CAA
2018

Jan Miera et al.
https://dx.doi.org/10.15496/publikation-87758

Modeling Timescapes: Delineating Site Exploitation Territories (SET) by Using Topography Derivates and the Open-Source Statistical Language R

Jan Miera*
Historisches Seminar, Westf. Wilh.-Universität Münster
jmiera@uni-muenster.de
**previously published under the name Jan Johannes Ahlrichs*

Karsten Schmidt
eScience-Center, Universität Tübingen
karsten.schmidt@uni-tuebingen.de

Philipp Gries
SFB 1070 RessourcenKulturen, Universität Tübingen
philipp-matthias.gries@uni-tuebingen.de

Abstract

This paper provides a review of the history and archaeological applications of Site Exploitation Territories (SET) and presents the first seamless workflow for defining SET using the open source statistical language R. The concept of the SET was developed in the 1970s as an analytical tool to study finds from archaeological sites in relation to their geographical environment. A SET designates a time-distance based territory, which is visited on a daily basis by sedentary farmers or mobile groups as they deal with their subsistence. Therefore, the shape of a SET depends on the topography surrounding a site: In landscapes with a flat relief SET have an almost circular shape, in mountainous regions they are more distorted. Until recently, the determination of SET was performed manually using simple walking distances. Today, these results are hardly reproducible. The presented workflow is easy to use and calculates SET in a fast and reproducible way while taking into account walking speed and topography (slope) via Tobler's Hiking Function. It is tested on four digital elevation models (DEM) using 87 settlements dating to the pre-Roman Iron Age, located in the Baar region in south-western Germany. Based on the results of the case study, we recommend the use of open source CGIAR-CSI SRTM data. The results are nearly identical to those based on LiDAR data and require significantly less computational time for processing.

Keywords: Site Exploitation Territory, Settlement Archaeology, Archaeological Theory, Slope, Toblers Hiking Function

Introduction

With the advent of the Processual Archaeology in the 1960s, the research interest in economic issues started to grow increasingly (Trigger 2008: 386–444). Within the so-called "New Archaeology" scholars criticized the fact that archaeological studies on economy mostly focused on the analysis of material remains from single archaeological sites and did not discuss the finds in relation to their geographical environment (Higgs & Vita-Finzi 1972: 27–28; Jarman, Vita-Finzi & Higgs 1972: 61–62). At the University of Cambridge, a research group led by Eric S. Higgs developed a methodological concept, which enabled archaeologists to overcome this way of "isolated" analysis and to study archaeological sites in the context of their geographical environment. Inspired by the work of geographers (von Thünen 1826; Christaller 1933; Chrisholm 1968), archaeologists (Thomson 1939) and anthropologists (Lee 1969), they developed the concept of Site Exploitation Territories (SET) along with the Site Catchment Analysis (SCA) (Higgs & Vita-Finzi 1966: 23–29; Higgs et al. 1967: 12–19; Vita-Finzi & Higgs 1970; Roper 1979). The concept was developed and introduced in the series Studies by Members and Associates of the British Academy Major Research Project in the Early History of Agriculture (Higgs 1972; Higgs 1975; Jarman, Bailey & Jarman 1982). The term 'Site Exploitation Territory' refers to a territory that is defined by time-distances and is commonly used by the inhabitants of a site (Vita-Finzi & Higgs 1970: 7; Higgs & Vita-Finzi 1972: 30; Jarman 1972: 708). The fundamental difference between SCA and SET is that SCA does not consider time-distances. In SCA, the territory belonging to a site is not determined by walking distances but by a fixed radius of several hundred meters. Therefore, SCA works with circular territories and does not take into account the heterogeneity of the terrain that surrounds a site (Roper 1979; Brooks 1986; Miera 2020: 329–333).

Archaeological Applications

Researchers took the view that comparative studies on the changing human-environment relationships in mobile and sedentary societies require an analysis of the land use potential of territories belonging to archaeological sites (Vita-Finzi & Higgs 1970: 1; Higgs & Vita-Finzi 1972: 28–29; Foley 1977: 163). Within the framework of SET, they did not only study the availability and usage of natural resources in the catchment area of individual sites, but also how economic strategies of prehistoric societies contributed to environmental changes and how they interact (Vita-Finzi & Higgs 1970: 5; Higgs & Vita-Finzi 1972: 27). The concept of SET and SCA facilitated a description of the economic function of an excavated site through an in-depth analysis of archaeological finds with respect to the ecological and geographical environment of the site (Higgs & Vita-Finzi 1972: 28; Jarman 1972: 725; Jarman, Vita-Finzi & Higgs 1972: 61–62). Thus, sites were no longer considered as isolated case studies but as part of economic 'systems' (Jarman 1972: 715; Davidson 1981: 21–23). Based on a comparative analysis of archaeological sites dating to different epochs and periods Higgs and his co-researchers were able to obtain general conclusions about long-term trends in human-environment relationships (Jarman 1972: 714; Jarman 1976: 546). Geoff N. Bailey and Iain Davidson (1983: 88) summarized the strengths of SET:

1. Definition of a territory used on a daily basis within the framework of the subsistence strategies practiced at the site.

2. Analysis of the origin of natural resources recovered at archaeological sites.

3. Reconstruction of the vegetation history of the vicinity of a site in order to assess the changes in the botanical and zoological data from the site.

4. Reconstruction of the potentially available food for the inhabitants of a site and the subsistence strategies associated therewith.

5. Reconstruction of the function of a site (permanently inhabited, etc.).

6. Reconstruction of social and economic relations between sites within a regional settlement system.

In addition, the results of SET can be used in order to estimate potential site distributions (Jochim 1976; Tiffany & Abbott 1982). Altogether, the concept of SET provides an analytical approach, which enables researchers to link theory with data. Therefore, it qualifies as a ‚middle-range theory' (see Trigger 1995; Tschauner 1996).

Theoretical Premises

The concept of SET operates with the idea that human behaviour in the past can be described by 'laws' (Clarke 1968: 441–511; Higgs & Jarman 1975; Jarman 1976: 523). One of the main assumption is that people have a territorial behaviour and do not select sites at random (Vita-Finzi & Higgs 1970: 2; Higgs & Vita-Finzi 1972: 30; Jarman 1972: 706, 712). Furthermore, it is assumed that each site has an optimal geographic location considering its economic function. Consequently, it is expected that mobile groups, whose subsistence was pasture farming, preferred locations, which were favorable for grazing. On the other hand, archaeological sites from sedentary societies are expected to be located in areas suitable for agriculture

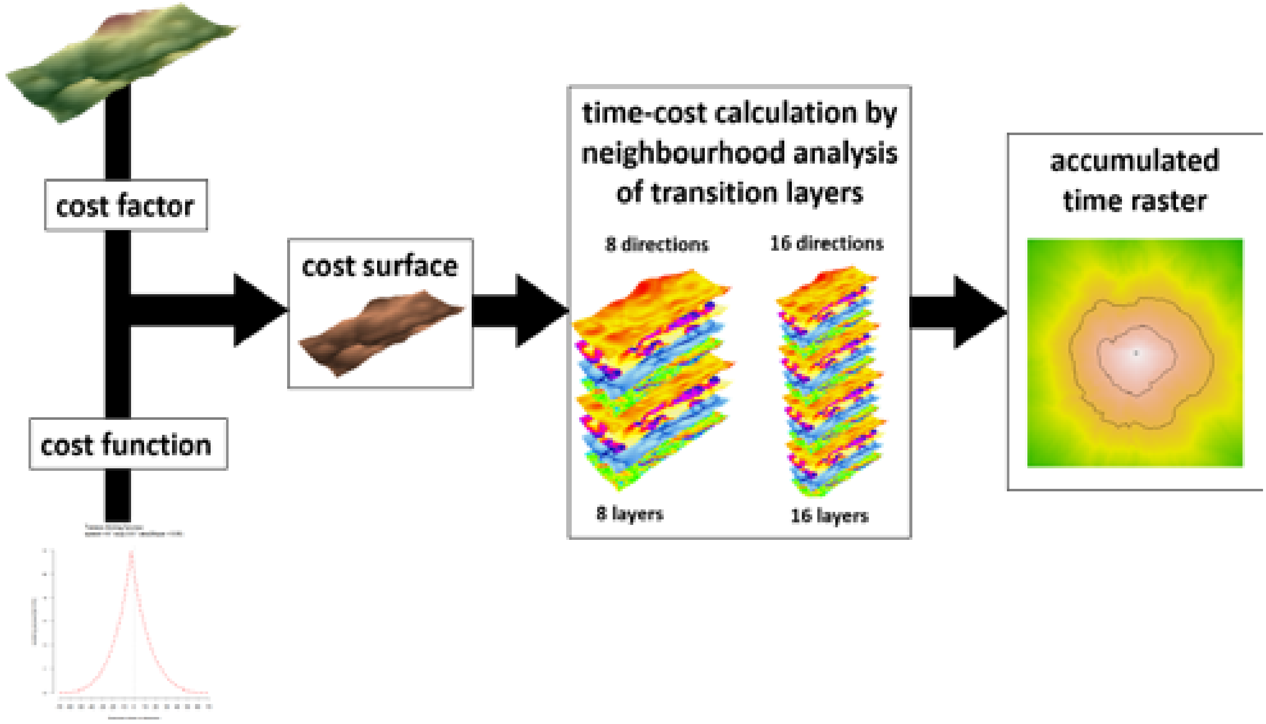

Figure 1. General workflow for time-cost analysis in four steps.

(Vita-Finzi & Higgs 1970: 2; Jarman 1972: 706; Jarman, Vita-Finzi & Higgs 1972: 62–63). Closely related to this premise is the notion that human action is determined by cost-benefit calculations and is constantly focused on efficiency, i. e. to meet ones economic needs with the lowest possible effort (Jarman 1972: 710 [citing Zipf 1965]; Jarman, Vita-Finzi & Higgs 1972: 62–63; Tiffany & Abbott 1982: 313–314). This behaviour ultimately leads to the premise that the probability to exploit an area decreases with distance (Vita-Finzi & Higgs 1970: 7; Jarman, Vita-Finzi & Higgs 1972: 62–63).

Time-Distance Factors

One of the key ideas of the concept is the assumption that the geographic scope of SET in mobile and sedentary societies differs from one another and can be described by time-distance factors. Referring to Lee (1969) on the !Kung San it was assumed that the SET of mobile groups includes a maximum radius of 10 km, which equates on flat terrain a maximum distance of two hours' walk (Higgs & Vita-Finzi 1972: 30–31; Jarman, Vita-Finzi & Higgs 1972: 62–63; Bailey & Davidson 1983: 91–92). With reference to Chrisholm (1968) Higgs and his team proposed a maximum radius of 5 km for sedentary societies (Higgs & Vita-Finzi 1972: 30–31; Jarman, Vita-Finzi & Higgs 1972: 62–63). In this context, they pointed out that the degree of exploitation within that radius decreases with increasing distance. Especially for sedentary societies, the nearest neighbourhood (radius < 1 km) is most important for the economic analysis (Higgs & Vita-Finzi 1972: 30–31; Jarman 1972: 713; Bailey & Davidson 1983: 92).

However, as Bailey and Davidson (1983: 93) pointed out, there are no universally valid time-distance factors for the analysis of prehistoric sites. The above mentioned time-distance factors represent idealized values whose ethnographic origin loses all its meaning as soon as they are applied to archaeological case studies (Davidson 1981; Bailey & Davidson 1983: 91). The differentiation between a 10 km SET for mobile groups and a 5 km SET for sedentary societies has to be understood as a model providing an analytical access to the discussion of the economic function of archaeological sites.

Field methods

Until the beginning of the 21th century the determination of SET was performed manually (see Valde-Nowak 2002: 65). In the 1970s, pedometers and maps were used (Jarman 1972: 712). Depending on the location of the site, four or more transects in different directions were used to determine its potential exploitation territory by analysing the walking distance within a specific time frame. Based on the experiences and notes from the field survey, 'time-contour lines' or 'isochronic distances' were drawn on a map (Jarman 1972: 713; Higgs 1975: appendix A; Bailey & Davidson 1983: 93). Obviously, this approach is very time consuming and expensive. In addition, the SET that were defined using this approach are subjective and no longer reproducible today. Bailey and Davidson summarized some of the major difficulties in determining the ‚isochronic distances': „In practice the walks were often carried out by students who were unfamiliar with the terrain, unused to walking long distances, and whose transects were influenced one way or another by modern roads and footpaths, barbed wire fences, bulls, unfriendly dogs or landowners, and the location of bars! The original Mt. Carmel study also had to allow for minefields and military manoeuvres" (Bailey & Davidson 1983: 93). In order to deal with some of these hurdles, Bailey and Davidson combined field surveys with the analysis of topographic maps. They applied rules developed by William W. Naismith, which were used by mountaineers to calculate time-distances. In principle, Naismith assumed that in two hours on flat ground a distance of 10 km can be covered on foot, for each 300 meters altitude difference an additional half hour is added: *„On a map at scale 1:25.000 with contours at 50 m intervals, isochronic limits may be calculated with a pair of compasses. With the compasses set at 1 cm, each unit of distance on the map is equivalent to 3 min. on the ground, and each contour is equivalent to an extra 5 min*" (Bailey & Davidson 1983: 94).

The form of a SET depends on the terrain surrounding a site. In landscapes with a balanced and flat terrain SET often have an almost circular shape. As one might expect, in mountainous regions this is not the case. Due to strong terrain differences SET tend to have a distorted form (Higgs & Vita-Finzi 1972: 33; Jarman 1972: 710, 713; Bailey & Davidson 1983: 93, 96). Because of that, SET based on time-distance factors provide a more realistic picture of the potentially used surroundings of a site in mountainous regions.

The concept and the development of SET and SCA had a huge impact in archaeological research (Findlow & Ericson 1980; Bailey 1983; Gilman & Thornes 1985; Brooks 1986; Bailey and Parkington 1988; Mytum 1988). However, in the 1990s and early 2000s, hardly any research was done with SET (Valde-Nowak 2002; Uthmeier, Ickler & Kurbjuhn 2008; Roubis et al. 2011; Cappenberg 2014; Henry, Belmaker & Bergin 2017; Miera et al. 2022). For example, in Germany, sites were not investigated with SET but with SCA (Gringmuth-Dallmer & Altermann 1985; Paetzold 1992; Fries 2005; Miera et al. 2020). Even though, this method does not do justice to the local topography, it was preferred in research, because back then there were no technical possibilities to model SET (Saile 1998: 101–103; Mischka 2007: 141–142). In contrast, SCA can be effortlessly performed in a Geographical Information System (GIS) since the early 1990s (Hunt 1992).

Computational Methods

The increasing availability of spatial data and fast developments in computing technologies as well as GIS enables implementing time-cost-functions in various ways. Well known commercial GIS software products offer different functions to compute cost surfaces and cost distances to estimate the effort needed to cross a certain landscape (Rogers, Collet & Lugon 2014; Rogers, Fisher & Huss 2014). Especially with the increased availability of high resolution as well as large-scale DEMs as provided by the Shuttle Radar Topographic Mission (Rodriguez et al. 2005; Farr et al. 2007; Jarvis et al. 2008) the methods and their results become more and more interesting for the scientific community to study societies, functions and resources. In general, the common workflow for time-cost analysis comprises four steps (Figure 1). The first step is to create a cost surface based on an input dataset and an arbitrary cost function measuring cost in time. The second step is a neighbourhood analysis based on a set of multiple transition layers. The number of these layers depends on the number of moving directions from the centre cell

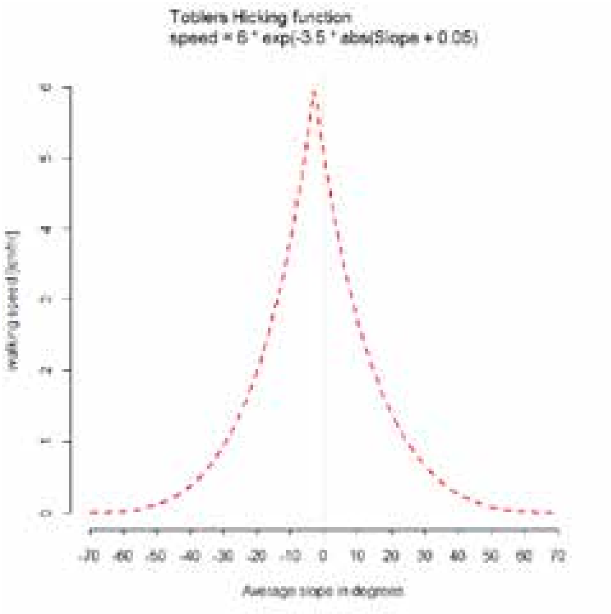

Figure 2. Tobler's Hiking Function (Tobler 1993).

to the neighbouring ones. The chosen cell is the surrounding one being reachable by the smallest expenditure of time. Thirdly, accumulating the time along the fastest path provides the final time-cost raster. Finally, the visualization of the spatial expansion of the moving patterns results from isochrones.

However, for many purposes using commercial software is cost and time intensive. In addition, using different software implementations of time-cost analysis on the same data produces dissimilar results that are incommensurable (Herzog 2013). Therefore, we implemented one of the most famous time-distance functions in an open source environment (Programming Language R) to address a wide-range of scientists and to enable a potential use in analytical questions.

Tobler Hiking Function

As mentioned before, there are various ways to apply and/or implement least-cost analysis within a wide-range of archaeological research. There are numerous studies using the hiking function by Waldo R. Tobler (1961; Herzog 2013; Herzog 2014) first implemented by Gorenflo and Gale (1990). Tobler (1993) developed an empirical model based on the marching data of the Swiss military given by Imhof (1950). Marching time depends on multiple factors, such as length and quality of path, altitude difference, weather conditions and darkness as well as marching competence and luggage. In addition, hiking speed is greater for short distances than for long-lasting marches and small groups cover distances faster than columns (Imhof 1950). The Tobler Hiking Function is the empirical quantification of the walking velocity to cross a certain terrain by using a DEM as well as the first derivative (dh/dx):

$$V = 6e \{ -3.5 \text{ abs } (s + 0.05) \}$$

where V is the walking velocity in km/h, e is the base of the natural logarithms, and s is dh/dx [dh and dx must be measured in the same unit; slope] (Tobler 1993). This formula calculates a maximum velocity of around 6 km/h on gently downslope direction from -5 to -2 degrees and on flat terrain around 5 km/h (Fig. 2). In addition, Fig. 2 also shows a decreasing speed of hiking with an increasing slope gradient because overcoming steeper slopes is time-consuming and exhausting. The empirical data of Imhof (1950) is limited to small groups hiking on defined paths and ways with average speed of 4.5 to 5 km/h on flat terrain. To address off-path traveling, reducing mean hiking speed to 3 km/h (Imhof 1950), Tobler (1993) argued to include an off-path multiplier of 0.6.

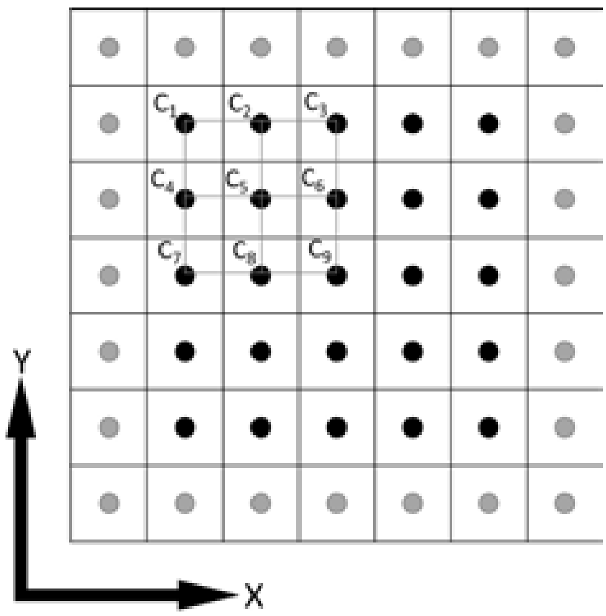

Figure 3. Moving Window approach for deviating terrain attributes (e.g. slope) from a digital elevation model (see Behrens 2003).

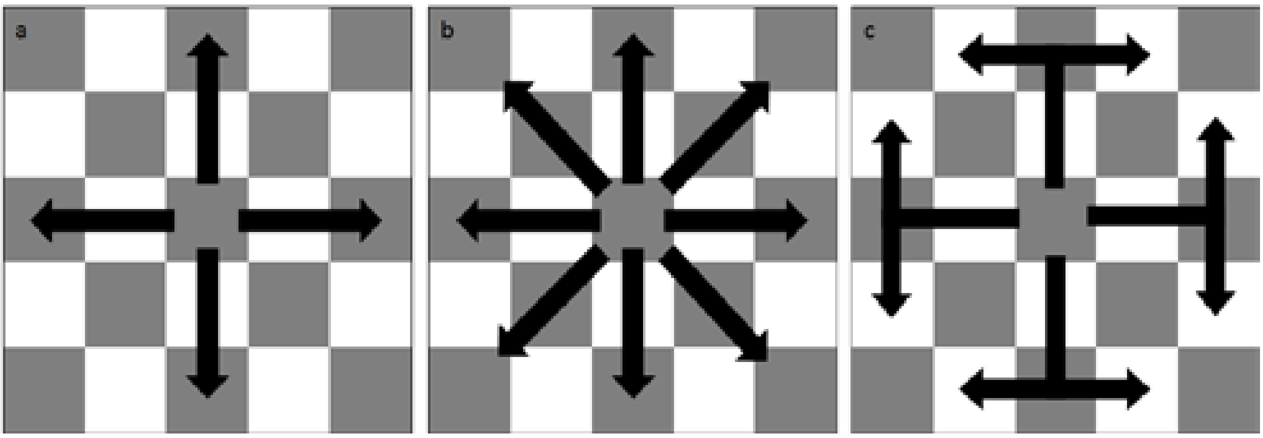

Figure 4. Moving characteristics using four (a, rook move), eight (b, queen move) and 16 directions (c, knight move).

Main Cost Factor: Slope

According to Tobler (1993), slope is the foundation of time-cost analysis. Therefore, almost all archaeological studies use slope as a cost factor (Herzog 2014). Slope is an anisotropic cost factor depending on the directions of movement (Herzog 2013). However, there is a huge number of different slope algorithms using pixel-based analysis, each addressing particular questions and certain landscape conditions or data quality. Slope is the first derivative of the terrain representing the vertical change of the elevation (Behrens 2003).

The ultimate principle of deriving slope from an elevation model is calculating the difference of height between the centre cell and its surroundings. Depending on the slope algorithm chosen, the number and combination of the cells nearby varies. The most common slope algorithms are the mean slope gradient (Zevenbergen & Thorne 1987) for smooth terrains as well as the maximum slope gradient (e.g. Guth 1995) for identifying streamlines (Behrens 2003). Both approaches are using a moving window technique to calculate a slope angle (Fig. 3) between the centre cell and its neighbourhood. Using Zevenbergen and Thorne (1987), the slope angle bases on accounting the cardinal cells only (C2, C4, C6, C8, Fig. 3), whereas the maximum slope algorithm by Guth (1995) uses diagonal neighbours additionally. Using cardinal neighbours has the advantage of including the nearest pixels only, resulting in a high local accuracy, but tends to get noisy if the terrain is very heterogeneous or the quality of the DEM is low. This slope angle is the average slope gradient of the neighbourhood. In contrast, the maximum slope angle results from the pixel showing the maximal difference in altitude to the centre of the moving window (Behrens 2003). Besides these two widespread approaches, there are other popular algorithms as Fleming and Hoffer (1979) as well as Ritter (1987) for smooth surfaces and Horn (1981) for rough surfaces, both being included in the r-package “raster” (Hijmans 2016).

Other Cost Factors

Besides slope as an anisotropic cost factor, there are isotropic cost factors including topographic, social and cultural factors, which influence crossing the landscape (Herzog 2013). Particular types of land cover or water bodies complicate traversing any region. The water volume of mountain streams can vary between passable and impassable during the day. Besides, vegetation age, stand diversity and density influence the hiking speed and energy effort. Moreover, substrate, bedrock, subsoil and general underground cause tough sledding (Imhof 1950). In addition, the terrain includes areas hardly passable for human beings. Pixels of steep slopes represent areas with lower velocity. Allocating these zones as impassable barriers leads to their exclusion from the time-cost analysis. In addition to anisotropic factors, the time-cost analysis uses friction layers to include isotropic cost factors that influence spatial moving patterns.

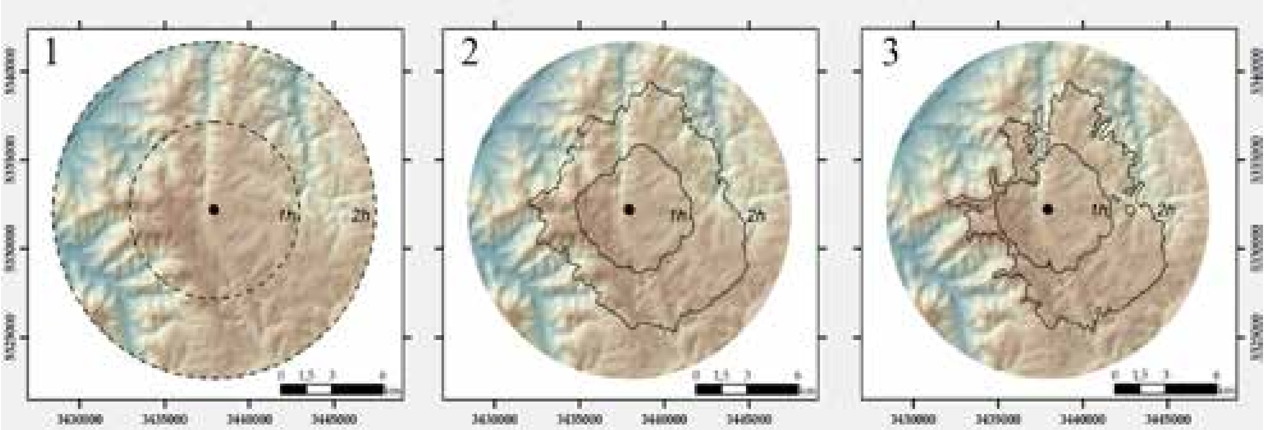

Figure 5. Vineuil, France. a) TPI revealing several micro-reliefs corresponding to archaeological remains; b) current topographic map; c) vectorization of the embankment/ditch system; d) vectorization of the embankment system (C. Laplaige © SOLIDAR, IGN)

Time-cost calculation

As mentioned above, slope and the Tobler Hiking Function are a reliable foundation of numerous time-cost analysis (Herzog 2013; Herzog 2014). Therefore, we use the Tobler Hiking Function to calculate the velocity to cross each pixel cell using a slope raster dataset. The Tobler Hiking Function is best suited for flat terrain over gently to moderate slopes (Herzog 2014). Thus, for reducing errors at steep slopes (e.g. >16°) we implemented an optional damping cost factor lowering the hiking velocity tremendously at these areas. The (damped) velocity raster is the final cost surface.

The final step computing the time-cost surface by a stepwise or cell-by-cell-based approach to account for traversing the landscape is the most time and computational intensive part. As the number of moving directions from one cell to a neighbouring cell is relevant, four, eight and 16 directions are differentiated. The naming of moving characteristics originates from chess moves. Rook move (four directions) means just following cardinal directions, queen move (eight directions) additionally enables diagonally shifting and knight move (16 directions) respects a combination of cardinal and diagonal movements (Fig. 4). An increasing number of directions results in a growing computational time but also in moving patterns of humans being more realistic.

To address the spatial resolution of each individual DEM dataset we implemented a geo-correction of the time-cost raster considering the cardinal and diagonal movement through pixel cells. Finally, each pixel of the time-cost raster contains the accumulated time needed to reach it from the initial location.

Fig. 5 exemplifies the SETs of a one-hour and a two-hour hike starting from a neolithic test site in the Black Forest disregarding (1) and respecting (2, 3) the local terrain. Hence, the scaling down of the potential exploitation territory is 23.3% considering the local terrain. Including a damping factor of 16° (3) effects another reduction of 4% from original 254 km² to 186.5 km². The spatial restriction enables the purposive focus on particular questions.

Methodical workflow and script example

The following R-script is a stepwise implementation of the Tobler Hiking Function into spatial time-cost analysis using a user-specific DEM and/or a slope gradient dataset (cf. Supplementary Material).

A successful application of the script requires the installation of all packages of Tab. 1 on a local machine or given computational environment and their implementation via library command. Note: Missing lines below are script related comments.

```
– R-Script Part 1 – Libraries
[6]       library(raster)
[7]       library(gdistance)
[8]       library(sp)
[9]       library(lattice)
[10]      library(gstat)
```

Package	Version	Description	Citation
raster	2.5–8	Geographic Data Analysis and Modeling	Hijmans 2016
gdistance	1.1–9	Distances and Routes on Geographical Grids	Van Etten 2015
sp	1.2–3	Classes and Methods for Spatial Data	Pebesma & Bivand 2005 Bivand et al. 2013
lattice	0.20–34	Trellis Graphics for R Spatial and Spatio-Temporal	Sarkar 2008
gstat	1.1–3	Geostatistical Modelling, Prediction and Simulation	Pebesma 2004
rgeos	0.3–20	Interface to Geometry Engine – Open Source (GEOS)	Bivand & Rundel 2016

Table I: R-packages used for the delineation of Site Exploitation Territories (SET).

Spatial Dataset	Minimum	Maximum	Mean	Standard Deviation
DEM [m]	766	1177	995.76	73.03
Slope [°]	0.11	33.14	8.08	4.87

Table II: Zonal statistics of the terrain as example of the descriptive analysis of the spatial datasets (Digital Elevation Model and Slope) using the Minimum, Maximum, Mean and Standard deviation measurements of the spatial area defined by the first walking hour.

```
[11]      library(rgeos)
```

The implementation and visualisation of Tobler's Hiking Function results from the following lines.

```
– R-Script Part 2 – Tobler's Hiking
Function
[29]      ToblersHikingFunc-
tion <- function(x){ 6 * exp(-3.5 *
abs(tan(x*pi/180) + 0.05)) }
[32]      TheoreticalSlopes <- seq(-
70,70,1)
[33]      WlkSpeed <- ToblersHiking-
Function(TheoreticalSlopes)
[34]      plot(TheoreticalSlopes,
WlkSpeed, type="l", col ="red", lwd = 2,
lty="dashed",
     ylab="walking speed [km/hr]",
xlab="Average slope in degrees", axes=F)
[35]      axis(1, tck=-.01, at= Theore-
ticalSlopes[seq(1,length(TheoreticalSlo-
pes),10)],
     labels= TheoreticalSlopes[-
seq(1,length(TheoreticalSlopes),10)])
[36]      axis(2)
[37]      abline(v=0, lty="dashed", col
="gray")
[38]      title(expression(„Toblers
Hiking function\nspeed = 6 * exp(-3.5 *
abs(Slope + 0.05)"))
```

The user has to adjust the general setting related to working directories (1), datasets (2–3) and environmental variables (4). A slope gradient dataset is optional. If no slope data is given, the user has to choose a slope algorithm by defining the number of neighbours (4 or 8 neighbours) in line [66]. The input of the X- and Y-coordinates defines the initial spatial location (e.g. settlement, artefact location, etc.) for the time-cost-analysis and means the starting point for site exploitation.

```
– R-Script Part 3 – Settings (1) direc-
tories
[45]      InDir <- "Path/To/Your/Input-
Data"
[46]      OutDir <- "Path/To/Your/Out-
putData"
```

```
– R-Script Part 3 – Settings (2) input
data
[50]      DEM            <- "FileNameOf-
DigitalElevationModel.rasterformat"
```

```
  [51]      SLOPE   <- “FileNameOfSlopeG-
radient.rasterformat”
  [52]      POINT   <- c(X,Y-CoordinateO-
fInitialPoint)
```

```
 – R-Script Part 3 – Settings (3) output
data
  [55]      TCR     = “FileNameOfTimeCos-
tRaster”
  [56]      SLG     = “FileNameOfSlopeRa-
ster” # optional
  [57]      CTL     = “FileNameOfContour-
Lines”
  [58]      rdt     = “RasterDatatype”
```

```
 – R-Script Part 3 – Settings (4) envi-
ronmental variables
  [66]      NumbersOfNeigbors     <- 8
  [69]      Damping
<- TRUE
  [70]      DampingFactor         <- 16
  [78]      NumberOfDirections    <- 8
  [82]      TimeOfInterest
<- 2
  [88]      NumberOfIsochrones    <- 2
  [89]      IntervallOfIsochrones
<- 1
```

For handling big datasets, we implemented an isochronic mask layer to reduce the dataset to the related area of interest to reduce the computational demand and effort.

```
 – R-Script Part 4 – read DEM
  [95]      setwd(inDir)
  [98]      rDEM <- raster(DEM)
```

```
 – R-Script Part 4 – read/create SLOPE
  [101]     rSLOPE <- NULL
  [102]     if (nchar(SLOPE) > 0) {
  [103]             rSLOPE <- raster(SLO-
PE)
  [104]     } else {
  [106]             if(!is.na(projecti-
on(rDEM))) {
  [107]                     rSLOPE <- ter-
rain(rDEM, opt=’slope’, unit=’degrees’,
neighbors=NumberOfNeighbors)
  [108]             } else {
  [110]     print(“PROJECTION ERROR: no
projection is set for ELEVATION input
file.”)
  [111]             }
  [112]     }
```

```
 – R-Script Part 4 – set initial spatial
location
  [115]     SPATIALPOINT <- data.fra-
me(x=POINT[1],y=POINT[2])
  [116]     coordinates(SPATIALPOINT) <-
~ x+y
  [117]     projection(SPATIALPOINT) <-
projection(rDEM)
```

```
 – R-Script Part 4 – Reduce dataset to
AOI (Area-Of-Interest)
  [120]     rSLOPE4TimeCost <- rSLOPE
  [121]     rDEM4Statistics <- rDEM
  [123]     if (TimeOfInterest > 0) {
  [126]             maxHikingDistan-
ce <- round(max(WlkSpeed)* (TimeOfInte-
rest+0.25)*1000)
  [129]             bufferMaxHikingDistance
<- buffer(SPATIALPOINT, maxHikingDistance)
  [132]             rDEM_clip <-
crop(rDEM,extent(bufferMaxHikingDistance))
  [133]             rSLOPE_clip <-
crop(rSLOPE,extent(bufferMaxHikingDistan-
ce))
  [136]             rDEM4Statistics <-
rDEM_clip
  [139]             rSLOPE4TimeCost <-
rSLOPE_clip
  [140]     }
```

The next part calculates the velocity of crossing the landscape based on the delineated slope raster while including a slope-based damping factor if chosen. Additionally, some time and space conversions are needed for the final estimations. Finally, spatial correction and time-cost accumulation is done while calculating the accumulated cost surface. Some visualisation outputs are provided via plot-function to self-test and validate the computed spatial datasets.

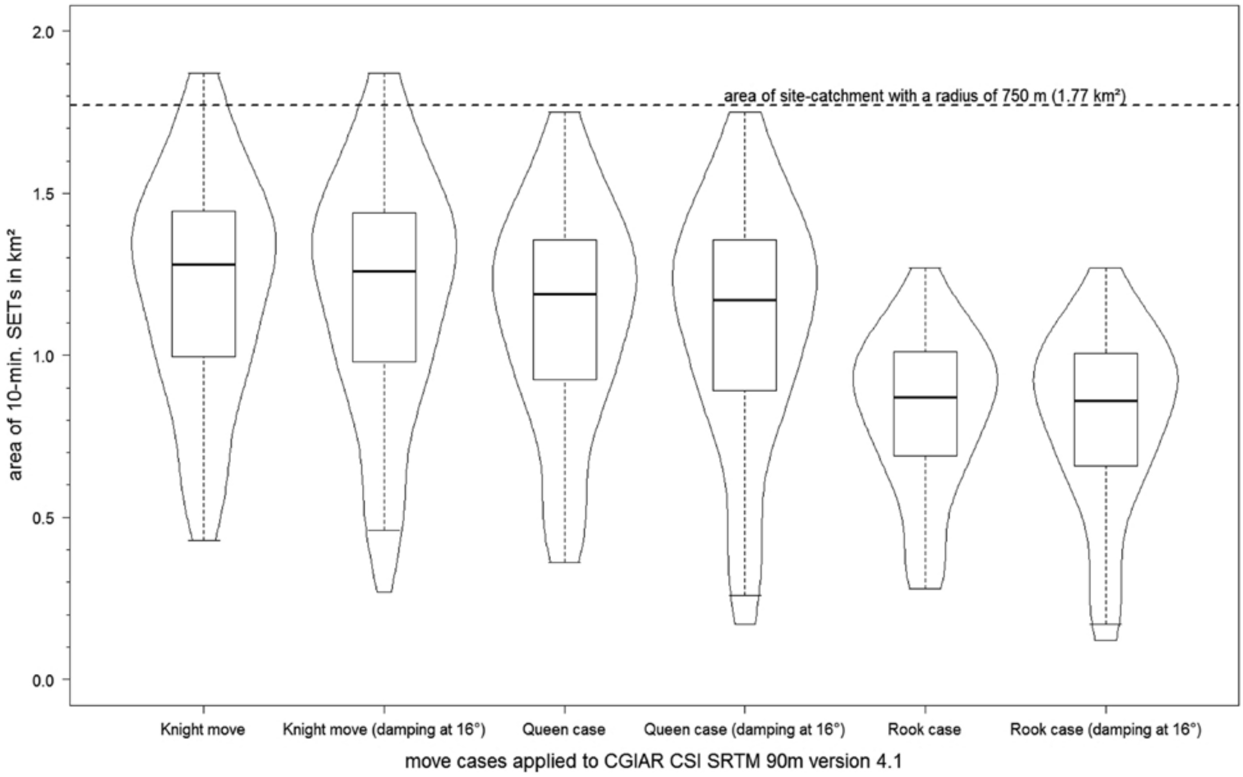

Figure 6. On the left: TPI of an area near Blois. On the right: representation of the probability for each pixel being an embankment (black = 100%, white = 0%) (C. Laplaige)SOLIDAR, IGN)

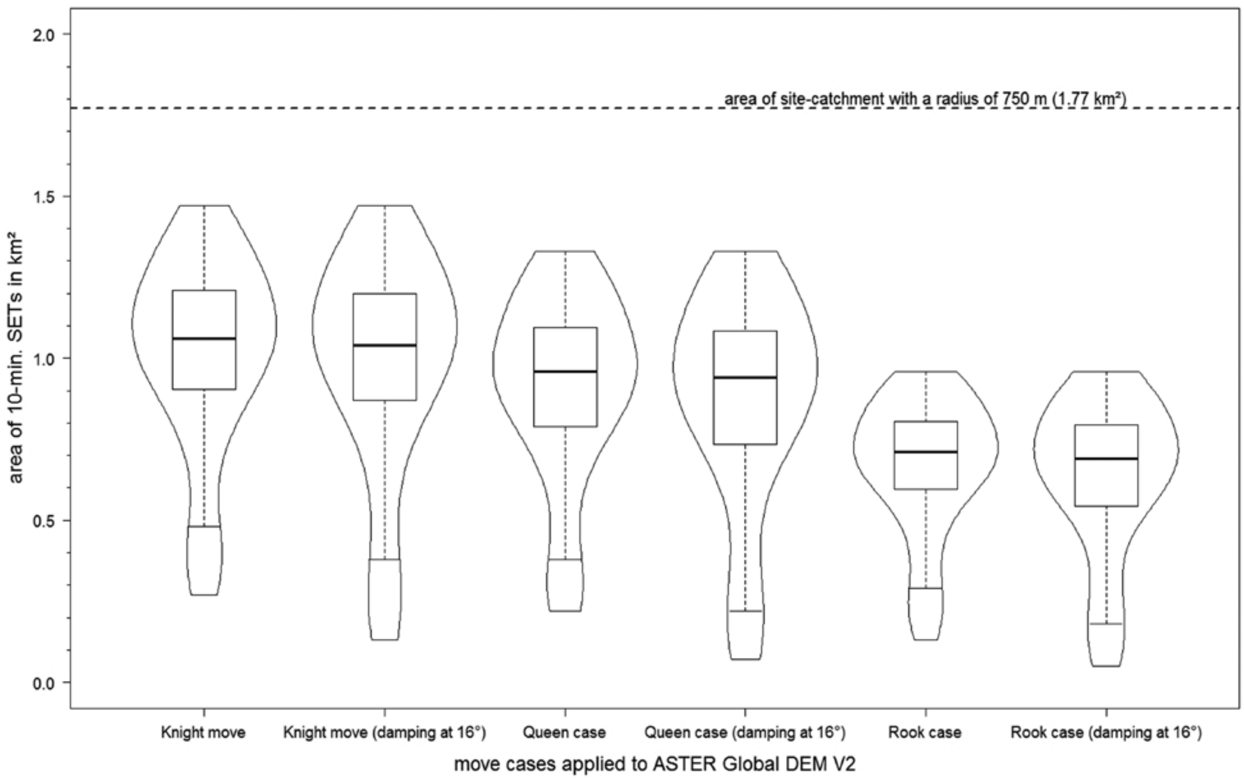

Figure 7. Applying different move cases and damping factors to ASTER Global DEM V2 (30 x 30 m).

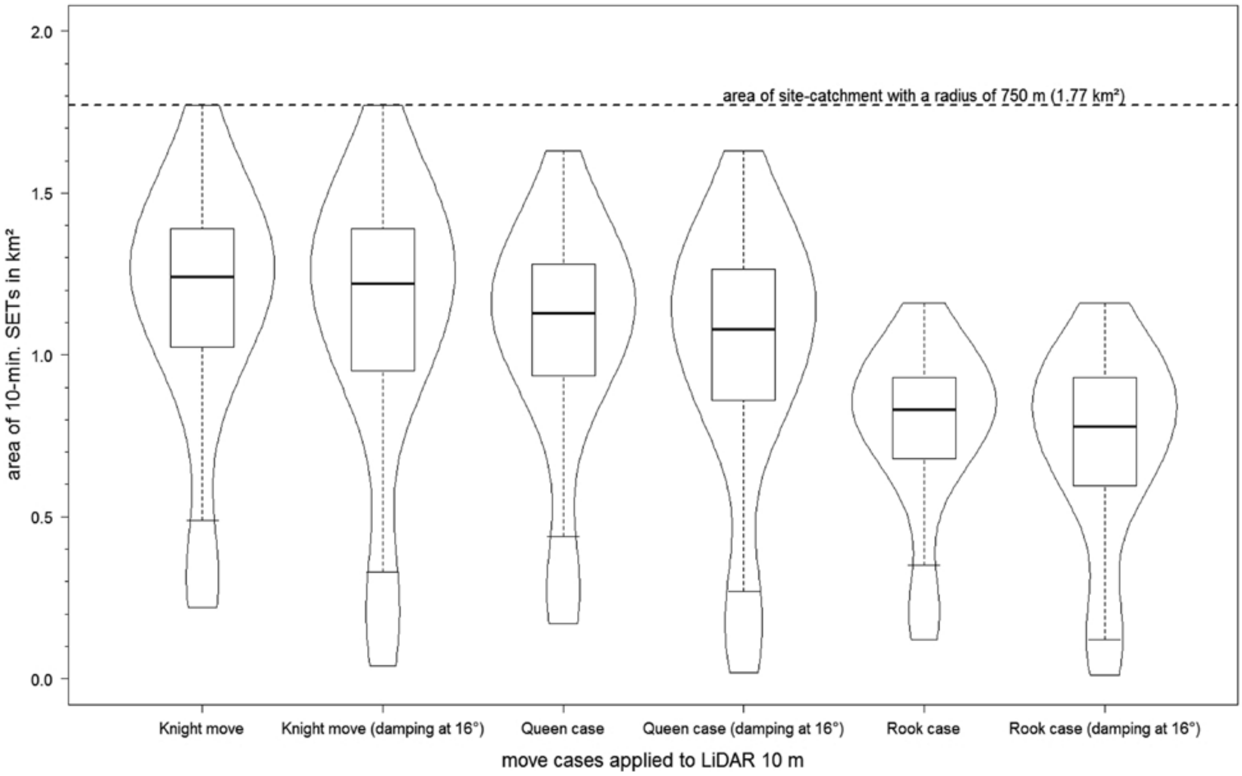

Figure 8. Applying different move cases and damping factors to LiDAR data (10 x 10 m).

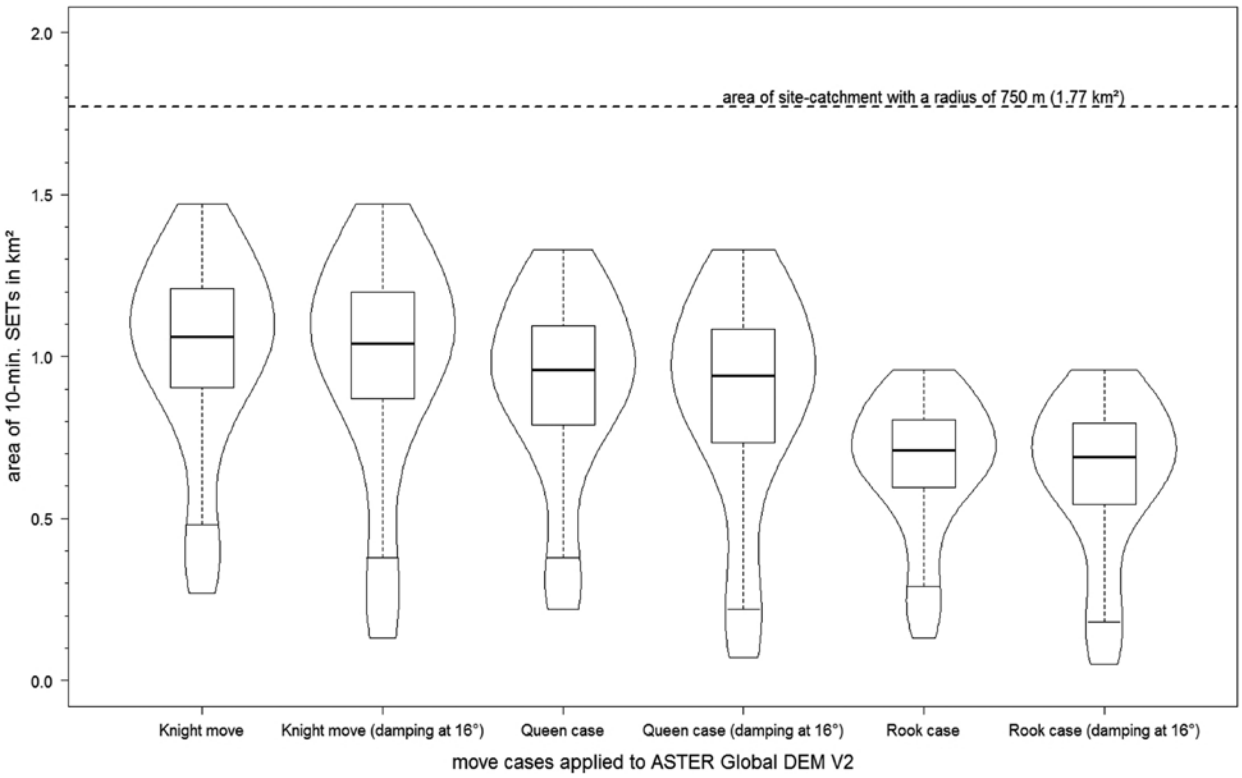

Figure 9. Applying different move cases and damping factors to DLR SRTM X-SAR DEM (25 x 25 m).

Digital elevation model	Move case	Damping factor	Minimum	1st quantile	Median	Mean	3rd quantile	Maximum	Stand. Deviation
SRTM 90 m	Knight move	none	0.430	0.995	1.280	1.215	1.445	1.870	0.339
	Knight move	16°	0.270	0.980	1.260	1.196	1.440	1.870	0.364
	Queen case	none	0.360	0.925	1.190	1.123	1.355	1.750	0.335
	Queen case	16°	0.170	0.890	1.170	1.099	1.355	1.750	0.368
	Rook case	none	0.280	0.690	0.870	0.823	1.010	1.270	0.244
	Rook case	16°	0.120	0.660	0.860	0.804	1.005	1.270	0.271
ASTER Global DEM V2	Knight move	none	0.270	0.905	1.060	1.011	1.210	1.470	0.304
	Knight move	16°	0.130	0.870	1.040	0.975	1.200	1.470	0.346
	Queen case	none	0.220	0.790	0.960	0.904	1.095	1.330	0.293
	Queen case	16°	0.070	0.735	0.940	0.863	1.085	1.330	0.335
	Rook case	none	0.130	0.595	0.710	0.661	0.850	0.960	0.212
	Rook case	16°	0.050	0.545	0.690	0.627	0.795	0.960	0.244
LiDAR 10 m	Knight move	none	0.220	1.03	1.240	1.148	1.390	1.770	0.386
	Knight move	16°	0.040	0.950	1.220	1.107	1.390	1.770	0.431
	Queen case	none	0.170	0.935	1.130	1.047	1.280	1.630	0.364
	Queen case	16°	0.020	0.860	1.080	0.996	1.265	1.630	0.408
	Rook case	none	0.120	0.680	0.830	0.767	0.930	1.160	0.262
	Rook case	16°	0.010	0.595	0.780	0.717	0.930	1.160	0.300
DLR SRTM X-SAR	Knight move	none	0.330	0.925	1.080	1.031	1.245	1.470	0.290
	Knight move	16°	0.210	0.880	1.040	0.997	1.230	1.470	0.325
	Queen case	none	0.250	0.795	0.940	0.891	1.100	1.340	0.282
	Queen case	16°	0.100	0.755	0.910	0.846	1.090	1.340	0.324
	Rook case	none	0.190	0.550	0.690	0.647	0.790	0.970	0.204
	Rook case	16°	0.050	0.480	0.650	0.604	0.785	0.970	0.243

Table III: Comparison of site exploitation territory sizes using different move cases, damping factors and different digital elevation models.

```
– R-Script Part 5 – time cost analysis
[147]     rVelocity.kmh <- calc(rSLOPE4TimeCost, ToblersHikingFunction)
[150]     rVelocity.ms <- calc(rVelocity.kmh, fun=function(x) { ((x*1000)/3600) })
[156]     if (Damping) {
[157]             rDamping <- rSLOPE4TimeCost
[158]             rDamping[rDamping > DampingFactor]  = 1000
[159]             rDamping [rDamping <= DampingFactor]  = 1
[160]             rVelocity.ms <- rVelocity.ms/rDamping
[162]     }
[166]     lTransition <- transition(rVelocity.ms, transitionFunction=mean,
                                 directions=NumberOfDirections)
[170]     lGeoCorrection <- geoCorrection(lTransition, type=”r”)
[171]     rAccumulatedCostSurface.s <-

– R-Script Part 6 – zonal statistics
[189]     zonalStatistics   <- data.frame(matrix(0,2,5))
```

```
  [190]     statNames <- c(‚1st
hour‘,‘min‘,‘max‘,‘mean‘,‘sd‘)
  [191]     names(zonalStatistics) <-
statNames
  [192]     zonalStatistics[1,1] <- ‚DEM‘
  [193]     zonalStatistics[2,1] <- ‚SLO-
PE‘
  [196]     rasterZones <- rAccumulated-
CostSurface.h
  [197]     rasterZones[rAccumulatedCost-
Surface.h <= 1] = 1
  [198]     rasterZones[rAccumulatedCost-
Surface.h > 1]   = 2
  [201]     for(st in 2:length(statNa-
mes)) {
  [202]     zonalStatistics[1,st] <- zo-
nal(rDEM4Statistics, rasterZones, statNa-
mes[st])[1,2]
  [203]            zonalStatistics[2,st]
<- zonal(rSLOPE4TimeCost, rasterZones,
statNames[st])[1,2]
  [204]     }
  [206]     print(zonalStatistics)
```

The final commands produce an output of raster and vector files in the given output directory.

```
 – R-Script Part 7 – write files
  [212]     setwd(outDir)
  [213]     writeRaster(rAccumulatedCost-
Surface.h,TCR, format=rdt)
  [214]     if (nchar(SLOPE) == 0) {
  [215]            writeRaster(rSLOPE4Ti-
meCost,SLG, format=rdt)
  [216]     }
  [217]     shapefile(vContourLines,filena-
me=CTL)
  [217]     shapefile(vContourLines,filena-
me=CTL)
```

Case Study: Pre-Roman Iron Age Land Use in the Baar Region and Adjacent Landscapes

The practical application of the script can best be described using different scenarios based on an archaeological test dataset from south-western Germany. As an example, we will use 87 sites from the pre-Roman Iron Age from the Baar and the adjacent landscapes. The prehistoric and early historic land use of this area was studied during the first funding phase of the Collaborative Research Center 1070 with both archaeological and pedological methods (Ahlrichs et al. 2016; Henkner et al. 2017; Knopf & Ahlrichs 2017; Ahlrichs, Riehle & Sultanalieva 2018; Ahlrichs et al. 2018a; Ahlrichs et al. 2018b; Henkner et al. 2018a; Henkner et al. 2018b; Miera et al. 2019; Miera 2020). The region is particularly suitable for the application of the described SET workflow, because it covers the gentle rolling terrain of the Baar and extends into the adjacent low mountain ranges of the Black Forest and the Swabian Jura, where the topography is far more heterogeneous.

Each of the following scenarios focuses on the size of the SET. Based on four different DEMs, it will be shown how the move cases affect the time-cost-raster and therefore the shape of the SET (see also Becker et al. 2017). In addition, it can be demonstrated how the grid cell sizes influence the final results and how the resolution of the cells affects the time needed for processing the data.

For the analysis, we used both the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global DEM Version 2 (GDEM V2) with a resolution of 30 x 30 m, as well as data from the Shuttle Radar Topographic Mission (CGIAR-CSI SRTM) with a cell size of 90 x 90 m provided by the National Aeronautics and Space Administration (NASA). In addition, we used the SRTM X-SAR DEM from the German Aerospace Center (DLR) with a cell size of 25 x 25 m and a DEM with a resolution of 10 m based on Light Detection And Ranging (LiDAR) technology, kindly provided by the State Office for Cultural Heritage Baden-Wuerttemberg.

Atmospheric noise, radar shadowing effects as well as vegetative and anthropogenic structures have been removed from the CGIAR-CSI SRTM and LiDAR data (Rodriguez et al. 2005; Farr et al. 2007; Jarvis et al. 2008; Hesse 2012). Regional studies from the US and Thailand have shown that even in low mountain ranges CGIAR-CSI SRTM data have a height accuracy of ± 7 m and thus very well reflect the general terrain trend (Gorokhovich & Voustianiouk 2006). Comparable minor errors can be demonstrated for the GDEM2 data (Gesch et al. 2012; Li et al. 2012; Purinton & Bookhagen 2017).

In contrast to the three DEM mentioned, the DLR X-SAR data appear much noisier. Technically, this dataset is a digital surface model, because the elevation data include urban structures, vegetation and other objects (Ludwig & Schneider 2006). In addition, steep west-facing slopes are affected by radar shadows. Here, errors of up to 200 m can be demonstrated (Ludwig and Schneider 2006: 343). In general, the DLR X-SAR data have a horizontal accuracy of ± 20 meters (Keydel, Hounam & Werner 2000; Rabus et al. 2003).

The results of our comparative analysis can be seen in Figures 6-9 as well as in Table 3. With respect to the different move cases the following general tendencies can be observed: The Knight move always produces the largest SET, followed by slightly smaller SET produced by the Queen case. Using the rook case will result in very small SET. This can be seen in DEM with a high resolution of 10 m as well as in those with a cell size of 90 m. In addition, it can be stated that the resolution of the elevation models leads only to slightly different results. On average, the SET based on the GDEM2 and the DLR X-SAR data cover an area of about 1 km². The SETs obtained using the CGIAR-CSI SRTM data and the LiDAR data are on average 0.23 to 0.27 km² larger. This observation is important, because the script is able to calculate SET for 87 sites in less than five minutes (Windows 7, 2.70 GHz, 8GB Ram, SSD) using the CGIAR-CSI SRTM data. In contrast, the processing of the LiDAR data took hours for the same number of sites.

Finally, as one might expect, the use of a damping factor results in a slight reduction of the modeled SET. This is recognizable in particular in the minimum values. The fact that the use of a damping factor generally has only a small influence on the sizes of the modeled SET can have different reasons. On the one hand, it should be remembered that the SET were modeled for small areas with a time-distance of ten minutes. In principle, it can be assumed that with larger time-distances greater deviations can be observed between the SET modeled with and without a damping factor. On the other hand, it is strongly affected by the general topographic arrangement around the given study sites especially in heterogeneous landscapes accompanied with steep slope areas the effect of the damping will be increased and only the valley ranges will be used by the algorithm. In general, damping effects can be enhanced by choosing a small slope and/or by increasing the weight of the damping factor. However, one has to decide on their own for each case study, which values they want to work with.

Conclusion and Remarks

Even though the concept of site exploitation territories is now almost 50 years old and remains central to archaeological research. On the basis of an intensive literature research, it could be shown that this concept was primarily used to discuss economic research questions. These were often linked to natural deterministic assumptions. In addition, analyzes are often based on the premise that people always make rational choices and choose the optimal path with the least effort to meet their everyday economic needs. However, the concept of the SET plays not only a central role in system theory within processual archaeology. In principle, it can also be combined with modern approaches from post-processual archaeology, which lie beyond economic questions. For example, the factors space and time can easily be combined with phenomenological research as well as viewshed analyzes and thus contribute to studies on landscape perceptions. In addition, the R script can also be used to model territories that were surveyed by archaeologists. Based on the case study of the pre-Roman Iron Age settlement of the Baar using different DEM products with resolution ranging from 10–90 m, the use of CGIAR-CSI SRTM data is recommended. The proposed workflow is able to process DEM with a resolution of 90 m for a large datasets within minutes. In addition, this dataset produces nearly identical results as the high-resolution LiDAR data. Altogether, we encourage our colleagues to use the R-script presented in this paper. Please feel free to adapt it to your own needs and to expand and improve its functionality by adding new lines of code.

References

Ahlrichs, J J, Henkner, J, Teuber, S, Schmidt, K, Scholten, T, Kühn, P and Knopf, T 2016 Archaeological and Archaeopedological Approaches to Analyze the Development of Marginal Areas in Prehistory: A Case Study from the Western Baar, SW Germany. In: Kolodziejczyk, P and Kwiatkowska-Kopka, B (eds) *Landscape in the past & forgotten landscapes. Cracow Landscape Monographs 2: Landscape as impulsion for culture: research, perception and protection*. Cracow: Institute of Archeology Jagiellonian University, pp. 39–49.

Ahlrichs, J J, Riehle, K and Sultanalieva, N 2018 The Production of Liminal Places: An Interdisciplinary Account. *Ethnographisch-Archäologische Zeitschrift*, 56(1–2): 205–242.

Ahlrichs, J J, Henkner, J, Schmidt, K, Scholten, T, Kühn, P and Knopf, T 2018a L'utilisation des terres pendant la période néolithique sur la colline du Fürstenberg à la bordure sud du Baar en Allemagne du sud-ouest. In: Lemercier, O, Sénépart, I, Besse, M, Mordant, C (eds) *Habitations et habitat du Néolithique à l'âge du Bronze en France et ses marges. Actes des IIe Rencontres Nord/Sud de Préhistoire récente, Dijon, 19.–21. Novembre 2015*. Toulouse: Archives d'Écologie Préhistorique, pp. 619–622.

Ahlrichs, J J, Henkner, J, Schmidt, K, Scholten, T, Kühn, P and Knopf, T 2018b Bronzezeitliche Siedlungsdynamiken zwischen der Baar und angrenzenden Naturräumen. In: Neumann, D, Nessel, B and Bartelheim, M (eds.) *Bronzezeitlicher Transport. Akteure, Mittel und Wege. RessourcenKulturen 8*. Tübingen: Tübingen University Press, pp. 269–303. DOI: 10.15496/publikation-26722

Bailey, G N 1983 *Hunter-Gatherer Economy in Prehistory: A European Perspective*. Cambridge: Cambridge University Press.

Bailey, G N and Davidson, I 1983 Site Exploitation Territory and Topography: Two Case Studies from Palaeolithic Spain. *Journal of Archaeological Science*, 10(1): 87–115. DOI: 10.1016/0305-4403(83)90044-4

Bailey, G N and Parkington, J 1988 *The Archaeology of prehistoric coastlines*. Cambridge: Cambridge University Press.

Becker, D, De Andrés-Herrero, M, Willmes, C, Weniger, GC and Bareth, G 2017 Investigating the Influence of Different DEMs on GIS-Based Cost Distance Modeling for Site Catchment Analysis of Prehistoric Sites in Andalusia. *International Journal of Geo-Information*, 6(2): 36. DOI: 10.3390/ijgi6020036

Behrens, T 2003 *Digitale Reliefanalyse als Basis von Boden-Landschafts-Modellen am Beispiel der Modellierung periglaziärer Lagen im Ostharz. Boden und Landschaft 42*. Giessen: Universität Giessen.

Bivand, R S and Rundel, C 2016 *Interface to Geometry Engine – Open Source (GEOS). R-packages 'rgeos'*. Available at https://cran.r-project.org/web/packages/rgeos/ [Last accessed 10 August 2018].

Bivand, R S, Pebesma, E and Gomez-Rubio, V 2013 *Applied spatial data analysis with R*. New York: Springer.

Brooks, R L 1986 *Catchment Analysis revisited: A Critique and Application of a Test Case*. Unpublished thesis (PhD), University of Kentucky.

Cappenberg, K 2014 Landscape as a Feature: Using GIS and Statistics to Compare Two Types of Early Neolithic Sites in Lesser Poland. In: Kienlin, T L, Valde-Nowak, P, Korczyńska, M, Cappenberg, K, and Ociepka, J (eds.) *Settlement, communication and exchange around the Western Carpathians: International Workshop held at the Institute of Archaeology, Jagiellonian University, Kraków, October 27–28th, 2012*. Oxford: Archaeopress, pp. 51–66.

Chrisholm, M 1968 *Rural Settlement and Land Use*. London: Hutchinson.

Christaller, W 1933 *Die zentralen Orte in Süddeutschland. Eine ökonomisch-geographische Untersuchung über die Gesetzmäßigkeit der Verbreitung und Entwicklung der Siedlungen mit städtischer Funktion*. Jena: Fischer.

Clarke, D L 1968 *Analytical Archaeology*. London: Methuen.

Davidson, I 1981 Can we study prehistoric economy for fisher-gatherer-hunters? - a historical approach to Cambridge „Palaeoeconomy". In: Sheridan, A and Bailey, G N (eds) *Economic archaeology: towards an integration of ecological and social approaches. British Archaeological Reports, International series 96*. Oxford: British Archaeological Reports, pp. 17–33.

van Etten, J 2015 *Distances and Routes on Geographical Grids. R-package 'gdistance'. Available at https://cran.r-project.org/web/packages/gdistance/* [Last accessed 10 August 2018].

**Farr, T G, Rosen, P A, Caro, E, Crippen, R, Duren, R, Hensley, S, Kobrick, M, Paller, M, Rodriguez, E, Roth, L, Seal, D, Shaffer, S, Shimada, J, Umland, J, Werner, M, Oskin, M, Burbank, D and

Alsdorf, D 2007 The Shuttle Radar Topography Mission. *Reviews of Geophysics,* 45(2): 1–33. DOI: 10.1029/2005RG000183

Findlow, F J and Ericson, J E 1980 Catchment analysis: essays on prehistoric resource space. *Anthropology UCLA 10*. Los Angeles: University of California.

Fleming, M D and Hoffer, R M 1979 Machine processing of landsat MSS data and DMA topographic data for forest cover type mapping. *LARS Technical Report*, 062879: 377–390.

Foley, R 1977 Space and Energy: A Method for Analysing Habitat Value and Utilization in Relation to Archaeological Sites. In: Clarke, D L (ed.) *Spatial Archaeology*. London: Academic Press, pp. 163–187.

Fries, J 2005 Methodische Überlegungen zur Ressource Boden. *Archäologische Informationen*, 28(1–2): 139–147.

Gesch, D, Oimoen, M, Zhang, Z, Meyer, D and Danielson, J 2012 Validation of the Aster Global DEM Version 2 over the conterminous United States. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXIX–B4: 281–286. DOI: 10.5194/isprsarchives-XXXIX-B4-281-2012

Gilman, A and Thornes, J B 1985 *Land-use and prehistory in South-East Spain. The London Research Series in Geography 8*. London: Allen & Unwin.

Gorenflo, L J and Gale, N 1990 Mapping Regional Settlement in Information Space. *Journal of Anthropological Archaeology*, 9(1): 240–274. DOI: 10.1016/0278-4165(90)90008-2

Gorokhovich, Y and Voustianiouk, A 2006 Accuracy assessment of the processed SRTM-based elevation data by CGIAR using field data from USA and Thailand and its relation to the terrain characteristics. *Remote Sensing of Environment*, 104(4): 409–415. DOI: 10.1016/j.rse.2006.05.012

Gringmuth-Dallmer, E and Altermann, M 1985 Zum Boden als Standortfaktor ur- und frühgeschichtlicher Siedlungen. *Jahresschrift für mitteldeutsche Vorgeschichte*, 68: 339–355.

Guth, P L 1995 Slope and aspect calculations on gridded DEMs: examples from a geomorphometric toolbox for personal computers. *Zeitschrift für Geomorphologie, Neue Folge, Supplement Band*, 101: 31–52.

Henkner, J, Ahlrichs, J, Downey, S, Fuchs, M, James, B, Knopf, T, Scholten, T, Teuber, S and Kühn, P 2017 Archaeopedological analyses of colluvium: a proxy for regional land use history in southwest Germany. *CATENA*, 155: 93–113. DOI: 10.1016/j.catena.2017.03.005

Henkner, J, Ahlrichs, J, Fischer, E, Fuchs, M, Knopf, T Rösch, M, Scholten, T and Kühn, P 2018a Land use dynamics derived from colluvial deposits and bogs in the Black Forest, Germany. *Journal of Plant Nutrition and Soil Science*, 181(2): 240–260. DOI:10.1002/jpln.201700249

Henkner, J, Ahlrichs, J, Downey, S, Fuchs, M, James, B, Junge, A, Knopf, T, Scholten, T and Kühn, P 2018b Archaeopedological analysis of colluvial deposits in favourable and unfavourable areas: reconstruction of land use dynamics in SW Germany. *Royal Society Open Science*. DOI: 10.1098/rsos.171624

Henry, D O, Belmaker, M and Bergin, S M 2017 The effect of terrain on Neanderthal ecology in the Levant. *Quaternary International*, 435: 94–105. DOI: 10.1016/j.quaint.2015.10.023

Herzog, I 2013 The Potential and Limits of Optimal Path Analysis. In: Bevan, A and Lake, M (eds.) *Computational Approaches to Archaeological Spaces*. Walnut Creek, California: Left Coast Press.

Herzog, I 2014 A review of case studies in archaeological least-cost analysis. *Archaeologia e Calcolatori*, 25(1): 223–239.

Hesse, R 2012 Using lidar-derived Local Relief Models (lrm) as a new tool for archaeological prospection. In: Kluiving, S J and Guttmann-Bond, E B (eds.) *Landscape Archaeology between Art and Science. From a Multi- to an Interdisciplinary Approach*. Amsterdam: Amsterdam University Press, pp. 369–378.

Higgs, E S 1972 *Papers in Economic Prehistory. Studies by Members and Associates of the British Academy Major Research Project in the Early History of Agriculture*. Cambridge: University Press.

Higgs, E S 1975 *Palaeoeconomy: being the second volume of Papers in Economic Prehistory by members and associates of the British Academy Major Research Project in the Early History of Agriculture*. Cambridge: University Press.

Higgs, E S and Jarman, M R 1969 The origins of agriculture: a reconsideration. *Antiquity*, 43(1): 31–41. DOI: 10.1017/S0003598X00039958

Higgs, E S and Vita-Finzi, C 1972 Prehistoric economies: a territorial approach. In: Higgs, E S (ed.) *Papers in Economic Prehistory. Studies by Members and Associates of the British Academy Major Research Project in the Early History of Agriculture*. Cambridge: University Press, pp. 27–38.

Higgs, E S and Jarman, M R 1975 Palaeoeconomy. In: Higgs, E S (ed.) *Palaeoeconomy: being the second volume of Papers in Economic Prehistory by members and associates of the British Academy Major Research Project in the Early History of Agriculture*. Cambridge: University Press, pp. 1–7.

Higgs, E S and Vita-Finzi, C 1966 The Climate, Environment and Industries of Stone Age Greece: Part II. *Proceedings of the Prehistoric Society*, 32(1): 1–29.

Higgs, E S, Vita-Finzi, C, Harris, D R, Fagg, A E and Bottema, S 1967 The Climate, Environment and Industries of Stone Age Greece: Part III. *Proceedings of the Prehistoric Society*, 33(1): 1–29.

Hijmans, R J 2016 *Geographic Data Analysis and Modeling. R-package 'raster'. Available at https://cran.r-project.org/web/packages/raster/ [Last accessed 10 August 2018].*

Horn, B K P 1981 Hillshading and the reflectance map. *Proceedings of IEEE*, 69(1): 14–47. DOI: 0018-9219/81/0100-0014$00.75.

Hunt, E A 1992 Upgrading Site-Catchment Analyses with the Use of GIS: Investigating the Settlement Patterns of Horticulturalists. *World Archaeology*, 24(2): 283–309.

Imhof, E 1950 *Gelände und Karte*. Zürich: Rentsch.

Jarman, M R 1972 A territorial model for archaeology: a behavioral and geographical approach. In: Clarke, D L (ed.) *Models in Archaeology*. London: Methuen, pp. 705–733.

Jarman, M R 1976 Prehistoric economic development in sub-Alpine Italy. In: Sieveking, G de G, Longworth, I H and Wilson, K E (eds.) *Problems in Economic and Social Archaeology*. London: Duckworth, pp. 523–548.

Jarman, M R, Vita-Finzi, C and Higgs, E S 1972 Site catchment analysis in archaeology. In: Ucko, P J (ed.) *Man, settlement and urbanism: proceedings of a meeting of the research seminar in archaeology and related subjects held at the institute of archaeology*. Gloucester Crescent: Duckworth, pp. 61–66.

Jarman, M R, Bailey, G N and Jarman, H N 1982 *Early european Agriculture. Its foundation and development: being the third volume of Papers in Economic Prehistory by members and associates of the British Academy Major Research Project in the Early History of Agriculture*. Cambridge: University Press.

Jarvis, A, Reuter, H I, Nelson, A and Guevara, E 2008 *Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database.* Available at http://srtm.csi.cgiar.org [Last accessed 10 August 2018].

Jochim, M A 1976 *Hunter-Gatherer Subsistence and Settlement: A Predictive Model*. New York: Academic Press.

Keydel, W, Hounam, D and Werner, M 2000 *X-SAR/SRTM: Part of a Global Earth Mapping Mission. Paper presented at the RTO SET Symposium on "Space-Based Observation Technology", held on the Island of Samos, Greece, 16-18 October 2000, and published in RTO MP-61.* Available at https://www.dtic.mil/dtic/tr/fulltext/u2/p010830.pdf [Last accessed 10 August 2018].

Knopf, T and Ahlrichs, J J 2017 Der Magdalenenberg in Raum und Zeit. *Archäologische Informationen aus Baden-Württemberg*, 77: 52–65.

Lee, R B 1969 Kung bushmen subsistence: An input-output analysis. In: Vayda, A P (ed.). *Environment and cultural behaviour: Ecological studies in Cultural Anthropology*. New York: Natural History Press, pp. 47–79.

Li, P, Shi, C, Li, Z, Müller, J-P, Drummond, J, Li, X, Li, T, Li, Y and Liu, J 2012 Evaluation of Aster GDEM Ver2 using GPS Measurements and SRTM Ver4.1 in China. *Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 1–4: 181–186. DOI: 10.5194/isprsannals-I-4-181-2012

Ludwig, R and Schneider, P 2006 Validation of DEMs from SRTM X-SAR for applications in hydrologic modeling. *ISPRS Journal of Photogrammetry & Remote Sensing*, 60: 339–358. DOI: 10.1016/j.isprsjprs.2006.05.003

Miera, J J 2020 Ur- und frühgeschichtliche Siedlungsdynamiken zwischen Gunst- und Ungunsträumen in Südwestdeutschland – Landschaftsarchäologische Untersuchungen zur Baar und den angrenzenden Naturräumen des Schwarzwaldes und der Schwäbischen Alb. *RessourcenKulturen* 10. Tübingen: Tübingen University Press. DOI: 10.15496/publikation-45820

Miera, J J, Henkner, J, Schmidt, K, Fuchs, M, Scholten, T, Kühn, P and Knopf, T 2019 Neolithic settlement dynamics derived from archaeological data and colluvial deposits between the Baar region and the adjacent low mountain ranges, southwest Germany. *E&G Quaternary Science Journal*, 68: 75–93. DOI: 10.5194/egqsj-68-75-2019

Miera, J J, Schmidt, K, von Suchodoletz, H, Ulrich, M, Werther, L, Zielhofer, C, Ettel, P, Veit, U 2022

Large-scale investigations of Neolithic settlement dynamics in Central Germany based on machine learning analysis: a case study from the Weiße Elster river catchment. *PLoS ONE*, 17(4): e0265835. DOI: 10.1371/journal.pone.0265835

Mytum, H C 1988 On-site and Off-site Evidence for Changes in Subsistence Economy: Iron Age and Romano-British West Wales. In: Bintliff, J L, Davidson, D A and Grant, E G (eds) *Conceptual Issues in Environmental Archaeology*. Edinburgh: University Press, pp. 72–81.

Paetzold, D 1992 Bemerkungen zum Siedlungsverhalten neolithischer bis latènezeitlicher Bevölkerungen zwischen Regensburg und Deggendorf. Gab es Besiedlungsschwerpunkte in Abhängigkeit von naturräumlicher Gliederung und Bodenbeschaffenheit? *Bayerische Vorgeschichtsblätter*, 57: 77–102.

Pebesma, E J 2004 Multivariable geostatistics in S: the gstat package. *Computers & Geosciences*, 30(1): 683–691.

Pebesma, E J and Bivand, R S 2005 *Classes and methods for spatial data in R. R News* 5(2). Available at http://cran.r-project.org/doc/Rnews/ [Last accessed 10 August 2018].

Purinton, B and Bookhagen, B 2017 Validation of DEMs (DEMs) and comparison of geomorphic metrics on the southern Central Andean Plateau. *Earth Surface Dynamics*, 5(1): 211–237. DOI: 10.5194/esurf-5-211-2017

Rabus, B, Eineder, M, Roth, A and Bamler, R 2003 The shuttle radar topography mission — a new class of DEMs acquired by spaceborne radar. *ISPRS Journal of Photogrammetry & Remote Sensing*, 57: 241–262. DOI: 10.1016/S0924-2716(02)00124-7

Ritter, P 1987 A vector-based slope and aspect generation algorithm. *Photogrammetric Engineering and Remote Sensing*, 53(1): 1109–1111.

Rodriguez, E, Morris, C S, Belz, J E, Chapin, E C, Martin, J M, Daffer, W and Hensley, S 2005 *An assessment of the SRTM topographic products, Technical Report JPL D-31639, Jet Propulsion Laboratory, Pasadena, California.* Available at http://www2.jpl.nasa.gov/srtm/srtmBibliography.html [Last accessed 10 August 2018].

Rogers, S R, Collet, C and Lugon, R 2014 Least cost path analysis for predicting glacial archaeological site potential in central Europe. In: Traviglia, A (ed.) *Across Space and Time. Computer Applications and Quantitative Methods in Archaeology (CAA), Proceedings of the 41st International Conference (Perth, Australia, March 25–28, 2013)*. Amsterdam: Amsterdam University Press.

Rogers, S R, Fisher, M and Huss, M 2014 Combining glaciological and archaeological methods for gauging glacial archaeological potential. *Journal of Archaeological Science*, 52, pp. 410–420. DOI: 10.1016/j.jas.2014.09.010

Roper, D C 1979 The Method and Theory of Site Catchment Analysis: A Review. *Advances in Archaeological Method and Theory*, 2(1): 119–140.

Roubis, D, Sogliani, F, Gabellone, F, Danese, M and Gnesi, D 2011 Archaeological Landscapes through GIS (Cost Surface Analysis) and Virtual Reality: A Case Study on the Monastic Site of Jure Vetere (Calabria, Italy). In: Jerem, E, Redö, F and Szeverényi, V (eds) *On the Road to Reconstructing the Past. Computer Applications and Quantative Methods in Archaeology (CAA). Proceedings of the 36th CAA Conference, Budapest, 2–6th April 2008*. Budapest: Archaeolingua Foundation, pp. 476–484.

Sarkar, D 2008 *Lattice: Multivariate Data Visualization with R.* New York: Springer.

Thomson, D F 1939 The seasonal factor in human culture. *Proceedings of the Prehistoric Society*, 5(1): 209–221. DOI: 10.1017/S0079497X00020545

von Thünen, J H 1826 *Der isolierte Staat in Beziehung auf Landwirtschaft und Nationalökonomie, oder Untersuchungen über den Einfluss, den die Getreidepreise, der Reichthum des Bodens und die Abgaben auf den Ackerbau ausüben*. Hamburg: Perthes.

Tobler, W R 1961 *Map transformation of geographic space.* Unpublished thesis (PhD), University of Washington.

Tobler, W R 1993 *Three presentations on geographical analysis and modelling: non-isotrophic modelling, speculations on the geometry of geography, global spatial analysis. National Center for Geographic Information and Analysis. Technical Report* 93–1. Available at https://escholarship.org/uc/item/05r820mz [Last accessed 10 August 2018].

Tschauner, H 1996 Middle-range theory, behavioural archaeology, and post-empiricist philosophy of science in archaeology. *Journal of Archaeological Method and Theory*, 3(1): 1–30.

Tiffany, J A and Abbott, L R 1982 Site Catchment Analysis: Application to Iowa Archaeology. *Journal of Field Archaeology*, 9(1): 313–322. DOI: 10.1179/009346982791504634

Trigger, B G 1995 Expanding middle-range theory. *Antiquity*, 69(294): 449–458. DOI: 10.1017/S0003598X00081862

Trigger, B G 2008 *A History of Archaeological Thought*. Cambridge: Cambridge University Press.

Uthmeier, T, Ickler, S and Kurbjuhn, M 2008 Site catchment Analysis in the Late Crimea Middle Palaeolithic: a GIS Based Approach. In: Chabai, V P, Richter, J and Uthmeier, T (eds) *Kabazi V: Interstratification of Micoquian and Levallois-Mousterian campsites, Part II*. Simferopol: National Academy of Sciences of Ukraine, pp. 481–508.

Valde-Nowak, P 2002 *Siedlungsarchäologische Untersuchungen zur neolithischen Nutzung der mitteleuropäischen Gebirgslandschaften. Internationale Archäologie 69.* Rahden: M. Leidorf.

Vita-Finzi, C and Higgs, E S 1970 Prehistoric Economy in the Mount Carmel Area of Palestine: Site Catchment Analysis. With Contributions by Sturdy, D, Harriss, J, Legge, A J, Tippett, H. *Proceedings of the Prehistoric Society*, 36(1): 1–37. DOI: 10.1017/S0079497X00013074

Zevenbergen. L W and Thorne, C R 1987 Quantitative analysis of land surface topography. *Earth Surface Processes and Landforms*, 12(1): 47–56. DOI: 10.1002/esp.3290120107

Zipf, G R 1965 *Human Behavior and the Principle of Least Effort*. New York: Hafner.