Diachronic Perspectives on Upper Palaeolithic Landscape Accessibility

Jungpaläolithische Landschafts-Akzessibilität im diachronen Vergleich

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Abstract - Hunter-gatherer communities are highly dependent on the accessibility of their surrounding landscapes. Relief, as well as the predominant vegetation strongly influence walking speed and thus the size of foraging ranges around camp sites: the catchments.

Throughout the Upper Palaeolithic, landscapes are shaped by various climatic developments, requiring adaptations of subsistence strategies. A diachronic and supra-regional comparison of catchment sizes promises to shed light on such adaptive processes. This study seeks to model Upper Palaeolithic site catchments in consideration of different landcovers, depending on changing climatic conditions in Western and Central Europe. Such large-scale comparisons of catchment sizes have not yet been the topic of extensive research. As we are now able to show, changes in vegetation density led to a greater restriction of catchment sizes. This is partially compensated by the preferred settlement of level regions.

The climatic shift between the Last Glacial Maximum and the Late Glacial is known to have various effects on demography, tool technology and the mobility patterns of hunter-gatherer societies. This picture can now be complemented by one additional aspect: the adaptation of mobility as a response to changing landscape accessibility and its impact on land-use.

Zusammenfassung - *Jäger-Sammler Gemeinschaften sind stark von der Zugänglichkeit der sie umgebenden Landschaft abhängig. Das Relief sowie die vorherrschende Vegetation haben einen starken Einfluss auf die Laufgeschwindigkeit und dadurch auf die Größe des erreichbaren Gebietes um etwaige Lagerplätze herum: das Catchment.*

Über das Jungpaläolithikum hinweg werden Landschaften von unterschiedlichen klimatischen Entwicklungen geprägt, die zu einer Anpassung der Subsistenzstrategien führen. Ein diachroner und überregionaler Vergleich von Catchment-Größen verspricht derartige Wechselwirkungen zwischen dem Menschen und seiner Umwelt in einem neuen Licht darzustellen. In dieser Studie modellieren wir Catchments des Jungpaläolithikums unter Berücksichtigung unterschiedlicher Landschaftsbedeckungen, abhängig von wechselnden klimatischen Bedingungen in West- und Mitteleuropa. Großskalige Vergleiche von Catchment-Größen lagen bisher noch nicht im Fokus der Paläolithforschung. Wie wir nun zeigen können, führt eine dichtere Vegetation im Spätpaläolithikum zu einer Verringerung der Catchment-Größen. Dies wird teilweise durch die bevorzugte Besiedlung flacher Regionen kompensiert.

Die klimatischen Veränderungen zwischen dem Letzten Glazialen Maximum und dem Spätglazial hatten unterschiedliche Effekte auf Demographie, Werkzeugtechnologie und die Mobilität von Jäger-Sammler-Gesellschaften. Dieses Bild kann nun durch einen weiteren Aspekt ergänzt werden: die Anpassung mobiler Jäger-Sammler an eine veränderte Landschaftszugänglichkeit und ihren Effekt auf Landnutzungsmuster.

Keywords - Catchment modelling, diachronic comparison, GIS, Land-use, mobility-pattern
Einzugsgebietsmodellierung, diachroner Vergleich, GIS, Landnutzung, Mobilitätsmuster

Introduction

The European Upper Palaeolithic is a period of pronounced climatic changes (Badino et al. 2020; Maier et al. 2021; Straus 1995). As settlement pattern are closely related to climatic and ecological conditions, this period is particularly well suited for the investigation of human-environment interaction and its effect on landscape accessibility. In this study, landscape accessibility is understood as the distance an individual is able to travel within a specific time. We quantify landscape accessibility by modelling the variability of catchment sizes which can be accessed from a central point, such as a Palaeolithic site.

Landscape accessibility is determined by many factors, such as topography or land-cover but also by sociocultural limitations to human movements in space (Kuhn et al. 2016). The ability to roam through

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the terrain is linked to the accessibility of different task options, resources or social spaces. The focus of this work is this accessibility, with a particular emphasis on the catchment-level of Palaeolithic sites. This is not to be confused with mobility patterns of hunter gatherers between the micro and the macro scale. We investigate how impeding the general landscape in a given time-phase was and how prehistoric people moved within these different settings.

Site catchment analyses for archaeological purposes are conducted since the early 1970s (Higgs & Vita-Finzi 1972; Vita-Finzi et al. 1970). With increasing popularity of geographic information systems (GIS), modelling approaches became more complex and more accurate (Becker et al. 2017). Jobe and White (2009) pointed out that energetic costs for hiking are mainly driven by the slope of a specific terrain, followed by its vegetation landcover. Besides, several other authors empathize the importance of multi-criteria cost surfaces for the modelling of site catchments (Herzog 2010; Howey 2007). In addition, the modelling results are highly dependent on data quality such as the resolution of the digital elevation model (DEM) used to calculate the catchment extent (Becker et al. 2017 and cited literature within). A comprehensive description of the history of catchment modelling and analysis in archaeology was already reported by Becker et al. (2017).

Evolutionary, human movement on small and large scale have been an important driver of adaptation. Mobility is closely related to actions and opportunities in the everyday life of humans both in the present as well as deep history (Kuhn et al. 2016). It determines the availability of stationary and mobile resources, such as toolstone or faunal elements. This was described as so-called landscape-affordances by Gillings (2012) and Kempf (2020). Among other things, it indirectly influences and is influenced by technological and cultural adaptations of humans to the restrictions imposed by the landscape accessibility. For example, Kelly showed a close relationship between net primary biomass and the number of moves per year for tropical hunter-gatherers, determined by resource clustering and predictability (Kelly 1983). Consequently, the variability of net primary production (NPP) also determines landscape accessibility around individual sites, since denser vegetation impedes movement.

During the Upper Palaeolithic, climatic changes influence the NPP in Europe (Maier et al. 2022, see also Kelly 1983). Most vividly, this can be observed in the change from the Last Glacial Maximum (c. 20 ka calBP) to the Late Glacial Interstadial Complex (14 ka calBP). It is accompanied by a change from steppe-tundra to an increasingly forested landscape, ultimately leading to the dense forests of the Early Holocene. Catchment analysis has been used frequently in Palaeolithic landscape archaeology on a regional scale (Becker et al. 2017: References 6-11, Sauer & Uthmeier 2020). This paper seeks to apply a diachronic and supra-regional approach to trace changes and adaptations in the landscape accessibility of Upper Palaeolithic sites in Europe.

Understanding influences on mobility such as landscape accessibility is paramount to grasp the potential adaptations of prehistoric hunter-gatherers in a changing environment. During the Palaeolithic, subsistence is linked strongly with the ability to access space and the options therein. We compare daily catchments throughout the Upper Palaeolithic, using two different modelling approaches. Daily catchments encompass the space which “belongs” to a site, since they do not necessitate the establishment of new, ephemeral locations due to the same-day-return of the agent(s). Model A uses a slope-based approach, whereas model B additionally implements a landcover approximation. The comparison of these two approaches allows an estimation of site placement in the landscape vs. an actual environmental framework around the sites.

Therefore, the two main objectives of this paper are:

1. A diachronic comparison of landscape accessibility in the Upper Palaeolithic of Europe
2. A supra-regional comparison of landscape accessibility in the Upper Palaeolithic of Europe

Materials

The main study area is the region between the Atlantic, the Mediterranean, the Baltic and the Eastern Carpathians (between 34°N/11°W and 55°N/30°E). For this region, five datasets generated by the Collaborative Research Centre 806 “Our way to Europe” at the University of Cologne were used (Kretschmer 2016; Maier & Zimmermann 2015, 2016; Schmidt & Zimmermann 2018, 2020). The five archaeological datasets cover a range of about 31 ka (Tab. 1) (Schmidt et al. 2021). By clipping marginal areas and thus generating a smaller but more concise dataset, we increase the reliability of the statistical analyses. Sites with major external constraints for their daily catchment – as for example by modern coastlines, islands or former glaciers – were also excluded. A total number of 3,509 sites was used in this study (SI Tab. 1).

To permit a synchronic comparison of different regions, the study area is divided into several subunits. For this purpose, we used the Digital Map of European Ecological Regions (DMEER) (EEA 2003). It contains 33 contemporary ecological units in the main study area. As this classification is determined by topographic features and their related abiotic factors, we consider them to be of general interest for this study. We constrained the investigated subunits to four core regions of greater diachronic site density (Fig. 1: f). These units are the Western European broadleaf forests, the Southern Temperate Atlantic, North-eastern Spain & Southern France Mediterranean, and

Period	Code	Cal. BP	Sites	Selected Sites*	Reference
Late Palaeolithic	LPA	14–11.6 ka	1121	808	Schmidt et al. 2021
Magdalenian	MAG	20–14 ka	1721	1378	Kretschmer 2015
Last Glacial Maximum	LGM	25–20 ka	396	345	Maier et al. 2016
Gravettian	GRA	33–25 ka	654	578	Maier & Zimmermann 2017
Early Upper Palaeolithic (Aurignacian)	EUP	42–33 ka	487	400	Schmidt & Zimmermann 2019

Tab. 1. Archaeological datasets used in this study. (*) Sites selected from the original dataset and considered in this study.

Tab. 1. *In dieser Studie verwendete archäologische Datensätze. (*) Aus dem Originaldatensatz ausgewählte und in dieser Studie berücksichtigte Fundstellen.*

the Cantabrian mixed forests. The European scale considers the whole investigation area.

As digital elevation model, the EU-DEM provided by the European Environment Agency was used for large parts of the study area (EEA 2017). Only the easternmost regions had to be extended by SRTM data (Jarvis et al. 2008). The merged elevation model was rescaled from an initial projected resolution of 25 m to 250 m due to processing limitations imposed by the large extent of the dataset. An equal area projection (EPSG: 3035) was used.

As modern topography is applied to Palaeolithic environments, the geomorphological evolution of the terrain was evaluated. Part of this critical examination was to consider the maximum extend of glaciation during the Last Glacial Maximum (LGM). These areas could not be expected to represent Late Pleistocene morphology. Therefore, regions glaciated during the LGM (Becker et al. 2015) were excluded from the DEM. Also, the CORINE land cover dataset (EEA 2012) was used to exclude anthropogenic features such as surface minings and gravel pits.

Methods

Catchment modelling

To quantify landscape accessibility, we use the size of site catchments in km^2 as described below. Only travel on foot is considered.

In general, this approach models the movement speed depending on slope. Slower speeds are modelled on strongly sloping terrain, while the greatest movement velocity is achieved on level ground (Sauer 2020; Sauer & Uthmeier 2020). To calculate the catchment extent, we compare two different modelling approaches. Model A is based on the Van Wagtendonk and Benedict (1980) hiking function $V=V_0 * e^{-k*s}$, applying one single mean factor for uphill, downhill and cross-slope travel of $k = 3$ (Van Wagtendonk & Benedict 1980; Watts et al. 2003). As basic velocity we applied $V_0 = 1.3$ m/s (4.68 km/h), representing the optimal metabolic walking speed for unloaded walking (Bastien et al. 2005). The s in the equation is represented by the local slope, calculated with the GDAL tool in Quantum GIS 3.10 (QGIS 2020).

The second approach (Model B) adds a modelled vegetation cover to model A with the purpose of simulating landcover-induced speed reduction in the landscape. This allows to differentiate movement between colder periods with sparse vegetation cover and warmer periods with a denser vegetation. In this study, we assume that vegetation cover is an obstacle to human movement in the landscape. Dense vegetation decreases landscape accessibility more than open, sparsely vegetated environments would. Several studies have already analysed different travelling speeds depending on landcover (Becker et al. 2014; Becker et al. 2017; Ciesa et al. 2014; Soule & Goldman 1972; Watts et al. 2003). Vegetational landcover is, among other factors, strongly determined by the geomorphological makeup of the landscape (Guisan et al. 1999; Guisan & Zimmermann 2000). Such morphologically uniform landscape elements can be represented by landforms, which determine species performance. In this paper, we model varying landcovers depending on different landforms as proxies for vegetational variability. The workflow as described below is further summarized in figure 2.

To derive landforms from the DEM, two scales of topographic position index (TPI) are compared. Using a basic TPI-based landform classification algorithm (Weiss 2001), we classify 12 different landforms as listed in table 3 (see also De Reu et al. 2013 Table 2). The results of the classification are highly dependent on neighbourhood scale. 67 different pairs of small and large circular neighbourhoods ranging between 250 m and 5,250 m were calculated for a test region. The goal was to attain the best ratio between

A) a high diversity of different landforms and
B) large mean areas of landform patches.
This resulted in the choice of a small neighbourhood of 1,250 m and a large neighbourhood of 5,250 m.

We defined six different landcover classes for which we assigned a speed coefficient. This coefficient is a value between 0 and 1. By multiplying it with the cost raster, it determines the final walking speed. We derive the values as a reclassified mean value from different studies (Becker et al. 2014; Ciesa et al. 2014; Soule & Goldman 1972; Watts et al. 2003). Here, we grouped similar landcovers, as for example different types of forests, together and took the mean values (SI Tab. 2). The resulting speed coefficients are shown in table 2.

Instead of associating these classes with a specific plant community, we define them as unspecific and abstract landcover classes representing varying vegetation densities. For example, landforms which promote higher

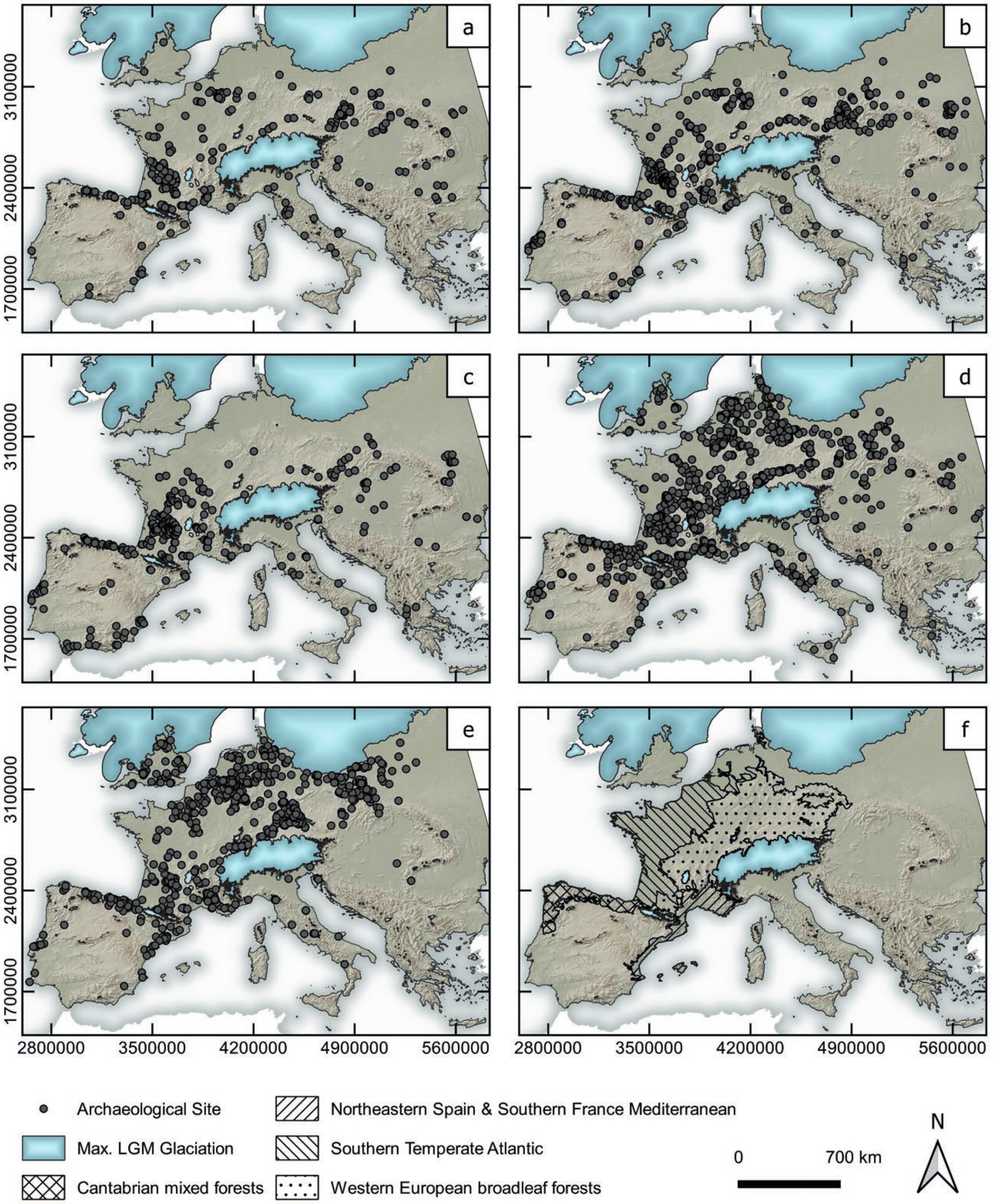

Fig. 1. Distribution of Sites used in this study. (a) Aurignacian, (b) Gravettian, (c) Last Glacial Maximum, (d) Magdalenian, (e) Late Palaeolithic. (f) extent of ecological core-regions as produced with the DMEER. (EPSG: 3035).

Abb. 1. *Verteilung besprochener Fundstellen. (a) Aurignacien, (b) Gravettien, (c) Letztes Glaziales Maximum, (d) Magdalénien, (e) Spätpaläolithikum. (f) Ausdehnung der ökologischen Kernregionen, erstellt mit DMEER. (EPSG: 3035).*

levels of humidity and protection would represent more densely vegetated patches during colder periods while they would represent swampy areas during warmer phases. However, we are not associating specific plant species or communities with these landform units. To assign landcover classes to landforms by period, the following a priori assumption was made: vegetation cover tends to be denser in protected landforms and sparse in exposed ones (Tab. 3). We take into account general vegetation trends for the different periods.

On the given scale we consider the Early Upper Palaeolithic (EUP) and the Gravettian (GRA) to have

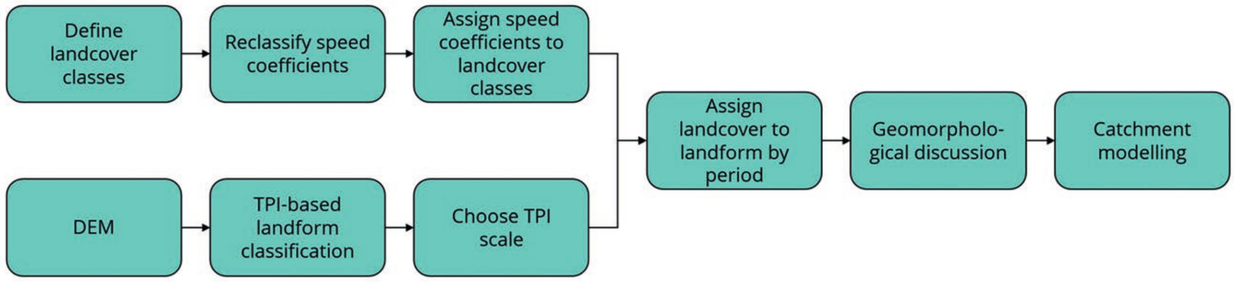

Fig. 2. Workflow for model B.

Abb. 2. *Arbeitsablauf in Modell B.*

a similar relative vegetation cover. During colder stages, a steppe or tundra like plant cover dominates, whereas trees predominantly spread from their southern refugia during warmer periods (Badino et al. 2020; Van Andel & Tzedakis 1996). The distribution of pollen and fauna indicates only few woodland species during the EUP and GRA in the NW of Europe (Holm & Svenning 2014; Markova et al. 2010). For the LGM, a retreat of arboreal species can be observed. However, during the last decades, evidence for the occurrence of trees north of the alps increased. Macrofossils, as well as modelling approaches on the spread of tree species indicate the presence of trees associated with river valleys (Binney et al. 2009; Holm & Svenning 2014; Svenning et al. 2008; Willis et al. 2000; Willis & Van Andel 2004). Also, the occurrence of forest birds in Central Europe points towards the presence of some forest tree species (Holm & Svenning 2014). With the Magdalenian (MAG), arboreal species spread again. Although not to be confused with exhaustive forestation, faunal remains indicate well developed forest in southern England (Holm & Svenning 2014). Southern Spain is dominated by a steppe vegetation with trees in valleys and canyons (Manzano et al. 2017). Even in parts of Central and Western Europe, a rise of *Pinus* pollen of up to 50-70 % can be listed (Maier 2015: 63-80). Still, a steppe like vegetation seems to dominate especially in the north European plain (Kuneš et al. 2008; Maier 2015). The Late Palaeolithic (LPA) is characterised by profound changes between warm periods in the Bølling-Allerød Interstadials and cold periods like the Younger Dryas (Straus 1995). Predominant vegetation switches between steppe/tundra and more forested landscapes (Holm & Svenning 2014). By 15 ka calBP, arboreal macrofossils increasingly occur apart from canyons or river valleys, also in northern Europe (Binney et al. 2009). Thus, on average a higher proportion of trees must be assumed (Aranbarri et al. 2014; Kuneš et al. 2008; Veski et al. 2012; Zawiska et al. 2015).

Based on the information presented in the different references, we heuristically decided on the assignment of the ground cover classes and the related speed coefficients as shown in table 3.

The catchments are calculated in ArcMap 10 (ESRI 2010) using a custom model built around the cost distance tool for a walking time of 14,400 seconds,

Landcover classes	Code	Speed coefficient
Barren surface	BS	1
Grassland	GR	0.9
Wooded Grassland	WG	0.68
Woodland	WD	0.63
Shrubland	SR	0.57
Wetland	WT	0.39

Tab. 2. Reclassified speed coefficients by landcover class.

Tab. 2. *Reklassifizierte Geschwindigkeitskoeffizienten nach Bedeckungsklasse.*

Landform	EUP/GRA	LGM	MAG	LPA
V-Valley	0.63 (WD)	0.68 (WG)	0.63 (WD)	0.39 (WT)
Local Valley	0.57 (SR)	0.9 (GR)	0.68 (WG)	0.63 (WD)
Midslope Drainage	0.57 (SR)	0.9 (GR)	0.68 (WG)	0.63 (WD)
Upland Drainage	0.57 (SR)	0.9 (GR)	0.57 (SR)	0.63 (WD)
U-Valley	0.68 (WG)	0.57 (SR)	0.63 (WD)	0.39 (WT)
Flat Plain	0.9 (GR)	0.9 (GR)	0.9 (GR)	0.68 (WG)
Sloping Plain	0.9 (GR)	0.9 (GR)	0.9 (GR)	0.68 (WG)
Upper Slopes	0.9 (GR)	1 (BS)	0.9 (GR)	0.68 (WG)
Ridge in Valley	0.9 (GR)	1 (BS)	0.9 (GR)	0.68 (WG)
Ridge in Plain	0.9 (GR)	1 (BS)	0.9 (GR)	0.68 (WG)
Midslope Ridge	0.9 (GR)	1 (BS)	0.9 (GR)	0.68 (WG)
High Ridge	1 (BS)	1 (BS)	0.9 (GR)	0.68 (WG)

Tab. 3. Speed coefficients by Landforms and period. See Codes in table 2.

Tab. 3. *Geschwindigkeitskoeffizienten nach Landform und Zeitstufe. Codes siehe Tabelle 2.*

representing four hours walking distance which we consider a daily catchment. Considering an average day with 12 h sunlight, we take into account 4 h of travel, 4 h of task execution and 4 h return-time.

Only site catchments that showed no major constrains were included in the study. Constraining areas are regions where modern topography is not representative for Palaeolithic conditions (see chapter Geomorphological discussion). One of these factors are modern coastlines. A catchment is considered as unconstrained, when its smallest radius is not less than half the size of its biggest. This procedure reliably determined constrained catchments in this model.

Effects of DEM resolution

One main issue concerning the extent of site catchments is caused by the DEM resolution. As the mean slopes are strongly correlated with the resolution of the DEM, these effects the size of the modelled catchments (Becker et al. 2017; Herzog 2014; Sauer 2018). However, a lower DEM resolution also has positive effects. While high resolution DEMs capture lots of anthropogenic features which influence modelling results, coarse resolutions reflect main topographic characteristics (Becker et al. 2017). By using a 250 m resolution, we also reduce small-scale geomorphological alterations of the terrain within the last 42 ka. To better understand the effects of the applied resolution, we calculated a dataset with a 100 m DEM resolution and tested both against equality of distribution.

Results

Geomorphological discussion

After a geomorphological consideration of topographic alterations for the evaluated periods, only few events are distorting the results of the landform classification. Therefore, these areas were excluded from the analysis. Besides the maximum extent of the LGM glaciation, the ecoregion of the Alpine conifer and mixed forests was also excluded due to strong glacial and periglacial activities. Another region that underwent major geomorphological changes is the Transylvanian Basin. Here, factors like lithology, hydrology and anthropogenic use led to deep-seated landslides, shaping the landscape during the Late Glacial and the Holocene (Demek 1984; Fărcaş et al. 2020; Surdeanu et al. 2011). A mid-scale example for landform alteration are Holocene dunes as could be found in the *Golfe de Gascogne*. These can reach elevations of up to 100 m and led to the formation of lagoons in their hinterland (Duphorn et al. 1984; Koster 2005; Kroon 2005). Small-scale features affecting local landforms are – besides surface mining – volcanic eruptions, as for example the Laacher See event, Vesuvius or Mount Etna. All three of them are associated with significant Holocene or Late Glacial eruptions (Bisson et al. 2021; Riede 2016; Sestini 1984). Although small- and mid-scale events might also influence the size of catchments due to a change in topography, large-scale processes have the greatest effect. Taking this into account, other processes like the formation of the north European Sand Belt or higher rates of paludification with the beginning of the Atlantic period do not significantly influence the classification results and did not seem to have had a significant effect on the analytical scale of this paper.

DEM resolution

As the resolution of the underlying DEM has a major impact on the modelling results, a better understanding of the effect on the data is vital. The size of a catchment will increase the more the resolution decreases (Becker et al. 2017). Consequently, calculated size has always to be regarded as relative. To check whether catchment sizes remain meaningfully comparable with changing resolution, 4h catchments were calculated for the LGM and the LPA. We used a 100 m and a 250 m DEM applying the methodological approach of model A, excluding landcover. By normalizing the results, we assure to consider the mere distribution without general difference in size (Fig. 3: a & b). Normalization was achieved by substracting the mean of the respective group from each value and dividing it by the groups standard deviation. A two-sided Kolmogorov-Smirnov Test was performed in R using the function ks.test {stats} to check for statistical independence of the different DEM resolutions in the modelling results (Fig. 3: c & d). We obtained D = 0.06, p = 0.532 for the LGM and D = 0.035, p = 0.694 for the LPA. This leads us to accept the null-hypothesis (H_0), in which case we see no significant difference between both distributions. Statistically, both modelling resolutions create comparable results.

Landcover compositions

By applying the given method and the values in table 3, we obtain different landcover intensities for the investigated periods (Fig. 4). On the European scale, landscapes are dominated by open landforms such as plains, which account for up to 75 % of the surface. During glacial phases we generally see open landcovers with variations of denser vegetations in the topographically heterogeneous areas. Only for the Late Palaeolithic phase during the warming of the Late Glacial Interstadial Complex we see a denser vegetation also covering the broad open landforms.

Variations in catchment size

Concerning median catchment size, we notice rather small diachronic variation within the defined zones for model A (no landcover; Fig. 5: a & b). The maximum spread of median distribution between the periods on a European scale is 75 km^2 between the LGM and the LPA (SI Tab. 3). The standard deviation (SD) ranges from 127 km^2 in the EUP to 160 km^2 for the LPA, which equals a variation of about 20 %. By comparison, model B (including landcover) shows a higher variation

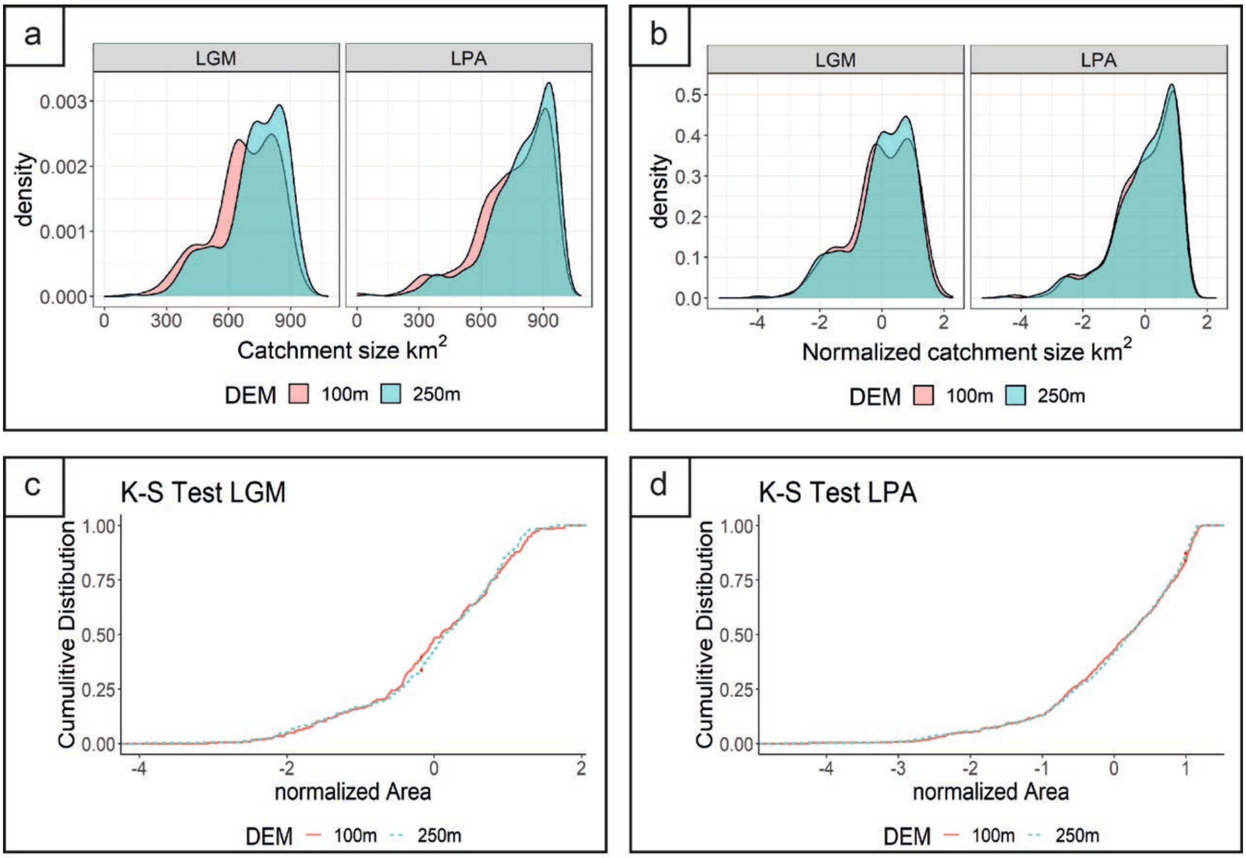

Fig. 3. Distribution of 4-houres site catchments by different DEM resolutions and periods. (a) Density plot for the LGM and the LPA with DEM resolutions of 100 m and 250 m, (b) Normalized density plot for the LGM and the LPA with DEM resolutions of 100 m and 250 m, (c) Cumulative distribution for the normalized LGM data, (d) Cumulative distribution for the normalized LPA data.

Abb. 3. *Verteilung der 4-Stunden-Catchments nach unterschiedlicher DEM-Auflösung und Zeitstufe. (a) Dichteverteilung für das LGM und das LPA mit DEM-Auflösungen von 100 m und 200 m, (b) Normalisierte Dichteverteilung für das LGM und das LPA mit DEM-Auflösungen von 100 m und 200 m, (c) Kumulative Verteilung der normalisierten LGM Daten, (d) Kumulative Verteilung der normalisierten LPA Daten.*

in the dataset. The smallest catchments are to be found in the LPA. The maximum spread of median distribution is at 245 km^2 between the LPA and the MAG. The SD is rather similar to model A, except for the LPA where it decreases to 96 km^2. The maximum variation occurs in the MAG, where the SD equals a variation of about 23 %. On average, daily catchments of the Upper Palaeolithic have an extend of ~780 km^2 when no landcover is applied and ~565 km^2 when we assume a vegetation cover as described above.

Considering a more regional scale, the pattern changes (Fig. 5: b; SI Tab. 3). In the Cantabrian mixed forests unit, catchments are about half as large compared to a European scale. The median size for model A is much smaller and averages around 444 km^2 with a SD between 87 km^2 in the EUP and 129 km^2 during the LPA. Added landcover results in smaller medians of 123 km^2 (LPA) to 290 km^2 (MAG) and a SD of 70 km^2 to 105 km^2.

The overall picture is similar in the other three main ecological regions: Median catchment size is rather similar for model A, as is the scatter of the data. The tendency for smaller catchments during the LGM and bigger ones in the LPA also occurs in the Cantabrian Mixed Forests unit and the Southern Temperate Atlantic unit. General tendencies are therefore independent between the different regions.

By adding a vegetation cover (model B) the variation between periods of similar landcover gets even smaller. However, these are contrasted by a pronounced difference to dissimilar periods like the LPA. In both models, the main diachronic variation can be observed between the different regions (inter-regional variation). The intraregional diachronic variation is small in model A, while model B shows an increased intraregional variation (Fig. 5). Generally, regions with higher median surface roughness (expressed topography) generate smaller catchments in model B (compared to model A), due to the denser modelled vegetation in protected landscape elements. Depending on the modelling approach, the catchment size can vary between 28 % and 44 % (Tab. 4). Surface roughness was calculated using the Gdal tool "Roughness" in QGIS.

Discussion

The two modelling approaches discussed in this study show different aspects of landscape accessibility.

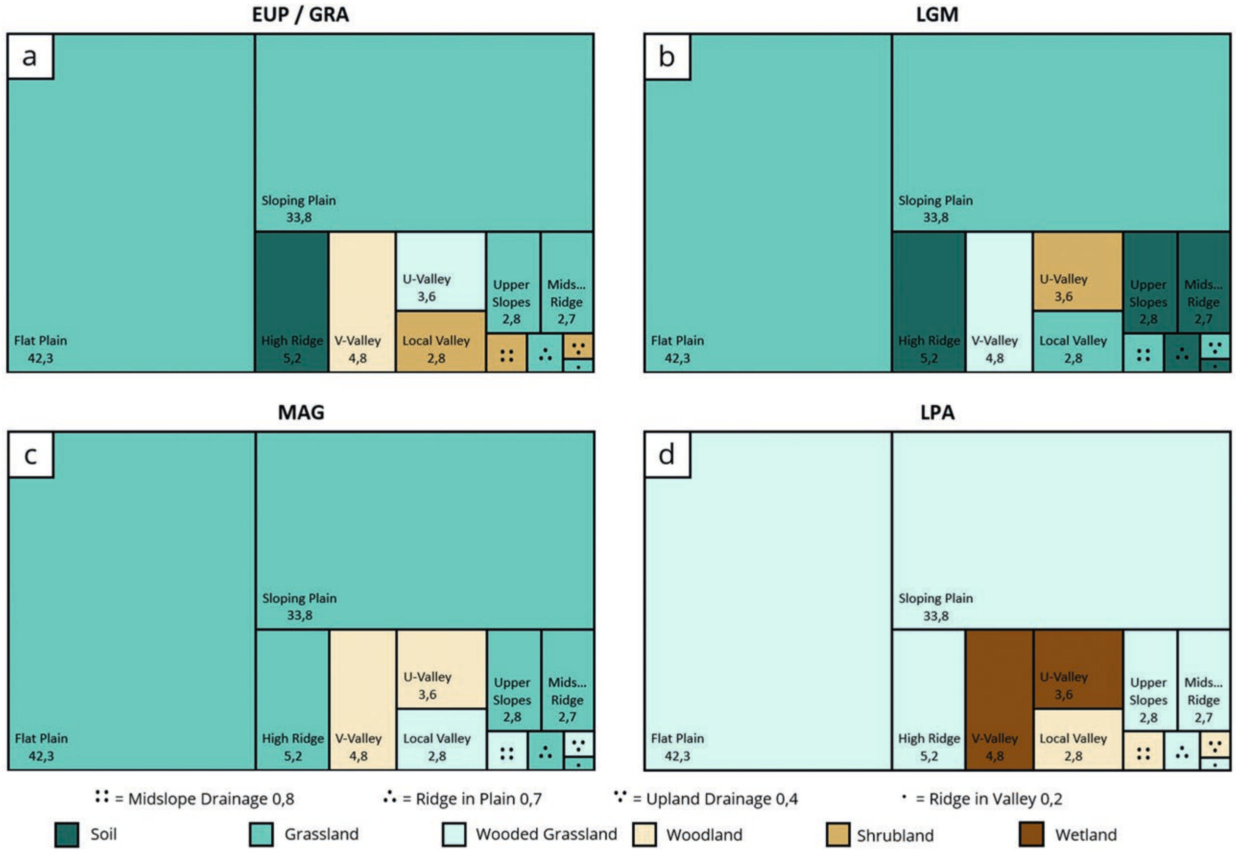

Fig. 4. Treemaps of landcover classes in relation with the proportion of Landforms on a European scale. (a) Early Upper Palaeolithic and Gravettian, (b) Last Glacial Maximum, (c) Magdalenian, (d) Late Palaeolithic.

Abb. 4. *Treemaps der Landbedeckungsklassen im Verhältnis zum Anteil der Landformen auf europäischer Skale. (a) Frühes Jungpaläolithikum und Gravettien, (b) Letztes Glaziales Maximum, (c) Magdalénien, (d) Spätpaläolithikum.*

Model A, without any additional landcover, allows inferences on general site placement. Bigger catchments represent "flat" regions, whereas small catchments tend to occur in hilly landscapes. At the same time, it allows a neutral comparison of different regions and time periods under equal conditions. In contrast, model B creates a more realistic picture of landscape accessibility around Palaeolithic sites.

Model A

The diachronic comparison throughout the Upper Palaeolithic shows that site location has a primary effect on catchment sizes when landcover is not included in the model. On a European scale, an increase of median catchment size from the Early Upper Palaeolithic (EUP) to the Late Palaeolithic (LPA) can be observed. Smallest catchment sizes appear during the cold phase of the Last Glacial Maximum (LGM). This decrease of catchment size during the LGM indicates a retreat into hilly regions as a possible response to particularly harsh climatic conditions. This could be associated with the exploitation of more diverse environments and clustered resources in hilly and thus more protected regions (compare Burke et al. 2017). In contrast, the increase of catchment size during the LPA reflects a settlement of flat and accessible areas. This could be seen as a reaction to the more closed vegetation during the Late Glacial Interstadial Complex. The climatic conditions could have necessitated the settlement of easily accessible landscape elements, since it facilitated the efficient exploitation of comparably scattered resources by covering larger areas. On the European scale, this pattern might be caused by the settlement of previously marginal areas such as the Northern European Plains. In many regions, a widening of the dietary spectrum towards the Late Glacial could be documented, which in turn might have supported the expansion into these landscapes (Mannino et al. 2011; Zeder 2012). Inter-regionally, coastal landscapes such as the Cantabrian Mixed Forests unit and the Mediterranean Ecozone behave differently to their continental counterparts. In those coastal areas, the median catchment size in model A decreases towards the Late Palaeolithic. This might be related to the intensified exploitation of marine resources (Colonese et al. 2011; Richards et al. 2005; Zeder 2012), leading to a different spatial behaviour. Aquatic resources are highly predictable. By their exploitation, the minimum foraging radius that is needed to meet the metabolic requirements of a group can be reduced. As modelled in a study

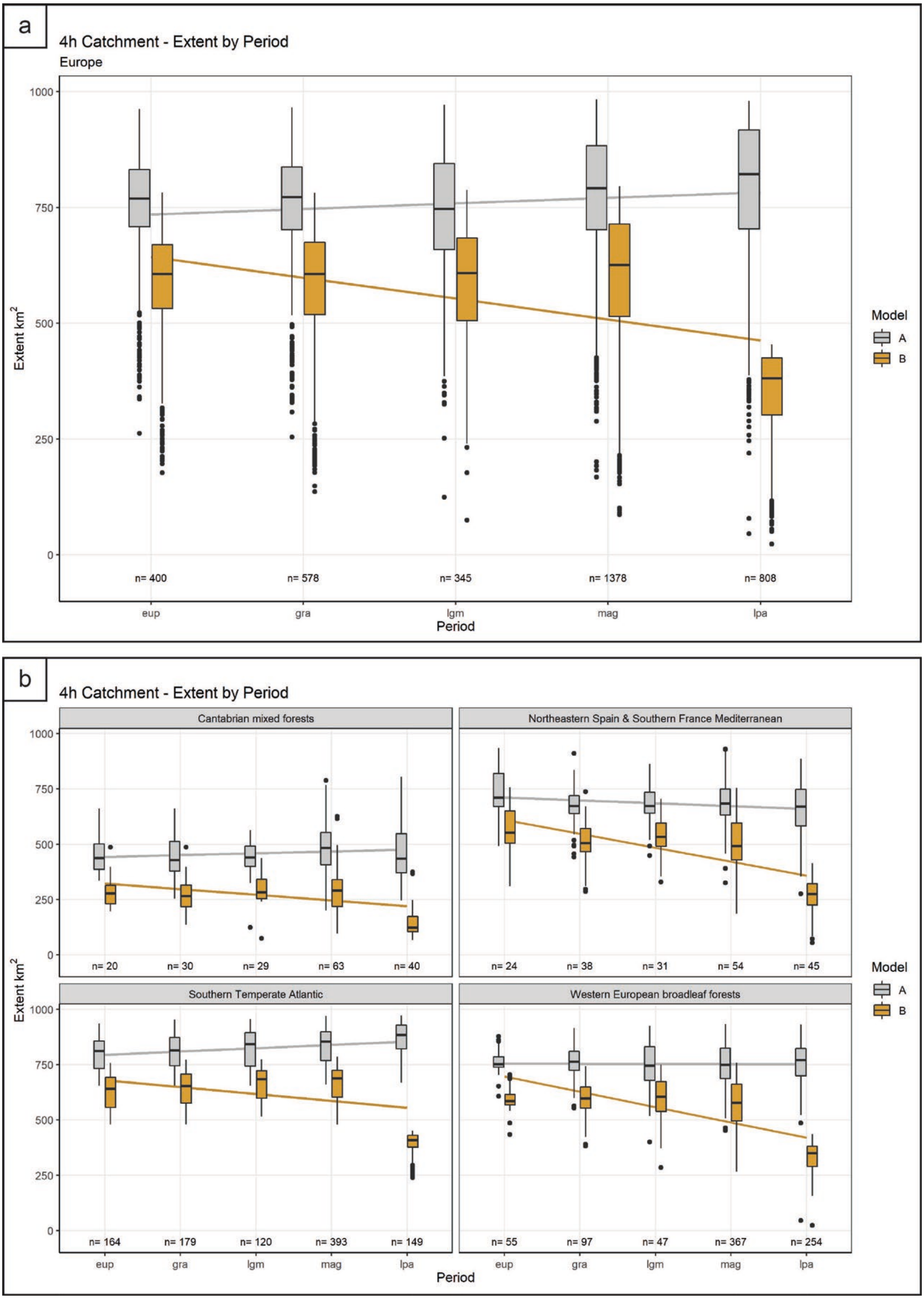

Fig. 5. Diachronic variation of 4-hours site catchment sizes. (a) Comparison between the variation of model A and B on a European scale, (b) Comparison between the variation of model A and B in the core ecoregions.

Abb. 5. *Diachrone Variation der 4-Stunden Catchmentgrößen. (a) Vergleich der Variation zwischen Modell A und B auf europäischer Skale, (b) Vergleich der Variation zwischen Modell A und B in den ökologischen Kernregionen.*

Ecological Region	Model	Average median	Average SD	Median Surface Roughness
Europe	A	780.6	143	26
	B	565.6	129.4	
	Δ	28 %	10 %	
Southern temperate Atlantic	A	841	76	13
	B	614.8	71.4	
	Δ	27 %	6 %	
Western European broadleaf forests	A	756.2	86.2	34
	B	542.4	80.4	
	Δ	28 %	7 %	
North-eastern Spain & Southern France Mediterranean	A	681.8	114	58
	B	471	104.6	
	Δ	31 %	8 %	
Cantabrian mixed forests	A	444.2	104.4	90
	B	247.8	80	
	Δ	44 %	23 %	

Tab. 4. Differences of modelling approaches throughout the periods.

Tab. 4. *Unterschiede der Modellierungsansätze über die Betrachtungszeiträume hinweg.*

by Hamilton et al. (2007, 4768) the "area of space used decreases with increasing proportion of aquatic resources in the diet". This seems to be confirmed by the drop of median catchment size in the LPA in the two ecoregions with a coastal character (see figure 5: b). Since inland sites are mainly dependent on terrestrial resources, behavioural responses to environmental and climatic stress appear more expressed, which is shown by model B.

Model B

Actual landscape accessibility seems to be better reflected by model B. It assumes a landcover assignment to different geomorphological units operating as friction factors on modelled mobility. These model parameters are based on inferences taken from various palaeoecological data sources. In our opinion, the differentiation of landcover by landform is more adequate than applying mean values by biome as it was done in previous studies (Becker et al. 2017). This especially holds true for colder periods with sparse vegetation. Here, the environmental gradient promotes greater resource clustering based on the harsh conditions. The general diachronic trend of changing catchment sizes remains the same when speed coefficients are applied. However, the LPA excusively shows a substantial decrease of median catchment size. With the increased spread of forests after around 15 ka calBP (Bølling-intertstadial), a significant impact of the vegetation cover on catchment sizes can be observed (Fig. 5).

The intraregional scatter in model B is similar among each ecological region, with exception to the Cantabrian Mixed Forests unit. Here, the distribution becomes less variable. As the general roughness of the topography is greater than in the other ecoregions, the variance in catchment size is reduced. It must be stressed that by omitting constrained catchments along the Cantabrian coastline, results might be skewed in favour of heterogeneous landscape elements.

For the non-costal ecozones, the strong general decrease in catchment size due to the dense vegetation cover in model B goes along with the settlement of generally more accessible landscapes during the Late Glacial Interstadial Complex in model A. This could be interpreted as a spatial reaction to the generally limited accessibility of the landscape in warmer time phases. This way larger catchments in a generally hindering environment could be exploited.

In contrast, the settlement of hilly regions during colder time phases reflects the exploitation of topographically and environmentally diverse landscapes in a generally accessible landscape. During cold phases, vegetation and landcover is less of an obstacle for movement.

Contextualising both models

Various reactions to fluctuations in net primary production (NPP) between cold and warm periods by hunter gatherers are known. Such can be changes in residential and logistical mobility (Grove 2014; Hamilton et al. 2016; Kelly 1983). As for example, the number and distance of residential moves vary depending on NPP (Kelly 1983, 2013). Sites such as Niederbieber (Baales 2001; Gelhausen 2011) or Wesseling (Heinen 2008) testify to a system of highly mobile and small bands of hunter-gatherers during the Late Palaeoltihic, representing an increase of residential mobility.

The adaptation of mobile behaviour on the micro- and mesoscale is – among other things – related to a variation in plant-animal subsistence ratio. Hunter-gatherers tend to rely to a larger proportion on plant-based food in tropical environments with a high NPP and on hunted or fished animal resources in climates with a low NPP as for example a Tundra (Cordain et al. 2000; Grove 2010). At the same time body mass and distribution of prey is influenced by environmental factors. Consequently, changes in mobility systems towards the Late Palaeolithic could be seen as reaction to a lower yield in high-ranking prey in warmer climates (Kelly 1983, 2013). Such climates provide higher frequencies of green vegetational biomass located in the treetops (Binford 2001), which leads to a reduced carrying capacity of the low-lying vegetation, resulting in a changed faunal spectrum.

In contrast, a low NPP would favour a higher logistical mobility, minimizing risk in a more hunting-based subsistence (see Grove 2010). Typically, in colder climates with a reduced NPP, the productive vegetational green mass is located close to the ground. This way, it provides sustenance for larger herbivores which are available to the Palaeolithic hunters.

We see changes of catchment sizes as a direct reaction to the factors described above. Further adaptations to changing environmental factors are of technological and sociocultural nature. Maier et al. (2021) show how rates of innovation are correlating with various factors such as climatic variation or relative population size. They show a substantial increase of population during the Magdalenian and the Late Palaeolithic, which is a time when innovation rates increase substantially. The change of the faunal spectrum during the Late Glacial Interstadial Complex is a clear driver for human adaptation to these changing conditions and economic opportunities (Boyle 2017). As a result of our research, maximizing the exploitable territory could be added to the potential spectrum of adaptations.

Conclusion

In this study, we modelled catchments for more than 3,000 sites. Comparing two different modelling approaches we calculated a total of ca. 7,000 catchments for sites of the Upper Palaeolithic in Europe between 42–11.7 ka calBP.

Based on this dataset we were able to compare various scales of landscape accessibility. Model A (excluding additional landcover) gives a better idea of the general site-placement in the landscape, as catchment size is solely dependent on slope. By including an approximate landcover, the catchment size in model B can be considered to better reflect the palaeolithic reality. Furthermore, the comparison of these two models allows a differentiated view on diachronic and supra-regional land-use patterns.

Diachronically, on a European scale we observe preferred site placement in flat regions during warmer periods and a tendency towards the settlement of hilly regions during colder phases. The impeding effect of denser vegetation in the Late Palaeolithic (LPA) is partly compensated by the settlement of level regions. In contrast, settlement strategy during colder phases such as the Early Upper Palaeolithic (EUP) and the Magdalenian (MAG) focusses on the exploitation of topographically diverse landscape elements. By changing the predominantly settled landscapes (level vs. hilly), the gap between the absolute catchment sizes of colder and warmer periods is minimized. The accessibility of landscapes changes throughout the different phases of the Upper Palaeolithic and the humans living therein react to these changing conditions. Therefore, favouring specific accessibility-settings at different times could be seen as one of many adaptive capabilities of human societies in times of changing environmental conditions. By supra-regional comparison of subregions, we see diachronic differences between coastal and landlocked ecoregions which we trace back to differences in the resource-layout.

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