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Modelling landscape transformation at the Chalcolithic Tripolye mega-site of Maidanetske (Ukraine): Wood demand and availability

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Abstract

Wood was a crucial resource for prehistoric societies, for instance, as timber for house construction and as fuel. In the case of the exceptionally large Chalcolithic Tripolye 'mega-sites' in central Ukraine, thousands of burnt buildings, indicating huge population agglomerations, hint at such a massive use of wood that it raises questions about the carrying capacity of the sensitive forest-steppe environment. In this contribution, we investigate the wood demand for the mega-site of Maidanetske (3990–3640 BCE), as reconstructed based on wood charcoal data, wood imprints on daub and the archaeo-magnetometry-based settlement plan. We developed a regional-scale model with a fuzzy approach and applied it in order to simulate the potential distribution and extent of woodlands before and after Chalcolithic occupation. The model is based upon the reconstructed ancient land surface, soil information derived from cores and the potential natural woodland cover reconstructed based on the requirements of the prevailing ancient tree species. Landscape scenarios derived from the model are contrasted and cross-checked with the archaeological empirical data. We aim to understand whether the demand for wood triggered the site development. Did deforestation and consequent soil degradation and lack of resources initiate the site's abandonment? Or, alternatively, did the inhabitants develop sustainable woodland management strategies? Starting from the case study of Maidanetske, this study provides estimates of the extent of human impact on both carrying capacity and landscape transformations in the sensitive transitional forest-steppe environment. Overall, the results indicate that the inhabitants of the Chalcolithic site did not suffer from a significant shortage in the wood resource at any time of inhabitation in the contexts of the different scenarios provided by the model. An exception is given by the phase of maximum house construction and population within a scenario of dry climatic conditions.

Keywords

charcoal, forest-steppe, imprints, landscape models, multi-proxy, timber, Trypillia

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Introduction

Research goal and frame

From an ecological perspective, permanent settlements exert a significant and sometimes irreversible impact on their environment, which is further conditioned by the range of demands placed on vegetation, for example, for timber, fuel, fodder and pasture. The Tripolye sites in the forest-steppe region of central Ukraine, whose nature is currently under intensive investigation, represent by far the largest concentration of population in European prehistory. Maidanetske, in the Cherkasy Province, is one of these Tripolye 'mega-sites'. Wood, a fundamental element of the natural environment, is considered a very sensitive resource in the economies of prehistoric populations, particularly in the presence of a stable settlement system (e.g. Asouti and Austin, 2005; Cremaschi, 2014). During the Chalcolithic, in temperate regions in Europe, woodland was extensive and wood is usually considered to have been a fundamental resource. The history of woodland was usually linked, for instance, to the expansion of arable land and the construction of dwellings. This study focuses in particular on the extent of woodland in the landscape around Maidanetske and on wood use during

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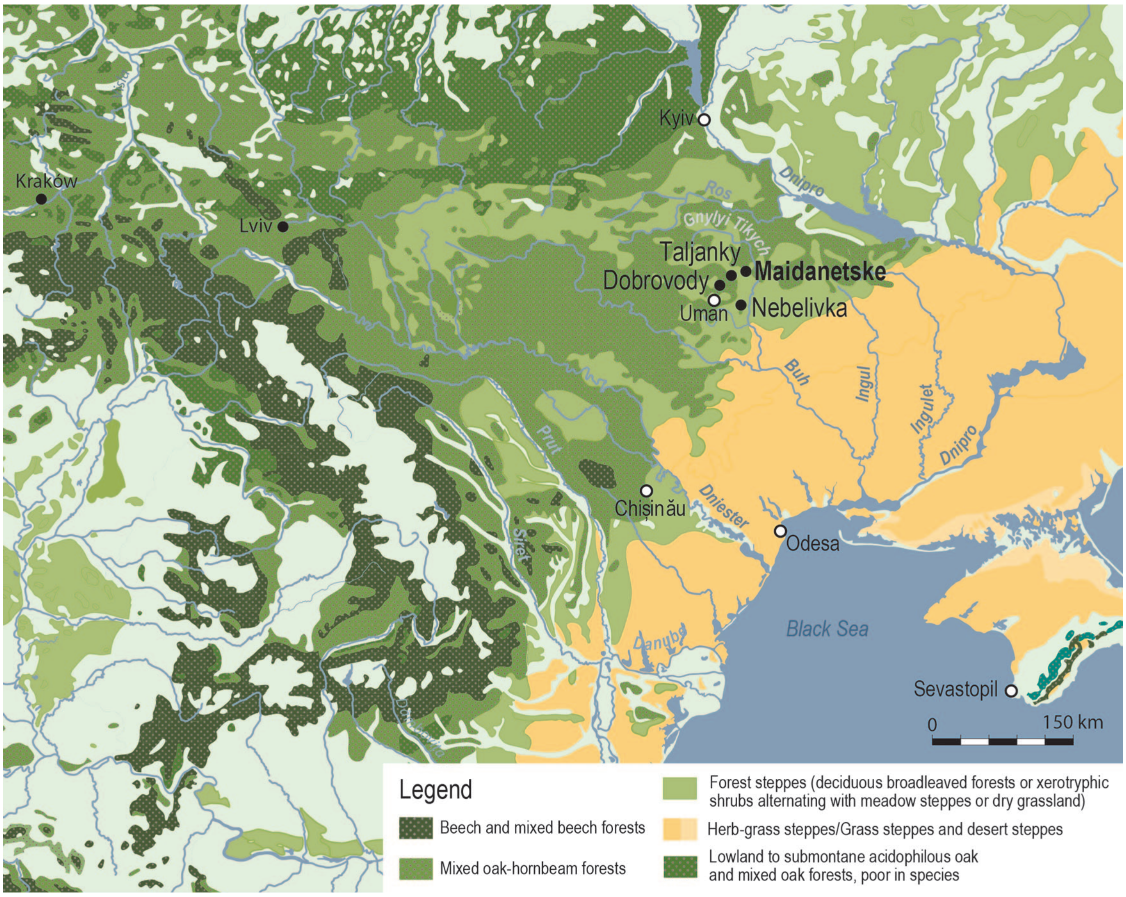

Figure 1. Map showing the location of the site and the potential vegetation in the study region. Graphic K. Winter (CAU Kiel).

the site development. Did the availability of wood play a determining role for the sustainability of the extreme population conglomeration occurring at the Tripolye mega-site of Maidanetske? How far did wood demand exhausted the natural resource in the landscape and interfere with prolonged settlement occupation? Different uses of wood can be envisaged for Tripolye archaeological sites. To trace these uses, we investigate direct sources of information, in the form of analysis of wood charcoal from archaeological stratigraphy, and indirect sources of information, in the form of dimensions of wood imprints in the daub from burnt houses and the representation of wood in ceramic models of houses. Two further sources of information to compare with the archaeological data are experimental archaeology and ethnographies. Experimental archaeology provides us with data on the use of wood during experimental reconstruction and burning of Tripolye dwellings and during experimental firing of ceramic vessels in kilns for pottery production. Ethnographic sources provide us with data for, for example, estimating the amount of wood needed in domestic activities. The resulting estimates of minimum/maximum amount of wood required by the population in Maidanetske for living are then inserted into a landscape model. The model was developed starting from information on the current environmental conditions in the area around Maidanetske (vegetation, climate, topography, pedology), strengthened by archaeological, archaeobotanical, zooarchaeological and pedological data, as detailed in the following sections. Faunal and an updated archaeobotanical datasets are used to assess subsistence economy, for which an evaluation of arable land is pursued through ethnographic comparisons according to previous studies (Ohlrau, 2015 and references therein).

In particular, we focus on the impact that the demand for wood had on tree cover in the landscape surrounding Maidanetske. Do we have indications for extensive deforestation? Would the consequent soil degradation through erosion and lack of resources have played a role in triggering the site's abandonment? Alternatively, was the demand for wood not critical? Can we trace a relatively sustainable wood use and identify woodland management strategies carried out by the site's inhabitants? To answer these questions, landscape scenarios derived from the model are contrasted and cross-checked with the empirical archaeological data.

Environmental setting of Maidanetske

Maidanetske is situated in central Ukraine (48°48′N, 30°38′E), in the Talne Rajon of Cherkasy Province. The topography of this area is characterized by a mosaic of Loess-covered plateaus dissected by valleys of different dimensions. The local relief gradient from the archaeological site on the plateau down to the valley of the Taljanky River is approximately 15 m. Today, the riverbed is dissected by barrages, giving it the property of a number of reservoirs. Investigations on soil and slope deposits at the site of Maidanetske revealed the presence of two different Holocene soils (Kirleis and Dreibrodt, 2016). Plateaus and slopes are covered with loess, deposited during the last glaciation. At a mid-slope position close to the site, a brownish Cambisol was found, buried below slope deposits (colluvial sediments). The colluvial layers, deposited no earlier than during the Bronze Age (ca. 2000 BCE), were derived from the Chernozems that covered the surface of the site in a layer of varying thickness (30–50 cm). Traces of erosion of the archaeological contexts are not detectable in nearby soil profiles, suggesting that the Chernozems developed after the site was abandoned. These steppe soils probably formed because of a combination of climate change and the creation of an open landscape during agricultural land use. Detailed sediment and soil investigation of profiles from the valley fills is ongoing.

The potential natural vegetation of the region in recent times (Figure 1) corresponds the ecotone of forest-steppes, a borderland with patchy forest stands of broadleaved woodland, riverine wetland forest and natural openings characterized by dry grassland vegetation (Feurdean et al., 2015; Kuzemko et al., 2014, 2016; Molnár et al., 2012). The updated archaeobotanical record and the new zooarchaeological data from Maidanetske, providing on-site information on past environment, are introduced in the next sections. Today, large-scale, intensive agricultural fields cover the site. Semi-natural sectors are present in the form of wetlands at the river's edge and hedges that subdivide the fields, where the trees planted during Soviet times show natural regeneration, for example, of oak.

The recent climate is humid continental (Dfb climate class according to Köppen and Geiger, 1939) and is characterized by a distinct seasonality of warm summers and cold but wet winters. The mean annual temperature is 7.1°C and the mean annual precipitation is 616 mm (http://de.climate-data.org/).

Reviews of the Holocene palaeoclimate of the North Pontic forest-steppe region have revealed the scarcity of data on palaeoenvironmental conditions during the fourth millennium BCE (e.g. Kirleis and Dreibrodt, 2016; Mitusov et al., 2009). Based on pollen data from southeastern Ukraine, Gerasimenko (1997) reported a dry period between ca. 4000 and 3500 cal. BCE. Based on pollen, plant macrofossil and testate amoeba datasets from three southwestern Russian peatlands, Novenko et al. (2016) suggest that a warm, dry phase occurred 5000–2800 cal. BCE and that steppe vegetation was widely distributed in the patchy forest-steppe landscape. Based on an analysis of buried soils, Demkina et al. (2003) report dry conditions for the period 4000–3000 cal. BCE. Based on palaeo-hydrological data, Sidorchuk et al. (2012) attested extremely low river runoff of the Don and Dnieper Rivers due to reduced precipitation during the so-called Holocene 'climate optimum' (ca. 4000 BCE) compared with today.

In a recent contribution, Harper (2017) discusses the coinciding of Holocene rapid climate change (RCC) events with developments in Tripolye demography and settlement systems. Since palaeo-environmental records of these RCC events are absent in the research region, Harper carried out a palaeoclimate reconstruction, based on a modern analogue technique, which considers pollen records from a very broad area – including parts of Romania, Ukraine and Hungary – that encompasses the current forest-steppe ecozone. Harper's reconstruction shows dry conditions ca. 4000–2000 cal. BCE (Harper, 2017). However, because the pollen records used by Harper are peripheral to the Tripolye core area (e.g. Kremenetski, 1995), and because the forest-steppe is a heterogeneous ecological transition zone, the modelled climatic conditions may be controversial for our study area.

Study site

The site of Maidanetske

Between about 4200–4100 and 3600 BCE, a unique agglomeration of huge settlements with sizes up to 320 ha emerged in the Southern Bug–Dnieper interfluve in central Ukraine. Very distinct, concentric spatial layouts; a central open space; public buildings; and thousands of mostly burned dwellings characterize these Chalcolithic settlements, labelled Tripolye mega-sites. For at least 100 years, these sites have been under intensive archaeological and remote sensing investigation, by means of aerial photography, extensive archaeo-magnetic surveys and several large-scale excavations (Müller et al., 2016; Videiko and Rassmann, 2016). In Tripolye mega-sites, highly developed and standardized ceramic vessels and kilns of a technologically advanced type indicate high levels of craft specialization (Korvin-Piotrovsky et al., 2012). Ceramic models of cattle-drawn sledges suggest the use of new transportation techniques that probably favoured such population agglomeration (Müller, 2013; Müller et al., 2016; Müller and Pollock, 2016; Shatilo, 2017).

The site of Maidanetske itself, with a size of about 200 ha, represents one of the largest mega-sites of the Thomashovka regional group, dating to an advanced stage of Tripolye development, in the first half of the fourth millennium BCE.

Site development and number of contemporaneous houses

The site chronology is based on 86 AMS-radiocarbon dates obtained by systematic sampling of various contexts throughout the settlement (Müller et al., 2016, 2017, in press). An in-depth evaluation of these samples and contexts, followed by Bayesian modelling, suggests that Tripolye activity at Maidanetske ranges from 3990 to 3640 cal. BCE and that the dwelling activity ranges from 3935 to 3640 cal. BCE (Ohlrau, 2019). This duration of occupation of 200–350 years suggested for Maidanetske (Müller et al., 2016; Ohlrau, 2019) is significantly longer than what assumed by earlier chronological models for Tripolye sites, which suggested a very short occupations of much less than 100 years.

So far, 82% of the site has been surveyed by state-of-the-art archaeomagnetic methods, revealing the presence of 1758 clearly burnt and 496 less burnt or less eroded buildings. The remaining parts were covered by the previous survey, conducted by Dudkin (1978). By comparing the results of the previous and current surveys, the total number of buildings can be estimated. The ratio between anomalies that were detected by the Dudkin survey and those that were not detected was determined to be 1.85:1 for assured and 4.02:1 for potential features (Ohlrau, 2015: 65). Thus, given that the Dudkin survey detected 249 definite and 21 potential anomalies, we can expect 461 clearly burnt and 84 less burnt/less eroded buildings for the remaining survey areas.

In addition, approximately 10 ha of the easternmost part of the settlement have been lost to a modern water reservoir. To estimate the number of buildings lost, we extrapolated the building density per hectare of the eastern slope, surveyed in 2016 (12 ha), to the 10 ha that were lost to the reservoir. The building density for this eastern slope part is 10.3 buildings/ha for burnt and 3 buildings/ha for less burnt or less eroded buildings. Accordingly, we expect that around 100 burnt and 30 less burnt or eroded buildings were lost to the reservoir. Taking the calibrated Dudkin data and the expected number of buildings lost in the easternmost part of the settlement into account, we expect a total of 2932 buildings for Maidanetske (Table 1 of the Supplementary Material, available online).

To estimate the number of potentially contemporaneous dwellings out of this total, we used the calibrated and modelled *termini ad quos* radiocarbon dates of 19 house contexts (Ohlrau, 2019). The construction activity shows a peak between 3765 and 3710 cal. BCE, with 10 intervals overlapping, resulting in 1542 (52.6%) out of 2932 (100%) buildings occupied contemporaneously (phase 3; Figure 2).

Wood as timber and as fuel in Tripolye sites

Wood as timber. Tripolye house remains of the Thomashovka regional group show specific architectural characteristics and a high degree of standardization (Chernovol, 2012). The most striking architectural element is a massive, originally elevated platform, consisting of a wooden sub-construction made of split wood planks or half beams laid transversely to the longitudinal axis of the buildings (e.g. Korvin-Piotrovskiy et al., 2012; Müller et al., 2013: 36). This platform was usually covered by a 10- to 30-cm-thick layer of chaff-tempered daub, after which a floor of un-tempered sediment was levelled on top of it. The walls of the upper storey were most likely made of vertical beams and

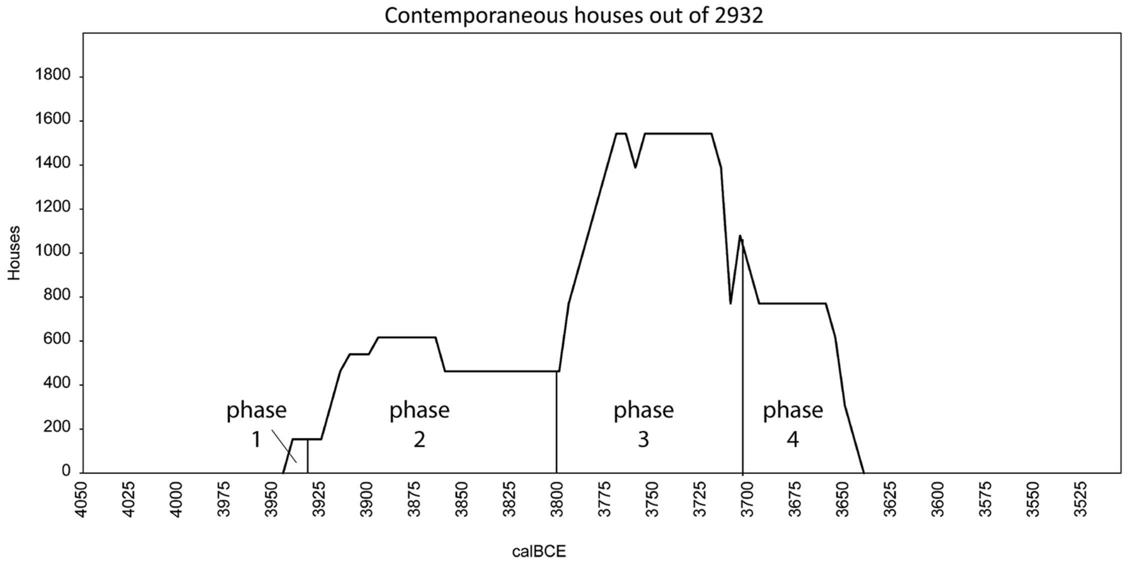

Figure 2. Number of potentially contemporaneous buildings per time interval based on the 68.2% probability distribution of calibrated and modelled *terminus ad quem* radiocarbon dates. Four archaeological phases can be detected.

horizontal timbers and perhaps occasionally wattle. The rounded roof was constructed using purlins, the endings of which can be identified over the walls in several house models (Shatilo, 2016). Since most of the regularly observed permanent elements, such as clay installations, and inventory items, such as vessels, of Tripolye houses are situated on top of the platform, it is argued that domestic activities mainly took place there (Chernovol, 2008, 2012). However, more rarely, vessels and installations are found also below this platform. Whether this key structural element may have existed in regular, two-storey houses or only in slightly elevated buildings is still under debate. The considerable weight on the platform is also under debate (cf. Chabanyuk, 2008); the most problematic issue concerns the nature of the structure supporting the platform, which would also influence calculations about the wood demand for house building.

The platform could have been supported by wooden blocks from foundation beams (Chapman et al., 2014; Korvin-Piotrovskiy and Shatilo, 2008), block constructions (Chabanyuk, 2008) or posts, none of which have been attested thus far in the archaeological record because of taphonomic disturbance (Ohlrau, 2019).

Wood as fuel for the intentional burning of houses. There is broad agreement about the deliberate character of the burning of Tripolye dwellings due to the regular occurrence of burnt dwellings. The majority of scholars assume that the houses were burnt after their abandonment (Chabanyuk, 2008; Chapman, 2017; Kruts, 2003). An alternative explanation views the phenomenon as part of the construction process, with fire being used to obtain higher stability of the house (Kolesnikov, 1993: 63–73; Passek, 1949). There is disagreement on whether fuel needs to be added in order to obtain results similar to those seen in the archaeological record and, if so, how much fuel (Cotiugă, 2009; Kruts, 1989). Based on experimental work, Johnston et al. (2018) suggest that additional fuel is needed, totalling 30 m^3 of wood per house. Harper (2017: 46), on the other hand, posits that there is no need for additional fuel to achieve the burning of Tripolye houses because of the advanced degree of dryness that is characteristic of older houses, compared with the freshly reconstructed house of the experiment. Due to such discrepancies, we proposed a large margin in the calculation of wood used for house burning (see Table 3). New, ongoing geophysical and geoarchaeological investigations focus on burnt houses from Maidanetske in the attempt to better understand firing dynamics and their archaeological signals (Pickartz et al., in press).

Wood as fuel for domestic activities. The consumption of firewood is highly variable in different cultural contexts, depending mostly on climate and weather conditions. These conditions influence the availability of wood and impact the form of subsistence adaptation, which determines the firewood aim (Asouti and Austin, 2005). The construction technique of the houses, their size and the number of inhabitants also influence the amount of firewood consumed (Rosenstock, 2009: 184). Ethnographic and archaeological data suggest that, besides wood from living trees, dry deadwood was a primary source of firewood (Asouti and Austin, 2005). Moreover, other fuel, such as herbivore dung, may have been used, and, in cases of shortage, increased effort invested in fuel acquisition might have resulted in an expansion of the catchment area (Agea et al., 2010). Being aware of these variables and of the difficulty of determining them with the record at hand, in this work we quantify the demand of firewood per person per year for domestic activities based on ethnographic sources, resulting in a range of 5–10 m^3/house with five persons (Rosenstock, 2009: 184).

Wood as fuel for pottery production. In addition to the demand for fuel for everyday domestic activities, there would also have been a demand for fuel for pottery production. In a standard Tripolye house (e.g. houses 44 and 54), ca. 50–70 vessels, in some cases of considerable size, were found (Müller et al., 2017). In an experimental case study in Germany using a kiln of similar size to Tripolye kilns, 1.5 m^3 of wood was required for the firing of 150 vessels (Dušek et al., 1984). These values are taken as a baseline in this study.

Methods

Charcoal and macrobotanical analyses

Systematic sampling for archaeobotanical investigations was applied on the excavations at Maidanetske in 2013–2016. Flotation was carried out in the field on 10-L soil samples, using sieves with a mesh width of 300 µm. Samples were then air-dried in the laboratory, after which microscope work was carried out.

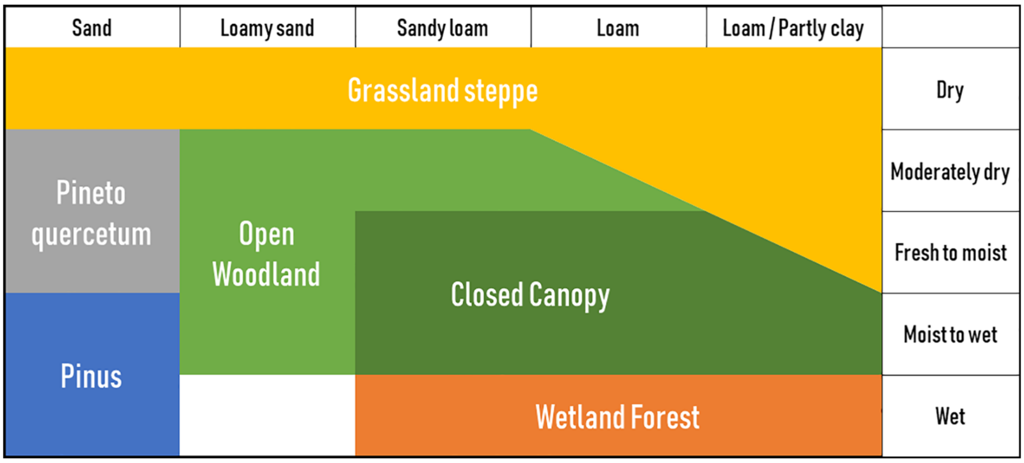

Figure 3. Ecogram of vegetation dependencies with respect to soil texture and moisture, based on information from Horvat et al. (1974) and Walter and Breckle (1997).

Taxonomic identification of charcoal pieces down to the genus or species level was carried out in the laboratory of the Laboratoire Interdisciplinaire des Environnements Continentaux (LIEC) at Université de Lorraine, with an incident light microscope at 100×, 200× and 500× magnification, using a reference collection and wood anatomy atlases (Greguss, 1955, 1959; Schweingruber, 1990). The 66 charcoal samples, which originated from eight different excavation trenches, yielded on average 15 charcoal fragments per sample.

Estimates of wood used for house construction and for fuel

During three excavation campaigns, from 2013 to 2016, daub from burnt houses was systematically documented (e.g. Müller et al., 2017: 29). This documentation included the mapping of daub fragments and the application of a daub typology based on their material properties and on the direction and dimension of imprints of structural (wooden) elements. This mapping and typing enabled us to distinguish between imprints of log wood and split wood. To address the questions posed at the beginning of this paper, we used the diameter of logs and the width of split wood planks. The latter measurements provide only a minimum diameter of the wood pieces that were used. Conclusions drawn from these sources have been tested against data obtained from the experimental construction of two-storey Tripolye houses as carried out in Legedzyne (Uman) in 2003 (Chabanyuk, 2008). During these experimental reconstructions, 20 m^3 of wood was needed for a two-storey house; the construction of the lower storey, in block construction, required 12 m^3 of that total (Chabanyuk, 2008). Another experiment, in Nebelivka (Johnston et al., 2018), where the sub-construction had foundation beams, required similar amounts of timber, between 12.5 m^3 (+1.38 m^3 for wattle) for a single-storey house and 23.29 m^3 (+2.72 for wattle) for a two-storey house.

Our estimate of the amount of firewood required is based on experimental and ethnographic data. The demand for firewood per person per year for domestic activities is assumed to have been between 5 and 10 m^3 of wood/house with five people (Rosenstock, 2009: 184). The production of 150 vessels in one round in a kiln is assumed to have required 1.5 m^3 of wood (Dušek et al., 1984).

Models for landscape reconstruction

The modelling of the potential vegetation cover in the Maidanetske area is based on a combination of an informed description of the vegetation, similar to the approach of Ellenberg and Leuschner (2010), and the fuzzification of the recent landscape features. Ellenberg and Leuschner (2010) provide ecological diagrams that show which tree species or plant communities, respectively, prevail depending on two main environmental gradients, that is, the degree of acidification and the amount of moisture in the soil. In a similar approach, we defined six potential main vegetation types and their relationship to soil texture and moisture based on modern vegetation descriptions by Horvat et al. (1974), Walter and Breckle (1997) and Doniță and Karamyševa (2003) (Figure 3).

The diagram does not contain absolute (crisp) descriptions with sharp boundaries to which the acidification of the soil can be fixed exactly. Accordingly, the spatial determination of the fulfilment of the parameters should be based on a fuzzified view of the environment. In addition, there are limited data available for the larger study area with regard to soil texture and average moisture content of the soil. To handle this, we created a fuzzy rule–based system, using the R package FuzzyLandscapes (Hamer and Knitter, 2018). To proceed, it was necessary, first, to implement and process data available on a large scale for the study area, such as a TanDEM-X elevation model (Rizzoli et al., 2017), used to obtain information about the potential of the soil to higher degrees of wetness. The applicability of this data set was then verified by comparing it with high-resolution elevation information derived from drone survey, which is only available for a small part of the study area. A correlation of 0.98 and a root mean square error (RMSE) of 1.76 m resulted from this comparison, which is persuasive in relation to the TanDEM-X dataset's applicability. Next, the wetness degree was derived by the elevation model using the Saga Wetness Index (Böhner et al., 2002). It extracts the potential moisture of the soil based on a catchment area calculation of the elevation raster (Böhner et al., 2002; Olaya and Conrad, 2009). We also took the soil texture into account for the modelling approach. The content of sand, silt and clay is available from the global SoilGrids system at 250 m resolution (Hengl et al., 2017). These data were checked in the field through test trenches. Soils were classified according to the German soil nomenclature and then transformed to the American classification method used by SoilGrids using the R package *soiltexture* (Moeys, 2018) to allow an approximate comparison (see Figure 1 in Supplementary Material, available online).

In the modelling process, these crisp data sets were fuzzified. For this purpose, absolute data, such as the percentage sand content, were assigned to statements, such as 'high sand content' or 'moderately dry' conditions, using fuzzificating functions, as shown in Figure 4 for the generation of wetness fuzzy classes.

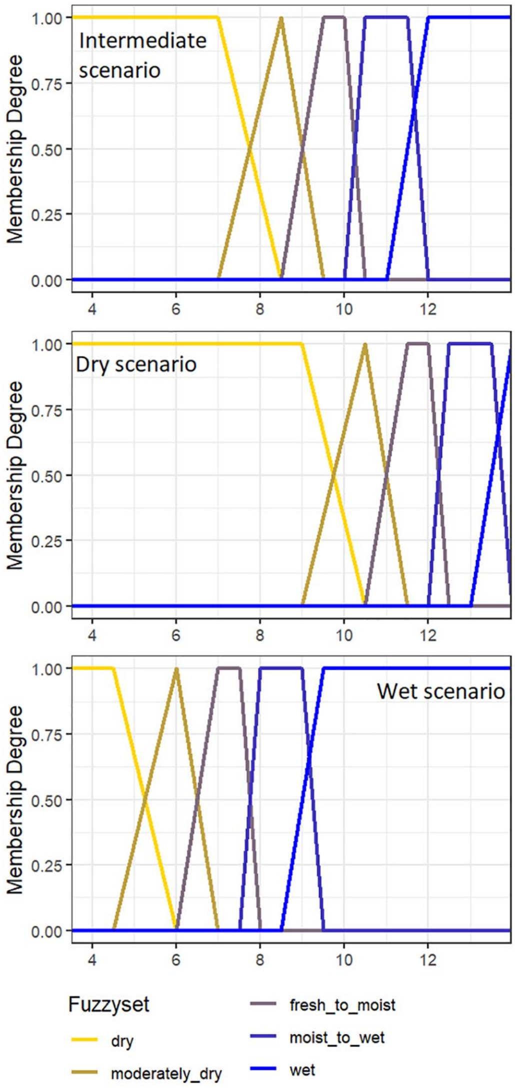

Figure 4. Membership of the fuzzy sets defining the wetness of the soil based on the terrain wetness index for intermediate, dry, and wet scenarios.

We also considered sun exposure, as calculated from the elevation model. North-facing locations were classified as more humid and south-facing locations as drier. A 'North' and a 'South' fuzzy set were calculated. For each grid cell, the membership degree of each wetness class has been reduced by the proportion of membership of the 'North' class and added to the respective wetter class. Conversely, for the 'South' membership, the values were added to the respective drier class. The average of the calculations, weighted by membership degree, resulted in the final wetness membership degrees (see Table 2 of the Supplementary Material, available online). Afterwards, the fuzzy datasets generated were combined according to two rule-based fuzzy systems (Tables 3 and 4 in Supplementary Material, available online). The first one is used to define which locations are of the soil texture types used in diagram 5 of Table 2 (Supplementary Material, available online). The second one is used to define the circumstances under which specific forest types predominantly grow as defined by diagram 5.

Using the R package FuzzyLandscapes, the rules of Tables 3 and 4 can be applied on the spatially available, fuzzified raster datasets and thereby used to calculate the membership degree of each raster cell to the resulting fuzzy sets, such as, for example, *Grassland* or *Closed_canopy*. The datasets are linked together according to the Zadeh (1996) regulations. For example, a *moderately_dry* fuzzy set with a membership degree of 0.4 and a *loam* fuzzy set with a membership degree of 0.6, combined with the operator 'AND', would result in a membership degree of 0.4 for *Open_woodland*. The minimum value of each fuzzy set is selected. Using the operator 'OR' takes the maximum value of both fuzzy sets. The fuzzified grids created in this way can also be defuzzified by the selection of the raster with the highest membership degree for each raster cell, which results in a crisp map of the area. For the grid cells in which several fuzzy sets have the highest membership degrees, all applicable sets were specified.

In a final step, the defuzzified raster is combined with the walking distance calculated using the function *r.walk* of GRASS GIS, which is based on the work of Aitken (1977) and Langmuir (1984). This function calculates, for each grid cell, the time it takes to run to Maidanetske based on the distance, the elevation model and the slope derived from it. It is assumed that the highest walking speed is reached when walking not too steeply downhill. The resulting rasters are fuzzified as well, to define which location is close to Maidanetske. Then, for each of the resulting classes of the diagram, an amount of wood per ha (Table 5 in Supplementary Material, available online) was assumed based upon Schober (1987), who reports the yields of managed forests, including remaining and eliminated tree stocks of different tree species, depending on the age and thinning of the forest stands. Accordingly, two management methods are defined: 'clearcutting' is the sum of the departing and remaining stock, and 'sustainable management' is the remaining stock (Schober, 1987). Based on the data on the wood imprints in Tripolye houses, young trees (⩽30 years) were chosen for the modelling. For *Pinus* and *Alnus*/Wetland forest, the respective yield tables were selected. Open woodland represents the first quartile of the average of *Quercus* and *Fraxinus*, while closed canopy represents the third quartile. A defuzzified cell with multiple maximum fuzzy sets is assumed to produce the average of the wood amount belonging to the vegetation class. The wood amount and the distance dataset were combined, under the assumption that there would have been a higher potential of depleting the wood reserves close to the settlement.

Scenarios were also modelled that reflect drier or moister conditions in the study area. For this purpose, the fuzzification of the wetness index was modified, as is also displayed in Figure 4.

A final step concerned the integration of land use during the site occupation. For this purpose, the estimates of population suggested by the house density in different chronological phases were related to the average agricultural usable area of 0.58 ha per person (Table 3 in Ohlrau et al., 2016: 209). This area was located in potential arable land as a function of the distance from the settlement and thus subtracted from the wood production of the respective grid cell.

Results

The charcoal record from Maidanetske

In total, 980 charcoal fragments were taxonomically identified (see Table 6 of the Supplementary Material, available online). In addition, a total of 111 fragments were not identifiable due to the extremely small size and badly preserved diagnostic features. Percentage values based on a charcoal sum excluding unidentifiable fragments are shown in Figure 5. Overall, the charcoal record at Maidanetske is dominated by ash (*Fraxinus*), which prevails in every trench, followed by deciduous oak (*Quercus*) and elm (*Ulmus*). These broadleaved trees belong to the mixed deciduous oak woodland typical for the forest-steppe area that is natural to the region (Kirleis and Dreibrodt, 2016; Kuzemko et al., 2016). The same taxa were also identified from the neighbouring site of Taljanky (Kruts, 2008). Other taxa are very rarely found, with only willow (*Salix*), indicative for the softwood belt of the riverine

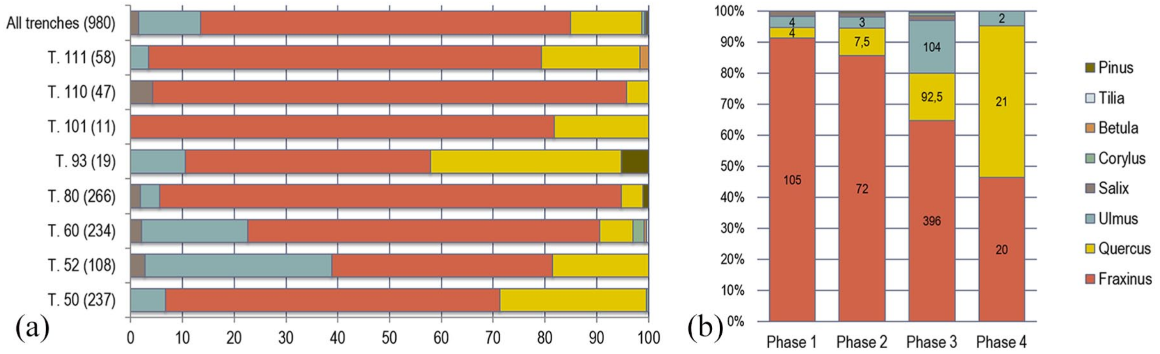

Figure 5. Charcoal assemblages (a) by trench, with the quantity of charcoal fragments used as base for the percentage values shown in parentheses, (b) and by chronological phase, with the average quantities of fragments per taxon per phase shown inside the bars.

woodland that most probably grew alongside the Taljanky River, which borders the site, being recorded in more than two trenches. Birch (*Betula*), hazelnut (*Corylus*) and pine (*Pinus*) were found in just two trenches each, and lime (*Tilia*) in only one sample. The archaeological contexts from which the samples were collected comprise 54 stratified fills of large pits (trenches 50, 52, 60, 80, 93), 11 cultural layers inside dwellings (trenches 101, 110) and a so-called mega-structure, which is different from standard houses (trench 111). The largest number of charcoal fragments was retrieved from trench 80, from pits connected to a kiln for pottery production. In this trench, the highest percentage of ash fragments (over 80%) is attested. Houses, whose stratigraphies are less deep than pit fills, provided less identifiable charcoal than pits, most probably due to the more intense taphonomic disturbance (weathering, bioturbation, ploughing) leading to strong charcoal fragmentation. Although the record is quite homogeneously composed almost exclusively of ash and some oak fragments, when we subdivided the charcoal samples by phase, we observed that phase 3 shows an increased relevance of oak and elm. Concerning the archaeological contexts, phases 1–3 are represented in pits and ditches, while phase 4 is represented in palaeo-soil and cultural layers. However, the sample size for phase 4 is too small to be considered representative. Among phases 1–3 (and 4), the charcoal record seems to vary from very ash-dominated to more mixed assemblages.

To test the statistical significance of this variation, we ran a chi-square test, which resulted in a very low p value (1.698). This result suggests a low probability of random distribution for the trend towards an increased relevance over time of oak and elm. A similar result emerges from the correspondence analysis in Figure 2 of the Supplementary Material, available online.

An updated archaeobotanical record for Maidanetske

Flotation was regularly carried out at Maidanetske in 2013–2016 (Kirleis and Dal Corso, 2016), resulting in a total of 722 macro-remain samples from ca. 6500 L of sediment from 161 features. Thanks to the fine mesh (300 μm), the samples contained not just large crop fruits and seeds but also subfossil threshing remains and small weed seeds and fruits, which included cultivated and wild plants. Altogether, about 4021 charred finds (seeds, fruits, threshing remains, awn fragments, slaggy remains) plus 3478 mineralized fruits of Chenopodiaceae were identified (Table 1). The average find concentration of botanical macro-remains is low, approximately one find per litre of soil, but it is comparable with that of excavations on central European Neolithic sites (Bogaard and Jones, 2007; Kirleis et al., 2012). Due to problematic preservation conditions of the charred remains, most of the identified fragments of cereal caryopses have been attributed to the Cerealia indet. group. The better preserved finds show that in Maidanetske the crop spectrum (Table 1) comprises emmer, barley, einkorn and garden pea as the main cultivars. The samples yielded just one find of lentil. Broomcorn millet, included in an earlier overview (Kirleis and Dal Corso, 2016), has been excluded from the plant list, because a new radiocarbon date on one grain of millet shows that it was an intrusion from the medieval period into the Chalcolithic stratigraphy (Poznan-97625: 1110 ± 30 BP; 2σ, 95.4% probability: AD 879–1013). In general, the Maidanetske finds are in accordance with the expected crop spectrum of Tripolye sites (Kruts, 2008, 2009; Pashkevich, 2014; Pashkevich and Videiko, 2006), although there is no hint of bitter vetch, which is known from Tripolye phases preceding the mega-sites. The only gathered plants in the archaeological plant assemblage from Maidanetske are hazel, a light-demanding tree species, and, possibly, black henbane (*Hyoscyamus niger*), which grows in disturbed areas. In addition to these cultivars, six weeds were identified to the species level. They indicate nutrient rich soils: cleavers (*Galium aparine*), caryopses of brome (*Bromus secalinus*-type), common knotweed (*Polygonum aviculare*), black nightshade (*Solanum nigrum*), many-seeded goosefoot (*Chenopodium polyspermum*) and, most numerous, fat hen (*Ch. album*). Furthermore, there is evidence for the Panicoideae species green foxtail (*Setaria viridis*) and cockspur (*Echinochloa crus-galli*).

Among the wild plants, charred, curled-up awn fragments of feather grass (*Stipa*), characteristic of steppe environments, regularly occur in the samples. Most of these fragments (918 altogether) were found in two trenches (51 and 60), in the uppermost layers of the excavation, covering the archaeological features. A recent radiocarbon date on some awn fragments from a profile confirms that these finds are Chalcolithic in age (Poznan-101976, 5090 ± 40 BP, 2σ: 3969–3794 cal. BCE).

The faunal record of Maidanetske

Systematic sampling for archaeozoological investigations was carried out during the excavations at Maidanetske in 2013–2016. This resulted in the identification of a total of 1334 individual specimens of domestic and wild mammals and some molluscs (Table 2). Domestic animals comprise 98% of the assemblage. Sheep/goat and cattle are the main domesticates, followed by pig. The high amount of sheep/goat differs from the overall picture of Tripolye sites, where cattle is dominant (Kirleis and Dal Corso, 2016). The herding of sheep/goat suggests grassland to open woodland habitats, whereas cattle and pig can cope with wooded landscapes. Among the 2% of wild mammals, species from densely forested as well as open woodland and steppe environment are present. This archaeozoological record thus shows that diverse ecological niches were accessible to the settlers.

Table 1. Results of the analysis of charred and mineralized seeds and fruits (unless indicated otherwise), Maidanetske 2013–2016.

Volume of soil (L)	6506.56	
Number of features	161	
Number of samples	722	
Cereal grains		161
Triticum dicoccum	26	Emmer
Triticum monococcum	13	Einkorn
Triticum sp.	4	Wheat
Hordeum vulgare	11	Barley
Cerealia indet.	107	Cereal
Threshing remains		116
Triticum dicoccum, glume bases	79	Emmer
Triticum monococcum, glume bases	1	Einkorn
Triticum monococcum/dicoccum, glume bases	3	Einkorn/Emmer
Hordeum vulgare, rachis segments	31	Barley
Cerealia indet., rachis segments	2	Cereal
Pulses		40
Lens culinaris	1	Lentil
Pisum sativum	31	Garden pea
Fabaceae (cult.)	8	Pulses
Gathered plants		10
Corylus avellana	8	Hazel
Hyoscyamus niger	2	Henbane
Stipa spec., awn fragments	918	Feather grass
Ruderal and segetal vegetation		2747
Chenopodium album	1868	Fat hen
Chenopodium polyspermum	1	Many-seeded Goosefoot
Chenopodium sp.	172	Goosefoot
Chenopodiaceae p. p.	588	Goosefoot family
Solanum nigrum	1	Black nightshade
Trifolium sp.	1	Clover
Galium aparine	17	Goosegrass
Polygonum aviculare agg.	1	Knotgrass
Polygonum sp.	1	Bindweed
Anagallis	1	Pimpernel
Silene sp.	1	Catchfly
Vicia sp.	1	Tare
Echinochloa crus-galli	4	Cockspur
Setaria viridis	1	Green bristle-grass
Bromus secalinus	2	Chess grass
Bromus sp.	2	Brome
cf. *Avena* sp.	1	Oat
Poaceae p. p.	3	Grasses
Lamiaceae	1	Mint
Rosaceae	1	Rose family
Indeterminata	79	Undetermined seeds/fruits
Indeterminata, slaggy remains	**29**	Undetermined slaggy remains
Ruderal and segetal vegetation, mineralized		3478
Chenopodium album	978	Fat hen
Chenopodium sp.	977	Goosefoot
Chenopodiaceae p. p.	1523	Goosefoot family

Table 2. Results of the analysis of faunal remains, 2013–2016.

Maidanetske 2013–2016	Total	
	NISP	Weight (g)
Domestic mammals	1307	27,592
Cattle	513	22,973
Sheep/goat	531	2280
Pig	263	2339
Wild mammals	15	
Open woodland	6	51
Red deer	4	43
Roe deer	1	4
Elk	1	4
Dense woodland	3	74
Wild boar	1	72
Red squirrel	2	2
Steppe	6	263
Wild horse	4	261
Hare	1	1
Hedgehog	1	1
Molluscs	12	–
Helix	8	–
Unio	4	–

Results from wood imprints on daub

Wood as timber. The dimensions of logs and split wood timbers documented through imprints on daub from three excavated buildings at Maidanetske (Figure 6) attest that 80% of logs are smaller than 5 cm in diameter and 95–99% are smaller than 10 cm. Imprints of split wood timbers showed slightly larger dimensions: about 50% $\leqslant$5 cm and 70–80% $\leqslant$10 cm. Consequently, we can assume the selection of timber from young trees or branches. Taking in consideration these results, the amount of wood needed for a house in Maidanetske would be 5–8 m^3 for a variant with walls in wattle technique and 6–9 m^3 for a variant with walls constructed with split wood beams (Table 7 in Supplementary Material, available online). These estimates are similar to those made by Rosenstock (2009: 207), who arrived at to 0.1 m^3/per m^2 house floor area of a standard Neolithic house. Taking into account the Rosenstock data, the wood demands for a Maidanetske house of average size with a floor area of 72 m^2 (Ohlrau, 2015) would be 7.2 m^3.

With the premise of a constant intensity of house construction within each of the four settlement phases previously described, the number of houses built annually, on average, was 2.7 in phase 1, 5 in phase 2, 15.5 in phase 3 and 12.8 in phase 4 (Table 3). Accordingly, the estimated average annual demand for timber for house construction for the entire settlement ranged between a minimum of 14 and 70 m^3, in phase 1, and a maximum of 78–403 m^3, in phase 3.

Wood as fuel. In the first phase of the Maidanetske habitation, with 150 houses built in 55 years, the requirements for firewood/year amounted to 750–1500 m^3. Later, the number of houses and therefore the wood demand increased, to 3100–6200 m^3 in phase 2 (620 houses in 135 years), 7750–15,500 m^3 in phase 3 (1550 houses in 100 years) and 6055–12,800 m^3 in phase 4 (770 houses in 60 years).

Concerning the amount of fuel needed for pottery making, assuming that 1.5 m^3 of wood was needed in order to fire 150 vessels and knowing that 50–70 vessels were found per house and some may have been broken and substituted, we need not assume more than one firing per house. On average, not more than about 10 pottery firings and 15 m^3 of firewood were necessary per year for the mega-site.

If additional fuel was needed for the burning of houses, experimental data indicate that the amount of firewood required would range from 81 m^3 in phase 1 to 465 m^3 in phase 3.

An overview of all these estimates is given in Table 3. Overall, the demand for firewood is higher than that for timber and wood for house burning. Therefore, wood for firewood may have been a crucial resource. However, we have to bear in mind that the calculation of firewood requirements for daily use is uncertain to define.

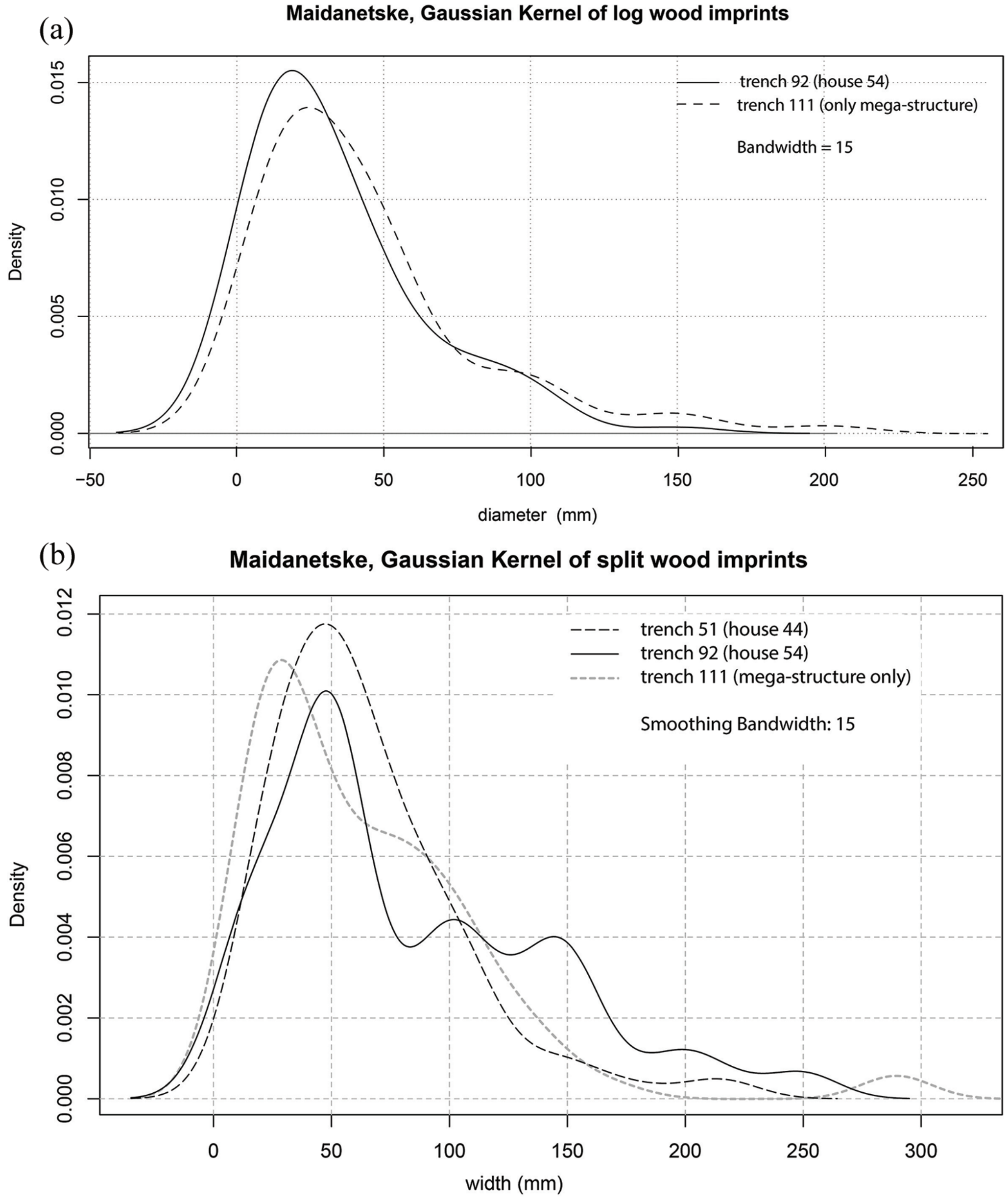

Figure 6. Widths of (a) log and (b) split wood imprints in archaeological daub based on 107 split wood imprint measurements from house 44, 101 log wood and 85 split wood imprints from house 54, and 316 log wood and 309 split wood imprints from the structure in trench 111.

Table 3. Estimated timber requirement in Maidanetske per settlement phase.

	Phase 1	Phase 2	Phase 3	Phase 4
Age (cal. BCE)*	3990–3935	3935–3800	3800–3700	3700–3640
Duration (years)	55	135	100	60
Houses (*n*)	150	620	1550	770
Average houses/year	2.7	5	15.5	12.8
Inhabitants*	750	3100	7750	3850
Timber for house construction (m^3 wood/house)	14–70	25–130	78–403	64–333
Firewood for routine activities (m^3 wood/house)	Max. 750–1500	Max. 3100–6200	Max. 7750–15,500	Max. 6055–12,800
Firewood for pottery kilns (m^3 wood/firing event)	2–4	4–8	12–23	10–19
Wood for house burning (m^3 wood/house)	0–81	0–150	0–465	0–384
Overall wood demand (m^3)	16–1655	29–6488	90–16,391	74–13,536

*Chronology and population estimates after Ohlrau (2019).

Results of models for landscape reconstruction

The model previously described generated both fuzzyfied and defuzzyfied predictions of potential vegetation distributions. The maps in Figure 7(a) illustrate, based on the defuzzified predictions, which vegetation type is most favourable for each raster cell in the landscape around Maidanetske under current ('intermediate') climatic conditions, under dry conditions and under wet conditions. The dry and wet conditions were created

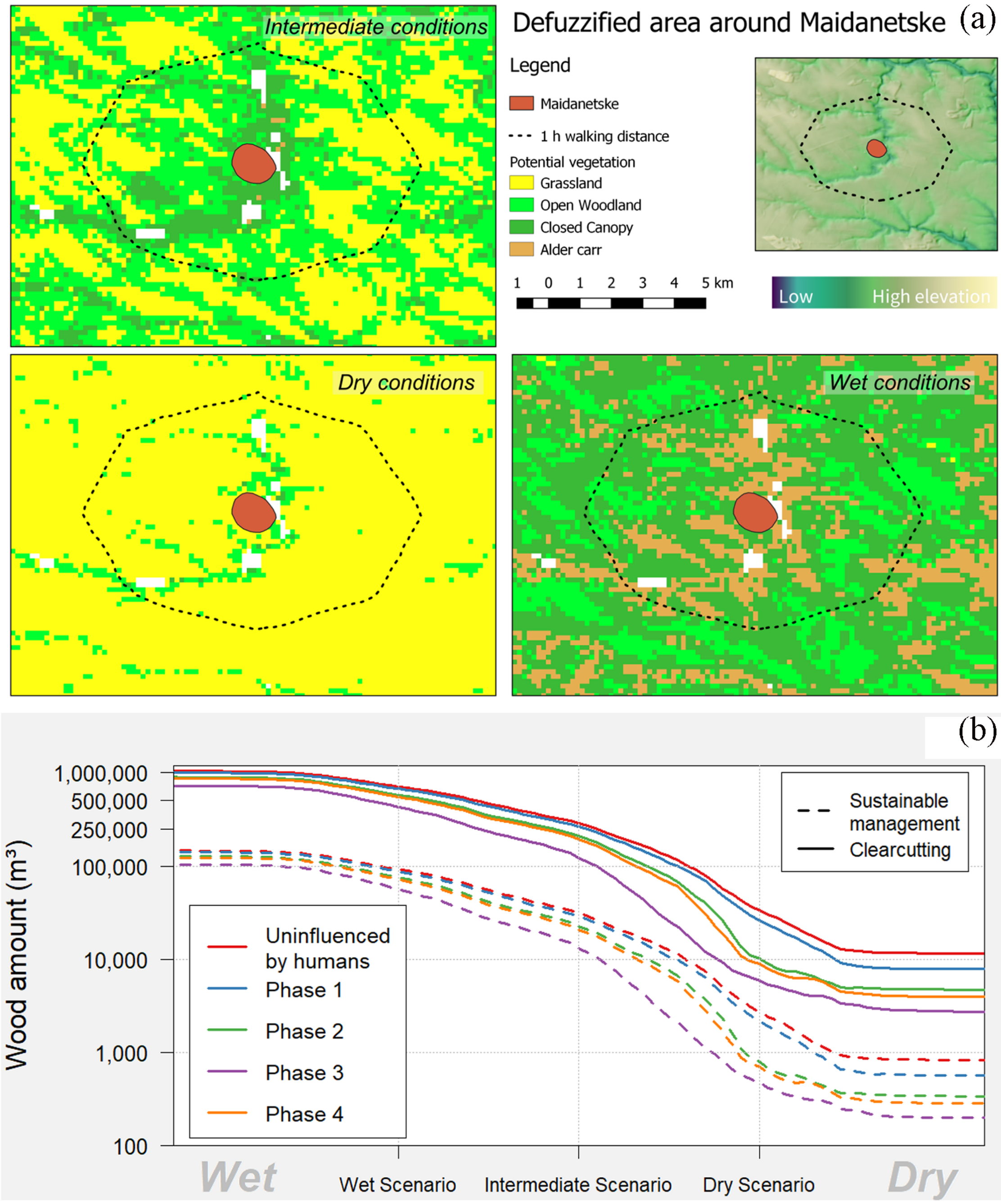

Figure 7. (a) Defuzzified simulation of the vegetation close to Maidanetske and (b) fuzzified simulation of amount of wood available close to Maidanetske.

through a modification of the fuzzification of the wetness index (Figure 4 top) to drier (Figure 4 centre) or moister (Figure 4 bottom) conditions. As expected, Grassland, Closed canopy and Open woodland are dominant under recent conditions. Grassland shows a higher distribution under the assumption of drier conditions, whereas Open woodland is receding to the more wet depressions. This area is occupied by Riverine woodland under more wet environmental conditions surrounded by a mixture of Closed canopy and Riverine woodland. Grassland is only represented here in combination with other potential vegetation units. The different scenarios lead to different amounts of wood, as depicted in Figure 7(b). Curve variations along the X-axis in Figure 7(b) show that in every settlement phase, under dry conditions, less wood may have been available around the site and, under wet conditions, more wood may have been available. Along the Y-axis, the amount of wood available is depicted, from which it is possible to subtract the sum of wood needed at Maidanetske according to estimations in Table 3. Despite the wood availability is reduced during the different settlement phases, the assumed management strategy has a strong influence on the availability of wood. The maps in Figure 8 illustrate the amount of wood potentially available to the population of Maidanetske during the different phases based on a fuzzy approach of the distance integration, whereby the timber yield decreases with increasing distance from the settlement.

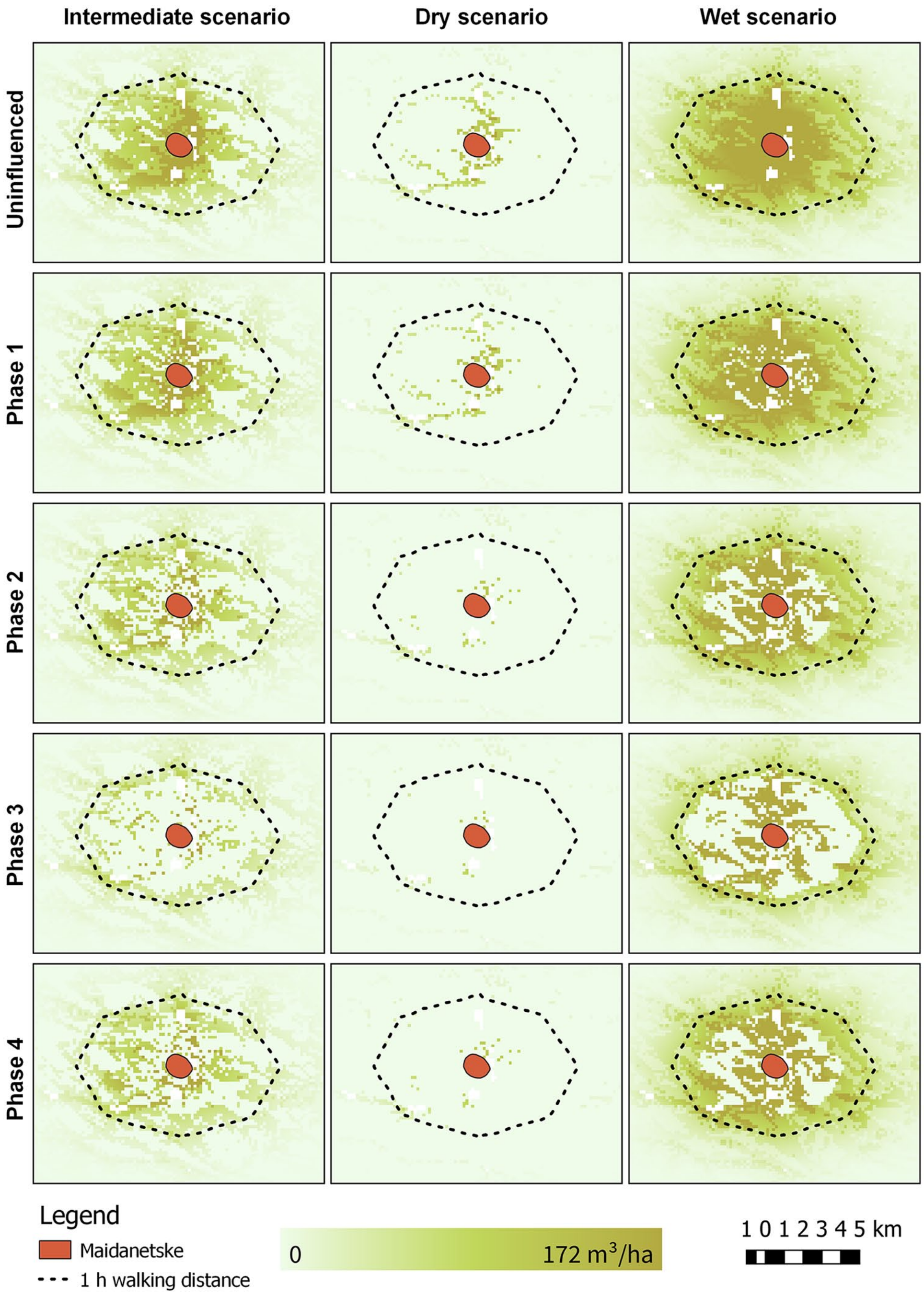

Figure 8. The maps show the potential wood amount available around Maidanetske in the different phases. The necessity of arable land and wood are here integrated according to the calculations given in the text and Supplementary Material, available online.

Discussion

Modelled vegetation versus proxy data

The North Pontic forest-steppe, where Maidanetske is located, is at an ecological 'borderland' intrinsically sensitive to climatic as well as human-induced changes. An informed reconstruction of the Chalcolithic climate and vegetation history is extremely difficult to achieve due to the patchiness of its vegetation types and the lack of suitable natural archives. In such a context, landscape modelling provides a valuable tool for reconstructing past landscape scenarios based on proxy data from the stratigraphic record of archaeological sites. For this reason, we modelled three main scenarios, based on water availability as the main factor (Figure 7(a)). Under climatic conditions comparable with those of today ('intermediate scenario'), excluding human impact, a large part of the territory surrounding Maidanetske could have been covered by sparse, broadleaved forest, with closed canopy on the slopes, and by wetland forests, being restricted to less well-drained areas along to the river valleys. Managed forest stands with oak, ash, hornbeam, sycamore, elm and lime have been observed in the region, where in some cases they take over abandoned marginal areas, relegating dry grasslands to very small, rocky spots. In the modelled reconstruction, dry grassland communities would mostly extend on the plateaus out of the area of first influence around the site, that is, at 1 h of walking distance, which would be covered by arable land. According to the model, these conditions would change very much in case of less ('dry scenario') or more ('wet scenario') availability of water. In the dry scenario, grasslands would dominate close to the site, and open woodland would be restricted to the river valley, where small stands with dense cover (closed canopy) would almost disappear to the northern slopes. In the wet scenario, grassland could not compete with the woodland cover, and forest, especially wetland forest in the valley, would expand. The catchment area around the site would have been prone to substantial changes in relation to the key variable, namely, water availability, which is directly influenced by climate, in particular precipitation.

All the vegetation types in the modelled scenarios have been attested by different proxies from the archaeological record of Maidanetske. Concerning the woodland species, charcoal data show a clear preponderance of ash, followed by oak and elm, that is, species that may grow in mixed open woodland, in dense forest with closed canopy, and in the hardwood belt of riverine woodlands. Ash is a fast-growing tree that, because of its adaptability to disturbance, can be quite competitive in mixed stands. With favourable conditions, that is, in the presence of deep, moist, fertile, pH-neutral, well-drained soils, for example, on slopes along river valleys, ash can be found also in almost pure stands, with a high regeneration rate (Dobrowolska et al., 2011). In the French Pyrenees, for example, ash has been observed to grow 6–15 m high within a period of 15–25 years in undisturbed (i.e. no grazing) environment (Marie-Pierre et al., 2006: 186), which is less than what can be expected for oak. Ash grows fast and straight, thus possessing good qualities for timber production. In particular when coppiced, it provides firewood and leaves and twigs for fodder, due to its good response to cutting (Dobrowolska et al., 2011; Out et al., 2013). The high nutritive value of its leaves makes it a favourable animal fodder (Hejcmanovà et al., 2014). Compared with ash, deciduous oak is less dependent on soil moisture and grows much more slowly. However, oak provides high-quality wood and acorns, used often in prehistory as animal fodder (e.g. Kirleis, 2018; Mason, 2000; Primavera and Fiorentino, 2013). Oak is also more resistant than ash to prolonged frost and drought (Beck et al., 2016). Elm prefers the hardwood belt of riverine woodlands. The charcoal record at Maidanetske shows a preference for ash, most probably due to the tree's abundance in the local environment, based on its ability to cover a broad ecological range. It would have grown in mixed open woodlands and dense forest stands on the plateaus, as well as in the hardwood belt of the riverine woodlands. The Maidanetske data suggest that the harvesting of wood was selective, which could have favoured the thinning of the forest and the re-growth of ash trees, which are not harmed by small-scale openings. The increased use of oak and elm observed around 3800–3700 BCE corresponds to the peak occupation at the site and the construction of many dwellings. It seems feasible that this peak in construction prompted an expansion of the range of resources to include oak and elm. The still-high amount of ash suggests that the broadening of the spectrum of tree species being harvested was not due to ash being less available. Also, considering the extreme scarcity of pioneer taxa, such as birch and pine, in the charcoal record, it seems improbable that the intensity of woodland use by Chalcolithic settlers crossed the threshold of sustainability significantly at any time.

Concerning the attestation of steppe vegetation, charred awn fragments of feather grass dating to the time of the site have been found in large quantities in the uppermost layers of the archaeological stratigraphy (Kirleis and Dreibrodt, 2016). The awns are light in weight, easily transported by wind, and easily spread by animals, as they stick to fur (e.g. of sheep and goat). Thus, the awn fragments may well have been transported over long distances and give a regional signal for the expansion of grasslands in the phase shortly before and after the abandonment of the mega-site. The phytolith assemblage from sediment from the cultural layers at Maidanetske (Dal Corso et al., 2018) is also comparable with that from steppe vegetation known from the literature, although the sample context from the settlement may have highlighted the signal due to plant use and due to the local grasses that would have grown in on-site open spaces. The plant remains from steppe vegetation at Maidanetske may thus hint at a patchy forest-steppe environment in the direct vicinity of the settlement or indicate natural or human activities that link to distant steppe environments.

From the archaeozoological results, a similar picture of the Chalcolithic landscape emerges. While the presence of sheep/goat indicates a certain amount of open space, cattle and in particular pig (together with the identified archaeozoological forest species) probably point to significant woodland use by the Chalcolithic inhabitants. A preference for raising pigs in oak woodlands (Kirleis, 2018, and references therein) may even explain the low frequency of oak in the charcoal spectra until the peak occupation in phase 3.

Viewed against the palaeo-pedological data available so far (Kirleis and Dreibrodt, 2016), the botanical and faunal remains could clearly indicate openings in the local environment during the Chalcolithic, but a presence of natural woodlands in the wider surroundings of the site is probable. The lack of evidence for soil erosion prior to the Bronze Age, even in the close vicinity of Maidanetske, indicates that the Chalcolithic impact on the environment was of rather moderate intensity (Kirleis and Dreibrodt, 2016).

Comparison between wood availability and demand: A human-induced landscape transformation?

Despite seasonal occupation of the mega-sites has been suggested (Chapman, 2017; Nebbia, 2017: 212–221), at Maidanetske the crops in the archaeobotanical record and the livestock in the faunal dataset seem to confirm the interpretation derived by the archaeological assemblages of standard buildings as related to permanent dwellings (e.g. Müller et al., 2017). People lived and conducted subsistence activities that required permanent settling of at least a relevant portion of the community. On these premises, the wood demand has been calculated based on archaeological data, ethnographic analogy and experimental work for the four phases of site development, which saw different numbers of inhabitants. Our results indicate that firewood for domestic activities could have been by far the most required material and hence a crucial resource. The amount of wood required for house construction seems of much less importance, and no fuel at all may have been needed for the burning of houses, considering that fire could have been set in the dry season, on an old and hence dry house.

By measuring the wood imprints from house wall remains, we were able to establish that the site's occupants selected wood of a certain diameter (5–10 cm) for house construction. Unfortunately, the high fragmentation of the charcoal does not allow for diameter reconstructions. Stakes of that diameter indicate either a selection of naturally available young trees or the harvesting of coppiced trees, both of which could have been sustained by ash (Out et al., 2013).

The graph in Figure 7(b) shows that, according to the values given in Table 3, all three water availability scenarios would have presented sufficient wood supply for house building and that none can be clearly excluded. However, during the peak occupation, in phase 3, higher wood demand could be expected, even more so if house building was not equally distributed over the one-century duration of the phase. A peak in construction might have had a harsher impact. According to the total wood demand for construction and fuel in the dry scenario and, in phase 3, in the intermediate scenario, conditions would have been critical and woodland stands would have been drastically reduced at the time of the site's decline. In these cases, the demand for wood would have reached critical levels due to the need for fuel for routine activities, more than any other purpose (see Table 3 and Figure 7(b)). However, fuel for making fire could have been provided by dung and by deadwood, both of which are difficult to trace in the archaeological record.

Conclusion

In this contribution, we tested the application of fuzzy model techniques to outline the carrying capacity of a Chalcolithic landscape in central Ukraine where traditional Holocene palaeoecological proxies are problematic. The modelling resulted in scenarios that are in line with the limited evidence about subsistence and economy deduced from the archaeobotanical and zooarchaeological records of the Maidanetske mega-site, from soils and sediment in the surroundings of the site, and from palaeoecological records of the region known from the literature.

For house construction, a conscious selection of wood could be proven based on a preference for certain tree species, as shown by the charcoal analysis, as well as the diameter (5–10 cm) of the wood, as shown by the daub imprints. Ash was the prevalent tree in use and was most probably a dominant species in the hardwood forest covering the slopes along the river in the direct vicinity of the site. During the occupational peak, an increase in oak and elm occurs. An increased demand for wood may have caused the inhabitants to extend their catchment towards the softwood belt of the riverine forest, for elm, and to the mixed oak woodland on the plateau, for oak. Three scenarios were modelled, with water availability as the main driver for woodland transformation. Only the scenario with drier conditions than today would have resulted in critical conditions with respect to requirements for wood and arable land. This scenario accounts for woodland management to gain sufficient resources, which fits with the major empirically proven wood supplier, the ash tree. However, both the intermediate and the wet scenarios, even in the phase of major population agglomeration, predict abundant resources in the naturally growing woodlands.

Overall, the results indicate that the inhabitants of Maidanetske did not suffer from a significant shortage of wood resources at any time according to the different scenarios provided by the model, with exception of the phase of maximum house construction and population within a scenario of drier climatic conditions. So far, soil erosion and degradation caused by clearcutting of the forest are not observed before the Bronze Age. Whether the formation of the Chernozems covering the landscape nowadays was influenced by ancient land use activities within the ecotone region of the forest-steppe remains an open question for further research.

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Supplemental material

Supplemental material for this article is available online.

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