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ORIGINAL ARTICLE

How many, how far? Quantitative models of Neolithic land use for six wetland sites on the northern Alpine forelands between 4300 and 3700 BC

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Abstract
Dendrochronological studies demonstrate a highly dynamic settlement system in prehistoric wetland sites in the northern Alpine forelands. In this article, we apply an agent-based simulation model of the human–environment system to better understand possible causes of these dynamics. Therefore, we formulate a generic quantitative model of land use and calorie supply in Neolithic wetland sites ca. 4300–3700 BC. Archaeological, geographical and palaeoenvironmental data together with information from an agronomic crop yield model (MONICA) are used in an agent-based simulation of Neolithic land use (WELASSIMO model). We fit the generic model to specific conditions at six archaeological sites and their surrounding environments, using local data. In our simulations, annual crop yields fluctuate markedly around a long term mean which starts to decrease after a few years of crop production. Crop plants supply 60–90% of the annual calorie demand. As sources of readily available non-crop calories are needed to compensate potential low crop yields, we argue that *Corylus avellana* (hazelnuts) were especially important to provide these extra calories; the simulated importance of non-crop calories is 10–40%. Records of human-induced fires are interpreted as being indicative of a strategy to generally open up the woodland canopy and promote the growth of light-demanding hazel. The extent of the different land use methods is quantified and visualized in tiles of 8 km^2 around the six study sites. The specific vegetation cover, the importance of hunting and the number of livestock animals have a major effect on the total area required.

Keywords Central Europe · Crop husbandry methods · Wetland archaeology · Pile dwellings · Agent-based modelling

Introduction

Agent-based modelling (ABM) is a computerized method that is particularly well suited to explore how the characteristics of a system arise from the behaviour of its parts (Lake 2015), by simulating the interaction of "agents" through

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prescribed rules. These agents are theoretical households and livestock units (LUs), as further explained below. The method has been increasingly applied in a wide range of disciplines from the late 1990s onward (An 2012, Fig. 2). From a geographical viewpoint, ABM has been described as a "virtual landscape lab for conducting numerical experiments" (Seppelt et al. 2009). This definition highlights important aspects: the method is like a laboratory where experiments are conducted, which allows for reproducibility and so provides an opportunity for a new way of dealing with archaeological questions; the lab is virtual, therefore parameters can be varied at will, and it is much cheaper than real-life projects such as archaeological cropping experiments (Louwagie and Langohr 2005); the method is numerical, which allows for (and requires) a clear and transparent presentation of the underlying assumptions; the ability to target landscapes highlights the scalability of the method from micro to macro.

These properties make ABM a valuable tool for the interpretation of the fragmentary archaeological or palaeoenvironmental record and may help to establish a better understanding of the past. Since the publication of the now famous "long-house model" (Dean et al. 2000; Axtell et al. 2002), a growing number of publications provide evidence of an increasing interest in ABM among archaeologists (Lake 2015; Wurzer et al. 2015). Although the method is often seen as very complex and is confronted with scepticism, there is a consensus among practitioners that "revolutionary advances can be obtained in the overall archaeological research paradigm", as stated by Cegielski and Rogers (2016). They identify six main themes that are addressed when using ABM in archaeological publications, comprising studies of social complexity (for example del Castillo et al. 2014; Altaweel 2015), studies addressing the formation of the archaeological record (Crema 2014; Premo 2014), evolutionary processes (Perreault and Brantingham 2011), as well as questions of human ecology and the history of interactions between humans and their environment (Wu et al. 2011; Balbo et al. 2014). Especially when they are used together with geographical information systems (GIS), these studies are a powerful tool that may provide a systemic understanding of how Neolithic societies interacted with their surrounding landscapes (Barton et al. 2012; Kohler et al. 2012). Recently, it has been stated that simulation models of past human–environment interactions in general are an important element in ongoing palaeoenvironmental and palaeoclimatic research to better understand the potential interrelations of prehistoric land use and climate change (Gaillard et al. 2018; Harrison et al. 2018).

Many archaeological modellers are facing the problem that the required data to set up a comprehensive model is scarce or at least fragmentary. For this reason, wetland sites offer great opportunities for modelling prehistoric human–environment systems and land use because in comparison to most dry land sites, organic remains are usually extremely well preserved there. Numerous remains from lake shore and peat bog settlements in six countries bordering the European Alps have been researched. Many of these have been studied by multi-proxy research especially in the northwestern Alpine forelands, using a wide range of analytical methods (Menotti 2004; Menotti and O'Sullivan 2013). In many projects, a high level of interdisciplinary collaboration has been achieved (Jacomet et al. 2004; Mainberger et al. 2015; Hafner et al. 2016a; Bleicher and Harb 2017). Many of these studies combine on-site research that provides highly detailed and mostly site-specific information on plant and animal foodstuffs (Jacomet 2009; Antolín et al. 2016; Kerdy et al. 2019), methods of crop production (Styring et al. 2016), consumption patterns and calorie provision (Gross et al. 1990; Ebersbach 2002, 2003), and timber and woodland management (Bleicher 2009; Billamboz 2014). To this is added off-site palaeoecological research that provides valuable evidence on regional patterns, trends and persistence of land use and its linkage to climate change (for example, Tinner et al. 2003; Rösch and Lechterbeck 2016; Hafner and Schwörer 2018; Rey et al. 2019). Further studies seek to disentangle causes and effects of land use, disturbance and climate on vegetation dynamics and/or the fire regime (such as Heiri et al. 2006; Colombaroli et al. 2010; Henne et al. 2013; Schwörer et al. 2014). GISs based models (Ebersbach 2003; Baum 2014) addressing theoretical carrying capacity and agent-based models, for example on the socio-ecological implications of different crop husbandry methods (Baum et al. 2016) still play a minor role in prehistoric wetland research.

One remarkable feature of most thoroughly studied prehistoric wetland sites around the Alps is that they show a very dynamic settlement system (Ebersbach 2010b; Bleicher 2017, 2019). As shown by dendrochronological dating, settlements were rather short-lived and were seldom inhabited for more than 20 years, and in many cases for only 5–15 years (Bleicher 2009; Ebersbach 2010a; Stapfer et al. 2019). These dynamic properties can be observed for wetland sites throughout a period of more than 1,000 years (Ebersbach 2010a, Abb. 97). Various reasons for this remarkably persistent pattern have been discussed. In some cases, short-term lake level fluctuations may have played a role in the relocation of a site (Haas and Magny 2004, p. 49). Catastrophic fire events may also have caused the abandonment and move of whole settlements (Dieckmann et al. 2001). A more comprehensive explanation is offered by Billamboz (2014), who used a dendrotypology approach to detect land over-use and woodland degradation as possible factors for settlement relocation and considers the interrelation of building activities and oak coppicing an especially crucial factor. Bleicher (2009, p. 143) also elaborates on the important role of the economic activities of the people in their woodland environment, yet states that it is nearly impossible to unambiguously correlate tree ring patterns to specific ways of using land. Baum et al. (2016) have designed an ABM (agent-based model) to explore the variability of prehistoric crop yields and the implications of different crop husbandry methods. Their results show that the depletion of soil nutrients due to crop cultivation might possibly have played a role, too—an interpretation that has an ethnological analogy. A description of a Huron settlement in south Ontario, Canada, mentions that "the fact the Indians abandoned their sites after 10–12, sometimes 20 years (…) was due to the depletion of soil nutrients on the one hand, and much reduced firewood supply near the sites on the other hand" (Schott 1936, p. 47). Ebersbach (2010a) formulates a more sociologically informed model and assumes that the discussed society had mobile and dynamic patterns on various levels, which are seen for example in the short settlement durations mentioned above. In this article, we want to better understand the system of interactions of humans with the environment at wetland sites in general, and more specifically to study possible interrelations of this system with the observed settlement dynamics, addressing the following questions:

(1) What were the general characteristics of calorie provision? Can any factor related to the calorie supply explain the observed settlement dynamics?
(2) What area was required for the land use methods at the wetland sites, and could a scarcity of land have been a reason for relocating the settlements after around 10–15 years?
(3) Could a shortage of timber or firewood close to the sites explain the observed dynamics?

We believe that a quantitative and dynamic agent-based model to simulate the land-use methods and the socio-economic system of the settlements and their reciprocal feedbacks with the environment offers great opportunities. To address these questions, we used the WELASSIMO modelling framework to develop a generic model of Neolithic land use in some northern pre-Alpine wetland sites (Baum 2016a, b, 2017; Baum et al. 2016). In a second step, this generic model is modified using local data to simulate land use at six sites located in Switzerland, Germany and Austria and dating to ca. 4300–3670 cal BC (Fig. 1).

This work is presented within the framework of the International BELAVI Project (2014–2017; Hafner et al. 2016a, 2019; Mainberger et al. 2019a, b). The idea of this inter- and multidisciplinary archaeological and palaeoenvironmental project was to look beyond the better-known sites on large lakes and focus on smaller lakes in order to better understand the human–environmental system. The choice of sites

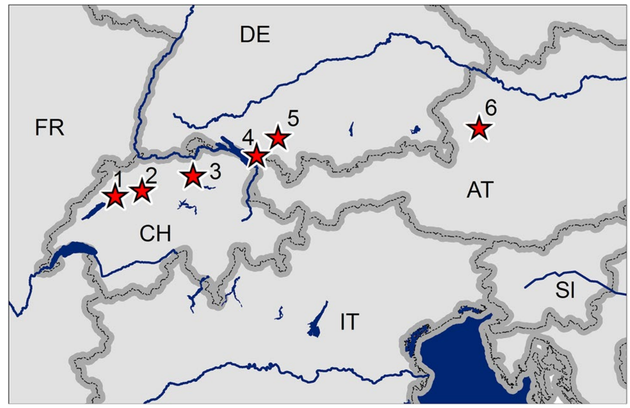

Fig. 1 Overview of the study area. Sites **1**, Sutz-Lattrigen, Hafen (CH); **2**, Burgäschisee-Süd/Südwest (CH); **3**, Zürich AKAD Layer 7/8 (CH); **4**, Degersee 1A (D); **5**, Leutkirch-Wilhelmshöhe (D); **6**, Weyregg, upper layer (A). Sites 2, 4, 5 and 6 were studied for the BELAVI Project

reflects this, as three of the chosen locations (2, 5 and 6) were studied for the BELAVI Project. The other sites were chosen because the research was very interdisciplinary (3 and 4) and/or there was a long lasting tradition of research (1 and 3).

Materials and methods

We modified and enlarged the existing spatially explicit crop husbandry simulation model WELASSIMO_crops (Baum et al. 2016), which uses the MONICA crop yield simulation model (Nendel et al. 2011) to estimate possible Neolithic yields (Fig. 2). To do this we created the spatially defined, agent-based simulation model WELASSIMO_area (ESM 1). A generic model of Neolithic land use at the pre-Alpine wetland sites was defined, which was based on a review of the literature. In a second step, we fitted the generic model to local conditions at six Neolithic sites in the northern Alpine foreland using published data and recent results from the BELAVI Project (Table 1). Both WELASSIMO_crops and WELASSIMO_area use the modelling platform NETLOGO (Wilensky 1999; Wilensky and Rand 2015) and have a temporal resolution of 1 year and a spatial resolution of 25 m.

In WELASSIMO_area, a digital flat landscape representation is designed that consists of cells with an area of 25 × 25 m each. The cells have a set of partly variable attributes which describe either environmental parameters such as soil type or an economic value for land use activities, such as availability of timber (ESM 2, Table 1). The economic value of the cells depends on their environmental attributes and the effect of the simulated land use processes. This landscape representation serves as the background for the simulation of land use activities of digital "agents" representing Neolithic

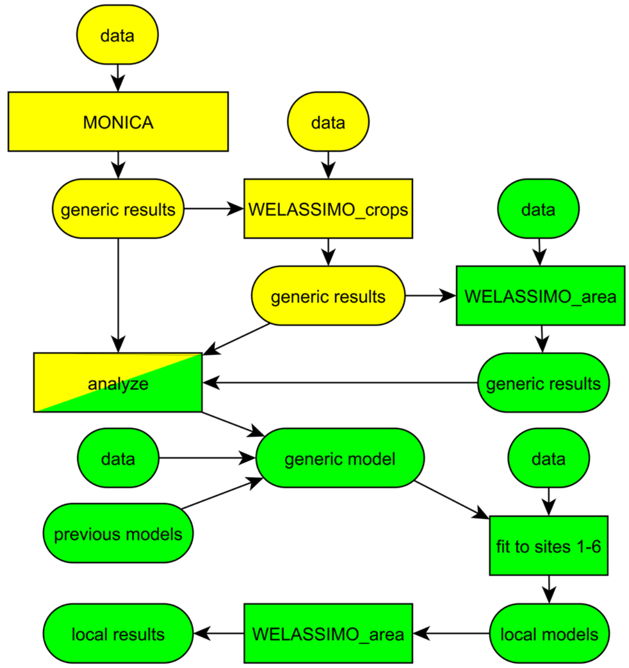

Fig. 2 Overview of the WELASSIMO models. Yellow, Baum et al. (2016); green, this article

settlements. Two different agent types "model households" (MH) and "livestock units" (LU) are programmed (Fig. 3). The MHs use the economic value of the cells in order to meet their defined annual calorie demand (ACD) and the requirements for timber and firewood, while the LUs use the cells to cover their defined spatial requirements for woodland pasture. The simulated human activities are crop cultivation, gathering, hunting, fishing, livestock husbandry, obtaining timber and collecting firewood. Further processes are simulated using simple sub-models such as the succession of woodland development phases and woodland openings created by humans, as well as soil nutrient depletion due to crop cultivation. A detailed description of the processes is given in ESM 2.

The generic model of Neolithic land use in the Alpine foreland, ca. 4300–3700 BC

The land use model is based upon data from publications and from the BELAVI Project, as given in Table 1. Recent studies confirm that mixed beech (-fir) woods had replaced the previously dominant woods of mixed elm–lime–maple–oak by around 4000 BC (Lang 1994; Kleinmann et al. 2015; Rey et al. 2017, 2019). These woodlands and their inherent dynamics were the natural environment of the Neolithic wetland settlements, while more open vegetation types were sparse and restricted to high altitudes or semi-wetland landscapes (Kalis et al. 2003). Natural mixed *Fagus* (*Abies*) woods have specific properties for the human economy, so due to reduced solar radiation influx from the tree canopy, the plant net primary production in the herb and shrub layers beneath is much lower than in more open vegetation types (Ellenberg and Leuschner 2010, p. 88). Fodder for wild or domestic animals would have been relatively sparse; edible plants such as hazelnuts (*Corylus avellana*) or wild fruit such as *Rubus* sp., *Fragaria vesca* or *Prunus spinosa* grow in more open or disturbed habitats.

Modern analogies are used to quantify the ACD of the MHs shown in Table 2 (FAO 2008). Calorie provision at the sites was based on a broad mixture of farming, hunting and gathering activities (Gross et al. 1990; Jacomet et al. 2004; Antolín et al. 2016; Kerdy et al. 2019). No evidence of large-scale trade of foodstuffs or storage facilities for more than 1 year has been found. Instead, food was produced or obtained locally. The relative importance of the individual foodstuffs certainly varied according to date and region, and probably also within settlements (Doppler et al. 2013). Nonetheless, an idealized or "average" economic system can be described. Cereals (*Triticum durum*/*turgidum*, *T. dicoccum*, *T. monococcum*, *Hordeum vulgare*), *Papaver somniferum* (poppy), *Linum usitatissimum* (flax, linseed) and *Pisum sativum* (peas) were grown (Maier 2004, 2015; Jacomet 2006, 2007, 2014; Antolín et al. 2017). In WELASSIMO_area, all cultivated plants are treated as cereals to keep the model simple, even though it is clear that oil plants have a different calorie content than cereals. This simplicity has the advantage of a higher level of transparency; if all calorie sources are considered, it would make the interpretation of the model results very difficult. However it is clear that some information is lost from the model this way.

Two different crop husbandry systems have been proposed: permanent cultivation (PC) and shifting cultivation (SC). For PC it is assumed that once the land had been cleared, fields were cultivated with a rather high work input in a more or less intensive manner for up to a few decades (Maier 1999; Bogaard 2004; Jacomet et al. 2016). For SC, a cycle of felling young trees, burning the brushwood, growing crops for a maximum of 1–3 years and moving to another area is proposed (Ehrmann et al. 2014; Rösch et al. 2014). From archaeobotanical studies, it is evident that the stored crops found at wetland sites were produced by PC (Bogaard 2004; Jacomet et al. 2016).

As varying yields from crops were normal, strategies were needed to obtain other sources of calories to "fill the gap", from wild plants. *Corylus avellana* (hazelnuts), *Quercus* spp. (acorns), *Malus sylvestris* (crab apples), *P. spinosa* (sloes), *Chenopodium album* (goosefoot) and many other wild plants were gathered (Jacomet 2006, 2009; Antolín et al. 2016). The most important foodstuff in this context was probably hazelnuts, because they are extremely rich in calories (Brufau et al. 2006), easy to gather and store and, as shown by

Table 1 Sources of information for the generic model and the local models; literature in italics is recent and partly unpublished data from the BELAVI Project

Model element	Details	Important publications used for the generic model	Local publications on the sites, by number
Consumption preferences	Calories from crops are flexibly complemented by some from gathered plants, meat and milk from domestic animals, also game and fish	Doppler et al. (2013), Ebersbach (2002) and Schibler and Jacomet (2010)	(3) Ebersbach (2003) and Gross et al. (1990)
Crops	*Triticum durum*/*turgidum*; *T. dicoccum*; *T. monococcum*; *Hordeum vulgare*; *Papaver somniferum*; *Pisum sativum*; *Linum usitatissimum*	Jacomet (2007, 2014)	(2) Hafner et al. (2019); (3) Brombacher and Jacomet (1997) and Jacomet et al. (1989); (4) Maier (2015); (5) *Heiss* (*2017*)
Crop yield data	Simulation based on *T. monococcum*; the function describes mean annual fertility decline for three crop husbandry methods (see Fig. 4): 0.88 $th^{-1} a^{-1}$; $y = -0.211\ln(x) + 1.0934$; 1.9 $th^{-1} a^{-1}$; $y = -0.151\ln(x) + 1.5226$; 2.24 $th^{-1} a^{-1}$; no decline	Baum et al. (2016), Miedaner and Longin (2012) and Nendel et al. (2011)	
Gathering	*Corylus avellana*; *Quercus* sp.; *Chenopodium album*; *Rubus* sp.; *Malus sylvestris*; *Fragaria vesca*; *Prunus spinosa*; *Rosa* sp. and several other plants	Antolín et al. (2016), Holst (2010) and Jacomet (2007, 2009)	(2) Hafner et al. (2019); (3) Brombacher and Jacomet (1997) and Jacomet et al. (1989); (4) Maier (2015); (6) *Heiss* (*2017*)
Animal husbandry	*Bos taurus*; *Sus domesticus*; *Ovis aries*; *Capra hircus*	Ebersbach (2002, 2013) and Schibler (2006)	(1, 2) Kerdy et al. (2019); (2) Boessneck et al. (1963); (3) Hüster-Plogmann and Schibler (1997)
Hunting and fishing	*Cervus elaphus*; *Sus scrofa*; *Bos primigenius*; *Capreolus capreolus*; several fish such as *Esox lucius*; *Salmo trutta*; *Coregonus wartmanni*; *Rutilus rutilus*, several cyprinids and other taxa	Hüster Plogmann (2004), Hüster Plogmann and Häberle (2017), Kerdy et al. (2019) and Schibler (2006)	(1, 2) Kerdy et al. (2019); (2) Boessneck et al. (1963); (3) Hüster-Plogmann and Schibler (1997); (4) Stephan (2015)
Timber	*Abies alba*; *Quercus robur*; *Fraxinus excelsior*; other trees such as *Fagus sylvatica* or *Alnus* sp. were used as well	Billamboz (2014), Bleicher (2009), Ebersbach (2010a), Luley (1991) and Pétréquin (1990)	(1) Stapfer et al. (2019); (3) Bleicher and Walder (2019); (4) Million and Billamboz (2015)
Firewood	No species distinction was observed	Dufraisse (2005, 2008)	
Environment and palaeoclimate	Mixed *Fagus* woodland dominating; Neolithic climate in central Europe similar to recent conditions, but slightly warmer and drier	Clark et al. (1989), Kalis et al. (2003), Magny (2003), Maise (1998), Mauri et al. (2015) and Rösch and Lechterbeck (2016)	(2) Rey et al. (2017, 2019); (4) Kleinmann et al. (2015)

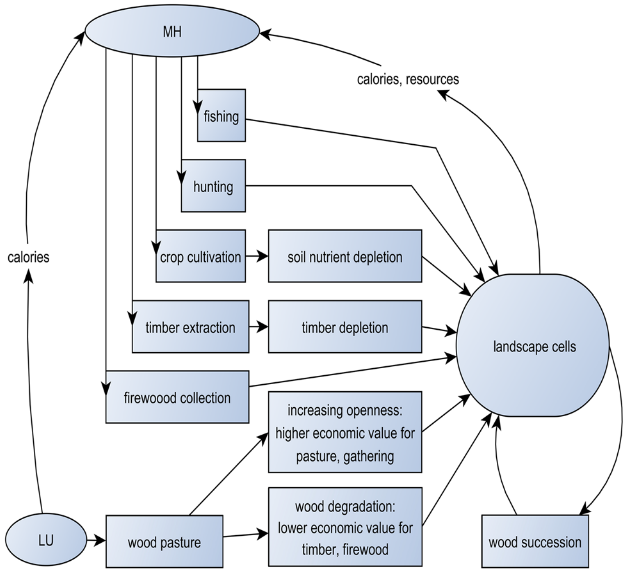

Fig. 3 Entities (ovals) and processes (boxes) in WELASSIMO_area. *MH* model households, *LU* livestock units

pollen analyses, readily available (Rösch and Lechterbeck 2016; Rey et al. 2019). Therefore, it is the only gathered plant considered in the model, the reason being the wish to keep the model simple, as in the case of crop plants. Calories were also obtained from cattle, sheep, goats and pigs which were kept (Schibler 2006; Kerdy et al. 2019), and their meat and milk consumed (Deschler-Erb and Marti-Grädel 2004, p. 238; Spangenberg et al. 2006). Wild animals were hunted and fish caught. The list of identified wild animal taxa is long (although not necessarily all were eaten) and includes, among others, red deer, roe deer, wild boar, bear, aurochs, common frog, pike, cyprinids and redfin perch (Hüster Plogmann 2004; Kerdy et al. 2019).

Quantifying consumption habits, wood requirements and resources provided by the environment

The following assumptions are made: (1) the total crop field size per MH was such that the workload was manageable for that household; (2) production of a surplus was not intended; (3) the aim of 90% calories from crop plants (CPC share) and 10% non crop calories (NCC share) as a minimum is more probable than the aim of 100% calories from crop plants, even if the latter was theoretically possible when there were good yields. Fields of 1–1.5 ha with PC or of 0.5 ha with SC represent an easily manageable workload for one MH and allow for a mean yield to supply the inhabitants with around 75% of the crop plant calories that would be needed (Baum et al. 2016). Due to the annual variability in the weather (Fig. 4), the crop plant calories would make up 60–90% of the ACD in 68% of years (Table 3).

The NCC (non crop) share from hunting (H), gathering (G), fishing (F) and meat/milk from LUs covers [10% + [90% – CPC share]] of the ACD. Due to the statistical distribution of crop yield values, an NCC share of 10–40% with a mean of 25% is needed in 68% of the years. The proportion of the individual NCC foodstuffs within H/G/F/LU of 10:60:10:20 is an assumption. It means that on average, 15% of the ACD of one MH is provided by gathered calories, 5% comes from meat and milk from livestock and 2.5% each from hunting and fishing.

A timber supply was needed for building houses for living in as well as for communal buildings. The annual timber demand for one MH was calculated using house building models and reconstructions based on the archaeological finds (ESM 2, Table 2). In the generic model, an annual mean timber demand of 1.5 m^3 per MH is assumed. The assumed amount of timber that can be obtained per hectare is highly dependent on the woodland structure; see ESM 2, Table 3 for data. In WELASSIMO_area, 1 ha allows for the

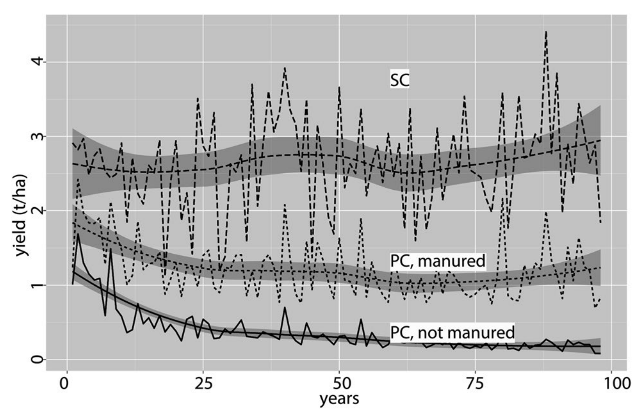

Fig. 4 Simulation of Neolithic crop yields in tonnes/ha from three different husbandry systems (from Baum et al. 2016)

Table 2 Specifications and annual requirements of the agents, MH, model households; LU, livestock units, in WELASSIMO_area

No. of inhabitants per MH	Calorie requirements per person	Annual calorie demand per MH	Timber requirements per MH	Firewood requirements per MH	Pasture requirements per LU
6	2,000 kcal/day	4,380,000 kcal/a	1.5 m^3/a	6 m^3/a	1.4–12 ha/a

Table 3 Percentage of crop plant calories (CPC share) and non-crop calories (NCC share), the importance of hunting/gathering/fishing/livestock (H/G/F/LU) in the NCC share, and the numbers of livestock units (LUs) per model household (MH)

CPC share (mean) %	NCC share (mean) %	H/G/F/LU ratio %	LU/MH
60–90 (75)	10–40 (25)	10/60/10/20	2

supply of a volume of timber sufficient to build 1–14 houses every 15–40 years.

A quantification of firewood consumption based on the archaeological record (Dufraisse 2005, 2008) is problematic and is more easily obtained by using ethnological analogies. For this study, the value of 6 m^3 firewood per MH and year (13 kg per MH and day) is used after comparing data from various sources (ESM 2, Table 4). We assume that collecting as much as 0.7–2 m^3 firewood per hectare is feasible every year, since the use only of dry dead wood is assumed (ESM 2, Table 5).

In WELASSIMO, the different domestic animal taxa in the wetland settlements are estimated as LUs equalling one head of cattle. The system of livestock husbandry has been described in detail before (Ebersbach 2002). The animals probably browsed for fodder nearby the settlements, while the possibility of seasonal movement (transhumance) for some of the herds cannot be ruled out completely (Deschler-Erb and Marti-Grädel 2004, p. 251). Fodder availability was limited by snow and the vegetation growing season, but the livestock probably browsed the vegetation for fodder even in winter and as early as possible in spring (Kühn and Hadorn 2004, p. 345; Wick 2015, p. 339). According to Ebersbach (2002, p. 35) and Adams (1975), one LU requires 1.4 ha of grassland pasture or up to 12 ha of woodland pasture in temperate natural woodland (ESM 2, Table 6).

A quantification of the economic value and the resource availability in different landscape types is the key to the simulation of land use and land demand by the inhabitants of the wetland settlement sites with WELASSIMO_area. However the evaluation is not straightforward and necessarily uses assumptions. The values used in WELASSIMO_area are given in ESM 2, Table 6.

Fitting the generic model to local conditions at six sites

The sites, their dating and basic geographical features are listed in Table 4 (1–6, from west to east). Figure 5 shows the sites and their surrounding physical landscapes, in tiles of 8 km^2.

The cell attributes have been adapted using local geographical data. Soil conditions vary due to topographic and geological factors within each area and between them. The most productive soils at each site were determined using national data (Pazeller 2000; Fleck and Fritz 2010; Land Salzburg 2018), but no attempt was made to compare the quality of the arable soils across borders, nor to consider soil quality in the past. Instead, modern soils well suited to agriculture on slopes below 25° have been defined as also suitable for Neolithic agriculture (this involves an assumption made for heuristic purposes; we are aware that the real-world situation must be more complex in terms of changes in soil quality through time). To consider different hypotheses on landscape development at the different sites, four landscape scenarios are set up (LS1–4) that integrate possible different states of vegetation cover and crop husbandry systems (Table 5). Each LS has a specific composition of landscape types with particular resource capacities calculated from ESM 2, Table 5. The different proportions of landscape types are assumptions; they are thought to result from a different duration, intensity and type of land use.

In the following, a summary of the relevant archaeological information available at the sites is given.

Site 1 Sutz-Lattrigen, Hafen (CH) (3827–3817 BC) lies on Bielersee (Hafner et al. 2016b; Stapfer et al. 2019). Two houses with dimensions of ca. 8.8 × 3.6 m can be fully reconstructed there, while a total number of 10–12 houses are probable. Kerdy et al. (2019) describe a high importance of cattle and pigs with a proportion of domestic vs. wild animal bones of nearly 80:20. Dendrochronological analyses show that at least one earlier settlement existed nearby, and that rather old oak trees were split and used as piles to support the houses (Stapfer et al. 2019). This might be interpreted as a landscape that was shaped by human land use for at least several decades and possessed a certain degree of openness. Accordingly, scenario LS3 is used for this site.

Site 2 Burgäschisee-Süd/Südwest (CH) (ca. 3750 cal BC) lies on the small Burgäschisee (Wey 2012). This lake and the Neolithic settlements along the shore were intensively studied in the BELAVI Project (Rey et al. 2017; Hafner et al. 2019). According to analyses by Boessneck et al. (1963), hunted animals were of much greater importance than livestock (see also Kerdy et al. 2019). For this landscape LS2 applies, as there were earlier settlements and pollen analysis shows evidence of land use from 4900–4800 cal BC onwards. However, this signal from pollen probably represents a much wider area than local pollen from individual trees discussed for the site of Sutz-Lattrigen, Hafen; a direct comparison of this information is therefore not applicable.

Site 3 Zürich-AKAD/Pressehaus Layer 7/8 (CH) (3709–3681 BC) is located at Zürich-Seefeld on the north-eastern shore of Zürichsee (Baum et al. 2019, Fig. 381). A total number of 16 houses of ca. 12 × 4 m are probable according to the combined archaeological evidence (Baum et al. 2019, Figs. 385, 399). The dendrochronologically determined occupation of 28 years was most probably

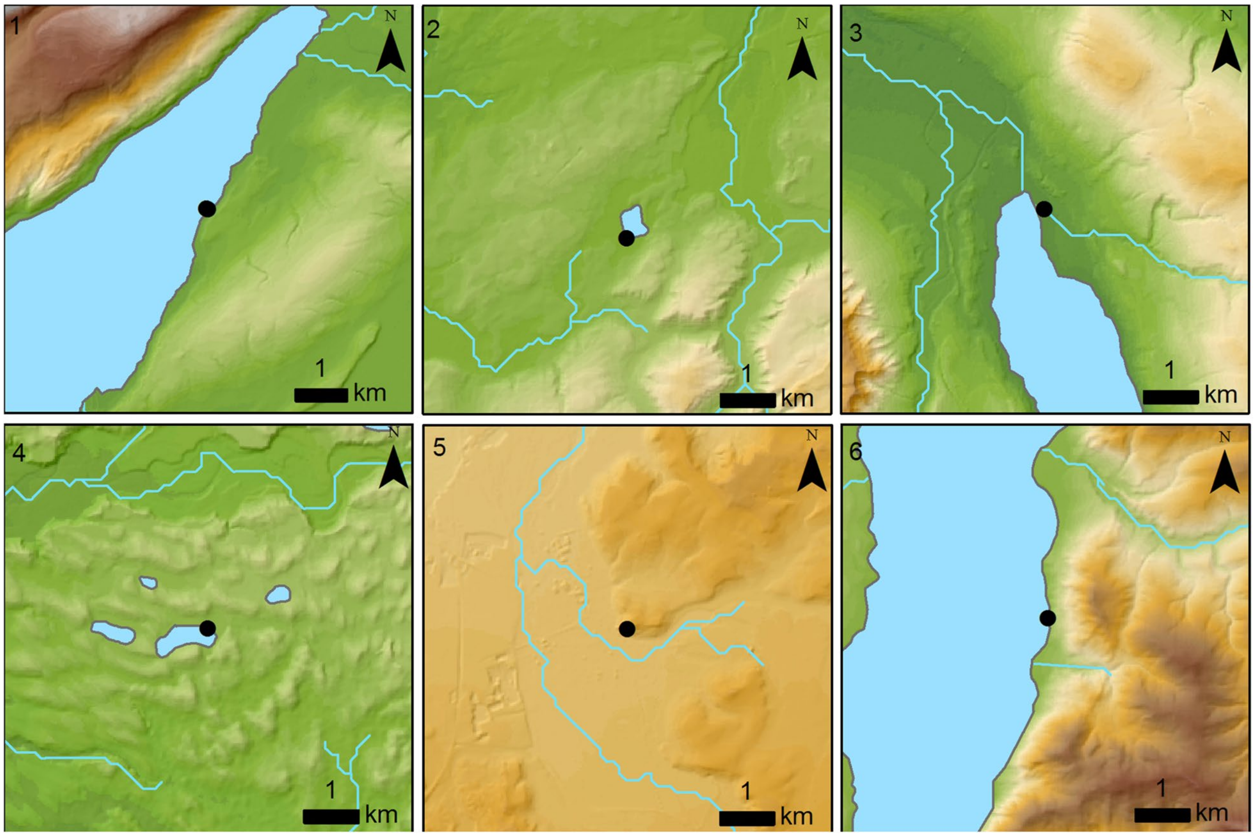

Fig. 5 Sites 1–6 and their topographical settings within a tile of 8 × 8 km^2. Data from Swisstopo, GBA Austria, LGRB Baden-Württemberg

Table 4 The study sites with archaeological and geographical features

Nos	Site names	Wet conditions	Dating (cal) BC	Elevation (m a.s.l.)[a]	Agriculture (BC)[b]	Precipitation[c]	Arable[d] (%)	Water[e] (%)
1	Sutz-Lattrigen, Hafen (CH)	+	3827–3820	420–1,180 (430)	4400–3400[f]	897	18	31
2	Burgäschisee Süd/Südwest (CH)	+	ca. 3750	430–660 (470)	4550[g]	945	86	1
3	Zürich AKAD/Pressehaus (CH)	+	3709–3681	390–800 (407)	5000[h]	1,085	58	10
4	Degersee 1A (D)	+	ca. 3980	390–590 (480)	4700[i]	1,104	72	2
5	Leutkirch-Wilhelmshöhe (D)	–	ca. 4300	620–760 (703)	4300[k]	1,020	75	0
6	Weyregg II (A)	+	ca. 3750	460–1,080 (473)	No local data	1,318	17	33

[a]Min/max/average

[b]Earliest local/regional pollen or archaeobotanical data

[c]Precipitation (mm/year)

[d]Fertile soils on slopes < 25°, in % of dry land

[e]Water surface in % of the total area

[f]Ammann (1989), 90 (data from Lobsigensee, distance 30 km; calibrated online using calpal-online.de)

[g]Rey et al. (2017)

[h]Erny-Rodmann (1996, p. 123), unpublished dissertation, University of Basel

[i]Kleinmann et al. (2015, p. 452)

[k]Mainberger et al. (2019a); references for sites: 1, Hafner et al. (2016b) and Stapfer et al. (2019); 2, Wey (2012) and Hafner et al. (2019); 3, Baum et al. (2019) and Schibler et al. (1997); 4, Mainberger et al. (2015); 5, Mainberger et al. (2019a, b); 6, Pohl (2019),

Table 5 Four landscape scenarios (LS1–4) used in WELASSIMO_area

Code	Landscape scenario
LS1	Natural woodland environment without human influence: woodland, lakes, fens: 100%
LS2	Land use < 200 years (permanent cultivation): natural woodland, lakes, fens: 80%; secondary woods: 15%; fallow land: 5%
LS3	Land use > 200 years (permanent cultivation): natural woodland, lakes, fens: 60%; secondary woods: 25%; fallow land: 10% woodland pasture 5%
LS4	Land use < 200 years (shifting cultivation): natural woodland, lakes, fens: 50%; secondary woods: 40%; fallow land: 10%

interrupted by short breaks of several years (Bleicher and Walder 2019, p. 191). Nonetheless, the full duration plus 2.3 years is used here to show the consequences of long settlement duration. With a proportion of domestic vs. wild animals of 80:20, the latter had a very low importance at this site (Schibler et al. 1997, p. 53). LS3 is assumed, because there was plenty of evidence for human land use at the Zürich-Seefeld site (Bleicher and Walder 2019, Fig. 310).

Site 4 the small lake site of Degersee 1A (D) (ca. 3980 cal BC) was important in the BELAVI Project. From comparison with contemporary sites in southwest Germany, house dimensions of ca. 6–8 × 3.5 m^2 can be assumed (Strobel 2000, p. 280). There were probably 5–15 houses, according to the area with wooden piles. Remains of wild plants indicate a significant role of food gathering (Maier 2015). With a proportion of 90:10, wild animal remains are far more important than domestic animals (Stephan 2015). The beech woodland was disturbed by human activities from 4670 cal BC onwards which were the beginning of repeated cycles of secondary woodland development (Kleinmann et al. 2015). Million and Billamboz (2015) provide evidence from tree rings for at least 50–80 years of land use preceding the site of Degersee 1A. LS 2 is used for this site.

Site 5 the site of Leutkirch-Wilhelmshöhe (D) was discovered in the course of the BELAVI Project. It is located on a hilltop at 703 m, which is 250–300 m higher than the other sites discussed here. As it is not a wetland site only relatively sparse information is available, so neither house nor settlement size can be reconstructed from the data. Pottery suggests sites of the Schulterbandgruppen as possible analogies (Mainberger et al. 2019a); 15–22 houses of 4–5 × 7–10 m may thus be assumed (Zeeb 1996). Although no indication of SC was found in Leutkirch-Wilhelmshöhe or any other similar site, this is assumed in the simulation for comparison. No information on animal economy or on the vegetation cover is available for this site. We assume that fish was not an important element of the diet because there was no suitable habitat nearby, except possibly in rivers. Since SC is assumed, LS4 applies.

Site 6 the lakeside site of Weyregg II (A) (lower layer, ca. 3750 cal BC) lies on Attersee. The analysis of the piles did not so far yield any building structures or precise dating (Pohl 2019). The extent of the cultural layer suggests that there were 10–30 houses. The size of the houses is unknown, so an analogy from another site of the Mondsee culture was used for an estimate (Maurer 2014, p. 166). Large amounts of wild apple and hazelnut remains highlight the importance of gathering and suggest that people may have encouraged these plants. As Maurer (2014, p. 173) states, animal husbandry was probably not very advanced during the time of the Mondsee culture, but both hunting and fishing were relatively important. We assume LS1 for this site.

This site-specific information is used to adapt the generic model to local conditions at the various sites. The resulting local models are given in Table 6. The amount and quality of the available information varies between the sites and between different aspects of Neolithic land use. Occupation of the site is the time span provided by dendrochronological analyses, if this is available (sites 1 and 3), plus 2 years, as houses were used on average 2.3 years longer than the date of the last repair (Ebersbach 2010b). Otherwise, values from the general model are used. The timber demand is calculated from the reconstructed or assumed house dimensions. Permanent cultivation is suggested for all sites except 5, where SC is assumed, although this is not supported by any data and is merely done to show the implications of SC. Manuring is assumed for sites 1 and 3, where higher livestock numbers are probable. Apart from theoretical calculations, no local data or indication was found for the probable ratio of crop plant to non-crop calories. Values in these categories are therefore identical in the generic model and all fitted models. The proportion of calories obtained from hunting, gathering, fishing and meat/milk from livestock (H/G/F/LU) is assumed using on-site data, mostly from bones. These are available from all sites except 5 and 6; here, the generic model applies. We do not apply archaeobotanical data for direct quantification, since for taphonomic reasons, archaeozoological remains provide a much more complete and reliable record of their relative importance (Schibler and Jacomet 2010, p. 175). Quantitative studies on the importance of gathered and produced plant foodstuffs are an exception (Antolín et al. 2016).

Table 6 The generic model of Neolithic land use (site 0) and the fitted models for the sites 1–6

Site nos	LS	Occup. (years)	No. of houses	House dimensions (m)	Timber demand (m^3/a)	Firewood demand (m^3/a)	CHM (f.size)	CPC share (mean) %	NCC share (mean) %	H/G/F/LU (%)	LU/MH
0	2	10	10	12×4	1.5	6	PC (1.25)	50–90 (75)	10–50 (25)	10/60/10/20	2
1	3*	13*	11*	9×3.5*	1.0*	6	PCm (1)	50–90 (75)	10–50 (25)	5/60/10/25*	4*
2	2*	10	10*	9×4*	1.1*	6	PC (1.25)	50–90 (75)	10–50 (25)	20/60/15/5*	1*
3	3*	30*	16	12×4*	1.5*	6	PCm (1)	50–90 (75)	10–50 (25)	5/60/10/25*	3*
4	2*	10*	10	7×3.5*	0.8*	6	PC (1.25)	50–90 (75)	10–50 (25)	20/60/15/5*	1*
5	4	10	19	4.5×8.5	1.2	6	SC (0.5)	50–90 (75)	10–50 (25)	20/60/0/20*	2
6	1	10	20*	10×5	1.6	6	PC (1.25)	50–90 (75)	10–50 (25)	15/60/15/10*	1

Values marked with an asterisk (*) are taken directly or at least inferred from the local archaeological/palaeoenvironmental record. Values without an asterisk are based on the general model or contemporary analogues. Shifting cultivation (SC) is assumed for site 5 in order to simulate the implications of this method, not due to local data

LS landscape scenario, *occup* duration of occupation in years, *CHM* crop husbandry method, *f.size* field size per model household, *PC* permanent cultivation, no manure, *PCm* permanent cultivation, manured, *SC* shifting cultivation, *CPC* share, annual share of calories from cultivated plants at desired annual calorie demand [max–min (mean)], *NCC* share, annual share of non-crop calories at desired annual calorie demand [max–min (mean)], *H/G/F/LU* (%) share of hunting/gathering/fishing/livestock at annual calorie demand, *LU/MH* Livestock units per model household

Results

Calorie supply and extent of land use around the sites

In Fig. 6, panels 1–6A, the composition of the calorie supply at the six sites presented in Table 4 is simulated. For this, the fitted local models as described in Table 6 are applied.

In all panels, the coloured bars indicate the variable proportion of the calorie sources. The driving force of the variability is the fluctuation of crop plant calories (CPC; yellow bars) due to changing weather conditions as shown in Fig. 4; the annual sum of calories from hunting/gathering/fishing/livestock units (H/G/F/LU; red/pink/blue/green bars in the panels A) is dependent on the crop plant (CPC) share. We assume field sizes per model household of 0.5 for SC, 1 ha for PC with manuring, or 1.25 ha for PC without the use of manure. Thus, using a synthetic weather dataset based on the period 1980–2010 for Bodensee (METEOSWISS; Baum et al. 2016), a simulated CPC proportion of 60–80% is frequently achieved. Higher values of 90% and very low values of 20% occur as well. A trend of yield decrease due to soil nutrient loss after only 10–15 years is visible in all sites but 5. There, neither nutrient loss nor long-term yield decline occur due to the annual moving of the fields.

Gathering (pink bars) provides the bulk of calories that are needed to buffer low crop yields. In some years, the amount of gathered calories is even greater than the CPC share (for example, year 3 at site 1).

Sites with large numbers of domestic animal remains such as sites 1 and 3 have a higher proportion of calories from meat and milk (LU) and a relatively lesser share of hunted calories, while at sites 2 and 4 this is reversed. These amounts reflect assumptions based on relative proportions, not the absolute quantities of the bone assemblages at the named sites. Fishing (blue bars) provides calories at all sites except for 5, because here there is no lake nearby.

The simulated space requirements for the most important land use activities at each site are also based on the fitted local models (Fig. 6, panels B1–6). In Table 7, the max/min and the mean of these values are given on a per capita basis. In our simulations, low crop yields never result in a shortage of the total amount of available calories, which adds up to 100% in every year, as can be seen in Fig. 6, panels A1–6. Instead, the use of other calorie sources increases, which results either in a larger area being used for hunting, gathering and fishing, or an increased slaughtering rate of domestic animals.

A very large area is needed to acquire the hunted calorie share of the ACD in all sites, as can also be seen in the

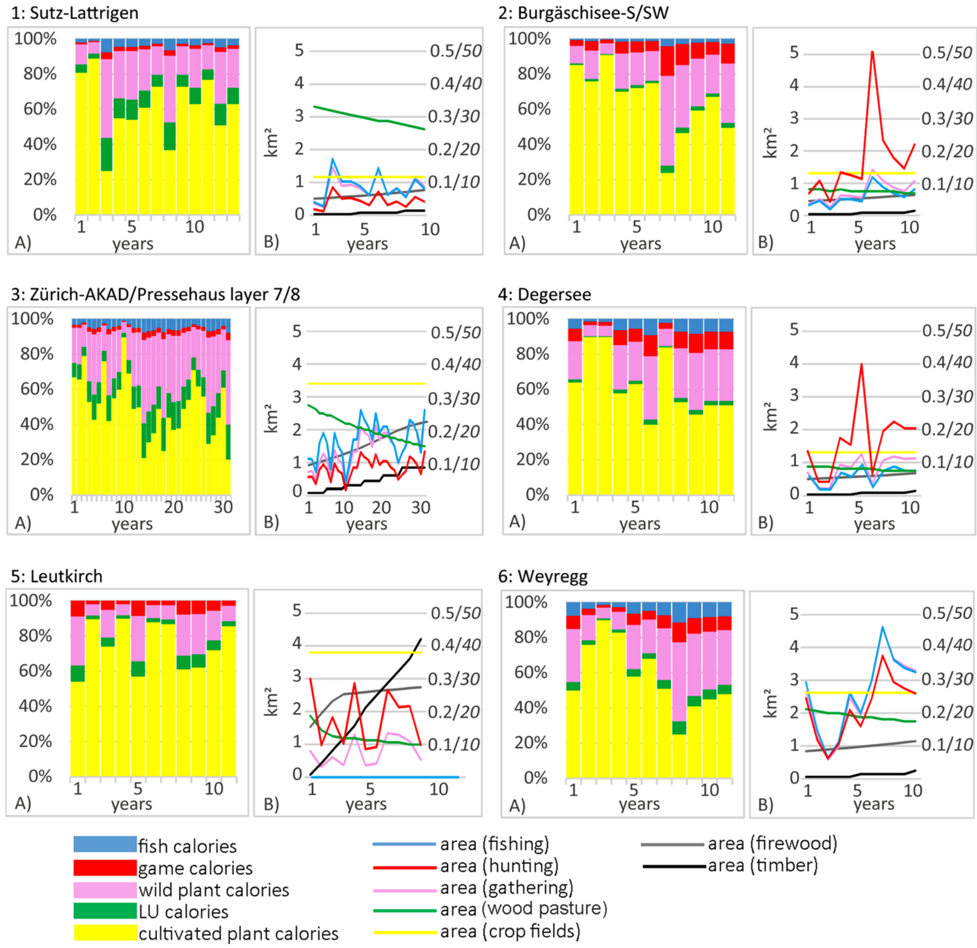

Fig. 6 Simulation of the annual food composition (A, on left) and the annual maximum areas needed for use of resources (B, on right) according to the fitted models (Table 5). The proportions are; crop plant calorie (CPC) share, 20–90%; gathered share, 6–45%; hunted share, 1–15%; fished share, 0–12%; meat/milk from livestock, 1–20%. Note that in panel B, the values for fishing and crop production are increased by a factor of 10 (y axis to the right of panel B, and the values for hunting and livestock pasture are decreased by a factor of 10 (y axis to the right of panel B, italics) to improve visibility

Table 7 Simulated area in ha needed for land use using permanent cultivation (PC) and shifting cultivation (SC), calculated on a per capita basis

	Crop fields	Gathering	Fishing	Hunting	LU pasture	Timber	Firewood
Min (PC)	0.17	0.4	0.0	2.1	3.0	0.1	0.7
Max (PC)	0.21	3.8	0.4	86.7	14.6	0.9	2.3
Mean (PC)	0.19	1.4	0.1	15.0	9.6	0.3	1.3
Min (SC)	0.3	0.3	0.0	6.9	4.7	0.1	1.2
Max (SC)	6.0	1.8	0.4	33.3	8.8	3.7	2.1
Mean (SC)	–	0.9	0.1	19.1	5.8	1.8	1.9

The column "LU pasture" indicates the spatial requirements for one livestock unit. No mean is given for the column with crop fields (SC), as every year the fields are moved. The maximum value in this column gives the land demand per person, for an occupation duration of 20 years

snapshot of year 10 of each simulation shown in Fig. 7. It reaches a maximum of 50 km^2 in years with poor yields at sites where hunting was important (Fig. 6, panel B2). The area necessary to obtain the calories from gathered plants is usually 0.5–1.5 km^2 and can be up to 4.5 km^2. Fishing requires typically 0.5–2 km^2/year with maximum values of 4 km^2 at sites on the shores of oligotrophic larger lakes with a relatively high number of fish (Fig. 6, panel B6).

The area for livestock husbandry (green) depends upon the number of animals assumed and the degree of openness in the applied landscape scenario. Extended areas are required especially at sites with more animals (sites 1 and 3) or denser woodland cover (site 6). The curve shows a downward trend in all cases, as in WELASSIMO it is assumed that small-scale browsing in woodland has a constant positive effect on the availability of leaf fodder due to increased radiation influx. In site 5 this effect is especially strong, as new open areas with high solar radiation influx are produced every year by abandoned fields from SC. The area indicated by the grey

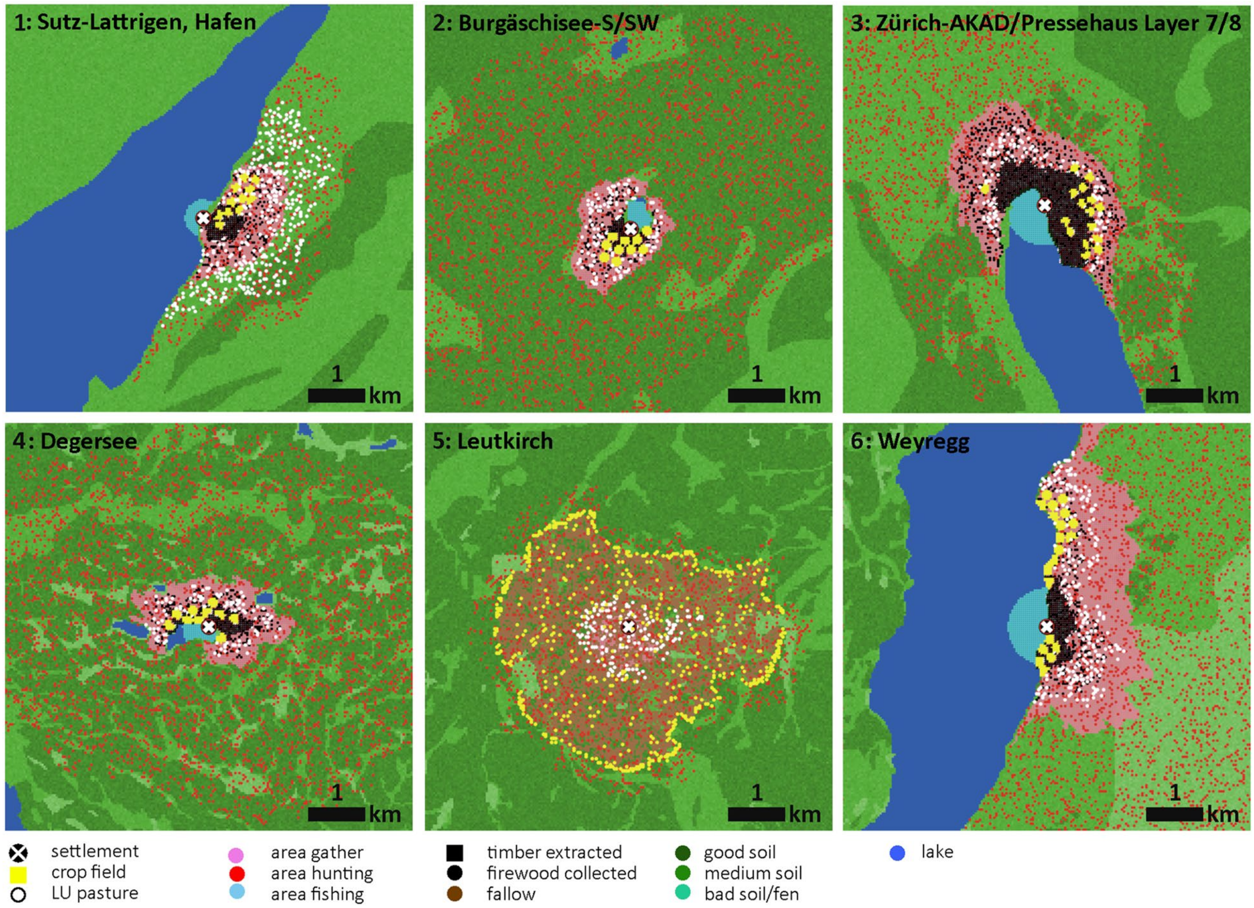

Fig. 7 Extent of land use around sites 1–6 in year 10 of the simulation. The large distance to the crop fields in panel 5 is due to the high land demand from shifting cultivation. In the other panels, permanent cultivation is assumed

line, for collecting firewood, increases slowly due to the assumption of resource degradation caused by continuous gathering. The area for obtaining timber shown by the black line increases slightly for all sites but 5 due to the need for wood for repairs to the houses, and the decreased regrowth of trees due to browsing by livestock. The total area needed for obtaining timber at sites with a shorter occupation duration of up to 13 years is 15–30 ha and up to 84 ha for the site of Zürich-AKAD/Pressehaus Layer 7/8, which was occupied for 30 years (Table 6). At site 5, the process of burning to clear land for fields requires a large amount of wood of small diameters (Ehrmann et al. 2014), which is also needed for the construction of buildings. The area for the annually cropped fields does not change with time. The total area for crop production depends on the crop husbandry system. At sites 1, 2, 4 and 6 with PC it equals the sum of field sizes needed for each household, which means an overall area of 10–20 ha. In site 3 this area is doubled, as fallows of 1 year are assumed. At site 5, the annual area of 4 km^2 results from the suggestion of SC and the high demand for firewood, which requires four times the area of the actual field. As fields are moved each year, the total affected area is very large.

Discussion

In the following, we interpret simulation results from the WELASSIMO model in order to identify a possible interdependence of land use methods and the described settlement dynamics. It is important to note that the intention of these simulations is not to (re-)construct a historical "reality", but to offer a method to explore existing data and build or test hypotheses. Therefore, the quantifications discussed here should be regarded as an approximation to Neolithic conditions under the assumptions which have been described.

Interdependence of crop production and settlement dynamics

Crop production using SC or PC, as discussed in the “Materials and methods” section, might be discussed as a motivation for settlement relocation. Under SC, one might speculate that this would create or require a dynamic settlement system due to the great demand for land. However, the typical duration of occupation of 5–15 years speaks against this: an area that has been burned and used for growing crops for 1 or 2 years, and then left fallow for 10–15 years, would make an ideal spot for repeating the cycle, which is typical for SC. An area covered with vegetation in an early stage of succession is much easier to prepare for the burning process than more mature stands. So it is probable that this shifting type of crop cultivation would lessen the need to move the settlement location. However, crop cultivation with PC might need some field relocation. If animal dung was not used and soil fertility was not maintained in any other way, such as a mixed cultivation with pulses, or fallows, crop yields on a typical soil of the Swiss Alpine foreland are shown to decrease to around 50–60% of the initial yields after 10–15 years (Fig. 4; Baum et al. 2016). Even on fields which are manured with 10 tonnes of animal dung per hectare each year, simulated average yields decrease to 80% of the initial amount after ten years, in our simulations. These numbers are in contrast to results obtained from long-term cropping experiments at Rothamsted, UK (Poulton 2006). However, these crops were grown on fields which had a long term agricultural legacy with soil organic matter being close to steady state conditions, while in our simulations, we assumed a woodland soil freshly cleared for cultivation, which might better reflect prehistoric conditions.

If this decrease in yield was as common as suggested by our simulations, it must have been standard agronomic knowledge of great importance for the Neolithic people. If enough areas with good soils were available, a mere opening of new fields and the use of fallow years might have been suitable to compensate for this reduction. At sites 1–5, an increase of crop field size would avoid the need to move the settlement, because either the area with high quality soil in the vicinity is sufficient (sites 1–4) or the simulated crop husbandry method allows for the use of medium quality soil (site 5). In areas with only a little high quality arable soil as in site 6, the soil nutrient loss alone may have justified moving the settlement after a few years, if no intensive manuring or other means to maintain fertility was practised. Crop growing may therefore have played a role in the motivation to move a settlement. On the other hand, Styring et al. (2016) analyzed crop nitrogen isotope values from stored crops at the site of Sipplingen. They argue that the well-known abandonment of the settlement after 3600 BC (Billamboz et al. 2010) was as a result of problems with calorie provision due to climatic deterioration, rather than from soil degradation.

The significance of non-crop calorie provision for the observed settlement dynamics

In our simulations, the annual fluctuation of crop yields causes variability of the non-crop (NCC) share. This dependence cannot be proved by archaeological data, as the record is highly incomplete, even with the relatively good preservation conditions of the prehistoric wetland sites. However, it is a reasonable hypothesis, since cultivated crops are a rather inflexible source of calories. They require high labour input to prepare the soil, thorough planning, and they cannot be increased in the course of the year. NCC calorie sources are in comparison more flexible.

As an example, we highlight the case simulated in Fig. 6, panel A2 where a pronounced reduction of crop yields (CPC) from 89 to 25% in years 6 and 7 is met by an increased share from all other calorie sources. The percentage of gathered calories rises from 7 to 45%, which in the model means an increased area of woodland needed with moderately frequent thickets of hazel bushes, from 2.3 to 13 ha per MH. In terms of workforce, this increase would require three extra people collecting hazelnuts for a period of 10 days. This is theoretically possible, if there was enough hazel in the woodland (calculations based on Holst 2010). These calculations are made as an example, as gathered calories come from a multitude of other plants, too. However, it shows that hazel probably was of great importance for the calorie supply, especially as it could easily spread into areas cleared by fire. There is an archaeological case in which hazelnuts were used to overcome calorie shortages after a catastrophic fire at the site of Hornstaad-Hörnle 1A (Maier et al. 2001). For fishing and hunting, an increase from 1 to 8% and from 0.5 to 4% respectively is simulated in the discussed example. As these resources were most probably not normally limited by human factors in prehistoric times, more use of them could easily have been achieved with more people and by using a larger area. However, Schibler and Jacomet (2010) discuss a decrease in some animals, especially *Cervus elaphus* (red deer), that is possibly related to climatically caused shortages of crop calories.

LU calorie provision might not have been as easily increased. In the example used above, the loss in crop calories was met by an increase in LU calories from 3 to 18%. The lower value could have been met by consuming the meat of one pig and two goats or sheep per MH, while the higher value required the slaughtering of one cow, four pigs and five goats or sheep per MH (calculation based on Deschler-Erb and Marti-Grädel 2004, p. 239). For herd sizes as reconstructed by Ebersbach (2013), such losses would be a serious threat to the size of the herds needed to maintain their stock in many cases, or might even exceed the total number of animals kept.

Based on our simulation, we cannot deduce a need for settlement relocation from the methods of non-crop calorie provision; instead, a more open woodland rich in hazel bushes might even avoid the need to move the settlement a long way, as it could serve as an important buffer against crop calorie shortages, provide good browsing areas for LU and attract game.

The interpretation of fire signals

In our view, SC is less likely than PC as the standard crop husbandry method (Baum et al. 2016; Jacomet et al. 2016). From an economic perspective, SC makes sense if good soils are not available, which is not generally the case for the environments of the wetland sites (Müller et al. 2007). Although an increase in clearance of woodland by burning beginning around 4500–4000 BC is well recorded in many pollen profiles (Clark et al. 1989; Tinner et al. 2005; Rösch et al. 2014; Rey et al. 2017), there is no indication that the purpose of these fires was for SC of crops. Instead, we support the interpretation that fires were used to open the woodland cover for farming and hunting activities through a "slash-and-burn" practice, which is different from SC (Clark et al. 1989; Tinner et al. 2005). This practice would increase solar radiation input and so increase the growth of the shrub and herb layers, thus raising the economic value of woodland pasture for both wild and domesticated animals. A further goal of opening up the wooded landscape was possibly to encourage the growth of hazel by fire. Taken together, these hypotheses explain the patterns observed in off-site pollen and charcoal studies, without contradicting the on-site archaeobotanical evidence from macroremains, as is the case with the SC hypothesis (Jacomet et al. 2016).

The significance of woodland pasture, obtaining timber and collecting firewood

Livestock browsed in the landscape for fodder and required a certain amount of leaf hay during winter. As the range of fodder available in different vegetation types is wide and the spatial requirements of one head of cattle relatively large (ESM 2, Table 6), the area for LU husbandry simulated in WELASSIMO is highly dependent on these factors. Furthermore, the topography plays an important role in calculating the required distances. At site 1, where the very high number of four LU and a rather open landscape (LS3) are assumed, the maximum distance from a settlement for LU pasture as shown in Fig. 7 is 2,500 m. At site 6, where one LU and a closed woodland canopy are assumed and the topography has steep areas, a maximum distance of 3,300 m is simulated. However, these numbers cannot be regarded as a problem for the prehistoric population, since they do not require a fundamentally larger work input for the herding of the cattle. As already stated by Schibler et al. (1997, p. 348) a much bigger task was probably to provide the leaf fodder for the winter months; the authors assume that a joint effort by all inhabitants of a settlement was required to obtain the required amount. While this is not simulated separately in WELASSIMO, it highlights the influence of relief and topography.

The simulation of firewood use and especially of timber extraction is implemented on a rather general level in WELASSIMO, as a detailed integration of the complex dynamics of woodland succession was beyond the scope of the project. According to analyses by Ebersbach (2010b, p. 42), in WELASSIMO houses are completely rebuilt after 5 years. Therefore, the area needed to obtain the timber for this is constantly increasing in our simulations. The simulated spatial requirements translate into a distance of 500–800 m if the area for resource allocation was rather circular, as in sites 2 and 5. For settlements with more houses located beside large lakes such as sites 3 or 6, a minimum distance of 1,000–1,300 m is simulated. Again, these numbers are not meant to reflect a prehistoric reality, but only to provide a quantitative approach for an interpretation of the archaeological record. Local scarcity of timber resources has been suggested (Billamboz 2014; Bleicher and Burger 2015, p. 143). The area of woodland needed for collecting firewood depends, among other factors, on whether only dead wood is collected, or if trees are also felled. Dufraisse (2008) interprets charcoal data from a wetland site as showing that firewood was probably collected while using daily walking paths, so in WELASSIMO this is the case, too. The simulated spatial demand translates into a distance of 1,000–1,800 m walking from the settlement that would be necessary to collect firewood; for site 6 only, the topography shows the need for a much larger distance of up to 3,000 m, since steep slopes are avoided.

From these results we believe that timber and firewood supply both played an important role in the observed settlement dynamics. It is much easier to repair or re-build a house that is close to suitable timber stands, instead of bringing the timber from up to 1,300 m away, as simulated above. The calculated daily demand of 13 kg firewood possibly played a role as well, since it needed to be carried back over distances of up to 3,000 m to obtain this amount.

Most probably, people were confronted with a trade-off-situation: the more a woodland canopy was opened up, the higher was the economic value for certain methods of land use such as gathering, hunting and animal husbandry. Yet as timber and firewood extraction continued and LU grazed an area for several years, the pressure on the woodland would have increased and led to a local degradation of its resources.

Opening up of the woods meant a net growth of the resource value of an area, yet continuing land use led to an increasing shortage of certain resources. Therefore it is highly probable that the socio-ecological systems of the wetland settlements were strongly influenced by ecological factors to a varying degree, and these might even have caused a relocation of the settlement.

The question why Neolithic communities built their settlements in flood-endangered zones on shallow lake shores and in peat bogs at all might point in a similar direction; the location of the wetland sites on the edge of various ecosystems *offers* the possibility to provide calories from fishing, fowling or collecting invertebrates from the lake without the need to *rely* on them. Regarding the high variability of crop yields (Fig. 4) and the need to be able to respond to calorie shortages, it is obvious that every additional source of calories increased resilience and was probably highly esteemed. So, we argue that living by a lake can generally be regarded as a strategy to reduce the risk of hunger or starvation.

Conclusions and perspectives

From our simulations of land use methods, we found that the total space requirements for land would have been directly related to the composition and the structure of the vegetation. The plant cover determines the quality and quantity of important resources. Large areas were needed, especially for hunting and animal husbandry. However, the influence of non-crop calorie provision most probably was not an important factor in the dynamics of the settlement. Instead, it may even be assumed that these land use methods may have caused an area to be used for as long as possible, since a more open landscape attracts game and encourages the growth of edible plants. We think that the local depletion of woodland resources for obtaining timber and firewood might be especially important in explaining the settlement dynamics discussed above. However, our simulations suggest that crop husbandry and soil nutrient dynamics may have been important, too. We think that two opposing factors may have influenced the dynamics of the wetland settlements. On the one hand, continuing land use including the use of fire opened up the vegetation cover and increased biodiversity, which increased its economic value for food production and feeding livestock. On the other hand, woodland resources and soil fertility would have gradually decreased. These environmental dynamics caused by humans might have been the reason for the settlement dynamics of the Neolithic wetland sites which we have described, with frequent settlement relocation after around 10–15 years.

The process of computer modelling and the analysis of the simulation results allow for an overall view of the otherwise isolated results of various disciplines. The formalization and identification of links between various sub-processes of the land use systems and of the landscapes around the sites allows for new perspectives on this intensively studied subject. However, a detailed simulation of woodland development was beyond the scope of this project. Therefore, we suggest that a more detailed simulation model of Neolithic land use and its effect on individual tree growth should be developed in the future.

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References

Adams SN (1975) Sheep and cattle grazing in forests: a review. J Appl Ecol 12:143–152

Altaweel M (2015) Settlement dynamics and hierarchy from agent decision-making: a method derived from entropy maximization. J Archaeol Method Theory 22:1,122–1,150

Ammann B (1989) Late-Quaternary palynology at Lobsigensee: regional vegetation history and local lake development. Cramer, Stuttgart

An L (2012) Modeling human decisions in coupled human and natural systems: review of agent-based models. Ecol Model 229:25–36

Antolín F, Bleicher N, Brombacher C, Kühn M, Steiner BL, Jacomet S (2016) Quantitative approximation to large-seeded wild fruit use in a late Neolithic lake dwelling: new results from the case study of layer 13 of Parkhaus Opéra in Zürich (Central Switzerland). Quat Int 404:56–68

Antolín F, Brombacher C, Kühn M, Steiner BL, Jacomet S (2017) Archäobotanik (Makroreste): Untersuchungen der Flächenproben im Hinblick auf Taphonomie, Ackerbau, Sammelwirtschaft und Umwelt. In: Bleicher N, Harb C (eds) Zürich-Parkhaus Opéra: eine neolithische Feuchtbodenfundstelle, vol 3. FO-Fotorotar, Egg bei Zürich, pp 50–92

Axtell RL, Epstein JM, Dean JS et al (2002) Population growth and collapse in a multiagent model of the Kayenta Anasazi in Long House Valley. Proc Natl Acad Sci USA 99(Suppl 3):7,275–7,279

Balbo AL, Rubio-Campillo X, Rondelli B et al (2014) Agent-based simulation of Holocene monsoon precipitation patterns and hunter-gatherer population dynamics in semi-arid environments. J Archaeol Method Theory 21:426–446

Barton CM, Ullah IIT, Bergin SM, Mitasova H, Sarjoughian H (2012) Looking for the future in the past: long-term change in socioecological systems. Ecol Model 241:42–53

Baum TG (2014) Models of wetland settlement and associated land use in South-West Germany during the fourth Millennium B.C. Veget Hist Archaeobot 23(Suppl 1):67–80

Baum T (2016a) Simulating land use of prehistoric wetland settlements: did excessive resource use necessitate a highly dynamic settlement system? In: Barceló JA, Castillo F (eds) Simulating prehistoric and ancient worlds. Springer, Cham, pp 255–279

Baum T (2016b) Computersimulation jungsteinzeitlicher Landnutzung. In: Schlichtherle H, Heumüller M, Haack F, Theune-Grosskopf B (eds) 4000 Jahre Pfahlbauten. Thorbecke, Ostfildern, pp 316–318

Baum T (2017) Modelle der Landnutzung in den neolithischen Feuchtbodensiedlungen des nordwestlichen Alpenvorlandes. Unpublished Dissertation, University of Basel

Baum T, Nendel C, Jacomet S, Colobran M, Ebersbach R (2016) "Slash and burn" or "weed and manure"? A modelling approach to explore hypotheses of late Neolithic crop cultivation in pre-Alpine wetland sites. Veget Hist Archaeobot 25:611–627

Baum T, Bleicher N, Ebersbach R, Ruckstuhl B, Walder F, Weber M (2019) Jungsteinzeitliche Ufersiedlungen im Zürcher Seefeld: Ausgrabungen Kanalisationssanierung, Pressehaus, AKAD, Utoquai, vol 3. Die Siedlungsgeschichte, FO-Fotorotar, Egg bei Zürich

Billamboz A (2014) Regional patterns of settlement and woodland developments: dendroarchaeology in the Neolithic pile-dwellings on Lake Constance (Germany). Holocene 24:1,278–1,287

Billamboz A, Maier U, Matuschik I et al (2010) Die jung- und endneolithischen Seeufersiedlungen von Sipplingen "Osthafen" am Bodensee: Besiedlungs- und Wirtschaftsdynamik im eng begrenzten Naturraum des Sipplinger Dreiecks. In: Matuschik I, Strahm C (eds) Vernetzungen. Festschrift für Helmut Schlichtherle zum 60. Geburtstag. Lavori, Freiburg, pp 253–286

Bleicher N (2009) Altes Holz in neuem Licht: Archäologische und dendrochronologische Untersuchungen an spätneolithischen Feuchtbodensiedlungen in Oberschwaben. Theiss, Stuttgart

Bleicher N (2017) Dorforganisation und Hausbau. In: Bleicher N, Harb C (eds) Zürich-Parkhaus Opéra: eine neolithische Feuchtbodenfundstelle, vol 3. FO-Fotorotar, Egg bei Zürich, pp 202–214

Bleicher N (2019) Siedlungsdynamik und Organisation. In: Baum T, Bleicher N, Ebersbach R, Ruckstuhl B, Walder F, Weber M (eds) Jungsteinzeitliche Ufersiedlungen im Zürcher Seefeld: Ausgrabungen Kanalisationssanierung, Pressehaus, AKAD, Utoquai, vol 3. FO-Fotorotar, Egg bei Zürich, pp 259–261

Bleicher N, Burger M (2015) Dendroarchäologie und Pfahlfeldanalyse. In: Bleicher N, Harb C (eds) Zürich-Parkhaus Opéra: eine neolithische Feuchtbodenfundstelle, vol 1. Schichten und Dendroarchäologie. FO-Fotorotar, Egg bei Zürich, pp 100–142

Bleicher N, Harb C (2017) Zürich-Parkhaus Opéra: eine neolithische Feuchtbodenfundstelle, vol 3. Naturwissenschaftliche Analysen und Synthese, FO-Fotorotar, Egg bei Zürich

Bleicher N, Walder F (2019). Dendroarchäologie von KanSan, AKAD und Pressehaus. In: Baum T, Bleicher N, Ebersbach R, Ruckstuhl B, Walder F, Weber M (eds) Jungsteinzeitliche Ufersiedlungen im Zürcher Seefeld: Ausgrabungen Kanalisationssanierung, Pressehaus, AKAD, Utoquai. Band 3, Die Siedlungsgeschichte. FO-Fotorotar, Egg bei Zürich

Boessneck J, Jéquier J-P, Stampfli HR (1963) Seeberg, Burgäschisee Süd, Teil 3. Die Tierreste, Stämpfli, Bern

Bogaard A (2004) Neolithic farming in central Europe: an archaeobotanical study of crop husbandry practices. Routledge, London

Brombacher C, Hadorn P (2004) Untersuchungen der Pollen und Makroreste aus den Profilsäulen. In: Jacomet S, Leuzinger U, Schibler J (eds) Die jungsteinzeitliche Seeufersiedlung Arbon-Bleiche 3: Umwelt und Wirtschaft. Amt für Archäologie des Kantons Thurgau, Frauenfeld, pp 50–63

Brombacher C, Jacomet S (1997) Sammelwirtschaft und Umwelt: Ergebnisse archäobotanischer Untersuchungen. In: Schibler J, Hüster-Plogmann H, Jacomet S, Brombacher C, Gross-Klee E, Rast-Eicher A (eds) Ökonomie und Ökologie neolithischer und bronzezeitlicher Ufersiedlungen am Zürichsee. FO-Fotorotar, Egg bei Zürich, pp 220–299

Bruckner G, Strohmaier P (2016) Holzvermarktung: Schwachholz und Durchforstungsholz. https://www.holz-von-hier.de/tools-services/waldvielfalt/holzvermarktung/. Accessed 10 Oct 2016

Brufau G, Boatella J, Rafecas M (2006) Nuts: source of energy and macronutrients. Br J Nutr 96(Suppl 52):24–28

Cegielski WH, Rogers JD (2016) Rethinking the role of agent-based modeling in archaeology. J Anthropol Archaeol 41:283–298

Clark JS, Merkt J, Müller H (1989) Post-glacial fire, vegetation, and human history on the northern Alpine forelands, south-western Germany. J Ecol 77:897–925

Colombaroli D, Henne PD, Kaltenrieder P, Gobet E, Tinner W (2010) Species responses to fire, climate and human impact at tree line in the Alps as evidenced by Paleo-environmental records and a dynamic simulation model. J Ecol 98:1,346–1,357

Crema ER (2014) A simulation model of fission–fusion dynamics and long-term settlement change. J Archaeol Method Theory 21:385–404

Dean JS, Gumerman GJ, Epstein JM, Axtell RL, Swedlund AC, Parker MT, McCarroll S (2000) Understanding Anasazi culture change through agent-based modeling. In: Kohler TA, Gumerman GJ (eds) Dynamics in human and primate societies: agent-based modeling of social and spatial processes. Oxford University Press, New York, pp 179–205

Del Castillo F, Barceló JA, Mameli L, Miguel F, Vila X (2014) Modeling mechanisms of cultural diversity and ethnicity in hunter–gatherers. J Archaeol Method Theory 21:364–384

Deschler-Erb S, Marti-Grädel E (2004) Viehhaltung und Jagd: Ergebnisse der Untersuchungen der handaufgelesenen Tierknochen. In: Jacomet S, Leuzinger U, Schibler J (eds) Die jungsteinzeitliche Seeufersiedlung Arbon-Bleiche 3: Umwelt und Wirtschaft. Amt für Archäologie des Kantons Thurgau, Frauenfeld, pp 158–252

Dieckmann B, Maier U, Vogt R (2001) Hornstaad: zur inneren Dynamik einer jungneolithischen Dorfanlage am westlichen Bodensee: Neue Ergebnisse der Archäologie, Botanik und Bodenkunde. In: Lippert A, Schulz M, Shennan S, Teschler-Nicola M (eds) Mensch und Umwelt während des Neolithikums und der Frühbronzezeit in Mitteleuropa. Leidorf, Rahden/Westf., pp 29–51

Doppler T, Pichler S, Röder B, Schibler J (2013) Coping with crises I: Subsistence variety and resilience in the Neolithic lake shore settlement Arbon Bleiche 3 (Switzerland). In: Kerig T, Zimmermann A (eds) Economic archaeology; from structure to performance in European archaeology. Habelt, Bonn, pp 163–174

Dufraisse A (2005) Économie du bois de feu et sociétés néolithiques: analyses anthracologiques appliquées aux sites d'ambiance humide des lacs de Chalain et de Clairvaux (Jura, France). Gall préhist 47:187–233

Dufraisse A (2008) Firewood management and woodland exploitation during the late Neolithic at Lac de Chalain (Jura, France). Veget Hist Archaeobot 17:199–210

Ebersbach R (2002) Von Bauern und Rindern: eine Ökosystemanalyse zur Bedeutung der Rinderhaltung in bäuerlichen Gesellschaften als Grundlage zu Modellbildung im Neolithikum. Schwabe, Basel

Ebersbach R (2003) Paleoecological reconstruction and calculation of calorie requirements at Lake Zurich. Forsch Archäol Land Brandenbg 8:69–88

Ebersbach R (2010a) About dynamics. Unpublished habilitation, University of Basel, Multiscale analyses and theoretical approaches to understand Swiss wetland sites

Ebersbach R (2010b) Vom Entstehen und Vergehen: Überlegungen zur Dynamik von Feuchtbodenhäusern und -siedlungen. In: Matuschik I, Strahm C (eds) Vernetzungen. Festschrift für Helmut Schlichtherle zum 60. Geburtstag. Lavori, Freiburg, pp 41–50

Ebersbach R (2013) Quantitative approaches to reconstructing prehistoric stock breeding. In: Kerig T, Zimmermann A (eds) Economic archaeology: from structure to performance in European archaeology. Habelt, Bonn, pp 143–160

Ehrmann O, Biester H, Bogenrieder A, Rösch M (2014) Fifteen years of the Forchtenberg experiment—results and implications for the understanding of Neolithic land use. Veget Hist Archaeobot 23(Suppl 1):5–18

Ellenberg H, Leuschner C (2010) Vegetation Mitteleuropas mit den Alpen: in ökologischer, dynamischer und historischer Sicht. 6., erweiterte Auflage. Ulmer, Stuttgart

Emborg J, Christensen M, Heilmann-Clausen J (2000) The structural dynamics of Suserup Skov, a near-natural temperate deciduous forest in Denmark. For Ecol Manag 126:173–189

Erny-Rodmann C (1996) Von der Urlandschaft zur Kulturlandschaft: pollenanalytische Untersuchungen an drei Uferprofilen aus dem "Zürcher Seefeld" zu anthroprogenen Vegetationsveränderungen seit dem Mesolithikum bis ins ausgehende Neolithikum. Unpublished dissertation at the University of Basel

FAO (2008) Updating the minimum dietary energy requirements. Resource document. https://www.fao.org/fileadmin/templates/ess/documents/food_security_statistics/metadata/undernourishment_methodology.pdf

Fleck W, Fritz C (2010) Digitale Bodenkarte von Baden-Württemberg 1:50 000: neue Wege in der bodenkundlichen Landesaufnahme. In: Etzold A (ed) Beiträge zur Geologie und Bodenkunde in Baden-Württemberg. LGRB, Freiburg, pp 83–94

Gaillard M-J, Morrison KD, Madella M, Whitehouse N (2018) Past land-use and land-cover change: the challenge of quantification at the subcontinental to global scales. Past Glob Changes Mag 26:3–4

Ghilardi A, Guerrero G, Masera O (2009) A GIS-based methodology for highlighting fuel wood supply/demand imbalances at the local level: a case study for Central Mexico. Biomass Bioenergy 33:957–972

Grimm V, Berger U, Bastiansen F, Eliassen S, Ginot V, Giske J, Goss-Custard J, Grand T, Heinz SK, Huse G (2006) A standard protocol for describing individual-based and agent-based models. Ecol Model 198(1):115–126

Grimm V, Berger U, DeAngelis DL, Polhill JG, Giske J, Railsback SF (2010) The ODD protocol: a review and first update. Ecol Model 221(23):2,760–2,768

Gross E, Jacomet S, Schibler J (1990) Stand und Ziele der wirtschaftsarchäologischen Forschung an neolithischen Ufer- und Inselsiedlungen im unteren Zürichseeraum (Kt. Zürich, Schweiz). In: Schibler J, Sedlmaier J, Spycher H (eds) Festschrift Hans R. Stampfli. Helbig & Lichtenhahn, Basel, pp 77–100

Günther S, Heurich M (2013) Bewertung der Naturnähe des Rothirschmanagements in mitteleuropäischen Nationalparken. Allg Forst-und Jagdztg 1(2013):1–16

Haas JN, Magny M (2004) Umwelt und Schichtentstehung. In: Jacomet S, Leuzinger U, Schibler J (eds) Die jungsteinzeitliche Seeufersiedlung Arbon-Bleiche 3: Umwelt und Wirtschaft. Amt für Archäologie des Kantons Thurgau, Frauenfeld, pp 41–50

Hafner A, Schwörer C (2018) Vertical mobility around the high-Alpine Schnidejoch Pass. Indications of Neolithic and Bronze Age pastoralism in the Swiss Alps from paleoecological and archaeological sources. Quat Int 484:3–18

Hafner A, Schlichtherle H, Taylor T, Tinner W (2016a) International und interdisziplinär. Archäologie und Umweltwissenschaften heute. In: Schlichtherle H, Heumüller M, Haack F, Theune-Grosskopf B (eds) 4000 Jahre Pfahlbauten. Ostfildern, Thorbecke, pp 48–49

Hafner A, Stapfer R, Francuz J (2016b) Die Bucht von Sutz-Lattrigen. In: Schlichtherle H, Heumüller M, Haack F, Theune-Grosskopf B (eds) 4000 Jahre Pfahlbauten. Thorbecke, Ostfildern, pp 116–118

Hafner A, Rey F, Laabs L et al (2019) Archaeological and paleoecological investigations at Burgäschisee (Swiss Plateau) provide first interdisciplinary insights in Neolithic settlement, land use and vegetation dynamics. (EAA monograph series "Themes in contemporary archaeology"). Routledge, London

Harrison S, Stocker BD, Klein Goldewijk K, Kaplan JO, Braconnot P (2018) Do we need to include anthropogenic land-use and land-cover changes in Paleo climate simulations? Past Glob Changes Mag 26:4–5

Hartter J, Boston K (2008) Consuming fuel and fuelling consumption: modelling human caloric demands and fuel wood use. Small Scale For 7:1–15

Heiri C, Bugmann H, Tinner W, Heiri O, Lischke H (2006) A model-based reconstruction of Holocene treeline dynamics in the Central Swiss Alps. J Ecol 94:206–216

Helfrich T, Konold W (2010) Formen ehemaliger Niederwälder und ihre Strukturen in Rheinland-Pfalz. Arch Forstwes Landsch 44:157–168

Henne PD, Elkin C, Colombaroli D, Samartin S, Bugmann H, Heiri O, Tinner W (2013) Impacts of changing climate and land use on vegetation dynamics in a Mediterranean ecosystem: insights from paleoecology and dynamic modeling. Landsc Ecol 28:819–833. https://doi.org/10.1007/s10980-012-9782-8

Holst D (2010) Hazelnut economy of early Holocene hunter–gatherers: a case study from Mesolithic Duvensee, northern Germany. J Archaeol Sci 37:2,871–2,880

Hüster Plogmann H (2004) Fischfang und Kleintierbeute. Ergebnisse der Untersuchung aus den Schlämmproben. In: Jacomet S, Leuzinger U, Schibler J (eds) Die jungsteinzeitliche Seeufersiedlung Arbon-Bleiche 3: Umwelt und Wirtschaft. Frauenfeld, Amt für Archäologie des Kantons Thurgau, pp 253–276

Hüster Plogmann H, Häberle S (2017) Archäozoologische Schlämmreste aus den Schichten 13 und 14. In: Bleicher N, Harb C (eds) Zürich-Parkhaus Opéra. Eine neolithische Feuchtbodenfundstelle. vol 3: Naturwissenschaftliche Analysen und Synthese. FO-Fotorotar, Egg bei Zürich, 127–144

Hüster-Plogmann H, Schibler J (1997) Archäozoologie. In: Schibler J, Hüster-Plogmann H, Jacomet S, Brombacher C, Gross-Klee E, Rast-Eicher A (eds) Ökonomie und Ökologie neolithischer und bronzezeitlicher Ufersiedlungen am Zürichsee. FO-Fotorotar, Egg bei Zürich, pp 220–299

Jacomet S (2006) Plant economy of the northern Alpine lake dwellings—3500–2400 cal. BC. Environ Archaeol 11:65–85

Jacomet S (2007) Neolithic plant economies in the northern Alpine foreland (central Europe) from 5500–3500 bc cal. In: Colledge S, Conolly J (eds) The origins and spread of domestic plants in southwest Asia and Europe. Left Coast Press, Walnut Creek, Cal, pp 221–258

Jacomet S (2009) Plant economy and village life in Neolithic lake dwellings at the time of the Alpine Iceman. Veget Hist Archaeobot 18:47–59. https://doi.org/10.1007/s00334-007-0138-2

Jacomet S (2014) Crop diversity in southwestern central Europe from the Neolithic onwards. In: Chevalier A, Marinova E, Peña Chocarro L (eds) Plants and people: choices and diversity through time. Oxbow, Oxford, pp 82–95

Jacomet S, Schibler J (1985) Die Nahrungsversorgung eines jungsteinzeitlichen Pfynerdorfes am unteren Zürichsee. Archäol Schweiz 8.3(1985):125–141

Jacomet S, Dick M, Brombacher C (1989) Archäobotanik am Zürichsee: Ackerbau. Sammelwirtschaft und Umwelt von neolithischen und bronzezeitlichen Seeufersiedlungen im Raum Zürich, Orell Füssli, Zürich

Jacomet J, Leuzinger U, Schibler J (2004) Synthesis. In: Jacomet S, Leuzinger U, Schibler J (eds) Die jungsteinzeitliche Seeufersiedlung Arbon-Bleiche 3: Umwelt und Wirtschaft. Amt für Archäologie des Kantons Thurgau, Frauenfeld, pp 379–416

Jacomet S, Antolín F, Akeret Ö et al (2016) On-site data cast doubts on the hypothesis of shifting cultivation in the Late Neolithic (c. 4300–2400 cal. BC): landscape management as an alternative paradigm. Holocene 26:1,858–1,874. https://doi.org/10.1177/0959683616645941

Kalis AJ, Merkt J, Wunderlich J (2003) Environmental changes during the Holocene climatic optimum in central Europe—human impact and natural causes. Quat Sci Rev 22:33–79. https://doi.org/10.1016/S0277-3791(02)00181-6

Kerdy M, Chiquet P, Schibler J (2019) Hunting, husbandry, and human–environment interactions in the Neolithic lakeshore sites of western Switzerland. Eur J Archaeol 22:3–21. https://doi.org/10.1017/eaa.2018.32

Kleinmann A, Merkt J, Müller H (2015) Sedimente des Degersees: ein Umweltarchiv – Sedimentologie und Palynologie. In: Mainberger M, Merkt J, Kleinmann A (eds) Pfahlbausiedlungen am Degersee. Theiss, Darmstadt, pp 409–472

Kohler TA, Bocinsky RK, Cockburn D et al (2012) Modelling prehispanic Pueblo societies in their ecosystems. Ecol Model 241:30–41

Kriso K (1958) Entstehung, Aufbau und Leistung von Eichen-Hainbuchenbeständen in Süddeutschland. Forstw. Forsch. Beih. 9 zum Forstwiss. Cbl. Parey, Hamburg, Berlin

Kühn M, Hadorn P (2004) Pflanzliche Makro- und Mikroreste aus dem Dung von Wiederkäuern. In: Jacomet S, Leuzinger U, Schibler J (eds) Die jungsteinzeitliche Seeufersiedlung Arbon-Bleiche 3: Umwelt und Wirtschaft. Amt für Archäologie des Kantons Thurgau, Frauenfeld, pp 327–350

Lake MW (2015) Explaining the past with ABM: on modelling philosophy. In: Wurzer G, Kowarik K, Reschreiter H (eds) Agent-based modeling and simulation in archaeology. Springer, Cham, pp 3–35

Land Salzburg (2018) Bodenfunktionsbewertung Land Salzburg. Resource document. www.data.gv.at. https://creativecommons.org/licenses/by/3.0/at/deed.de. Accessed 31 Oct 2018

Lang G (1994) Quartäre Vegetationsgeschichte Europas: Methoden und Ergebnisse. Fischer, Jena

Leibundgut H (1993) Europäische Urwälder: Wegweiser zur naturnahen Waldwirtschaft. Haupt, Bern

Lenk E, Kenk G (2007) Langfristiges Wachstum Schwarzwälder Plenterwälder. AFZ-Der Wald 3:132–135

Louwagie G, Langohr R (2005) Relevance of archaeological experiments on crop productivity for evaluating past land-use systems. In: Meyer M, Wesselkamp G (eds) Zu den Wurzeln europäischer Kulturlandschaft. Theiss, Stuttgart, pp 57–66

Luley H (1992) Urgeschichtlicher Hausbau in Mitteleuropa. Habelt, Bonn

Magny M, Bégeot C, Guiot J et al (2003) Contrasting patterns of hydrological changes in Europe in response to Holocene climate cooling phases. Quat Sci Rev 22(15–17):1,589–1,596

Maier U (1999) Agricultural activities and land use in a Neolithic village around 3900 B.C.: Hornstaad Hörnle I A, Lake Constance. Germany. Veget Hist Archaeobot 8:87–94

Maier U (2004) Archäobotanische Untersuchungen in jung- und endneolithischen Moorsiedlungen am Federsee. In: Köninger J, Schlichtherle H (eds) Ökonomischer und ökologischer Wandel am vorgeschichtlichen Federsee. Archäologische und naturwissenschaftliche Untersuchungen, Janus, Freiburg, pp 71–159

Maier U (2015) Degersee I und II: Ergebnisse der archäobotanischen Untersuchungen. In: Mainberger M, Merkt J, Kleinmann A (eds) Pfahlbausiedlungen am Degersee. Theiss, Darmstadt, pp 303–330

Maier U, Vogt R, Ahrens M (2001) Siedlungsarchäologie im Alpenvorland VI. Botanische und pedologische Untersuchungen zur Ufersiedlung Hornstaad-Hörnle I A. (Forschungen und Berichte zur Vor- Frühgeschichte in Baden-Württemberg 74). Theiss, Stuttgart

Mainberger M, Merkt J, Kleinmann A (eds) (2015) Pfahlbausiedlungen am Degersee: Archäologische und naturwissenschaftliche Untersuchungen. Theiss, Darmstadt

Mainberger M, Baum T, Ebersbach R et al (2019a) New perspectives on archaeological landscapes in the south-western German Alpine foreland—first results of the BeLaVi Westallgäu Project. (EAA monograph series "Themes in contemporary archaeology"). Routledge, London

Mainberger M, Baum T, Ebersbach R et al (2019b) Eine neue steinzeitliche Fundlandschaft. Beyond lake villages - Landschaftsarchäologische Untersuchungen im Westallgäuer Hügelland, Theiss, Darmstadt

Mainberger M, Baum T, Ebersbach R, Gleich P, Hesse R, Kleinmann A, Maier U, Merkt J, Million S, Nelle O, Stephan E, Schliechterle H, Vogt R, Wick L (forthcoming) New perspectives on archaeological landscapes in the south-western German alpine foreland—first results of the BeLaVi Westallgäu project. In: Hafner A, Dolbunova E, Mazurkevich A, Pranckenaite E (eds) Settling waterscapes in Europe: the archaeology of Neolithic and Bronze Age pile-dwellings. Propylaeum, Heidelberg

Maise C (1998) Archäoklimatologie - Vom Einfluss nacheiszeitlicher Klimavariabilität in der Ur- und Frühgeschichte. Jahrb Schweiz Gesell Ur- und Frühgesch 81:197–235

Maurer J (2014) Die Mondsee-Gruppe: Gibt es Neuigkeiten? Ein allgemeiner Überblick zum Stand der Forschung. Resource document. https://www.academia.edu/6830310/J._Maurer_Die_Mondsee-Gruppe_Gibt_es_Neuigkeiten_Ein_allgemeiner_Überblick_zum_Stand_der_Forschung._Vorträge_des_32._Niederbayerischen_Archäologentages_2014_145-190?auto=download. Accessed 12 Dec 2018

Mauri A, Davis B, Kaplan J et al (2015) The climate of Europe during the Holocene: a gridded pollen-based reconstruction and its multi-proxy evaluation. Quat Sci Rev 112:109–127

Menotti F (ed) (2004) Living on the lake in prehistoric Europe: 150 years of lake dwelling research. Routledge, London

Menotti F, O'Sullivan A (eds) (2013) The Oxford handbook of wetland archaeology. Oxford University Press, Oxford

Miedaner T, Longin F (2012) Unterschätzte Getreidearten. Einkorn, Emmer, Dinkel & Co. Agrimedia. Erling Verlag GmbH & Co. KG, Clenze

Million S, Billamboz A (2015) Bauen mit Esche. Dendroarchäologische Untersuchungen in den neolithischen Ufersiedlungen des Degersees. In: Mainberger M, Merkt J, Kleinmann A (eds) Pfahlbausiedlungen am Degersee: Archäologische und naturwissenschaftliche Untersuchungen. Darmstadt, Theiss, pp 285–330

Müller L, Schindler U, Behrendt A, Eulenstein F, Dannowski R (2007) The Muencheberg Soil Quality Rating (SQR): field manual for detecting and assessing properties and limitations of soils for cropping and grazing. Report, Leibniz-Zentrum für Agrarlandschaftsforschung (ZALF), Müncheberg

Nendel C, Berg M, Kersebaum KC et al (2011) The MONICA model: testing predictability for crop growth, soil moisture and nitrogen dynamics. Ecol Model 222:1,614–1,625

Nilsson SG, Niklasson M, Hedin J, Aronsson G, Gutowski J, Linder P, Ljungberg H, Mikusinksi G, Ranius Tl (2002) Densities of large living and dead trees in old-growth temperate and boreal forests. For Ecol Manag 161:189–204

Pazeller A (2000) Digitale Bodeneignungskarte der Schweiz. Resource document. https://opendata.swiss/de/perma/843de9c9-6feb-4577-ab3b-e4fb62a9c56a%40bundesamt-fur-landwirtschaft-blw. Accessed 31 Oct 2018

Perreault C, Brantingham PJ (2011) Mobility-driven cultural transmission along the forager–collector continuum. J Anthropol Archaeol 30:62–68

Pétrequin P (1991) Construire une maison 3000 ans avant J.-C. Le lac de Chalain au néolithique. Edition Errance, Paris

Pillonel D (2007) Technologie et usage du bois au Bronze final. (Hauterive-Champréveyres 14). Edition du Ruau, Neuchâtel

Pohl H (2019) Bericht zur unterwasserarchäologischen Grabung Weyregg II / Attersee 2017. Bericht Teil B. (Fundberichte aus Österreich 56). Berger, Wien

Poulton P (2006) Rothamsted research: guide to the classical and other long-term experiments, datasets and sample archive. Lawes Agricultural Trust, Harpenden

Premo LS (2014) Cultural transmission and diversity in time-averaged assemblages. Curr Anthropol 55:105–114

Remmert H (1991) Das Mosaik-Zyklus-Konzept und seine Bedeutung für den Naturschutz: Eine Übersicht. Laufen Semin 5(91):5–15

Rey F, Gobet E, van Leeuwen JFN et al (2017) Vegetational and agricultural dynamics at Burgäschisee (Swiss Plateau) recorded for 18,700 years by multi-proxy evidence from partly varved sediments. Veget Hist Archaeobot 26:571–586

Rey F, Gobet E, Schwörer C, Wey O, Hafner A, Tinner W (2019) Causes and mechanisms of synchronous succession trajectories in primeval Central European mixed *Fagus sylvatica* forests. J Ecol 107:1,392–1,408. https://doi.org/10.1111/1365-2745.13121

Rösch M, Lechterbeck J (2016) Seven millennia of human impact as reflected in a high resolution pollen profile from the profundal sediments of Litzelsee, Lake Constance region, Germany. Veget Hist Archaeobot 25:339–358

Rösch M, Kleinmann A, Lechterbeck J, Wick L (2014) Botanical off-site and on-site data as indicators of different land use systems: a discussion with examples from Southwest Germany. Veget Hist Archaeobot 23:121–133

Saqalli M, Salavert A, Bréhard S, Bendrey R, Vigne J-D, Tresset A (2014) Revisiting and modelling the woodland farming system of the early Neolithic Linear Pottery Culture (LBK), 5600–4900 B.C. Veget Hist Archaeobot 23(Suppl 1):37–50

Schäperclaus W (1936) Eine neue Klasseneinteilung für die Naturalroherträge mitteleuropäischer Binnenseen. Z Fisch 34(8)

Schibler J (2006) The economy and environment of the 4th and 3rd millennia BC in the northern Alpine foreland based on studies of animal bones. Environ Archaeol 11:49–64

Schibler J, Jacomet S (2010) Short climatic fluctuations and their impact on human economies and societies: the potential of the Neolithic lake shore settlements in the Alpine foreland. Environ Archaeol 15:173–182

Schibler J, Hüster-Plogmann H, Jacomet S, Brombacher C, Gross-Klee E, Rast-Eicher A (1997) Ökonomie und Ökologie neolithischer und bronzezeitlicher Ufersiedlungen am Zürichsee: Ergebnisse der Ausgrabungen Mozartstrasse, Kanalisationssanierung Seefeld. AKAD-Pressehaus und Mythenschloss in Zürich, FO-Fotorotar, Egg bei Zürich

Schott C (1936) Landnahme und Kolonisation in Canada am Beispiel Südontarios. Universität Kiel, Kiel

Schwörer C, Henne PD, Tinner W (2014) A model-data comparison of Holocene timberline changes in the Swiss Alps reveals past and future drivers of mountain forest dynamics. Glob Chang Biol 20:1,512–1,526. https://doi.org/10.1111/gcb.12456

Seppelt R, Müller F, Schröder B, Volk M (2009) Challenges of simulating complex environmental systems at the landscape scale: a controversial dialogue between two cups of espresso. Ecol Model 220:3,481–3,489

Spangenberg JE, Jacomet S, Schibler J (2006) Chemical analyses of organic residues in archaeological pottery from Arbon Bleiche 3, Switzerland—evidence for dairying in the late Neolithic. J Archaeol Sci 33:1–13

Stapfer R, Hafner A, Francuz J (2019) Struktur und Dynamik neolithischer Seeufersiedlungen. Beispiele aus Sutz-Lattrigen (Bielersee, Kanton Bern, Schweiz) zwischen 3900 und 3400 v. Chr. In: O'Neill A, Perschke R, Pyzel J (eds) Siedlungsstrukturen im Neolithikum - Zwischen Regel und Ausnahme. Fokus Jungsteinzeit. Berichte der AG Neolithikum. Welt und Erde Verlag, Kerpen-Loogh, pp 127–150

Stephan E (2015) Die Knochenfunde aus den Seeufersiedlungen im Degersee. In: Mainberger M, Merkt J, Kleinmann A (eds) Pfahlbausiedlungen am Degersee. Theiss, Darmstadt, pp 345–397

Strobel M (2000) Die Schussenrieder Siedlung Taubried I. Theiss, Darmstadt

Styring A, Maier U, Stephan E, Schlichtherle H, Bogaard A (2016) Cultivation of choice: new insights into farming practices at Neolithic lakeshore sites. Antiquity 90(349):95–110

TFZ Bayern (2016) Durchschnittlicher Holzzuwachs in Bayern. https://www.tfz.bayern.de/festbrennstoffe/brennstoffe/035110/index.php. Accessed 19 March 2019

Tinner W, Lotter AF, Ammann B, Conedera M, Hubschmid P, van Leeuwen JFN, Wehrli M (2003) Climatic change and contemporaneous land-use phases north and south of the Alps 2300 BC to 800 AD. Quat Sci Rev 22:1,447–1,460

Tinner W, Conedera M, Ammann B, Lotter AF (2005) Fire ecology north and south of the Alps since the last ice age. Holocene 15:1,214–1,226

Turcek F (1971) On vertebrate secondary production of forests. In: UNESCO, proceedings of Brussels symposium on productivity of forest ecosystems, pp. 379–384. Resource document. https://unesdoc.unesco.org/images/0001/000153/015360mo.pdf. Accessed 1 Nov 2018

Ustaoglu B (2012) The effect of climatic conditions on hazelnut (*Corylus avellana*) yield in Giresum (Turkey). Resource document. https://dspace.marmara.edu.tr/bitstream/handle/11424/2685/733-1425-1-SM.pdf?sequence=1&isAllowed=y. Accessed 25 Oct 2018

Wey O (2012) Die Cortaillod-Kultur am Burgäschisee. Stämpfli, Bern

Wick L (2015) Palynologische on-site Untersuchungen an Kurzprofilen vom Siedlungsplatz Degersee 1. In: Mainberger M, Merkt J, Kleinmann A (eds) Pfahlbausiedlungen am Degersee. Theiss, Darmstadt, pp 331–344

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

Wilensky U, Rand W (2015) An introduction to agent-based modeling: modeling natural, social, and engineered complex systems with NetLogo. MIT Press, Cambridge

Wu J, Mohamed R, Wang Z (2011) Agent-based simulation of the spatial evolution of the historical population in China. J Hist Geogr 37:12–21

Wurzer G, Kowarik K, Reschreiter H (eds) (2015) Agent-based modeling and simulation in archaeology. Springer, Basel

Zeeb A (1996) Der neue Siedlungstyp: Frühjungneolithische Dorfanlagen in Südwestdeutschland. In: H. Beier (ed.), Studien zum Siedlungswesen im Jungneolithikum. Beier & Beran, Weissbach