FLORIAN SAUER

LANDFORM-BASED MODELLING OF POTENTIAL BIOLOGICAL DIVERSITY

INFERRING ECOLOGICAL VARIABILITY IN SITE CATCHMENTS FROM DIGITAL ELEVATION DATA

Modelling ecosystems based on topographical attributes is an approach which is employed in environmental conservation to assess biological diversity (a list of case studies underlining the concept is given by Parker / Bendix 1996; Walz 2011; Zimmermann / Thom 1982). This powerful tool allows the generation of data about the biological composition of large areas based on remote sensing data like Digital Elevation Models (DEM). It is based on the assumption that local topography has a profound influence on geomorphic processes which determine the prevailing abiotic framework (Hobohm 2011; MacMillan et al. 2009; Swanson et al. 1988; Walz 2011; Zimmermann / Thom 1982). These conditions determine the presence of biocoenoses that adapted to these specific environmental circumstances. This approach can also be used to model the biological diversity and makeup of prehistoric landscapes, and it can give insight into the potential diversity of biotic resources in prehistoric site catchments. The methodology's benefit is especially prominent when it is used in landscapes where the traditional sources of information, like palynology and faunal assemblages, are absent or at least very scarce.

MATERIALS

The Late Palaeolithic period in north-eastern Bavaria (southern Germany) roughly spans the time from the onset of the Alleröd interstadial to the end of the Younger Dryas (12,000-10,000 years ^{14}C-BP), although this chronological placement is largely based on typological comparisons. Exceptions are the sites of the Sesselfelsgrotte in the Altmühl Valley (chronostratigraphy: Younger Dryas), and a worked antler out of the Main deposits at Bergrheinfeld in Lower Franconia (10,995-10,730 years cal. BC; Weidinger 1996). The influence of the Younger Dryas cooling phase on the vegetation in the study area seems to have been only very limited (Frenzel 1983, 147; Knipping 1989, 107). Thus, the biological background of the Late Palaeolithic in this area is considered to be quite uniform. The sites in the study area are assigned to the Arch-backed Point (ABP) technocomplex (Valde-Nowak / Kraszewska / Stefański 2012) due to the frequent presence of backed points in the assemblages. Traditionally, sites in the study area were also dated based on a supposedly »typical« raw-material utilisation (Cretaceous flint, Abensberg-Arnhofen chert, and lydite; Schönweiß 1992), but due to the obvious flaws of this approach these sites will not be used here. Accordingly, a total of 91 sites are present (**fig. 1**).

The study area was set based on the ecological classification of Germany. It subdivides Germany into units of great ecological, geomorphological, and hydrological homogeneity and therefore provides the best basis for delimitation. Accordingly, five units were chosen: the Keuper-Lias-Land, the Franconian Alb, the Franconian-Thuringian Mountain Range, the Upper Palatinate Valley, and the Upper Palatinate Forest (**fig. 1**). This article focusses mainly on the sites situated in the Upper Palatinate Forest.

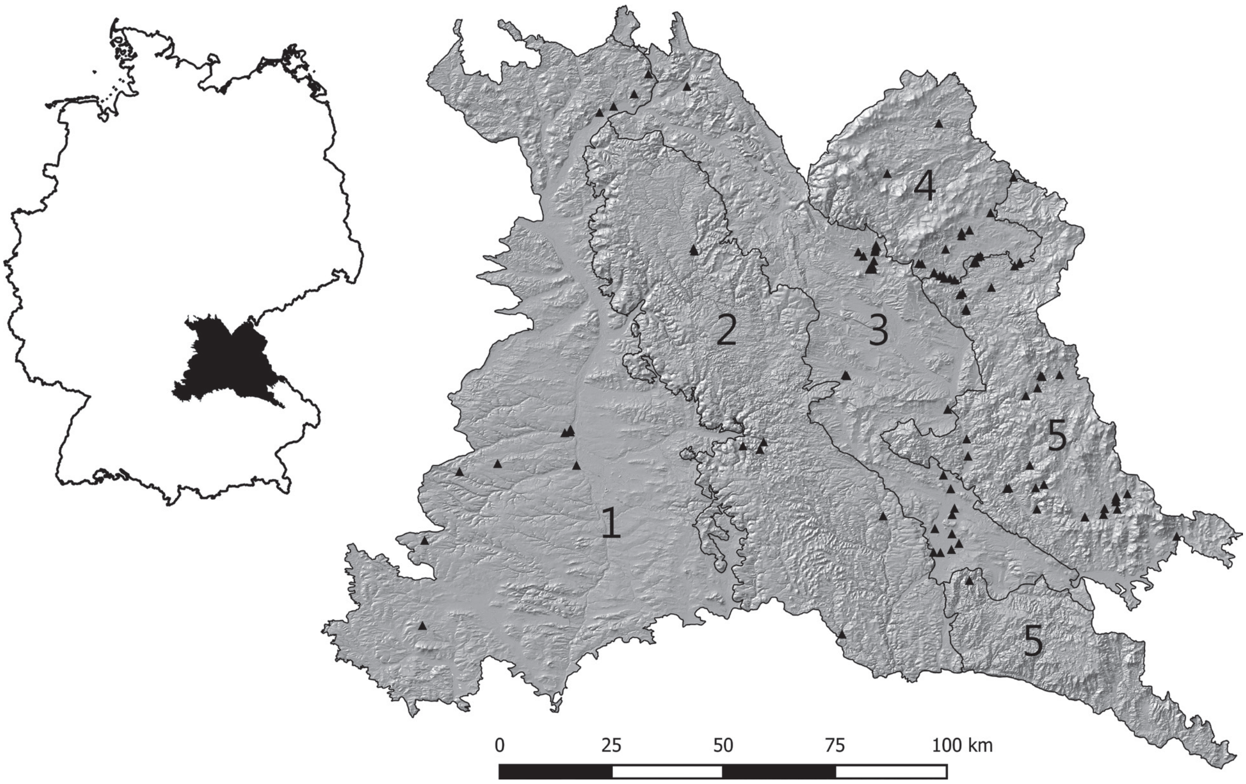

Fig. 1 Location of the study area in Germany (left) with subdivision into ecological landscape units (right): **1** Keuper-Lias-Land. – **2** Franconian Alb. – **3** Franconian-Thuringian Mountain Range. – **4** Upper Palatinate Valley. – **5** Upper Palatinate Forest. – Black triangles represent sites used in this study.

Information on Lateglacial fauna and vegetation is very limited in the study area. Though there is a small number of publications on Lateglacial vegetation history, they only present very selective information (Frenzel 1983; Hahne 1991; 1993; Knipping 1989; Kortfunke 1992; Stalling 1987). This way it is difficult to examine the biotic factors that may have led to the placement of a campsite in the landscape. This situation is amplified by the fact that nearly all of the sites known in the application area are represented by surface collections. These yielded no supplementary information concerning the use of organic resources. One of the few excavated locations is the site of Steinbergwand at Ensdorf, which could provide limited information on fauna and vegetation (Gumpert 1933). The methodology presented here aims towards providing an alternative approach to assess environmental conditions in the landscape. Based on the assumption that the location of a campsite is not selected randomly, but very much based on economic criteria of its immediate environment (Jochim 1976), the biotic factors, among others, in the catchment of the site could be linked to different adaptive strategies (Brouwer Burg 2012), and to intrasite activities. These activities are represented by the lithic assemblages, provided that the extraction of biotic resources was the dominant activity. However, it is obvious that other criteria like lithic raw material procurement or water availability are not covered by this approach, but can be equally important. They will be covered in the underlying PhD project this methodology is a part of.

The calculations were conducted using the digital ground model DGM25 for Bavaria with a resolution of 25 m and a Root Mean Square Error (RMSE) of ± 0.3 m. The DEM, generated by photogrammetry and airborne laserscanning, was provided by the Bavarian Geodesic Administration (Bayerische Vermessungsverwaltung).

This approach is part of the PhD project »Late Palaeolithic Land Use Patterns in Northern Bavaria« at the Friedrich-Alexander-University Erlangen-Nuremberg. The project also covers the typological analysis of lithic assemblages in the study area and the raw material procurement patterns. However, this line of investigation is not discussed in this paper. As this is only a presentation of the methodology, no statements will be made as to whether the connection between assemblage and catchment is visible on this scale.

METHODS AND THEORY

The approach is based on the interrelation of phytocoenosis composition and topography. The morphology of the landscape influences the environmental factors that limit or promote plant growth on many levels. Energy and mass flux, moisture, nutrition, precipitation and solar radiation rates, propagule transport and non-geomorphically induced disturbance factors, such as fires and floods, affect the pattern of phytocoenoses in the landscape in relation to their specific needs (Swanson et al. 1988). Plants are not randomly scattered throughout the landscape, but rather are related to its suitability (Zimmermann/Thom 1982, 50). Thus, certain topographic conditions are more suitable for specific plants and plant communities than others. A landscape providing a very heterogeneous morphology would consequently show a relatively high level of diversity in environmental conditions, and therefore in plant communities.

Geomorphic heterogeneity can be expressed in many different ways. Here, landforms were selected as units of measurement. They allow, on the one hand, the measurement of topographic diversity in any given area, and on the other hand, the measurement of regularities and irregularities in the composition of the specific areas. This way, different areas can easily be compared to one another.

Landforms are components of the landscape that separate themselves from the surrounding areas by their distinct geomorphologic characteristics (Bates/Jackson 1987). Another definition emphasises the links of the landforms to physical processes that take place within their boundaries: »a terrain unit created by natural processes in such a way that it may be recognised and described in terms of typical attributes wherever it may occur« (MacMillan/Shary 2009, 228). These different units, »valleys«, »plains«, »ridges«, or »slopes«, are the components that make up the landscape. They are also the scale on which physical processes are the dominant factor determining the spatial pattern of plant societies in the landscape (Zimmermann/Thom 1982, 52). The second definition shows that specific geomorphic and geophysical processes can be linked to specific landforms. This way, hypothetical plant communities can be assigned to these units. A high diversity of landforms therefore correlates with a high level of biological diversity.

In this archaeological approach to Predictive Ecosystem Mapping (PEM), biodiversity is understood as it was defined by the Convention on Biological Diversity: »Biological diversity means the variability among living organisms from all sources including, *inter alia* terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part« (United Nations 2014). This includes, but is not limited to, the flora and fauna that are understood as typical resources for prehistoric humans. Diversity therefore cannot be understood as a proxy that shows the availability of prehistorically important resources, but rather describes their potential variability, whether exploitable by prehistoric humans or not.

A plethora of different methods is available for landform classification (Barka/Vladovic/Malis 2011). In this case the Topographic Position Index (TPI) Based Landform Classification Algorithm, as it was developed by Jennes (2005; 2006) and Weiss (2001), was used. It compares the TPI on two different scales to classify the landscape into discrete geomorphological features (**figs 2-3**). The algorithm is part of the SAGA software and is capable of classifying any given DEM raster (Department of Physical Geography Göttingen/Department of Physical Geography Hamburg/SAGA User Group Association 2014). The benefit of using landforms

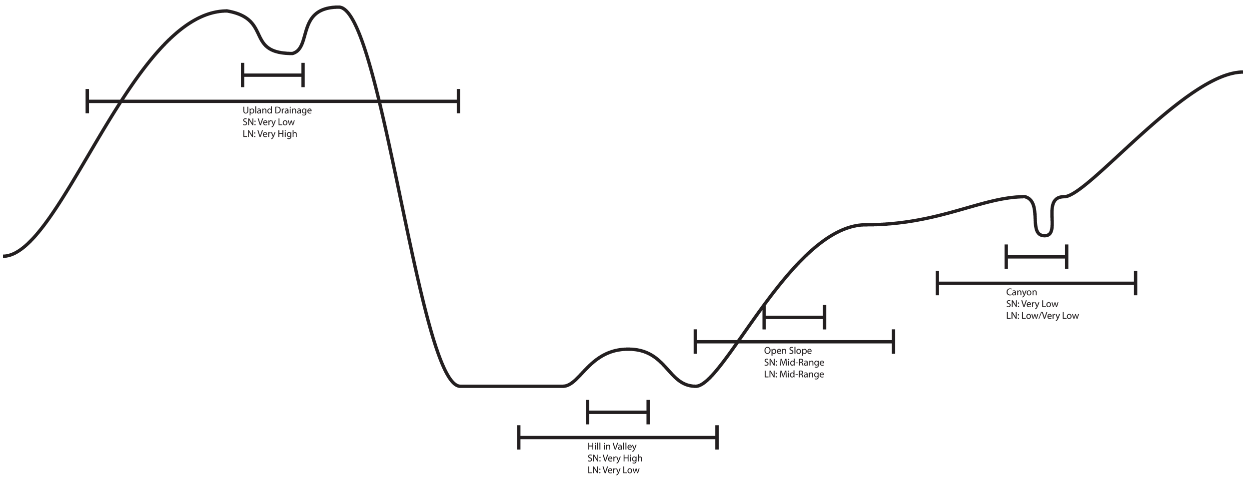

Fig. 2 Model of the landform classification using the Topographic Position Index (TPI). – SN: Small Neighbourhood; LN: Large Neighbourhood. – (After Jennes 2006).

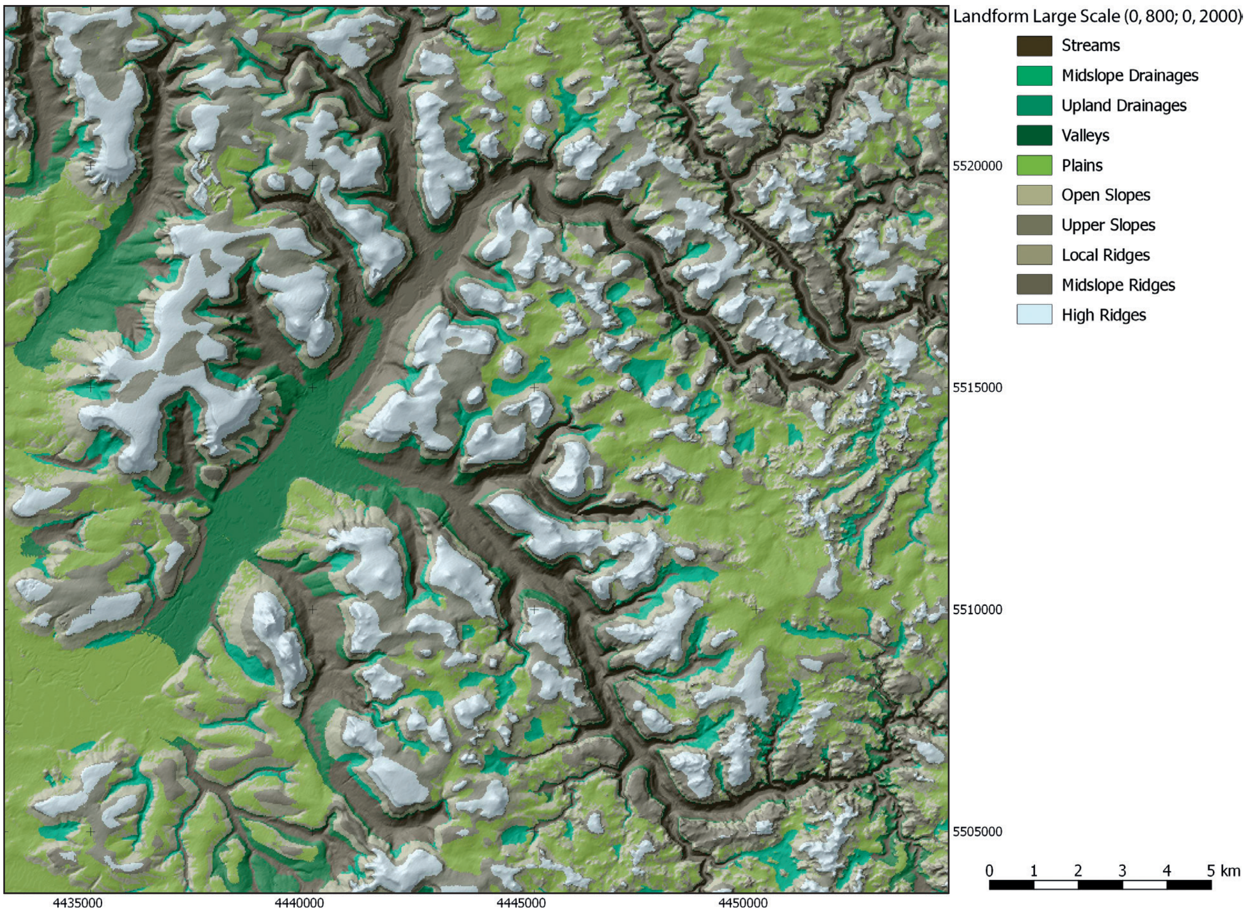

Fig. 3 Exemplary result of the landform modelling process (TPIs used for classification: SN [Small Neighbourhood] – 0 m, 800 m; LN [Large Neighbourhood] – 0 m, 2,000 m); Wiesent Valley and tributaries, Franconian Alb.

for classifying the landscape is the fact that they show a specific makeup of geomorphological and geophysical processes, which determine plant growth within their boundaries (Swanson et al. 1988). It allows to correlate hypothetical ecotypes with the landforms modelled using GIS software because of the plants' specific needs and limitations.

Landform	Wetness	Erosion/deposition	Disturbance	TPI
Canyon/V-shaped valley	very high wetness high flow rates	seasonal flooding and erosion events	intense seasonal disturbance	SN: low LN: low
Midslope drainages/shallow, local valleys in plains	medium wetness	seasonal erosion events or seasonal flooding	landslides	SN: moderate LN: low
Upslope drainages/headwaters	medium to high wetness	seasonal erosion or flooding events with moderate or intense deposition	storm damage	SN: low LN: high
Valley/U-shaped valleys	high wetness low flow rates	seasonal flooding events with intense deposition	landslides	SN: moderate LN: low
Plains	moderate wetness to dry	low to none	seasonal fire storm damage	SN: moderate LN: moderately low slope = 0
Broad open slope	dry	low erosion or low deposition rates	storm damage	SN: moderate LN: moderately high slope > 0
Upper slopes/mesas/flat ridge tops	dry to very dry	low to medium erosion rates	landslide storm damage	SN: moderate LN: high
Local ridges/hills in valleys	dry to very dry	low to moderate erosion rates	landslide storm damage flooding protection	SN: high LN: low
Midslope ridges/small hills in plains	very dry	low to moderate erosion rates	landslide storm damage	SN: high LN: moderate
High ridges/mountain tops	very dry	high erosion rates	storm damage	SN: high LN: high

Tab. 1 Landform units provided by the classification algorithm and related properties. – TPI: relation of Small (SN) and Large Neighbourhoods (LN) for classification.

By using the TPI, which calculates the relative position of a pixel in relation to the elevation of the surrounding pixels in a given radius on two different scales (SN: Small Neighbourhood; LN: Large Neighbourhood), the landform classification algorithm produces a thematic raster with ten different landform classes, ranging from »canyons« to »high ridges« (**tab. 1**). Based on the radii, which are entered for calculation, different classification scales can be obtained. Very small radii result in a very high resolution of the resulting map; small features in a very local context will be pronounced. A large scale will extract features on a more regional level, resulting in more extensive landform units. The use of different scales has a direct influence on the topographic diversity of the landscape. Small TPIs would result in a greater number of pixels that are classified as »plains«. The »plains«-landform represents areas where there is hardly any change in elevation. By expanding the scale, areas that are classified as something other than »plains« are expanded as well, because a change in elevation is more likely.

Therefore, choosing the right scale for analysing the landscape composition is paramount. In the case of this approach, three different scales, ranging from small to large will be employed. This allows for the examination of potential influences of topography on biodiversity in relation to scale.

Since prehistoric biological diversity is inferred from modern topographical information it has to be kept in mind that topography is not a constant through time, but, at least in some cases, subject to substantial change. In this case, though, the modelling is done on a relatively large scale, and therefore changes in relief may have only limited influence on the results of the examination of the Lateglacial landscape. Landforms exist over a relatively long time, compared to other geomorphological units (Ahnert 2009, fig. 1.3). However, there are cases in which there may be a significant influence on the results. These instances are, on the one hand, areas that show a high degree of geomorphological activity, and, on the other hand, time phases that date back a particularly long time. These changes should always be considered when examining a working area. A possibility to reduce the influence of geomorphological change on the results is to choose a relatively large scale of modelling. This way the modelling focus lies on larger landscape features, and spatially limited change in topography has only little influence on the results. However, this will also lead to relatively coarse modelling results.

For comparing the catchments of the different sites in respect to their potential biological composition, the catchments were modelled using a cost distance calculation (Uthmeier / Ickler / Kurbjuhn 2008). It examines the accessibility of the landscape based on the topography in relation to a point of origin. Tobler's »Hiking Function« (Tobler 1993) gives back an estimation of the time required to cross a raster pixel depending on its slope. A basic speed of 0.89 m/s was used for calculation, as it was measured for trail hikers in the Yosemite National Park (van Wagtendonk / Benedict 1980). By adding up the values to a threshold value, for example the maximum foraging distance, as it is known from ethnological comparison, it is possible to calculate the size of the foraging radius (Binford 1982; 2001). Within the boundaries of the catchment-radii the landforms are then sampled and form the basis for further analysis (**fig. 4**). The sampling was done using the ArcGIS Plugin GME 0.7.2.0 (Geospatial Modelling Environment for ArcGIS).

The benefit of cost distance calculation as a tool for catchment modelling is the fact that the sampling results are weighted by their accessibility. Local landform features that can be reached quite easily will play a much more important role than features which are situated further away from the site in an environment that shows a bad accessibility. To examine this change by distance, the catchment was divided into circular isochrone rings with a width of one hour each. This way it is possible to examine whether specific conditions were favoured in a specific distance to the site. These could be a favourable ecological diversity or a specific composition of ecotypes.

Many different models of interpretation could arise, looking at the distribution of diversities throughout the landscape. Sites that reflect a very low ecological diversity in their vicinity and a very high diversity further away could reflect a preference of a specific set of resources close to the camp. A very good accessibility of these specific resources could have been an important factor for site placement (Jochim 1976, 50-51). Furthermore, characteristics of a special task camp could be prominent in the site's lithic assemblage, reflecting the economic focus. In turn, if the situation was inverted, a broad resource basis could have provided a high level of economic security (Jochim 1976, 16). Characteristics reflecting a base camp could be prominent in these cases. Anyway, the site / catchment relationships probably are much more complex than these examples suggest.

As it was already stated at the beginning of this article, the landforms could be correlated with hypothetical ecotypes due to their specific environmental conditions and the individual needs of the vegetation. Therefore, the combination of ecotypes in the catchments of the sites could provide an insight into preferred combinations of ecological entities. Again, the subdivision of the catchment into circular rings could show the change of the ecological makeup in relation to distance.

PRELIMINARY RESULTS

Analysing the results of the modelling process, sites in the landscape can be categorised into three different sets of potential biological diversity in regard to their catchment radii and the transportation cost. The sites of Lindenloh (Lkr. Tirschenreuth), Schönthal (Lkr. Cham; **fig. 4D**) or Oberweiherhaus (Lkr. Schwandorf; **fig. 4B**), for example, show a very low level of diversity in close range. With increasing distance to the centre of the catchment it rises to a relatively high level. On the other hand, the sites of Schlattein (Lkr. Neustadt

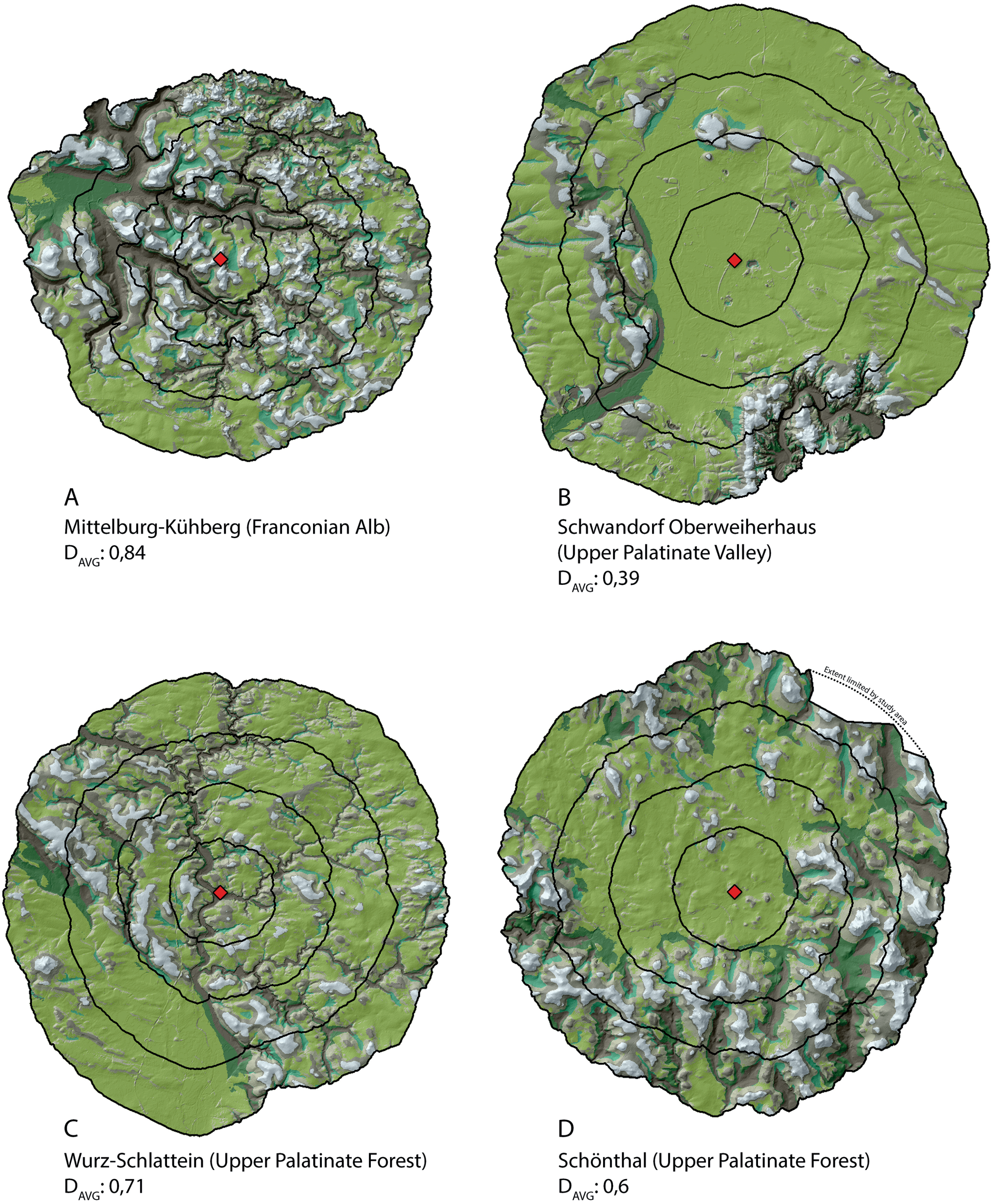

Fig. 4 Catchment-discs for the four sites mentioned in **tab. 1**. Subdivision: 1 h; landform classification: SN – 0 m, 800 m, LN – 0 m, 2,000 m.

a. d. Waldnaab; **fig. 4C**) and Weißenhof (Lkr. Schwandorf) show a decrease in potential diversity. The sites of Mittelburg-Kühberg (Lkr. Nürnberger Land; **fig. 4A**), Atzenhof (Fürth), Ritzmannshof (Fürth), and Zangenstein (Lkr. Schwandorf) show a consistent level of high or low diversity.

Site	1 h radius D_i	2 h radius D_i	3 h radius D_i	4 h radius D_i	D_{AVG}
Lindenloh	0.05-0.07	0.32-0.41	0.55-0.59	0.61-0.71	0.42
Oberweiherhaus	0.1-0.14	0.35-0.38	0.51-0.63	0.46-0.52	0.39
Schönthal	0.25-0.27	0.56-0.66	0.66-0.80	0.73-0.85	0.6
Schlattein	0.76-0.8	0.74-0.77	0.65-0.68	0.60-0.63	0.71
Weißenhof	0.78-0.8	0.77-0.81	0.53-0.55	0.60-0.66	0.7
Kühberg	0.84-0.87	0.84-0.88	0.83-0.87	0.78-0.82	0.84
Atzenhof	0.23-0.3	0.16-0.21	0.2-0.24	0.24-0.26	0.23
Ritzmannshof	0.25-0.33	0.18-0.24	0.24-0.28	0.25-0.27	0.26
Zangenstein	0.78-0.84	0.79-0.84	0.8-0.84	0.74-0.80	0.81

Tab. 2 Selection of changes of potential ecological diversity in relation to distance; the variance is due to the different scales in landform modelling (D_i: Diversity index of the individual circular ring; D_{AVG}: Diversity average).

Activities related to the sites of the first group would have to focus on the availability of a more or less limited set of biotic resources in the vicinity of the site and a greater bandwidth of resources further away from the camp. The ecological potential of the sites' catchment would allow only a limited range of different bioresource-exploitation tasks to be carried out, and the low transportation distance would suggest that the camp was placed in a convenient distance to the resource so that transportation costs to move the yield back to the camp would be relatively low (fig. 4B. D; tab. 2).

In contrast, tasks related to spots of the second category would focus on a great variety of potential organic resources close to the site and a more specific set in a greater distance. If one considers transportation costs, the possibility to easily exploit a great variety of nearby resources would have been the dominating factor in the decision making process that led to site placement. Furthermore, the great number of different organic resources would have permitted to carry out a great number of different tasks (fig. 4C; tab. 2).

The third group of sites does not seem to focus on the distance in which specific sets or diversities of biogenic resources are available, but rather on their general availability. Viewed from a logistical point of view, it would not have been necessary to travel far from the site to access a different variety of resources, because the biological potential is distributed more or less evenly throughout the catchment. In a sense, these sites could very well reflect the first two categories presented before, with a difference in the way resources placed in the hinterland contributed to the sites' economy (fig. 4A; tab. 2).

Another way to work with the results of the modelling process would be to look at the specific composition of different landform types in the varying catchments. This approach is based on the idea that the geomorphic processes that correlate with a specific landform type determine the ecotype that is placed within the boundaries of the geomorphic unit. Therefore, one can assume that throughout the landscape the same landform usually produces a more or less identical set of biotic resources. A preference for a specific landform by prehistoric humans thus would suggest a focus on the related organic resources, whatever they may be. Although this part of the methodology is still under development, and furthermore is aimed on the comparison of lithic assemblages and catchment composition, a brief example will be given here.

The sites analysed in this example all are situated in the ecological landscape unit of the Upper Palatinate Forest (fig. 5). It is an area that is composed of a very heterogeneous geomorphology. Landforms reflecting this topography, like »canyons«, »ridges«, and »slopes«, are prominent. A total of 37 sites were analysed using cluster analysis (1 h catchment; large landform modelling scale SN: 800 m; LN: 2,000 m). By using the

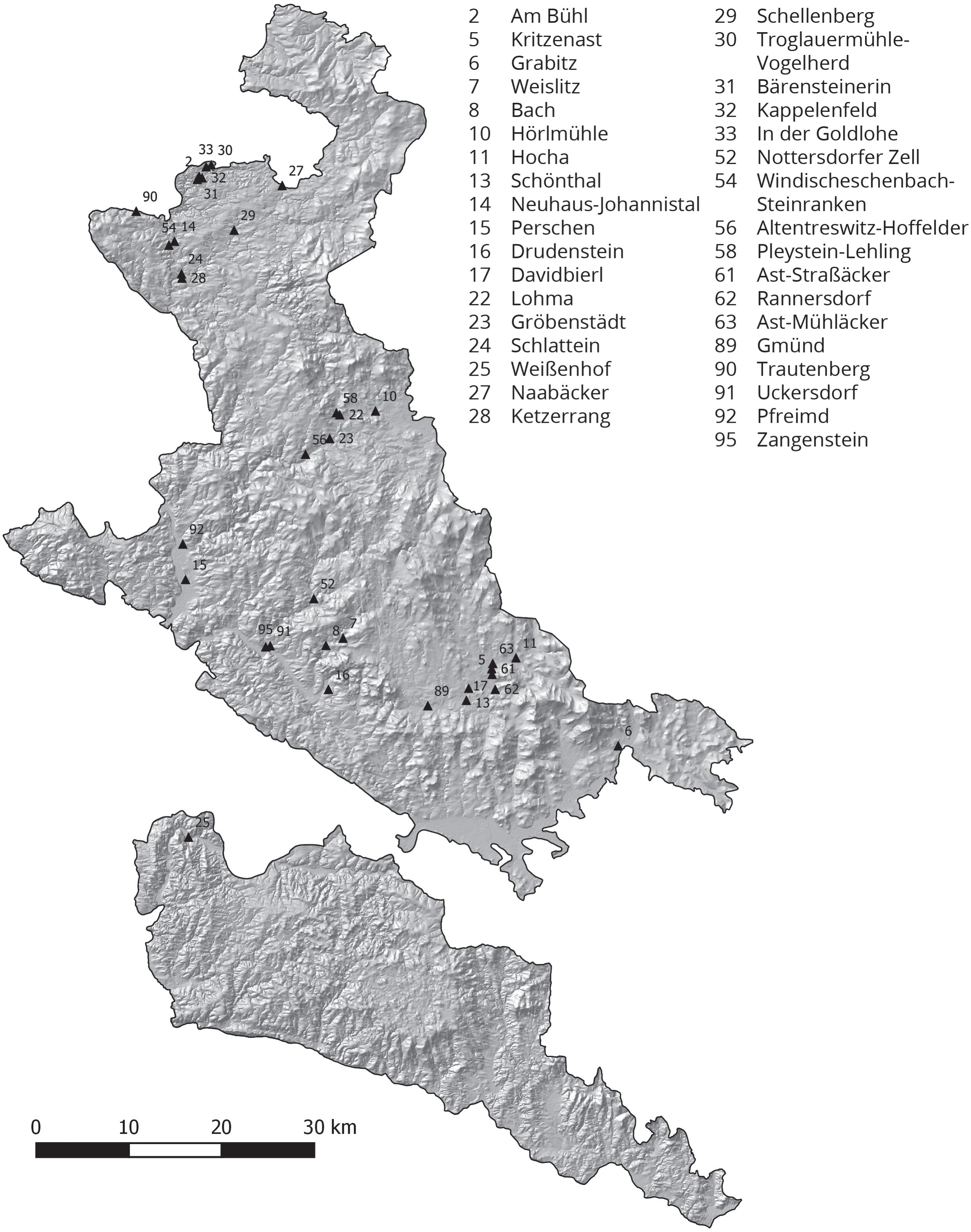

Fig. 5 Landscape unit and sites of the Upper Palatinate Forest. – Black triangles: sites used for cluster-analysis presented in **fig. 6**.

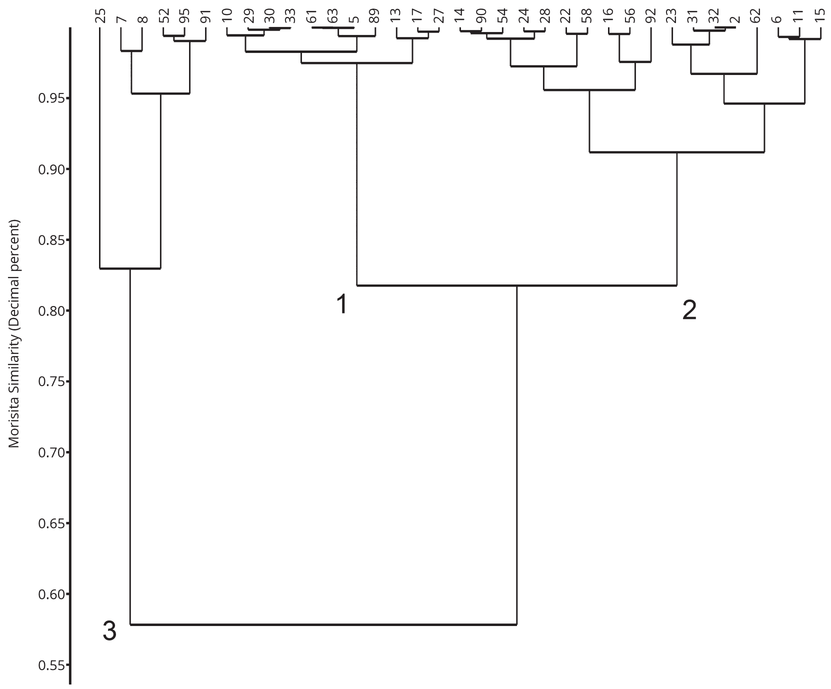

Fig. 6 Cluster analysis of 37 sites in the Upper Palatinate Forest; 1 h catchment radius, TPIs used for landform classification: SN – 0 m, 800 m; LN – 0 m, 2,000 m (Cluster analysis: PAST 3.04).

	LFT 1	LFT 2	LFT 3	LFT 4	LFT 5	LFT 6	LFT 7	LFT 8	LFT 9	LFT 10
	canyons	midslope drainages	upland drainages	valleys	plains	open slopes	upper slopes	local ridges	midslope ridges	high ridges
Cluster 1	2 %	2 %	0 %	4 %	70 %	16 %	1 %	0 %	2 %	3 %
Cluster 2	10 %	4 %	0 %	7 %	39 %	28 %	2 %	0 %	6 %	5 %
Cluster 3	24 %	5 %	0 %	13 %	10 %	24 %	5 %	0 %	9 %	11 %

Tab. 3 Arithmetic mean values of the different clusters' landform types (LFT).

»Morisita Similarity Index« (Hammer / Harper / Ryan 2001) for abundance data, the sites could be grouped into three main clusters. They suggest a division of the camps into three basic types in respect to their catchments' landform composition (**fig. 6; tab. 3**).

The first cluster reflects sites which are placed in a relatively flat landscape. »Plains« and moderately sloping areas make up the greatest percentage of the catchment. The second group is still dominated by flat surface landform types, but also shows a limited shift towards other units. The third group seems to be completely different to the other two. Here, »ridges« and »canyons« are the most important features. If one assumed the correlation and causation of landforms and ecotypes, this would show three types of sites that would have to focus on three different sets of resources.

The next step of this approach would be to analyse a possible correlation of the catchments' landform composition and diversity, and the accompanying lithic assemblages. The greatest problem probably will be the question whether the variations of the modelled biological composition of the landscape really translate to the lithic assemblages at the different sites. The resolution of both the assemblages and the modelling results could be too low to see correlations. Also different foci of the sites, for example on non-organic resources, as well as a small net production, which is not limited by specific compositions, could disturb the picture. This step, though, cannot yet be presented in this article, because it is part of the PhD project mentioned above.

CONCLUSIONS

The benefit of this methodology is not only to gain information about environmental conditions in areas where there is no other or only scarce information, but also the possibility to analyse the prehistoric use of organic resources throughout the landscape. Typical sources of environmental information, like palynology and fauna, can still be used in this approach to calibrate and compare the results of the modelling processes. Other information levels, like soil information or wetness indices, could also improve the resolution as well as the predictive capacities of this modelling approach. The basic question that will be tested in the PhD project mentioned earlier will be whether the differences in ecological makeup that can be modelled by PEM can be traced back to the lithic assemblages. It is possible, however, that this scale of changes in biological composition throughout the landscape does not translate to the level of the lithic assemblages. The approach is not limited to the Palaeolithic, but is usable in any case where insight into the interaction between site and environment is important.

Acknowledgements

This paper represents the state of work in 2014. Since then the project has been finished and a comprehensive analysis can be found with the published PhD (Sauer 2018). Many thanks for the support for my participation in the UISPP Congress in Burgos to the UISPP organisers and the reviewers of this article for their helpful comments.

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Summary

Insights into the ecological composition of a site's catchment are rarely possible in many cases. Usually, no information is available on the vegetational makeup of the surrounding landscape. In this article a methodology is presented which uses topographic information to model the potential biodiversity in the landscape. It is based on geomorphic processes that coincide with different geomorphological units, the so-called landforms. Furthermore, these processes influence the composition of the vegetation that yields important resources for hunter-gatherers. Hence, the geomorphic processes have a direct influence on the bio-economic potential of a site's catchment.

Keywords

Predictive Ecosystem Mapping, Catchment Analysis, Late Palaeolithic, Bavaria