; Stahr 2005)—were cambic luvisols in general, with gleysols and histosols replacing them with rising water content. Since then, the single important factor that has changed dramatically is the human influence as characterized by increasing erosion and sedimentation processes, resulting in the formation of colluvisols, floodplain soils and soil degradation (e.g. Niller 1998; see also Gerlach 2006). Thus, the soil mosaic has become more fragmented, so that on a very small scale, the palaeosoil distribution was probably different from today. It is likely that we have to subtract all colluvisols and alluvial soils. What was instead the corresponding local soil type in the Neolithic can be very hard to decide. But at a scale of 1:25,000, the overall distribution of soil types is transferable without relevant loss of accuracy, also because neither the spatial extent nor the overall proportion of colluvisols are prominent. Thus, for all three sites, the modern extent of luvisols is assumed to have been the same during the Neolithic. This is of importance as luvisols were certainly the most suitable soil type in the study area and formed the agrarian basis of the people; buried palaeosoils and the analysis of botanical remains yields evidence for similar soil properties during the Neolithic as today (Maier et al. 2001, p. 445). Although anthropogenic influence may have affected the vegetation cover in the study area during the Mesolithic period, the intensity was nevertheless so weak that it can hardly be detected before the spread of agriculture (Burga and Perret 1998, p. 673; Lechterbeck 2001, p. 34). The natural landscape was covered with dense forests during the Atlantic period with very few exceptions like peat bogs (Kalis et al. 2003). The reconstructed forest composition reflects the post-glacial vegetation succession as well as other ecosystem processes; while a mixed-oak forest covered the area during most of the Atlantic, *Fagus* became dominant in the late Atlantic and the Subboreal (Rösch 2008). This reduced the proportion of most other taxa to some extent, yet this happened most drastically for *Ulmus*. At the beginning of the Subboreal, however, all pollen diagrams of the Lake Constance area show human impact, indicated by an increase in cereal pollen as well as in pollen of taxa which indicate forest clearance, like *Corylus* and *Betula* (Rösch 1990; Haas and Hadorn 1998). The processes that produced these signals fluctuated in strength during the fourth millennium B.C., and show regional variability and interruptions. At the end of the millennium, human imprint on the landscape had grown larger (Lechterbeck 2001). Concerning the climatic conditions, I refer to Burga and Perret (1998) who state that during the Holocene, temperatures did not vary more than $\pm$ 0.7 °C. For this reason, I use recent climate data and assume validity and static conditions for the fourth millennium B.C. However, Magny (2004), among others, could synchronize mid-European lake-level changes with climatic oscillations on a continental scale. Together with other palaeoclimatic data from various proxies as compiled e.g. in Maise (1998), these studies demonstrate a fluctuating climate with warmer and colder, wetter and dryer periods throughout the Holocene. Derived from archaeobotany and archaeozoology, there is evidence for a direct relationship between the dietary composition of the wetland settlements and climatic phenomena (Jacomet and Schibler 2010a). Therefore in my future modelling projects, climatic variance will have to play an important role.

The people who used the land—the most important methods of the pile-dwelling people are shown in the lower left corner of Fig. 3 highlighted in grey—imprinted their actions into it, bringing about the formation of a cultural landscape. A rough idea of the most unambiguous anthropogenic elements is shown in the central part of Fig. 3. Due to a long tradition of economic and ecological research (Heer 1865; Rütimeyer 1861) performed on the remains of wetland sites in the North-Western pre-alpine forelands, the subsistence and land-use strategies of the relevant people are known in detail. The term "subsistence strategy" is defined by Jacomet and Schibler (2010b) as describing "all activities that are necessary to meet purely biologic requirements including clothing and habitation as well as the essential social and spiritual needs". In this article, I focus on the biologic requirements. High-resolution insights are provided by the analysis of plant remains found in the context of the settlement layers. The use of a broad spectrum of plant species in the fourth millennium B.C. is documented (Rösch 1998). Most important in terms of calories were cultivated plants such as various *Triticum* types, *Hordeum*, *Papaver*, *Pisum* and *Linum* (Jacomet 2012). The various *Triticum* species dominating at different times and places can even be distinguished, so while the people living in the settlement at Ho 1 in the 39th century B.C. cultivated mainly *T. durum/turgidum*-type (Maier et al. 2001), the people living in De 1 and in the Bay of

Fig. 3 Schema showing usage and elements of the landscape in the fourth millennium B.C. around a pile-dwelling or peat bog settlement



Sipplingen at the same time cultivated mostly *T. monococcum* (Herbig 2009). Later in the fourth millennium B.C., the settlers at Si preferred *T. dicoccon* (Billamboz et al. 2010). Jacomet (2004), p. 144) find evidence for a high significance of *Linum usitatissimum* in the settlement of Arbon-Bleiche (CH) at the Southern shore of Lake Constance, which she assumes to have been of equal importance as *Triticum* in the diet of the people living there around 3380 B.C. Proof of gathered species includes, among others, *Malus sylvestris*, different species of wild berries, rose hip (*Rosa* sp.) and fat hen (*Chenopodium album*). *Corylus* was of high importance; husks of it can be found in high abundances in many excavations (Brombacher 1995). Meat and other animal products were obtained from domesticates such as cattle (Ebersbach 2002; Schibler and Schlumbaum 2007), pigs, sheep and goats as well as from hunted species such as roe deer and many others (Schibler 2006), fish also serving as an important food source. Figure 4 shows the most important subsistence strategies used to provide the calories necessary for the pile dwelling people. Wetland settlements were thus not purely based upon farming, but their inhabitants were relying on a broad mix of nutritional resources.

While many details of the various nutritional elements are well described, much less is known about their proportional contribution to the diet, and the influence of the relevant economic and agricultural strategies on the settlement system as a whole. Various attempts have been made to model the linkage between dietary habits of the people inhabiting wetland sites and the corresponding

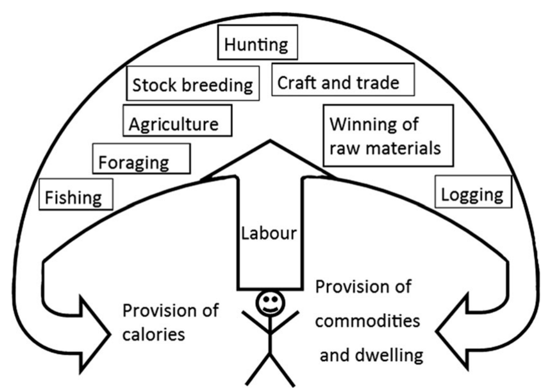


Fig. 4 Main subsistence strategies of the people in lakeside-dwellings

settlement system, probably the most comprehensive of which is implemented by Ebersbach (2003) based on the model presented by Gross et al. (1990). Maier et al. (2001, p. 449) calculate the necessary field size for the assumed 200 inhabitants of Ho 1 to have been around 23 ha of good farming soil, leading to a maximum field distance of 1,050 m. The relevance of the reconstructed nutritional elements for the settlement system varies, but especially the requirements connected with crop production have an important influence on settlement dynamics. Two different systems can be reconstructed, and each has a certain body of evidence and its advocates: Shifting Cultivation (SC) (e.g. Schier 2009; Rösch et al. 2002) and Intensive Garden Cultivation (IGC) (e.g. Bogaard 2004; Jacomet et al. 2004,

p. 136). The analysis of remains of crop weeds associated with larger quantities of well-preserved cereal grains found in wetland settlement contexts leads to their interpretation as being a result of the application of IGC (Maier et al. 2001). The fields in this system remain on the same spot for years, are probably intensely cared for and may be manured, with or without a short fallow phase of 1 or 2 years. In contrast to this model, palynological and palaeolimnological evidence seems to support the hypothesis of widespread application of a slash and burn procedure connected with SC in the fourth millennium B.C. (Ehrmann et al. 2009). Peaks in micro-charcoals correlating with pollen peaks of the early succession taxa *Betula* and *Corylus* are the main arguments brought forward for SC. Also, the highly dynamic settlement system might be interpreted in favor of SC, as the related land use system is characterized by annually shifted fields that are burnt with wood small in diameter in order to provide optimal conditions for the crop. The potential yield of 1 ha of land in the Neolithic is debated; Araus et al. (2003) propose yields of 1–2 t/ha and a seed:yield ratio of 1:10–1:20 for early agriculture in the Mediterranean based upon literature studies and physiological models. Dark and Gent (2001) propose a "yield honeymoon" during the early stages of agriculture in middle Europe. They emphasize that at least on base-rich soils, soil deterioration is unlikely to have been a limiting factor for cereal yields in the Neolithic. Experimental grain production on base-rich soils supports this view as no decline of the yields was documented during the course of 15 years (Reynolds 1999) and 30 years (Rothamsted_Research 2006), respectively. In experimental studies of SC in Forchtenberg (Germany), yields have reached 2–4 t/ha (Rösch 2005), and a seed:yield ratio of 1:25 was obtained. In a small-scale experiment by Jääts et al. (2011) in Estonia, a seed:yield ratio of up to 1:1,600 was obtained. Though these numbers are impressive, they do not make a point in the discussion about which system was applied, as more factors than merely the potential yield/ha certainly played a role for Neolithic people. Rösch (2005) argues that if under continuous cultivation, soil nutrients will consequently be extracted, fertility will be reduced, and yields will diminish to very low amounts in the course of a few years. This was certainly the case in medieval times, after soils had been used for many centuries, and seed:yield ratios had dropped to 1:5 or even 1:3. Following the specifications of the Forchtenberg experiment, the total area affected by the need of wood for burning is four times larger than the crop field alone. After use as a field, the patch needs a fallow time of at least 15 years until enough wood has grown again for the next burning; historic data for Estonia in Jääts et al. (2011) even suggest 20–60 years. A second year of cultivation on the same spot has proved to be very difficult in Forchtenberg because of the intensive growth of bushy plants such as raspberry (*Rubus idaeus*). The plot could serve as a pasture ground for cattle, yet this would probably hinder the growth of a secondary forest.

Regardless of the question of which system was applied, it is obvious that pile-dwelling people lived in close connection with, or even dependence on the forest. It provided hunting and gathering grounds, and was important for the extraction of timber and other raw materials. If a new settlement was to be constructed, it was likely that a forest had to be cleared, especially for the need of crop production area. This is directly linked to the question of the agrarian system applied; thus, the analysis of the forest management strategies can help in understanding the superordinate settlement system. Using the dendrotypology approach as described and applied by Billamboz and Köninger (2008) and Billamboz et al. (2010) forest management systems can be deduced from data sets of tree-rings from the piles of Neolithic houses preserved in anoxic conditions. He finds evidence for increasing intensity of woodland use in the bay of Sipplingen, with a felling phase in an old forest in the 39th century B.C. being followed by a coppiced forest and successive thinning. Until the 36th century B.C., only old trees are used (which are more difficult to work with stone tools)—this sequence might be interpreted as a proof of locally pronounced deforestation in the Neolithic. Nonetheless, a direct translation of the calculated demand in timber to the relevant necessary area is highly speculative if the age distribution and the species composition are not known. In a study of old forests in nature reserves in Switzerland, individual tree numbers of 250–700/ha were documented (Brang et al. 2011), while an intensively used coppiced forest can yield 1,200–1,600 stems/ha (Dohrenbusch 1982; Hartig 1847). Bleicher (2009, p. 96) calculated a minimum of 1 ha for the wood necessary for the construction of 11 houses in the peat bog settlement Seekirch-Stockwiesen (2980 B.C.).

Method

For this study, none of our own data were collected. Instead, applying a GIS-based approach, the natural environment of the settlement sites Ho 1, Si and De 1 is subjected to a landscape analysis based on published data. The results are used as a framework for the construction of scenarios of Neolithic land use in the fourth millennium B.C. in the three areas indicated. To achieve this aim, relevant literature is reviewed in order to compile hypotheses and formulate parameters concerning land-use strategies and settlement systems of the wetland sites in South-Western Germany in the fourth millennium B.C.

For each of the three sites, a virtual GIS-environment has been created that depicts the topographic parameters for a few km around the settlements (Fig. 2). The most important environmental data are the soil map at a scale of 1:25,000 (Kösel 1992; Weiss 2009; LGRB 2013) or finer (Vogt 2001), a digital elevation model (DEM) with a resolution of at least 5 m based on LIDAR Data (www.lgl-bw.de), geographical data on lakes and streams, and information on climatic conditions in the landscape (Leibundgut 2001). As this data is related to today, it is important to check if the data is valid for the time frame of the fourth millennium B.C. (see the above section). The relevant information is drawn from literature. Soil data can be added as a map with areas of the same soil type drawn as polygons, while geomorphic parameters such as elevation above sea level or inclination and cardinal direction of the slopes can be derived from the DEM using standard procedures of the software. This data is added in raster grid cells. Climate data is added as isolines of equal annual mean temperature, amount of rainfall or number of frost days. In the centre of the virtual environments lie the settlements. Hypothetically I assume 100 people living in 15 houses at the beginning of the fourth millennium B.C. for De 1, 250 persons living in 50 houses around 3910 B.C. in Ho 1, and 750 persons living in 150 houses around 3830 B.C. for Si. The main features in terms of economy, nutritional habits, and land use are not fundamentally different for the three sites, therefore I assume roughly the same general subsistence strategies: cultivation of cereal and other cultivated plants, fishing, foraging, stock breeding and hunting are the means of meeting the caloric demand, while logging and forest usage meet the requirements of habitation (Fig. 3). To evaluate the corresponding spatial demand, the respective amount in resources has to be assessed. I calculated a minimum of 2,234 kcal as the average caloric demand of one out of a group of 100 persons of both sexes and all age groups according to the handbook on human nutritional requirements (Passmore et al. 1974). This value is slightly higher than the value of 2,137 kcal that was found by (Ebersbach (2002), p. 119) in her ethnographic work as the median of 30 studied small farming communities. Since I intended to calculate a minimum demand, I used an even lower value of 2,000 kcal for further calculations. Following a scenario considered by Gross et al. (1990), I used as the most probable composition of the diet of the inhabitants of lakeside dwellings at Lake Zürich 52 % cereals, 29 % fish, meat and milk combined, and 19 % gathered species for further calculations. In order to assess the area for the production of the calculated amount of grain, two different models of Neolithic crop production have been consulted: for IGC, I use a rather low yield/ha of 800 kg, a seed:yield ratio of 1:10 and permanent fields without fallow for many years. For SC, I use a very high yield of 4 t/ha, a seed:yield ratio of 1:20, annually shifted fields and an additional area

Table 1 Specifications and number of wooden construction elements used in a 1:1 reconstruction of a Neolithic lakeside dwelling (Pétrequin 1991); an additional 24 *Tilia* trees were needed to produce bast fibers for construction ropes

Diameter (cm)	3–5	6–10		11–15			15–20	Total
Length (m)	4.5	4.5	19	3.5	5.5	9	4	
Number	306	17	18	10	10	4	6	371

necessary for the wood for burning the fields that is 4 times larger than the respective field (after Ehrmann et al. 2009). The fallow time before a patch is burned again is set at 25 years. Out of these specifications it follows that the required area for agriculture varies distinctly between the two systems. Considering only 1 year, a field the size of 1 ha will produce 1,000 kg of grain using SC (because only 0.25 ha can be cultivated, while 0.75 ha are needed to gain the wood for the ash fertilization), while 800 kg would be produced on the same field using IGC. In a time frame of 25 years, however, the total area affected to produce 1,000 kg of grain annually using SC is 25 ha, because of the fallow time necessary for forest succession. Using IGC, the required area to produce 800 kg of grain annually over a time frame of 25 years is still 1 ha. I assessed the demand for timber based on reconstructions of Pétrequin (1991) and Luley (1992) (see Table 1) and used research on coppiced forest (Dohrenbusch 1982; Hartig 1847) and forest reserves in Switzerland (Brang et al. 2011) to calculate the area necessary for timber harvesting.

The assumed number of logs, based on the construction elements specified in Table 1, is multiplied by the number of houses of the investigated site, and an arbitrary value of 20 % for necessary repairs is added. The result I divide by 324, as I assume this a realistic guess for the number of usable logs per ha in a Neolithic coppiced forest. For the calculations of the area necessary for stock breeding, I used rough assumptions: a herd size of 40 cattle regardless of the settlement size, and 5 ha of wood pasture per individual head of cattle (after Ebersbach 2002, p. 54), resulting in 200 ha of land required. All calculations of demand are transformed into land requirements for the assumed number of inhabitants of the settlement. The determined area had to meet various preconditions. For fields, the soil type had to be luvisol on slopes not exceeding an inclination of 25°; for wood pasture, any soil type other than peat bog was required; and for the wood harvesting area, site specific preconditions were chosen as described in the results section. Furthermore, all areas used should have been reachable in the minimal possible time. Because Euclidean distance does not reflect real walking time, a virtual cost-distance raster was generated that enables queries about areas of equal walking time around the settlements. This raster was sliced into zones of equal walking distance from the settlement and a feature

Table 2 Specifications and procedure for the calculation of the Carrying Capacity *k* based on 25 years of crop production

	IGC applied	SC applied
Annual consumption per person (kg):	110	110
+ Next year's seed (kg)	11 (ratio 1:10)	5.5 (ratio 1:20)
+ Annual loss (5 %) (kg)	7	7
= Annual demand of cereals per p. (kg)	128	122.5
Yield/ha of field (kg)	800	4,000
Field size required per p. year^{-1} (ha)	0.16	0.03
Field size required per p. 25 years^{-1} (ha)	0.16	0.75
Yield/ha of area (additional forest area for ash fertilizer considered) (kg)	800	1,000
Area required per p. year^{-1} (ha)	0.16	0.12
Total area required per. p. 25 years^{-1} (ha)	0.16	3
Factor reducing crop area according to local conditions (cultivable soils)	X	X
Carrying Capacity *k*: Persons nourished per ha of land according to local conditions in 25 years	?	?

layer was produced. Then the stated preconditions were overlaid and the preferred areas were clipped. The area of the resulting clipped slices was then calculated and the required area could be deduced. For the scenario Si shown in Fig. 7, the relevant areas are directly derived from a raster layer in order to generate transitional zones of decreasing land use and to indicate a zone of uncertainty. Based on the landscape analysis, the next step in modelling was to give an estimation of the Carrying Capacity *k* of an area with respect to the application of a particular land use. The term is used in various contexts, and involves some difficulties (Sayre 2008). I use it to describe a theoretical maximum of people that 1 ha of land is able to nourish given specific cultivation practices under the specific local conditions. I do not use it as an absolute figure for the population in the fourth millennium B.C.! The benefit of the approach thus lies less in its ability to reconstruct Neolithic population densities, but in the evaluation of the potential a given landscape exhibits with respect to the assumed land use. The Carrying Capacity is a function of the yield/ha of field, the proportion of agriculturally suitable soil/ha, and the demand/person (see Table 2). With an assumed daily need of 2,000 calories per person and an energetic yield of 3,300 kcal per 1 kg of cereal, I can calculate an amount of approximately 0.3 kg of cereal per day and person, if 52 % of the diet is met by cereal calories. This adds up to an annual demand of 110 kg/person, to which I added a hypothesized 5 % loss and the seeds for the next season as calculated from the assumed seed:yield ratio.

Models of land use at the three sites

Figure 5a, b illustrate the spatial demand for forest fallow and grain cultivation according to the calculations in the methods section for an assumed population of 100 inhabitants living in 20 houses during a hypothetical settlement duration of 25 years for the settlement De 1.

The area of 16 ha used for IGC as shown in Fig. 5a is assumed to be static during the 25 years of use. The surrounding area in lighter green is the area necessary to provide the leaf fodder for an assumed herd of 40 cattle, if each head of cattle needs 5 ha of wood pasture (see Ebersbach 2002, p. 54). I suppose that each of the 20 houses was built of 120 logs, needed 24 logs for repairs, and had to be rebuilt after 12 years (Ebersbach 2010 discussed even shorter "average house ages" of 8.7 years for the settlement Arbon-Bleiche 3). The total amount of timber for the time span is thus (144 × 20) × 2 = 5,760 logs, the relevant area of coppiced forest required 5,760/324 = 18 ha. As 50 % of the timber is needed to build the houses in year 1, it can be obtained from the area to be cleared for the fields, so only 9 ha are displayed as the additional spatial requirement. In Fig. 5b, the depicted crop system is SC. Considered the cereal demand for only 1 year, the necessary field size for the grain production of 100 persons is much lower than in Fig. 5a (not illustrated). For a time span of 25 years, however, the total area affected accumulates to 300 ha, as the fields are shifted annually (see Table 3). The maximum travel time to the most distant fields is 50 min, as derived from the cost-distance analysis. No extra space is required as pasture for domestic stock, as the different fallowing patches probably provide even better fodder than the full-grown forest. Similarly, all timber is assumed to be obtained from the SC fields.

The history of the settlement Hornstaad-Hörnle 1A is known in detail thanks to a scrutiny of the analyses of the archaeologists and dendrochronologists in charge (Dieckmann et al. 2006; Maier et al. 2001). In the year 3911 B.C.,

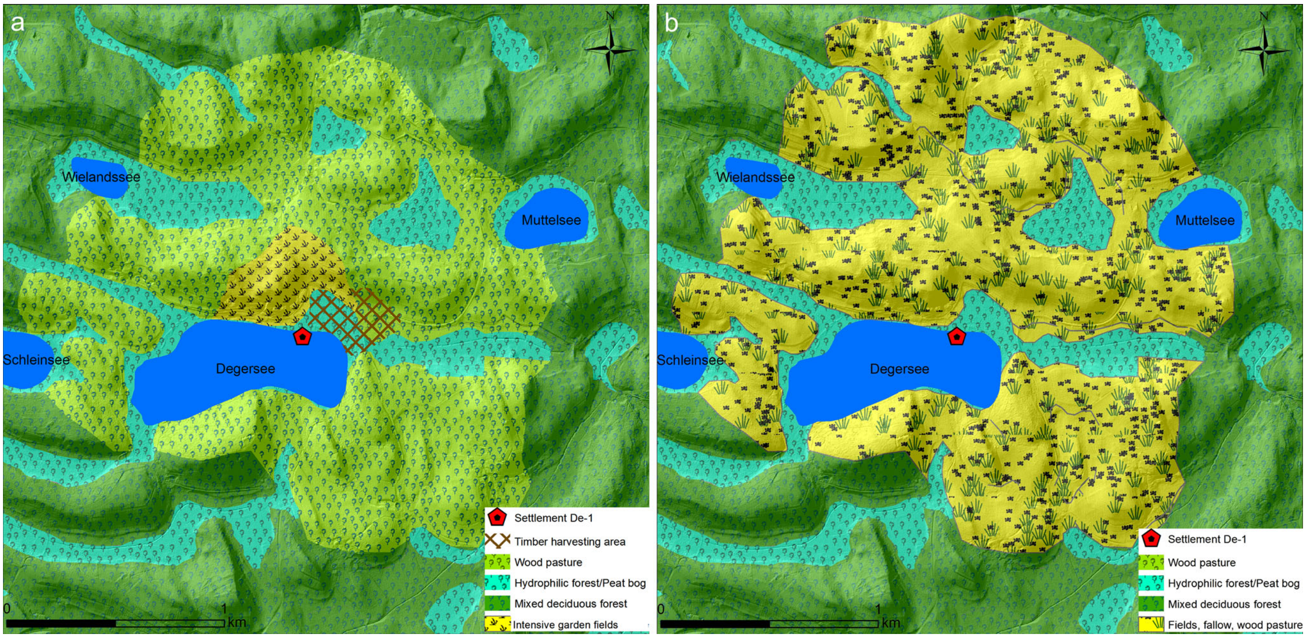


Fig. 5 Two scenarios depicting the area used for subsistence strategies around the settlement De 1 for a duration of 25 years. **a** 16 ha of intensely cultivated fields are supposed to yield 800 kg of grain annually, **b** 12 years of annual demand add up to 300 ha during the whole time span. This high amount is the result of a large area needed for wood for the ash fertilization and annually shifted fields. Cattle feed in an assumed 200 ha of wood in ***a***, and on the fallowing fields in (**b**). Very wet ground is supposedly not used for cattle herding and crop cultivation. © LGL Baden-Württemberg (www.lgl-bw.de)

Table 3 Specifications for the land demand of an assumed 100 settlers living in De 1 for 25 years

Land requirements of 100 persons (ha)	IGC	SC
Field size/year	16	3
Total area/year	16	12
Total area/25 years	16	300
Additional wood pasture	200	–
Additional area for timber harvesting	9	–

the inhabitants can be assumed to have numbered 250 persons, if all 50 houses of this time frame were inhabited by five persons. As there is evidence of precursory as well as of subsequent settlements nearby, the landscape of the peninsula was probably exhibiting many aspects of a cultural landscape typical of the fourth millennium B.C.—although what this means exactly is not yet evident. Figure 6a–c depict three different scenarios of land use using the same variables as for the De Model (see above). Figure 6a depicts the scenario if IGC is applied. The area of 200 ha for wood pasture is shown in light green, and the smaller light blue-green area at the tip of the peninsula is the calculated area necessary for the extraction of timber as described above. Many of the houses are constructed using *Fraxinus excelsior* (Dieckmann et al. 2006), which grew probably in the forests near the settlement rather than in the mixed deciduous forest that covered the luvisols further inland. Figure 6b depicts the same situation if SC is applied. As can be seen, a very large area is necessary for cultivating grain for a hypothetic duration of 25 years; the maximum travel time to reach the most distant fields is more than 100 min. For this reason I calculated a hypothetical alternative scenario displayed in Fig. 6c. Here, the same population of 250 years is hypothesized to have shifted their settlement every 8 years in order to minimize walking time to their fields. No archaeological evidence has been found for these settlements.

Figure 7 illustrates the situation in the Bay of Sipplingen and uses a slightly different illustration technique. While it is difficult to assess the absolute population number of the settlement, a strong rise and fall throughout the fourth millennium B.C. can be deduced from the distribution and number of house posts and the cultural layers (Billamboz et al. 2010). Very large villages with more than one hundred contemporaneous houses can be reconstructed for some phases. I have hypothesized a very large community of 750 persons in order to model the spatial demand of crop cultivation. Of special interest is the question whether the field resources inside the Bay area would be sufficient for the production of the calculated amount of cereals using the

Fig. 6 Three scenarios illustrating different hypotheses on land use connected with the pile-dwelling settlement at Hornstaad-Hörnle 1, calculated for an assumed 250 settlers over a time span of 25 years; **a** relatively small IGC fields are sufficient to meet the grain demand, **b** a much larger space is required for SC, **c** an alternative with SC applied and a shortened duration of habitation of only 8 years per (hypothetical) settlement. © LGL Baden-Württemberg (www.lgl-bw.de)

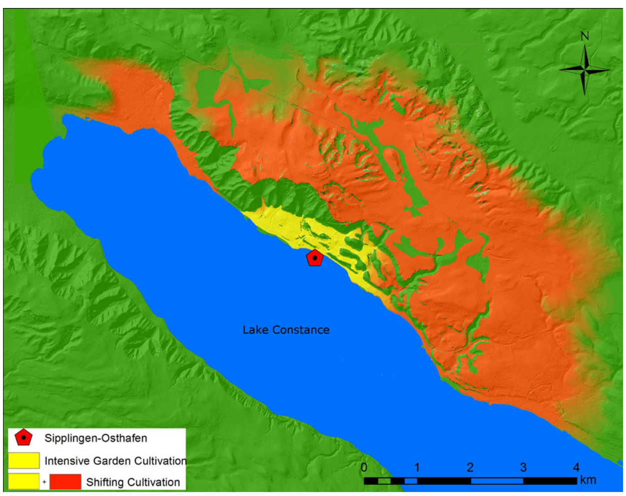


Fig. 7 Comparison of the spatial demand for IGC (120 ha) and for SC (2,250 ha), respectively, of 750 assumed inhabitants of the pile-dwellings at Sipplingen-Osthafen. © LGL Baden-Württemberg (www.lgl-bw.de)

52 % proportion of the total diet as above. The steep areas of >25° inclination and the inappropriate soil types are considered unsuitable for cultivation and are thus shown in green. The area for IGC is coloured in yellow, the area for SC is the aggregated area coloured in yellow and red. As can be seen, for this high number of inhabitants the area inside the Bay would be sufficient for IGC, while for SC, a very large area would have been affected that would reach far beyond the margin of the Bay. The Carrying Capacity (k) calculated as described in the "Methods" section for the three sites is shown in Table 4. The differences in k are due to the amount of agriculturally suitable soil in the vicinity of the settlements.

Table 4 Comparison of the Carrying Capacity k of a 2-km radius around the three studied sites as described in the methods section

Site	Local proportion of potential fields (%)	Local k within 2 km radius with SC (pers/ha)	Local k within 2 km radius with IGC (pers/ha)
Imaginary	100	0.33	6.25
De 1	71	0.23	4
Ho 1	47	0.15	2.9
Si	43	0.14	2.7

Discussion

The scenarios presented in the above section represent a hypothetical snapshot at the beginning of the fourth millennium B.C. in the history of three wetlands. The basic problem behind the study is a discrepancy between a large body of evidence on economic aspects of these people's lives on the one hand and some very basic questions that are as yet unanswered on the other. If one of the ultimate aims of archaeology is to reconstruct ancient societies, it is fundamental to assess the processes, mechanisms and limitations of the system that is composed of the people and their environment. One difficulty is that we cannot study the processes themselves, but only the resulting patterns and outputs, whether they were produced intentionally or unintentionally. Certain recurring patterns in the human-environment relationship of the wetland sites are seemingly evident, for example, nearly 100 % of the well-known settlements that were constructed in the Lake Constance area in the fourth millennium B.C. were built in peat bogs or on shallow lake-shores. One could hypothesize that the people explicitly chose these locations for specific reasons that are not fully understood today. Yet it is reasonable to imagine another scenario—people settled in various places on dry ground as well as in wetland contexts, but as on dry land the edaphic conditions are less well suited for preservation due to natural or anthropogenic erosion, decomposition and other reasons, archaeology has much less information on these places today (Ebersbach 2012, p. 296). In this case, the interpretation of people settling preferably in proximity to wetland would arise from edaphic conditions, and would not reflect the prehistoric situation. The societies behind the two scenarios are fundamentally different, as the first one has a very distinct relationship to a certain aspect of the environment that the other does not have. A similar problem is connected with the strategies used to meet the nutritional requirements. We know what people ate by the residues of their nutrition (e.g. animal bone refuse or stocks of grain preserved charred or waterlogged) or certain devices of known use, such as stones with a carved groove used as net sinkers. But the question of whether the grain was produced using SC or IGC is not answered by the mere grains themselves; interpretation of additional data is needed, and this has led to contradicting hypotheses. While pollen and charcoal analyses are interpreted as indicating SC (Schier 2009; Rösch 2005; Ehrmann et al. 2009), the archaeobotanical data cannot be interpreted in this way, but instead yield evidence for permanent fields (Bogaard 2004; Maier et al. 2001; Jacomet 2008). The answer to this question has implications for the reconstruction of the society. A group of people who burn down large strips of annually shifted land in order to produce grain supposedly shifts its habitation frequently as well in order to fulfil the land requirement for this system. People who care intensely for fields once opened may have very different habits, requiring or producing more stable conditions. The appreciation of a field would assumedly be very different in the two systems. If highly dynamic conditions can be reconstructed (Ebersbach 2010), these may be a result of shifted fields—on the other hand, they may also arise out of the forcing of some other limiting resource, such as forests rich in suitable timber for constructing habitations, or the abundance of roe deer for hunting. Maybe the system was not exclusive, and both systems were used simultaneously. This could be an appropriate strategy to improve the resilience of the system, reducing the risk of crop failure as described by Jääts et al. (2010) for modern Swidden Cultivation in Estonia. The reason might even be meaningless in economic terms and be related to religion or belief, however, this possibility is rejected here for the very long persistence of the phenomenon "wetland occupation" (Schlichtherle and Suter 2009) and the high variance the settlements exhibit. Instead, the key to the answer is more likely to be found in investigating the economic strategies and the ecological framework they are based upon. The question "what, if…?" should be predominant, instead of "what was…?", for the database is good, but new ways of interpreting it are required. The present study tries to interpret the known data in a systemic analysis of the wetland sites that is capable of filling the gaps in between the data. The scenarios discussed in this article represent an interim step in the generation of an adequate method for modelling the implications of different land use strategies. They provide the database and the framework necessary for more comprehensive studies to generate a broader understanding of the wetland settlement system as a whole. An important output is the understanding of the limiting factors for agrarian systems and the huge difference it made for a society which kind of agrarian system was applied. The models generate valuable output for the question of the extent of the affected area under different cultivation practices. In Lechterbeck (2013), population densities for the western Lake Constance area during the beginning of the fourth millennium are estimated on the basis of a pollen-based investigation. It is remarkable that the numbers calculated for SC (IGC is not integrated in her approach) are very similar to the 14–23 persons/km^2 as given above. Yet, as Ebersbach (2013) makes clear, an assessment that is based solely on one factor in the whole system (although arguably the most important one in terms of the diet) is not adequate if the system is to be reconstructed. It is necessary to consider not only the "hard facts" such as the amount of cultivable soils but also the work force that is available. As Kerig (2008) shows, a person can harvest 1 ha/season, which is in accordance with the specifications given in this paper. The interpretation of the landscape in terms of the Carrying Capacity is a helpful tool for an assessment of an area's general suitability for the subsistence practices applied by the inhabitants of the pile dwellings. However, a more dynamic approach is needed to answer the questions stated above. The reconstructions of the regional climatic conditions have not been further integrated; this is not practicable in a static approach. The problem is that static conditions and linearity are assumed in the presented models where change and random events have surely played an important role. The assumed yields as described in the methods section are chosen to highlight the extreme differences of the two systems. A more sophisticated modelling procedure could yield more detailed insight into the basic processes behind the settlement system, as well as more realistic scenarios considering locally differentiated weather conditions and other processes that result in good and bad years and a variance in yields. This has been addressed by the author who at present is setting up an agent-based modelling approach. This is more capable of introducing stochasticity and dynamic processes related to human–environment systems. However, we have to accept that a single "reality" is today impossible to reconstruct.

Conclusions

The subsistence strategies of the wetland settlements in the study area in the fourth millennium B.C. are described as drawn from the relevant literature. The system, composed of the people and their actions and the environment with its inherent processes, is described as provoking the formation of a cultural landscape. Scenarios depicting the implications of reconstructed subsistence strategies show largely different model outcomes. The great importance that is connected with the question of the agrarian system is highlighted. Applying SC, for a group of 100 persons that meets 52 % of their caloric demand by cereal, a relatively small annual field size of 3 ha is sufficient, if very high yields of 4 t/ha are assumed. However, the total area affected will add up to 300 ha in 25 years through the need for shifting fields and the additional space needed for the wood for ash fertilization. Applying IGC, the same group would need larger fields of 16 ha annually, yet the total area affected in a time frame of 25 years is still only 16 ha if quite low yields of 800 kg/ha and no fallowing of the fields are assumed. Further area for timber harvesting and wood pasture can either be assumed to be located on the fallowing fields in the SC system—in this case, however, the natural succession would be delayed. In the IGC system, additional space is assumed for wood pasture and wood harvesting. The total extent is even more difficult to assess than the field size because of a high degree of uncertainty concerning the species composition and the age distribution of the forest and the difficulty of assessing the exact number of cattle in a settlement. Further subsistence strategies such as fishing, hunting and gathering have not been included quantitatively into the model, as only qualitative data are present for them. The landscape itself is perceived as an important factor in the system of wetland occupation, for it is the framework and the economic basis of all actions performed by its inhabitants. The theoretical agrarian Carrying Capacity k of a landscape is described as a function of the yield/ha of field, the proportion of agriculturally suitable soil/ha, and the demand/person. It varies between 14 and 23 persons/km^2 for SC and 270–400 persons/km^2 for IGC.

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