Technical note 3: Collaborative Research Center 1070 – Geoscientific and archaeological research

Distance relationships or does distance matter – calculating a non-isotropic spatial relationship by integrating human energy expenditure in terrain based estimations

– A seamless workflow for defining archaeological Site Exploitation Territories (SET) using the open source (geo-)statistical language R –

Ahlrichs, Jan Johannes[1,2], Gries, Philipp[4] and Schmidt, Karsten[1,3,4]
[1] Collaborative Research Center 1070 ResourceCultures, University of Tübingen
[2] Institute of Pre- and Protohistory and Medieval Archaeology, University of Tübingen
[3] eScience-Center, University of Tübingen
[4] Department of Geosciences, Soil science & Geomophology, University of Tübingen

Historical background

Already in early studies on the chronological classification of Prehistory one can find a general awareness about different subsistence strategies and thus different spatial perceptions in early societies (Lubbock 1865). Nonetheless, until the second half of the 20th century, few studies on prehistoric economies and their development were published. Probably the most famous example in this regard is "*Prehistoric Europe: The Economic Basis*" (Clark 1952), which was published a few years after the Second World War by Sir John Grahame Douglas Clark (1907–1995). With the advent of the Processual Archaeology during the 1960s, the research interest in economic issues started to grow increasingly (see 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 and Vita-Finzi 1972: 27–28; Jarman et al. 1972: 61–62). At the University of Cambridge, a research group led by Eric S. Higgs (1908–1976) developed a methodological concept in the early 1970s, which enabled archaeologists to overcome this way of "isolated" analysis of archaeological sites and to study the archaeological material in the context of its geographical environment. 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 et al. 1982). Inspired by the work of Johann Heinrich von Thünen (1826) Walter Christaller (1933), Donald Fergusson Thomson (1939), Michael Chrisholm (1968) and Richard Borshay Lee (1969), they developed the concept of SET along with the site catchment analysis (Higgs and Vita-Finzi 1966: 23–29; Higgs et al. 1967: 12–19; Vita-Finzi and Higgs 1970)[1].

General aims

The team around E. S. Higgs 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 catchment areas of related archaeological sites (Vita-Finzi and Higgs 1970: 1; Higgs and Vita-Finzi 1972: 28–29; Foley 1977: 163; Bailey 1981: 99). 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 and Higgs 1970: 5; Higgs and Vita-Finzi 1972: 27). The concept of SET and the site catchment analysis enabled archaeologists to determine the economic function of an excavated site through an in-depth analysis of all archaeological findings and the ecological as well as geographical environment (Higgs and Vita-Finzi 1972: 28; Jarman 1972: 725; Jarman et al. 1972: 61–62). Thus sites were no longer considered as isolated case studies but as part of an economic 'system' (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). The strengths of the concept were summarized by Geoff N. Bailey and Iain Davidson (1983: 88) as follows:

I. Definition of a territory that was visited daily by the inhabitants of a site to deal with the subsistence.
II. Analysis of the origin of natural resources that were recovered at archaeological sites.
III. 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.
IV. Reconstruction of the potentially available food for the inhabitants of a site and the subsistence strategies associated therewith.
V. Reconstruction of the function of a site (permanently inhabited, etc.).
VI. Reconstruction of social and economic relations between sites within a regional settlement system.

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[1] cf. Higgs and Vita-Finzi 1972; Jarman 1972; Jarman et al. 1972; Hodder and Orton 1976: 229–236; Jarman 1976; Roper 1979; Bailey 1981: 98–100; Bailey and Sheridan 1981: 1–2; Davidson 1981; Rood 1982: 29–30; Tiffany and Abbott 1982: 313; Birkett 1985: 132–135; Kipfer 2000: 517; Williams 2004: 24–29; Bailey 2005; Kanter 2005: 1191–1193.

In addition, the results of site catchment analysis were used as an indicator to estimate potential site distributions (Jochim 1976; Tiffany and Abbott 1982). As noted by Bailey and Davidson, the concept of SET has to be located in the range of ‚Middle-range theories' (Binford 1975; Binford and Sabloff 1982; Trigger 1995; Tschauner 1996), because it provided an analytical approach, which enabled researches to link theory with archaeological data (e.g. Bailey and Davidson 1983: 88).

Premises

The concept of SET operates with the idea that human behaviour in the past can be described by 'laws' (Clarke 1968: 441–511; Clarke 1972; Higgs and Jarman 1975)[2]. One of the main assumption is that people have a territorial behaviour and do not select sites at random (Vita-Finzi and Higgs 1970: 2; Higgs and Vita-Finzi 1972: 30; Jarman 1972: 706, 712)[3]. Further, 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 (Vita-Finzi and Higgs 1970: 2; Jarman 1972: 706; Jarman et al. 1972: 62–63)[4]. Closely related to this premise is the notion that human action is determined by cost-benefit calculations and is constantly focused on efficiency, e.g. to meet ones economic needs with the lowest possible effort (Jarman 1972: 710 [citing Zipf 1965]; Jarman et al. 1972: 62–63; Tiffany and Abbott 1982: 313–314). This behaviour ultimately leads to the premise that the probability to exploit an area decreases with distance (Vita-Finzi and Higgs 1970: 7; Jarman et al. 1972: 62–63). Finally, SET is also based on environmental deterministic ideas. It is assumed that the close-range environmental situation had a significant impact on a site's economic function as well as its potential to develop (Jarman 1976: 546).

Time-distance factors

For the comparative study of economic strategies in mobile and sedentary societies different analytical terms were developed, that act on different spatial scales (see Champion et al. 1984: 62). The term *home base* describes the main site, from which a territory is economically exploited (Vita-Finzi and Higgs 1970: 6; Higgs and Vita-Finzi 1972: 30). Temporarily used sites along paths or other migration routes were termed *transit sites* (Vita-Finzi and Higgs 1970: 7; Higgs and Vita-Finzi 1972: 30). These two types can be differentiated by a discussion of their archaeological finds in relation to the SET. The

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[2] cf. Jarman 1976: 523; Bailey and Sheridan 1981: 1–2.

[3] cf. Jarman et al. 1972: 61; Tiffany and Abbott 1982: 313; Bailey and Davidson 1983: 89.

[4] cf. Bailey 2005: 172.

term *Site Exploitation Territory* designates a catchment area, which is commonly used by the inhabitants of a site (Vita-Finzi and Higgs 1970: 7; Higgs and Vita-Finzi 1972: 30; Jarman 1972: 708). The term *annual territory* described the entire area, which is used by a group in the course of a year. This territory may cover more than one SET (Vita-Finzi and Higgs 1970: 7; Higgs and Vita-Finzi 1972: 30; Jarman 1972: 709; Bailey and Davidson 1983: 88).

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 different time-distance factors. Referring to R. B. Lee (1969) on the !Kung San it was assumed that the catchment area of mobile groups includes a maximum radius of 10 km, which equates on flat terrain a maximum distance of two hours‘ walk (Higgs and Vita-Finzi 1972: 30–31; Jarman et al. 1972: 62–63; Bailey and Davidson 1983: 91–92). With reference to M. Chrisholm (1968) Higgs and his team proposed a maximum radius of 5 km/h for sedentary societies (Higgs and Vita-Finzi 1972: 30–31; Jarman et al. 1972: 62–63; Bailey and Davidson 1983: 91–92). 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 and Vita-Finzi 1972: 30–31; Jarman 1972: 713; Bailey and Davidson 1983: 92).

However, as Bailey and Davidson (1983) pointed out, there are no universally valid time-distance factors for the analysis of prehistoric sites (Bailey and Davidson 1983: 93). 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 and 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 20th 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 analyse possible exploitation territory by analysing the walking distance (experimental study) within in 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 and 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 and Davidson 1983: 93). In order to deal with some of these hurdles, Bailey and Davidson combined field surveys with the analysis of topographic maps. In order to do so, they used rules developed by William W. Naismith (1856–1935), which were used by mountaineers to calculate time-distances. In principle Naismith assumes 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 and Davidson 1983: 94).

The form of a SET depends on the terrain surrounding a site. In landscapes with a balanced and flat relief SET often have an almost circular shape. As one might expect, in mountainous regions this is not the case. Due to strong relief differences SET tend to have a distorted form (Higgs and Vita-Finzi 1972: 33; Jarman 1972: 710, 713; Bailey and Davidson 1983: 93, 96; Valde-Nowak 2002: 65). Because of that, SET based on time-distance factors provide a more realistic picture of the potentially used catchment area of a site in mountainous regions.

The concept and the development of site catchment analysis had a huge impact in archaeological research[5]. In Germany, site catchment is often used in order to perform comparative studies on soil preferences in prehistoric time periods (Gringmuth-Dallmer and Altermann 1985; Paetzold 1992; Fries 2005). However, only a few examples can be found, in which archaeologists use SET based on time-distance factors and topography (Valde-Nowak 2002; Uthmeier et al. 2008; Roubis et al. 2011; Cappenberg 2014).

Computational methods

The increasing availability of spatial data and fast developments in computing technologies as well as geographical information systems (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 et al. 2014a; Rogers et al. 2014b). Especially with the increased availability of high resolution as well as large-scale digital elevation models as provided by the Shuttle Radar Topographic Mission (Rodriguez et al. 2005; Farr

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[5] cf. Bintliff 1977; Findlow and Ericson 1980; Bailey 1983; Gilman and Thornes 1985; Brooks 1986; Bailey and Parkington 1988; Mytum 1988; Kreuz 1990.

et al. 2007; Jarvis et al. 2008) the methods and their results become more and more interesting for the scientific community to analyse societies, functions and resources. In general, the common workflow for time-cost analysis comprises four steps (**Fig. 1**). The first step is to create a cost surface based on an input dataset and an arbitrary cost function, where cost is measured 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 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.

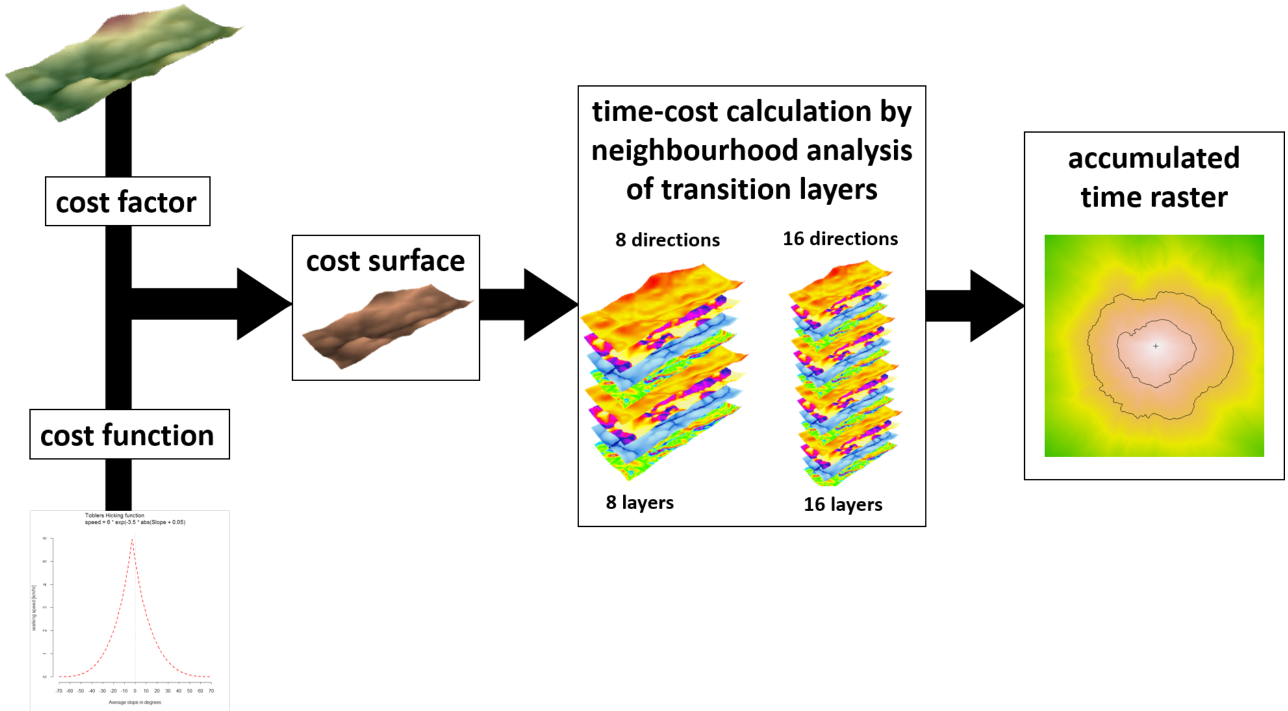

Fig. 1: General workflow for time-cost analysis in four steps.

Tobler Hiking Function

As mentioned before, there are various ways to apply and/or implement least-cost analysis within a wide-range of archaeology research. Numerous studies use the hiking function by Waldo R. Tobler (1961; see also Herzog 2013 and Herzog 2014) first implemented by Gorenflo and Gale (1990). Tobler (1993) developed an empirical model based on the empirical 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 digital elevation model (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**). **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.

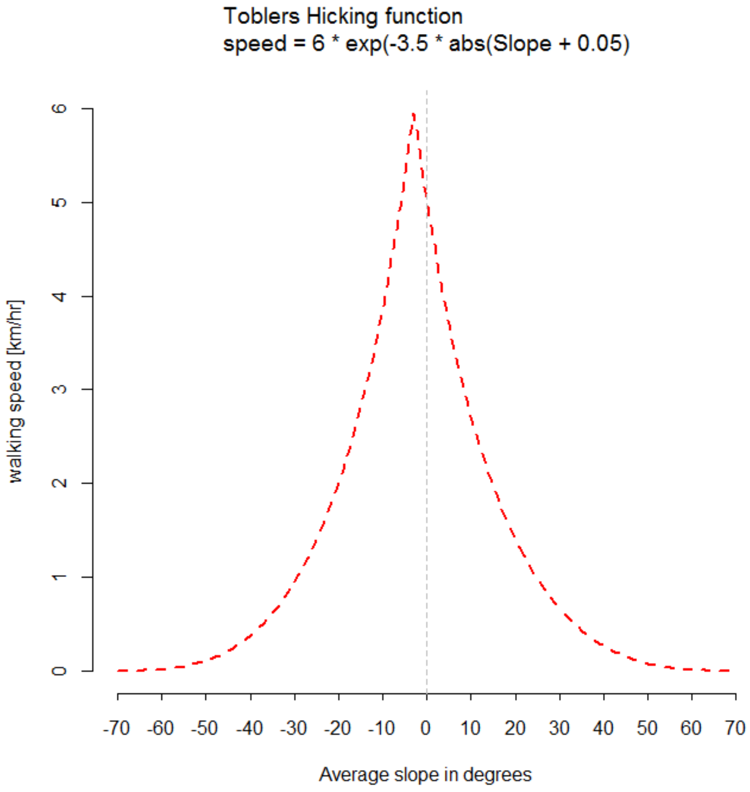

Fig. 2: The Tobler Hiking Function (Tobler 1993).

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 2010; 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 which use 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 calculation of the slope gradient bases on a neighbourhood analysis using a moving window (**Fig. 3**).

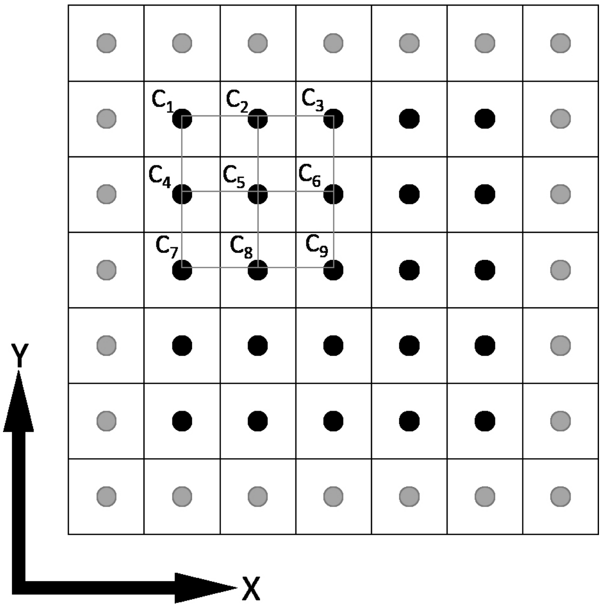

Fig. 3: Moving Window approach for deviating terrain attributes (e.g. slope) from a digital elevation model (see Behrens 2003).

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 and 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 between the centre cell and its neighbourhood. Using Zevenbergen and Thorne (1987), the slope angle bases on accounting the cardinal cells only (C_2, C_4, C_6, C_8, **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.

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. >16–20°) 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 computing 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 km^2 to 186.5 km^2. The spatial restriction enables the purposive focus on particular questions.

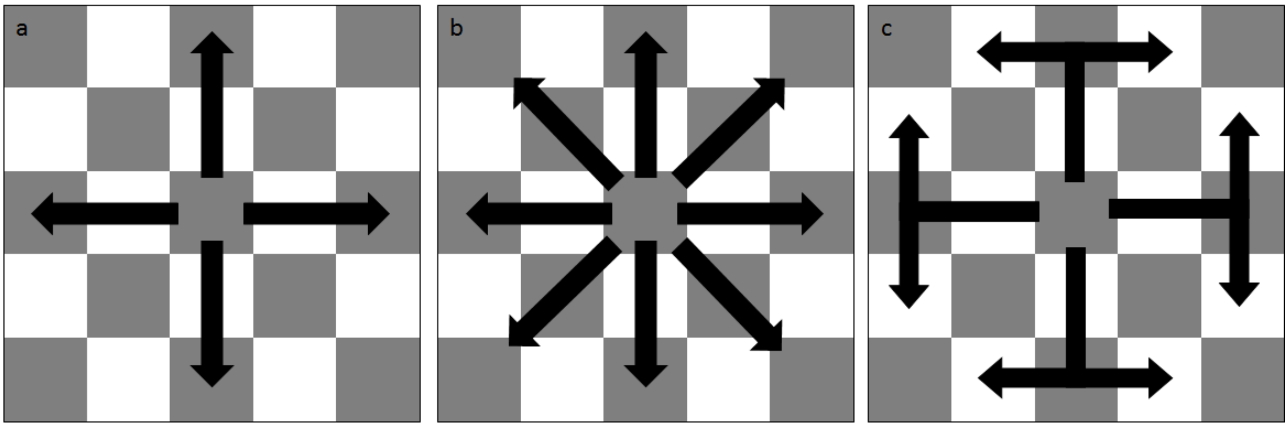

Fig. 4: Moving characteristics using four (a, rook move), eight (b, queen move) and 16 directions (c, knight move).

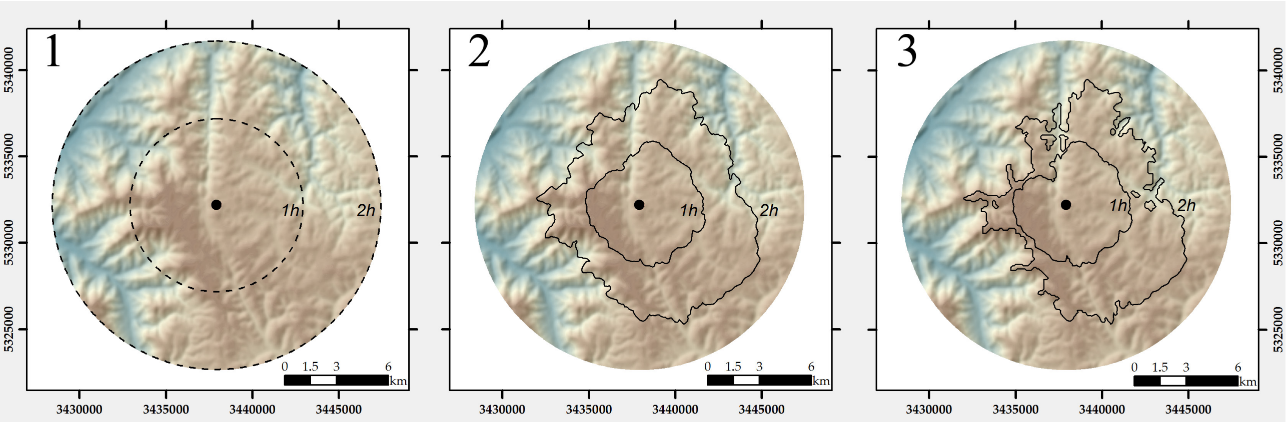

Fig. 5: Three plots of time-cost-analysis using different terrain information. Excluding the terrain results in circular isochrones around the initial point (1). By including the slope gradient, the covered distances per time interval continue along the terrain (2). The exaggeration of steep slopes creates moving patterns continuing strictly along high-angle hillsides (3). The contour lines represent the covered distance per hour.

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 digital elevation model and/or a slope gradient dataset.

Tab. 1: R-packages used for the delineation of archaeological Site Exploitation Territories (SET).

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 and 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 and Rundel 2016

A successful application of the script requires the installation of all packages of **Tab. 1** on a local machine 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)
[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]    ToblersHikingFunction <- function(x){ 6 * exp(-3.5 * abs(tan(x*pi/180) + 0.05)) }
[32]    TheoreticalSlopes <- seq(-70,70,1)
[33]    WlkSpeed <- ToblersHikingFunction(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= TheoreticalSlopes[seq(1,length(TheoreticalSlopes),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) directories

```
[45]    InDir <- “Path/To/Your/InputData”
[46]    OutDir <- “Path/To/Your/OutputData”
```

– R-Script Part 3 – Settings (2) input data

```
[50]    DEM          <- “FileNameOfDigitalElevationModel.rasterformat”
[51]    SLOPE  <- “FileNameOfSlopeGradient.rasterformat”
[52]    POINT  <- c(X,Y-CoordinateOfInitialPoint)
```

– R-Script Part 3 – Settings (3) output data

```
[55]    TCR     = “FileNameOfTimeCostRaster”
[56]    SLG     = “FileNameOfSlopeRaster” # optional
[57]    CTL     = “FileNameOfContourLines”
[58]    rdt     = “RasterDatatype”
```

– R-Script Part 3 – Settings (4) environmental 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(SLOPE)
[104]   } else {
[106]           if(!is.na(projection(rDEM))) {
[107]                   rSLOPE <- terrain(rDEM, opt=’slope’, unit=’degrees’,
                        neighbors=NumberOfNeighbors)
[108]           } else {
```

```
print("PROJECTION ERROR: no projection is set for ELEVATION input file.")
		}
}
```

– R-Script Part 4 – set initial spatial location

```
SPATIALPOINT <- data.frame(x=POINT[1],y=POINT[2])
coordinates(SPATIALPOINT) <- ~ x+y
projection(SPATIALPOINT) <- projection(rDEM)
```

– R-Script Part 4 – Reduce dataset to AOI (Area-Of-Interest)

```
rSLOPE4TimeCost <- rSLOPE
rDEM4Statistics <- rDEM
if (TimeOfInterest > 0) {
		maxHikingDistance <- round(max(WlkSpeed)* (TimeOfInterest+0.25)*1000)
		bufferMaxHikingDistance <- buffer(SPATIALPOINT, maxHikingDistance)
		rDEM_clip <- crop(rDEM,extent(bufferMaxHikingDistance))
		rSLOPE_clip <- crop(rSLOPE,extent(bufferMaxHikingDistance))
		rDEM4Statistics <- rDEM_clip
		rSLOPE4TimeCost <- rSLOPE_clip
}
```

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.

– R-Script Part 5 – time cost analysis

```
rVelocity.kmh <- calc(rSLOPE4TimeCost, ToblersHikingFunction)
rVelocity.ms <- calc(rVelocity.kmh, fun=function(x) { ((x*1000)/3600) })
if (Damping) {
		rDamping <- rSLOPE4TimeCost
		rDamping[rDamping >  DampingFactor]  = 1000
		rDamping [rDamping <= DampingFactor]  = 1
		rVelocity.ms <- rVelocity.ms/rDamping
}
lTransition <- transition(rVelocity.ms, transitionFunction=mean,
directions=NumberOfDirections)
lGeoCorrection <- geoCorrection(lTransition, type="r")
rAccumulatedCostSurface.s <-
```

– R-Script Part 6 – zonal statistics

```
zonalStatistics   <- data.frame(matrix(0,2,5))
statNames <- c(‚1st hour‘,‘min‘,‘max‘,‘mean‘,‘sd‘)
names(zonalStatistics) <- statNames
zonalStatistics[1,1] <- ‚DEM‘
```

```
zonalStatistics[2,1] <- ‚SLOPE‘
rasterZones <- rAccumulatedCostSurface.h
rasterZones[rAccumulatedCostSurface.h <= 1] = 1
rasterZones[rAccumulatedCostSurface.h > 1]   = 2
for(st in 2:length(statNames)) {
zonalStatistics[1,st] <- zonal(rDEM4Statistics, rasterZones, statNames[st])[1,2]
        zonalStatistics[2,st] <- zonal(rSLOPE4TimeCost, rasterZones, statNames[st])[1,2]
}
print(zonalStatistics)
```

Tab. 2: Zonal statistics of the terrain as example of the descriptive analysis of the spatial datasets (Digital Elevation Model and Slope) using the Min (Minimum), Max (Maximum), Mean and SD (Standard deviation) measurements of the spatial area defined by the first walking hour.

Spatial Dataset	Min	Max	Mean	SD
DEM [m]	766	1177	995.76	73.03
Slope [°]	0.11	33.14	8.08	4.87

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

– R-Script Part 7 – write files

```
setwd(outDir)
writeRaster(rAccumulatedCostSurface.h,TCR, format=rdt)
if (nchar(SLOPE) == 0) {
        writeRaster(rSLOPE4TimeCost,SLG, format=rdt)
}
shapefile(vContourLines,filename=CTL)
shapefile(vContourLines,filename=CTL)
```

This technical section is made to evolve! Please share your thoughts, requirements and suggestions regarding the described issues to Jan Ahlrichs (Jan(dot)Ahlrichs(at)uni-tuebingen(dot)de) and Karsten Schmidt (Karsten(dot)Schmidt(at)uni-tuebingen(dot)de.

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