A comprehensive spatial model for historical travel effort – a case study in Finland

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Contributing to multidisciplinary studies of human population history, this paper presents an analysis chain to comprehensively model the historical travel environment in Finland, based on a study of spatial patterns of overall accessibility within the country. We created a spatial historical travel environment model over the whole country using high-quality terrain and landscape spatial data, combined with information from historical sources that characterize the landscape in terms of travel effort given the environmental and human-related factors current up until the late 19th century. Spatial analyses of historical travel effort based on the travel environment model indicate travel speeds for different parts of the country, ranging from 0.6 to 5.3 km/h. This is nearly a tenfold range, potentially highly significant for studies relying on historical travel effort and contacts between population groups in Finland. The results show that the overall travel effort in southern Finland is significantly smaller than in the north: almost all areas in southern Finland have average travel speeds above 3 km/h, whereas the average travel speeds below 2.5 km/h are typical in the north. A more detailed study using random 100 km transects highlights the variability of the least-cost routes in different landscapes and between different source data combinations in each cost surface. The paper identifies great potential in combining the existing spatial data archives with archaeological, linguistic, and genetic data in a GIS analysis, to study the travel effort and its impact on the observed spatial patterns of languages, genetic traits, and archaeological findings.

Keywords: cost-distance modeling, GIS, human history, travel environment, multicriteria approach, human dispersal

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Introduction

Coupling human and cultural spread with the temporal and spatial heterogeneity of the natural environment is an innovative approach in studies on the human past (Gavin *et al*. 2013). This has been discussed theoretically for decades (e.g. Meggers 1954), but the current emergence of the topic takes advantage of advanced spatial computing, as well as accumulating datasets on the spatial variation of cultures (Hua *et al*. 2019). To understand the spatial patterns and dispersal mechanisms of people and cultures, it is important to reconstruct the accessibility of early landscapes: how did the geographical constraints and affordances affect the spread and contacts of early human populations?

Accessibility can be measured as the distance between locations. Geographic (Euclidean) distance, the straight-line route between two points, is a common and easily perceivable way to measure the distance between locations. In reality, Euclidean distance seldom reflects the actual accessibility in the landscape because people tend to seek out a route which requires the least time and energy (Naismith 1892; Pandolf *et al*. 1977). Many landscape features, such as topography, land cover, surface water, and roads or other routes form both hindrances and pathways, greatly influencing travel time and effort. Thus, the overall accessibility of a landscape is a complex function of landscape heterogeneity. With modern computational tools and high-quality spatial data, it can be modeled comprehensively, accounting for relevant environmental and socio-cultural features.

The concept of travel effort is used to integrate the impact of numerous landscape features to represent the ease of movement. Geographic information systems (GIS) provide digital spatial tools, such as cost-distance modeling, for comprehensive assessment of travel effort. Travel effort computation through cost-distance (or least-cost) modeling requires applicable geographical data, and quantification of the ease of travel related to selected landscape features (e.g. Tomlin 2013). To compute the least-cost routes in cost-distance modeling, the ease of travel can be measured, for example, as travel time, speed, or energy expenditure (Douglas 1994). This approach enables a much more realistic simulation of landscape heterogeneity, and consequently the travel effort, than Euclidean distance.

Cost-distance modeling was initially developed in transportation geography and engineering to optimize routes across heterogeneous landscapes, to define suitable landscape corridors for the construction of highways for instance (Warntz 1957; McHarg 1967). Since the method was included in GIS software early on (Tomlin 1990), it has been applied for a variety of purposes. The approach has been popular in landscape genetics (e.g. Manel *et al*. 2003; Spear *et al*. 2010; van Strien *et al*. 2012; Yu *et al*. 2015), and in landscape ecology (e.g. Adriaensen *et al*. 2003; LaRue & Nielsen 2008; Richard & Armstrong 2010; Stevenson-Holt *et al*. 2014; Etherington 2016), where it has been used to study the functional connectivity of patches of different species in the landscape, often for conservation purposes.

There is a growing interest in unraveling the human-nature interaction of the past. Globally scaled studies indicate environmental variation, which has affected past human populations (Nettle 1998; Gavin *et al*. 2013, 2018; Hua *et al*. 2019; Pacheco Coelho *et al*. 2019; Racimo *et al*. 2020). In human history research, the cost-distance approach has been utilized in studies of linguistic dispersion, where the effect of landscape has been explained through individual distance correlations instead of creating a model with several factors. Usually, the modeling has been based on factors such as roads (Gooskens 2004; Szmrecsanyi 2012; Jeszenszky *et al*. 2018) or elevation (Catchart 2015). Haynie (2012), however, used the combination of several landscape features – elevation, vegetation, surface water, and watershed boundaries – to study linguistic distance among North American indigenous languages. In archaeology, the cost-distance method has commonly been utilized to reconstruct historical trails and routes (e.g. Howey 2011; ten Bruggencate 2016; Supernant 2017; Seifried & Gardner 2019), often containing several factors such as slope, vegetation, water and land area, and visibility information (e.g. Howey 2007; White & Barber 2012; Gustas & Supernant 2017).

We constructed a comprehensive spatial historical travel environment model to support interdisciplinary studies of human and cultural spread in Finland. The Finnish landscape provides an interesting case for human history studies in multiple temporal depths since agriculture was introduced relatively late and, as recently as AD 1000, the area was presumably divided by hunter-gatherer groups and Iron Age farmers. In addition, it is likely that linguistic boundaries were still clear between Finnic, Saamic and Germanic languages, as well as already extinct languages (Aikio 2012;

Frog & Saarikivi 2015). Currently the area is mainly Finnish speaking, and the Finnish dialects have distinctive local variations (reviewed in Syrjänen *et al*. 2016). Honkola and colleagues (2018) studied the drivers of linguistic differences in the country and found that environmental differences, in addition to cultural differences, were associated with dialectal differences. The role of environmental variation was strong, even though there are no large-scale natural barriers for movement in Finland. Genetic studies show a clear division between the populations of eastern and western Finland (e.g. Salmela *et al*. 2008; Kerminen *et al*. 2017), and the reconstruction of past genetic boundaries separate southwestern Finland from other parts of the country (Neuvonen *et al*. 2015).

The availability and coverage of high-quality terrain and landscape spatial data are excellent in Finland. In our study, we made use of publicly available data to characterize the landscape in terms of travel effort and complemented these with information concerning routes and boundaries from historical sources. We were thus also able to use the source data to portray the past travel environment in recent centuries. In Finland, where topographical variation is moderate but detailed, a wide variety of environmental features are needed to capture the overall landscape heterogeneity.

Human movement has usually been modeled along roads and pathways or in off-road terrain on foot (Xiang 1996; Balstrøm 2002; Jobe & White 2009; Etula & Antikainen 2012). However, there are some cost-distance studies that consider travel by horse (e.g. Sunseri 2015), and by watercraft (Leidwanger 2013; Gustas & Supernant 2017). To achieve a more realistic picture of travel opportunities, different means of travel can be included for the same surface. We model travel effort allowing different means of travel: on foot, by horse, or by watercraft, including the possibility to switch from one to another en route.

We create a spatial historical travel environment model, and use it to analyze the travel effort in Finland for two time periods: a) the Pre-Medieval period, covering the time before intra-regional roads and administrative borders were in place, in this case approximately from the 12th to the 15th centuries, referred to as the *Early environment* model, and b) the Post-Medieval period, from the late medieval time to the late 19th century, containing the intra-regional road network and administrative borders, referred to as the *Environment and human* model. We carry out spatial analyses to study the overall variation in historical travel effort in Pre-Medieval and Post-Medieval times from different aspects and compare the differences between these two time periods. We also estimate the impact of different environmental parameters on the most economical routes between locations using five travel environment models. Our ultimate goal is not to find the most suitable routes between locations, which is often the case in cost-distance studies, but to study the variation in overall accessibility within the country, in order to better assess the potential for contacts between population groups in the past.

Material and methods

Outline of the workflow

We compiled a set of cost surfaces in raster format by classifying and arranging various source data, first in vector format (Fig. 1). The five cost surfaces were compiled using a different composition of source data to assess the impact of the respective source data on travel effort. The cost-distance computation was carried out with raster surfaces with a cell size of 1 km^2.

Creation of a spatial historical travel environment model

Study area

Finland is a sparsely populated country with a total area of 390,909 km^2, of which 77.8% is land, 13.4% sea, and 8.8% fresh water (National Land Survey of Finland 2020). The topography is relatively low, and there are no major hindrances, such as mountain ranges. Nevertheless, the terrain is variable due to vast boreal forest cover, thousands of lakes and rivers, and post-glacial formations. During the last glaciation that ended about 10,000 BP the continental ice sheet, mostly over 2,000 m thick, covered

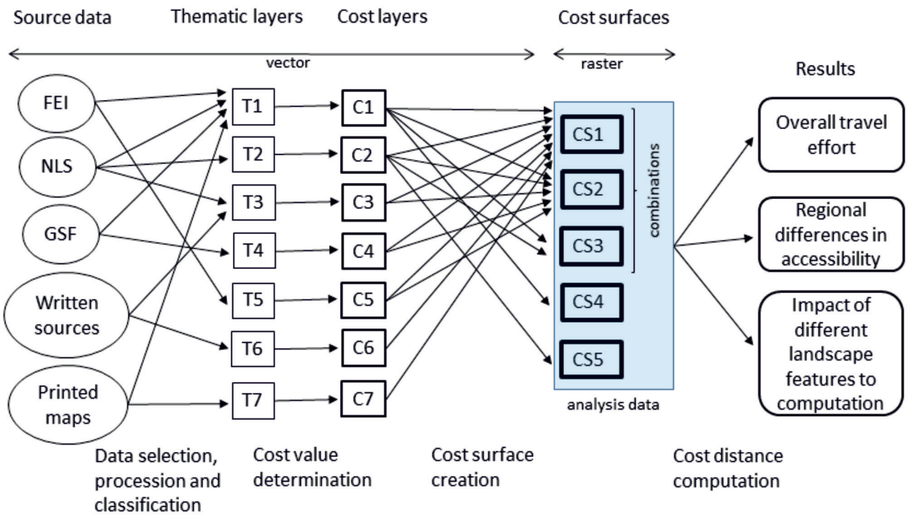

Fig. 1. Summary of the work steps containing vector-based dataset creation, the analysis of raster surfaces and overall results. The flow chart indicates the most crucial operations and the names and abbreviations of layers and surfaces in this process. Source data were produced by the Finnish Environment Institute (FEI), the National Land Survey of Finland (NLS) and the Geological Survey of Finland (GSF).

the country and caused a depression of several hundred meters in the continental plate (Mörner 1979). After deglaciation, the depression began to rebound quickly altering the landscape drastically, and the slowing rebound continues at a current rate of 3–9 mma^{-1} (Kakkuri 1997).

Over the recent centuries, human populations have shaped the living environment, for example by clear-cutting forests and drying wetlands and lakes for farming and forestry. Road network development began more than 1000 years ago and intensified in the 16th century (Viertola 1974; Masonen 1999a), facilitating the movement of people within the country.

Selecting landscape features

We identified environmental features which have potentially influenced human movement in Finland in the past. These include both hindering and facilitating factors related to the natural environment and human influence. We used the following landscape features to draw conclusions about travel environment: 1) land cover, 2) topography, 3) water bodies and water routes, 4) eskers and end moraines, 5) watersheds, 6) the road network in the 16th century, and 7) a compilation of historical administrative borders.

Land cover and topography are comprehensive landscape features covering the whole country and consist of areas both favorable and unfavorable for human movement. Land cover indicates the vegetation type and landscape openness, and is divided into forest, wetlands, water, agricultural land, and artificial areas. In terms of travel effort, the differences between the land cover types originate from visibility (density of trees), bearing capacity of terrain (e.g. wetlands), local variation in ease of travel (boulder field vs. flat terrain), and the means of transportation (walking, carriage, boat) (Masonen 1999a; Etula & Antikainen 2012). Topography describes local variation in elevation and slope, indicating terrain accessibility relative to the surrounding areas: larger altitude differences mean steeper slopes, which, consequently, requires a higher travel effort (Naismith 1892; Tobler 1993).

The other landscape features can be treated as either hindering or facilitating factors for human travel. Water bodies and water routes include both inland waters (lakes and rivers) and the sea. In general, travel by foot in a forested landscape without roads or paths is slower than by boat or on ice along the water, even though some challenges, such as rapids and shallowness of rivers, impede the movement along a water in some locations (Masonen 1999a; Salminen 2006). In the case of Finnish water routes, the means of travel differ greatly by seasons: in the summer, a boat or canoe is needed, while during the winter, iced-over bodies of water can be crossed on foot, by skis or by sleigh. Documented historical water routes, and actually all water bodies, can thus be seen as significant facilitators for human travel.

Eskers and end moraines are glacial and glaciofluvial formations of sand and gravel deposits. These appear as oriented ridges in the terrain with a noticeable structure and scarce vegetation. These landforms are considered to facilitate human travel in the historical context (Fogelberg 1974; Halinen 1999), and pathways and roads often follow them (Fogelberg 1974).

Watersheds are elevated terrain areas that separate neighboring drainage basins. They appear in all scales, dividing surface water and groundwater flow towards different river systems. For example, in Finland, the Suomenselkä region separates the water flow between the Gulf of Bothnia and the lake district of central Finland. The Suomenselkä region forms a distinct, 300 km long watershed from the lake Oulujärvi towards the southwest. Due to the elevated terrain and lack of water routes, watersheds may be seen as gentle hindrances in historical human movement. Even though Finnish watersheds do not form notable physical hindrances, it is assumed that humans have traveled within a certain drainage basin than crossed the watershed to another drainage basin.

The road network was developed first in the southern part of the country, which was more densely populated. In the 16th century, roads only existed between the largest settlements, especially to ease travel between medieval castles (Viertola 1974; Masonen 1999b). During the next centuries, the road network was gradually developed in the central and northern parts of the country (Viertola 1974; Nenonen 1999a). This development enabled more efficient long-distance travel within the country on foot, or by horse, carriage, or sleigh. Historical roads are considered as the most significant facilitators for human travel.

Administrative borders – in our case including regional administrative borders from varying times – often follow natural features, such as watersheds or rivers. They are seen as gentle slowing features (Solantie 2012). It is assumed that travelling within an administrative region was generally easier and somewhat more frequent than between administrative regions (Diener & Hagen 2012), as the state controlled the movement and living through various means, taxation among others.

Arranging source data into classified thematic layers

We used relevant data sources to create classified thematic layers representing the historical landscape features introduced in the previous section. The available source data can be roughly divided into digital datasets (rows 1–6 in Table 1) and into written historical sources or printed maps (rows 7–9 in Table 1). The historical sources consist of national and regional studies, where the exact route, timing and significance for travelers are presented in writing. This information was digitized into spatial data to cover water routes and the road network. The administrative borders were digitized from printed maps.

This research was limited to cover the area of modern-day Finland due to data availability. The source data have high but variable spatial detail. Along with the fairly large study area (390,909 km^2), this required careful consideration about the target spatial resolution for the cost-distance model. After experimenting with different spatial resolutions, we ended up creating the model in a 1 km^2 polygon grid (total number of cells 393,567). The selected resolution incorporates sufficient spatial detail for cost-distance modeling at the national level, while maintaining a manageable number of grid cells to operate – also from the perspective of computational capacity.

The time frame of this study extends hundreds of years before the present. However, the available source data mainly correspond to the current situation (Table 1). To model the past travel environment, we collected, evaluated, and processed source data for landscape features and arranged these into customized thematic layers. This was done feature by feature and, in some cases, by combining several source datasets (Table 2). To categorize the impact on travel speeds, separate classes were created within each thematic layer (Table 2).

The data concerning the location of water bodies, land areas, eskers and end moraines, watersheds, and topography (Table 1) were directly usable in the historical context. The changes in these features caused by the post-glacial land uplift, for instance, are slow, and the present-day data represent the whole study period in the applied spatial scale. However, changes to the land cover due to human influence have been rather extensive in Finland during the last centuries. To adjust the land cover layer to represent historical time more precisely, we constructed it by using and combining several present-day source datasets and by fitting these with the arable land data from the year 1891 (Table 1).

Information concerning the water routes, road networks and administrative borders were digitized into spatial data from historical sources (Table 1). The road network layer reflects the distribution of the official roads in the 16th century, while water routes indicate the most important waterways documented to have been in use since AD 800. The administrative border layer covers the most important borders from the 13th to the 19th century.

Table 1. Basic information about the source data. Geospatial data were produced by the Finnish Environment Institute (FEI), the National Land Survey of Finland (NLS), the Geological Survey of Finland (GSF). The Topographic Map was generalized based on the Topographic Database.

No.	Source data	Derived features	Producer	Type	Scale
1	Corine Land Cover 25 ha	Inland and coastal wetlands, peatbogs, bare rock, forest (coniferous, mixed, broad-leaved, shrub and/or herbaceous vegetation associations), transitional woodland/shrub, natural grassland	FEI (2012)	Geospatial	1:100 000
2	Topographic map (Topographic database)	Lakes, rivers, seas, open bog, forested bog, resources extraction areas, organic material, rocky areas	NLS (2015)	Geospatial	1:250 000 (1: 10 000)
3	Superficial deposits of Finland	Peat deposits, uncovered bedrock, stone fields	GSF (2010)	Geospatial	1:200 000
4	Digital elevation model	Elevation values	NLS (2007)	Geospatial	25 m
5	Aggregate sand and gravel	Eskers and end moraine formations	GSF (2013)	Geospatial	1:50 000
6	Catchment areas	Location of drainage basin boundaries	FEI (2010)	Geospatial	1:50 000
7	Economic map of Finland	Arable land in 1891	NLS (1891)	Printed map	1:1 260 000
8	Descriptions of historical water routes and roads	Digitized water routes since AD 800 and the road network of the 16th century	Several written sources	Written sources	-
9	Compilation of historical administrative borders in Finland	Digitized historical administrative borders	Several printed sources	Printed maps	-

Table 2. Thematic layers derived from the source data (* see Table 1, ** see Fig. 2).

Code	Name	Variable	Source data *	No. of classes **
T1	Historical land cover	Land cover type	1, 2, 3, 7	10
T2	Topography	Slope angle	4	Continuous
T3	Water bodies and water routes	Type of water route/water body	2, 8	8
T4	Eskers and end moraines	Occurrence of formation	5	2
T5	Watersheds	Occurrence of watershed	6	2
T6	Road network of the 16th century	Type of road	8	5
T7	Administrative borders	Occurrence of border	9	9

The *Land cover* (T1) layer was created by processing and combining the original data from four different sources (Table 1; sources 1–3, 7). This was done, first, to compare the land cover classes used in different source datasets and, even more importantly, to accommodate for human-induced land use changes that had taken place during the last centuries. During the past centuries, the most dramatic changes in the landscape were caused by the conversion of forest and wetlands into agricultural land, while some wetlands have also been turned into forests (Valmari 1982; Simola 2006). Instead of using the modern datasets to directly illustrate the historical land cover, we selected several information sources to account for the changes that have occurred in different classes of land cover. For example, the wetland class is based on data from Corine Land Cover (peatbogs and other wetlands), the Topographic map (open bogs, forested bogs, sites for the extraction of organic soil), and Superficial deposits of Finland (peat deposits). Similarly, the forest cover is based on the classification of Corine Land Cover, and agricultural land on the Russian Land Cover map from 1891 (more detailed information on the original data is found in Table 1).

When creating the land cover layer, we needed to assign each 1 km^2 cell to a certain land cover class. We first selected the cells where the historical land cover type was distinct (in other words, one class had more than 50% of coverage for the cell in question), and then analyzed the cells with uncertainties. In the first phase, we selected the cells in which water, bare rock, peatland or arable land from 1891 covered more than 50% of the cell. Based on the majority rule, we classified those as belonging to the class water, rock, wetland or agricultural land, respectively. In the next phase, we made second and third classification rounds with the cells featuring 30–50% coverage for the particular land cover type in the source data.

We evaluated different datasets simultaneously (as explained above with various datasets including wetland areas), using the following order for determining the status, moving from the most stable land cover class to those which have changed the most during the last few hundred years: 1) lakes and sea, 2) wetland (including peat bogs and wood-growing bogs), 3) rock (bare rock, boulder fields), 4) agricultural land, and 5) forest (coniferous forest, mixed forest, sparsely vegetated areas). After careful consideration and reasoned designation, values were assigned to more than 95% of the 1 km^2 cells. The remaining, undesignated cells, mostly around reservoirs and at the edge of the study area, were defined as either forest or wetlands based on neighboring cells. The total number of land cover classes after compiling the dataset was ten (Table 2) (generalized to five classes for visualization in Fig. 2; T1).

The *Topography* (T2) layer quantifies the elevation variation in the local terrain for each 1 km^2 cell. The topographical values for this layer are based on a digital elevation model (DEM) covering the whole country (Table 1). The vertical resolution of the data is 0.1 m and the spatial resolution is 25 m. Thus, there are 1,600 DEM cells and correlating elevation values for each 1 km^2 cell. The average slope for each 1 km^2 cell was calculated through three steps. First, we used focal statistics to compute the standard deviation of elevation values within the closest 25 elevation points (5 x 5 moving window) to determine the local variation. Second, the resulting 1,600 standard deviation values for each 1 km^2 cell were averaged to one value. In this procedure, the raster cells were converted into vector points. Third, the defined average standard deviation values were transformed into average slope angle (Table 2, Fig. 2; T2). This enabled us to use Tobler's hiking function (Tobler 1993) to convert the slope angle value into travel speed.

The *Water bodies and water routes* (T3) layer contains inland waters and sea areas, as well as historically documented water routes commonly used since AD 800. The layer was created using two separate datasets: historical water routes and a water area layer. We digitized the water routes based on the historical sources (Table 1), which were written from national (e.g. Julku 1987; Masonen 1999a) and regional (e.g. Luukko 1950, 1954; Niitemaa 1955; Jokipii 1999) perspectives. Water routes mostly traverse along the water surface, but they also consist of short legs of land wherever watersheds between two drainage basins were crossed. Digitization accuracy was 1:60 000 on average and, in the process, we utilized an NLS basemap (1:80 000). Digitization of rivers and legs of land was unambiguous. In the case of lakes, the exact location of water routes was usually unknown, thus we drew a route in the middle of the lake to be able to manage such uncertainties.

The digitized historical water routes were classified into four classes: 1) significant water route, which has documented long-term use, 2) moderately significant water route, 3) minor water route

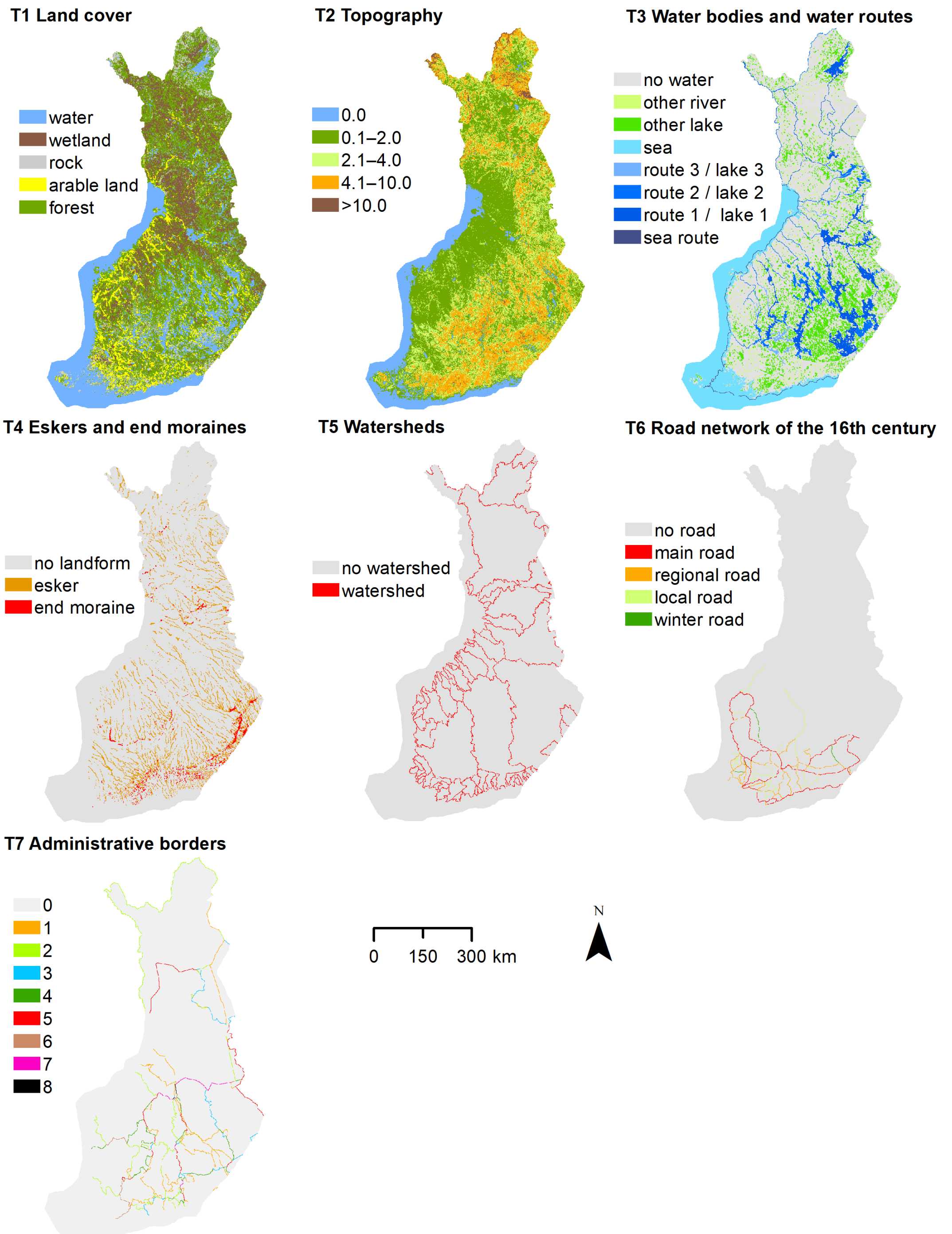

Fig. 2. Map visualization of the classified thematic layers, cell size 1 km^2 (Table 2). T1: generalized classification of land cover types, T2: average slope in degrees, T3: water route classification based on importance of the water route, T4: landforms (eskers and end moraines), T5: watersheds, T6: classification of 16th century roads, T7: number of overlapping administrative borders (temporal stability indication).

with only local importance and 4) sea route. This classification was based on the portrayal of travel conditions provided in the documented sources (Julku 1987; Luukko 1950, 1954; Masonen 1999a; Niitemaa 1955; Jokipii 1999; Appendix 1). Instead of directly discussing the importance of different water routes, these sources include descriptions how internal variation of rivers, seasonality and method of travel affected the navigability and the possibility for utilizing particular water routes. In addition, different authors emphasized different activities in their respective descriptions of the water-route use (transporting people/goods, hunting activities, *etc*.); this made it more complicated to evaluate the differences between water routes. Nevertheless, the classification used in our study captures the essentials, and accounts for the differences between the water routes.

To extend the classification to all cells which were overlapping with water areas (inland water and sea), we used the classification of historical water routes created by ourselves. For example, if a water route overlapped with a lake, the lake as a whole was assigned the same value as the water route. After evaluating bodies of water which intersected known water routes, there were still plenty of lakes, rivers and sea areas which did not belong to any category. We created three more categories for these: 5) lakes without water routes, 6) small rivers outside of historical water routes, and 7) the sea. In the last phase, we combined all the information into one layer, which formed the Water routes and water bodies layer (Table 2, Fig. 2; T3).

Creating the thematic layers of *Eskers and end moraines* (T4) and *Watersheds* (T5) was more straightforward, as both are based on only one existing digital dataset (Table 2). In these thematic layers, two classes were used: we assigned a value of 1 to those cells which overlap with a feature (esker/end moraine or watershed), and a value of 0 to the other cells (no landform or watershed) (Table 2, Fig. 2; T4 and T5).

The overall target of compiling the *Road network of the 16th century* (T6) was to model the movement possibilities in Finland before the large-scale expansion of the road network. Thus, instead of using the current roads, we digitized the main roads from the 16th century. Accuracy of digitization was 1:40 000 (Table 1) and the digitization process was executed on an NLS basemap (1:80 000). The collected dataset is based on both regional (e.g. Luoto 2011; Perälä 2012; Museovirasto 2014) and national (e.g. Viertola 1974; Masonen 1999a; Huikari 2014; Table 2, Appendix 1) investigations, and it consists of the most important summer and winter roads. The summer road data are comprehensive and precise, but many important winter roads are lacking because of uncertainties about the exact location of these roads. We classified the roads into four categories based on the information concerning their significance for human travelling: 1) main road, 2) important regional road, 3) local road, and 4) winter road (Fig. 2; T6).

The thematic layer *Administrative borders* (T7) is a digitized dataset of historical borders, first used in Honkola and colleagues (2018). It consists of nine sets of borders divided into national (border of the Second Swedish Crusade in the mid-13th century and the Treaty of Nöteborg, 1323), provincial (from 1475, 1540, 1635, 1721, 1776, 1831) and bishopric (from 1554) boundaries (Jutikkala 1959; Atlas of Finland 1992; Haapala 2007; Table 1). All borders were assigned the same importance on the layer. The significance of the borders as hindrances is reflected in the number of borders occurring in the same location. Thus, the coefficient of cells varied between 0 and 9 overlaps (the observed range was 0 to 8 overlaps) (Table 2, Fig. 2; T7). The more overlaps, the more significant the barrier was for human travel.

Finally, to assimilate all data into a comparable and manageable form, we added each feature set to the 1 km^2 polygon grid, which resulted in the seven thematic layers (T1–T7, Table 2, Fig. 2).

Converting thematic layers to cost layers

Next, we defined class-specific cost values for each thematic layer, that is, we created cost layers based on existing information about human movement in different environments. When determining the cost values, we accounted for different means of travel, and the effects that seasonality may have had on travelling. On average, skis, boats, and horses enable faster travelling than walking, while walking in sparsely vegetated area is faster than in a dense forest. Furthermore, studies on human travel speed on foot (Tobler 1993; Bastien *et al*. 2005; Etula & Antikainen 2012) and on horseback (Nenonen 1999b; Wickler *et al*. 2001) in terrain and on roads, as well as studies on canoeing (Horvath

& Finney 1969; Fitzhugh & Habu 2002) and sailing (Casson 1951) along water surfaces were used to quantify travel speeds for different means of travel.

One key to determining cost value was to first define an average off-path walking speed and use this as a comparison value to guarantee that all classes were assigned a value in correct relation to each other. We defined the average travel speed on average terrain to be 3.06 km/h (0.85 m/s). This

Table 3. Cost value determination by class. Each class from every thematic layer was assigned an individual travel speed value (km/h). The process formed cost layers (C1–C7). The average travel speed in average terrain used in this study was 3.06 km/h. The values were created based on the following means of travel; for roads: horseback, for water: passage across the water surface by boat, canoe, sleigh or skis, and for the rest of the cost layers: human on foot.

Thematic layer	Class	Features	Speed (km/h)	Cost layer
(T1) Land cover	Land cover 1	Lake	3.70	C1
	Land cover 2	Sea	4.00	
	Land cover 3	Peat bog	3.50	
	Land cover 4	Wood growing bog	1.60	
	Land cover 5	Bare rock	2.75	
	Land cover 6	Boulder field	0.60	
	Land cover 7	Agricultural land	2.90	
	Land cover 8	Coniferous forest	2.70	
	Land cover 9	Mixed forest	2.50	
	Land cover 10	Sparsely vegetated area	2.85	
(T2) Topography	Continuous	Average slope	0.00–3.02	C2
(T3) Water bodies and water routes	Water 1	Route 1 & lake 1	5.50	C3
	Water 2	Route 2/lake 2	4.50	
	Water 3	Route 3 & lake 3	4.00	
	Water 4	Sea route	6.00	
	Water 5	Other lake	3.30	
	Water 6	Sea	3.60	
	Water 7	Other river	3.15	
	Water 8	No water	3.06	
(T4) Eskers and end moraines	Esker 1	Esker or end moraine	3.60	C4
	Esker 2	No landform	3.06	
(T5) Watersheds	Watershed 1	Watershed	2.50	C5
	Watershed 2	No watershed	3.06	
(T6) Road network of the 16th century	Road 1	Main road	10.00	C6
	Road 2	Regional road	8.00	
	Road 3	Local road	7.00	
	Road 4	Winter road	8.00	
	Road 5	No road	3.06	
(T7) Administrative borders	No classes	Barrier effect 0–50 %	-	C7

value was based on evaluations by Tobler (1993), Bastien and colleagues (2005) as well as Etula and Antikainen (2012), who all used different methods, but ended up with very similar values (range between 3.0 km/h and 3.6 km/h). As people seldom walk along a straight line in typical Finnish terrain, we considered that minimal meandering would push the final value estimation closer to the slower edge of the estimated range.

A cost value was individually assigned for each class in every thematic layer (Table 3). The *Topography* cost layer (C2) was defined based on Tobler's hiking function, which allows conversion in a straightforward way from slope degrees to human walking speeds in terrain and along a path (Tobler 1993). Here, we utilized off-path values and excluded, also, the impact of travel direction (upward/downward slope) by using only upward values (Table 3). The speed values for different land cover classes were determined using the study in Etula and Antikainen (2012) that quantifies human movement in Finnish forests. This study was conducted in a modern environment, but as the land cover types are the same, it also applies to the historical context. Etula and Antikainen (2012) present relative coefficients for each land cover type, which we then converted to walking speeds with slight fine-tuning (Table 3). In the *Land cover* layer (C1), water areas were assigned with uniform travel speeds (for lakes, 3.70 km/h, and for the sea 4.00 km/h, see Table 3). The speed values for the *Eskers & end moraines* (C4) and *Watersheds* (C5) layers were also defined based on human walking speed, even though there were no direct estimates of speed values in these environments. However, the historical evidence indicates that eskers, due to their clear orientation and sparse vegetation, were easier to travel on than the average travelling environment, and thus were often utilized (Fogelberg 1974; Halinen 1999). Watersheds were seen as a minor slowing feature for human movement because these decrease the probability of crossing watersheds and thus hinder travel from one drainage basin to another (Kaitanen *et al*. 2003).

Water bodies and water route classes were determined based on proven rowing, canoeing (inland water) and sailing (sea) speeds, and weighted with available information about winter travelling with sleighs and skis. Due to easier passage across a water surface compared to terrain, a major part of the speed values in *Water bodies and water routes* layer (C3) are higher than in other cost layers (Table 3). The values for different road classes on the *Road network* layer (C6) were based on the expected average travel speed of horses in each road class. The more significant the road, the higher the speed value. The road cells were assigned higher values than the other features (Table 3). The values on the *Administrative borders* layer (C7) do not indicate the speed values, but the slowing (barrier) effect assigned to each cell (Table 3).

In summary, all the cost layers (C1–C7, Table 3) were assigned cost values one by one, and we carefully managed the process to guarantee that the cost layers are also comparable with each other. The cost value determination is ultimately subjective, but we relied on relevant literature, while keeping in mind that the relative difference between travel speed values is more important than the speed values as such.

Table 4. Cost surfaces used in the cost-distance analyses. Each cost surface has a travel speed value for each 1 km^2 grid cell over the whole country. Selected statistical values of the parameters are presented here.

Cost surface		Cost layer							Speed (km/h) / cell			
Code	**Name**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Min**	**Max**	**Median**	**Mean**
CS1	Environment and human	X	X	X	X	X	X	X	0.00	10.00	3.15	3.10
CS2	Early environment	X	X	X	X	X			0.00	6.00	3.25	3.05
CS3	Combined topography and land cover	X	X						0.00	4.10	2.62	2.78
CS4	Land cover	X							0.60	4.00	2.70	2.85
CS5	Topography		X						0.00	3.02	2.70	2.62

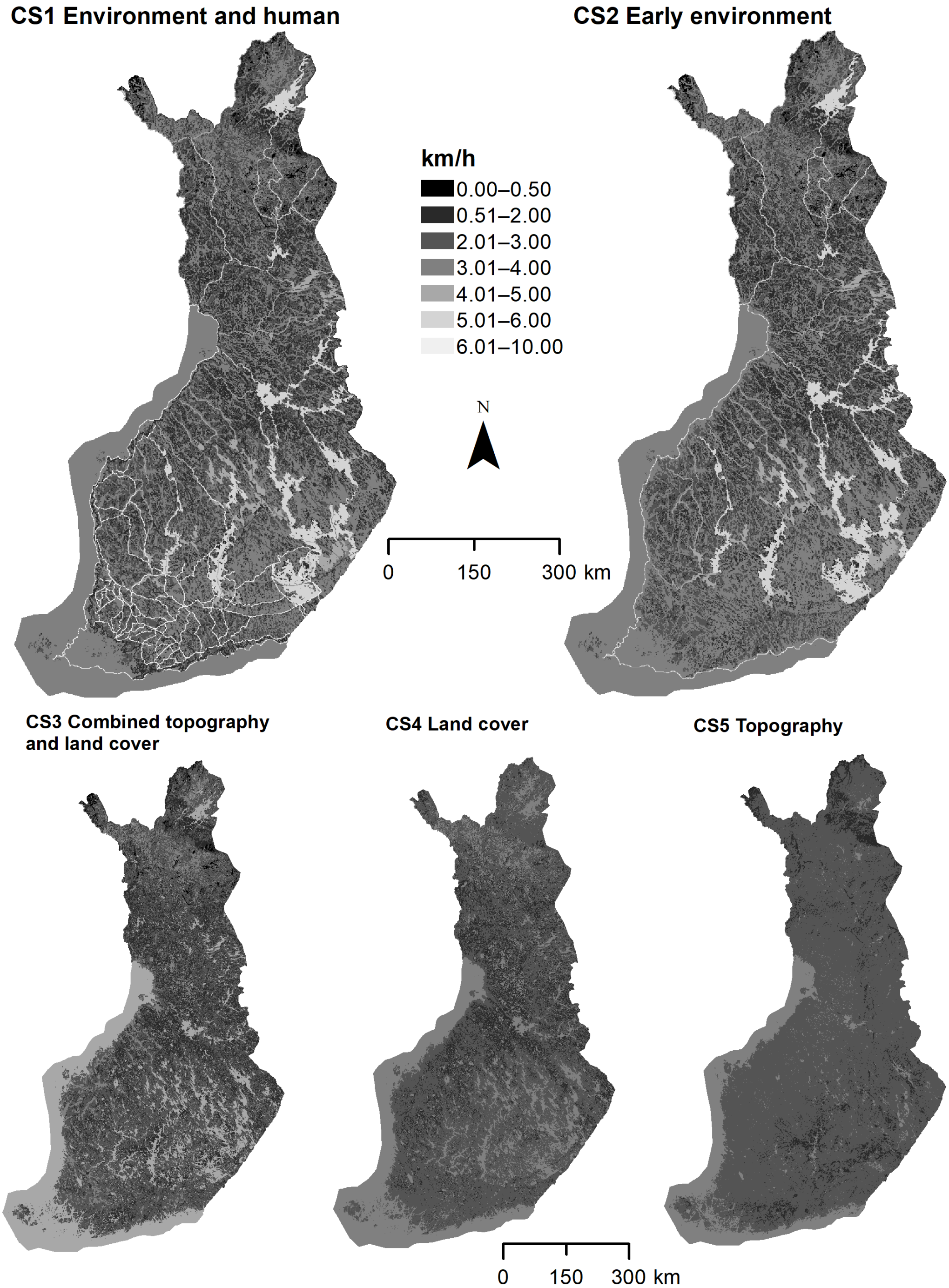

Fig. 3. Map visualization of the cost surfaces (see Table 4). The Environment and human (CS1) and Early environment (CS2) surfaces are the most comprehensive simulations of Finland, and thus play a main role in the analysis.

Turning cost layers into cost surfaces

A mathematical cost surface can be based on one cost layer or it can be a combination of several layers. For this study, we used both options to study the travel effort from many angles (Table 4, Fig. 3). To model the past travel environment comprehensively, we created two combination surfaces simulating the two different time periods with all facilitating and hindering features. A surface called *Environment and human* simulates the post-medieval time and consists of all seven landscape features of this study (CS1 in Table 4, Fig. 3). The *Early environment* surface is a simulation of an earlier, pre-medieval travel environment and was created by using all the features except the road network and administrative borders (CS2 in Table 4, Fig. 3).

As people can combine different means of travel (Masonen 1999a; Salminen 2006), the cost value for each cell was defined by selecting the maximum speed value from all individual cost layers. For CS1 this means, for example, that a cell which intersected a road was assigned the value of the road travel speed (7–10 km/h, Table 3), because the travel speed on roads was the highest of all possible classes. In turn, for CS2, the highest values originate from water classes 1–4 (Table 3). In the areas outside the road network or water routes and water bodies, each cell was assigned a value from either the combination of topography and land cover, or from overlapping eskers; for each cell, the higher of these two possible speed values was chosen. To include the hindering effect caused by watersheds, intersecting cells were given the watershed value (Table 3) when overlapping with combined topography and land cover value without facilitating features (such as eskers and roads). In addition, where documented water routes included legs of land from one water body to another, the water route value was used. The defined barrier effect of the administrative borders was accounted for in CS1: for those cells which intersected with administrative borders, the slowing features were assigned up to 50% lower values (when eight overlapping administrative borders were present) than corresponding cells without any overlapping slowing features (Table 3). It should be noted that relying on maximum values per cell when creating the cost surface assumes that the most cost-efficient way of travel was actually used.

We also created a *Combined topography and land cover surface* (CS3) based on two features: land cover and topography. Compared to CS2, it assigns a more simplified view of the earlier travel environment, while covering the whole study area uniformly. It puts less emphasis on individual travel routes and slowing features, but still simulates the travel environment comprehensively. The combined values are primarily based on the topography cost layer and the values were weighted based on the speed values of the land cover cost layer per class. In practice, the biggest relative impact of land cover type on the combined values occurs in the area of bare rock and boulder fields, and the smallest impact on values occur in peat bogs and wood growing bogs. The range of *Combined topography and land cover surface* values is 0.00–4.10 km/h (Table 4, Fig. 3).

To compare how different landscape features affect accessibility in different parts of Finland, we included two existing single-theme cost surfaces to the analysis. These were *Land cover* (CS4) and *Topography* (CS5) (Table 4, Fig. 3). In these cases, converting from vector to raster format was straightforward, and the travel speed values were derived from cost layers C1 and C2 as such (Table 3). The rest of the single-theme cost surfaces (specifically water routes, eskers and end moraines, road networks and administrative borders) were excluded from the analyses because of their poor ability to model the past travelling environment individually throughout the country.

Spatial analyses of historical travel effort

Spatial analyses of constructed historical travel environment model were conducted using cost-distance approach. Cost-distance modeling is based on a raster surface (a regular cell grid), which is a cost surface in which each cell has a numerical value corresponding to the amount of effort required to move across the area covered by the cell. In practice, the cost surface cell values represent conductance or resistance for passing the cell, and these can be expressed in terms of either distance, time, speed, energy expenditure or money. In this context, a cost raster cell – which in the real world covers mountainous terrain – would be given a lower conductance value than flat, unforested terrain. We determined the cost values using velocity units, which are conductance values. To use ArcGIS's cost-distance tools in which the Dijkstra algorithm (Dijkstra 1959) is the standard and utilizes resistance values, we needed to compute inverse values for each cell. The algorithm determines a chain of adjacent cells which form a route for which the cumulative sum of resistance values is lowest, thereby indicating the route which requires the least travel effort.

We made two overall travel effort maps; these indicate two different periods of historical time. We created a regular point grid to cover the whole country with 20 km N-S and E-W intervals between points (979 points). For each point, we computed the surrounding area that can be reached from the point within 60 minutes using ArcGIS's *Cost Distance* tool. This area is in most cases irregularly shaped since the travel speeds in the surrounding 1 km^2 cells vary. For each point, the area of the irregular 1-hour-zone was transformed into the area of a circle whose radius was then assigned the average travel distance per hour from the center point. Finally, the average travel distance values of the 979 points in the 20 km grid were spatially interpolated onto a surface representing the mean travel speeds over the whole country. The same process was carried out for both cost surface CS1 (all variables) and cost surface CS2 (all variables except the road networks and administrative borders). In addition, to study the spatial trends of the travel effort more precisely, we studied the travel speed variability within sub-regions. For this purpose, we used the historical provinces (Fig. 6b) which existed from late medieval times onward (e.g. Jutikkala 1949).

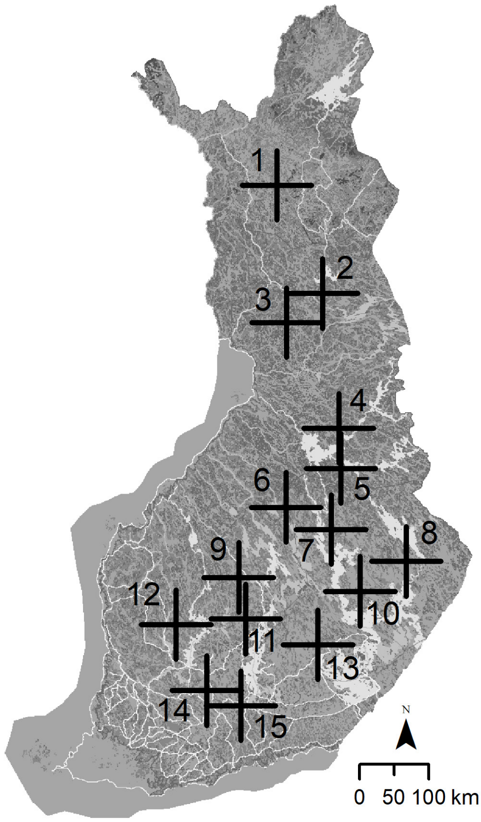

Fig. 4. 15 randomly selected sample areas within Finland. Each consists of one N-S and one E-W transect with a length of 100 km.

We studied the regional differences in travel effort and the impact of which cost layers were used in each cost surface (CS1–CS5) by selecting 15 sample areas (Fig. 4) with a stratified random sampling method (forced to not intersect with country borders). In each area, two 100 km transects were created: one in a north-south direction, and one in an east-west direction. The transects intersect in the middle. The least-cost route between each transect's start and end point was computed on each of the five constructed cost surfaces using ArcGIS's *Cost Connectivity* tool.

Statistical testing of historical travel effort

Complementing the geographical approach and spatial analysis, which form the core of this work, we studied the travel effort variation by applying statistical methods. We focused on the overall travel effort data, and analyzed the travel speed differences between the provinces by running a 1-way ANOVAs (*Analysis of variance*) for cost surfaces CS1 and CS2 having all the provinces and data points along (n=979 for both cost surfaces).

We further used 2-way ANOVA to study if the travel speeds of the historical provinces varied between the cost surfaces CS1 and CS2. The main factor "Cost surfaces" simultaneously indicates if there were variation in the travel speeds in the Pre-Medieval (CS2) versus Post-Medieval (CS1) periods. Historical provinces of Åland and Laponia were eliminated from the 2-way ANOVA because there were no differences in travelling between these points in CS1 and CS2. All data points located on the sea area were also left out from the 2-way ANOVA, for the same reason. The data points were randomly divided into two groups, one representing the CS1 model and the other representing the CS2 model; each point had an equal probability

(0.5) of being selected for either group. Leaving out the sea area, Åland and Laponia and randomly dividing the points between the cost surfaces lead to 372 data points for CS1 and 339 data points for CS2.

For the models CS1 and CS2, we studied the normality assumption of the residuals with visual inspection and Shapiro-Wilk normality test and homoscedasticity with Levene's test. The assumptions were not met for in the 1-way ANOVAs; the variances for the provinces were heteroscedastic, due to Åland, Laponia and sea areas, as was mentioned above. Leaving out these three from the 2-way ANOVA solved the heteroscedasticity problem.

Results

Cost surfaces as historical travel environment models

Our analysis chain provides the opportunity to produce customized cost surfaces that simulate historical travel effort in Finland. In this study five historical travel environment models were created using different feature combinations (Fig. 3). The main models CS1 (Environment and human) and CS2 (Early environment) are comprehensive and simulate Post-Medieval and Pre-Medieval times. CS3 is a combination of land cover and topography, while CS4 and CS5 are individual land cover and topography surfaces. By producing different simulations of the historical travel environment, past human movement can be studied from different aspects. In this study, the cost surfaces have been used to study the overall geographical variation of historical travel speeds (CS1 and CS2 only), as well as more precise least-cost paths with 100 km transects (all the cost surfaces). In addition to characterizing the past travel environments in Finland, the selected analyses serve as demonstrations of opportunities concerning past human movement studies with a cost distance approach.

Geographical variation of historical travel effort in Finland

Travel speeds in Finland range from 0.6 to 5.3 km/h (the average is 2.86 km/h for CS1, and 2.84 km/h for CS2) (Fig. 5ab). Spatial inspection of the Figure 5 suggests that traveling in the southern part of the country was easier than in the north during both time periods. On the CS1 map, which represents the more recent time period and also contains the 16th century road data (see T6 in Fig. 2), the travel speed

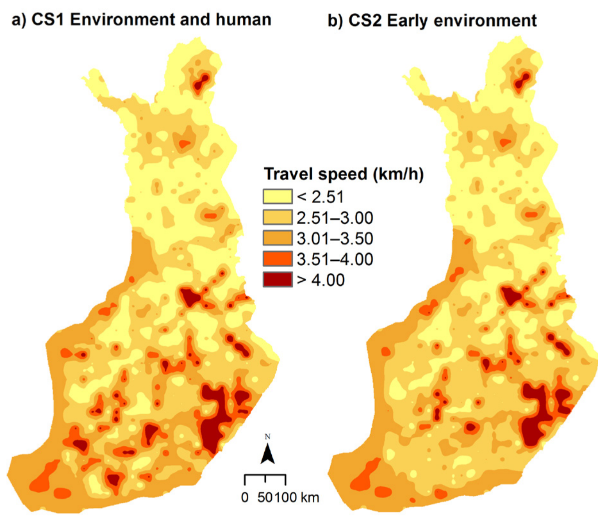

Fig. 5. Differences in overall travel speeds around Finland based on cost surface combination a) CS1 (Environment and human) and b) CS2 (Early environment). The costdistance calculation is based on a 20 km regular point grid, n=979.

difference between the northern and southern parts of the country is more notable than on the CS2 map (Fig. 5ab). Further, the Figure 5 indicates faster travel speeds in South-West Finland in the Post-Medieval period (CS1) than in the Pre-Medieval period (CS2).From a statistical perspective, the travel speeds between the historical provinces varied for both cost surfaces (Fig. 6a for CS1, $p<0.001$, df=8, F=18.3 and Fig. 6b for CS2, $p<0.001$, df=8, F=16.5). In both cost surfaces, travel effort was higher in Laponia and Ostrobothnia than in other parts of the country (Tukey pairwise comparisons with adjusted p-values, data not shown). This supports the inference of the Figure 5 that there is a north-south gradient within the country. The among-province variation is further visualized for CS1 in Figure 6b: the median travel speeds in the southwestern provinces are around 3.5 km/h, which is 40% more than the approximate 2.5 km/h value in the northern provinces.

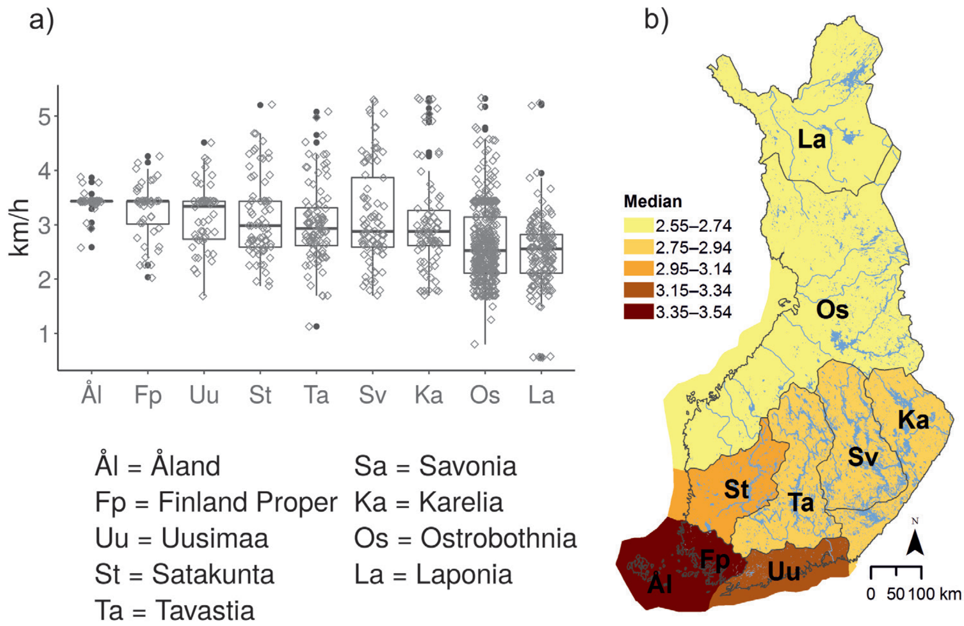

Fig. 6. a) Travel speed variation among the historical provinces using the Environment and human (CS1) cost surface as median, interquartile range, 1,5x interquartile range. Original data points indicated in gray, and b) historical provinces classified according to the median travel speed using CS1 cost surface and all data points (n=979).

The 2-way ANOVA further studied the difference in province-specific travel speeds between the two cost surfaces. In general, they did not vary (main factor "Cost surface", $p=0.512$, df=1, F=0.43). However, when excluding Laponia, Åland and sea area (Fig. 7), the historical provinces had variation in the travel speeds ($p<0.0001$, df=6, F=12.3). The interaction between main factors was not significant ($p=0.094$, df=6, F=1.8), but gave a hint of among-province differences between the models for the further use of the cost surfaces. The main difference was that in the Post-Medieval travel environment (CS1), with road network and administrative borders, travel effort was higher in Ostrobothnia than elsewhere in the country (Fig. 7b, Tukey pairwise comparisons with adjusted p-values, data not shown). Instead, before the introduction of road network and administrative borders (in the Pre-Medieval travel environment), Ostrobothnian travel effort was similar to Uusimaa and Finland Proper, but differed from Satakunta, Tavastia, Savonia and Karelia. It must be noted that excluding sea data points naturally affected the travel speed values of Uusimaa and Finland Proper. However, in the Pre-Medieval travel environment even without sea area, Uusimaa had lower values than Savonia (Fig. 7ac), which is reflected also in the visual differences between the cost surfaces (Fig. 5).

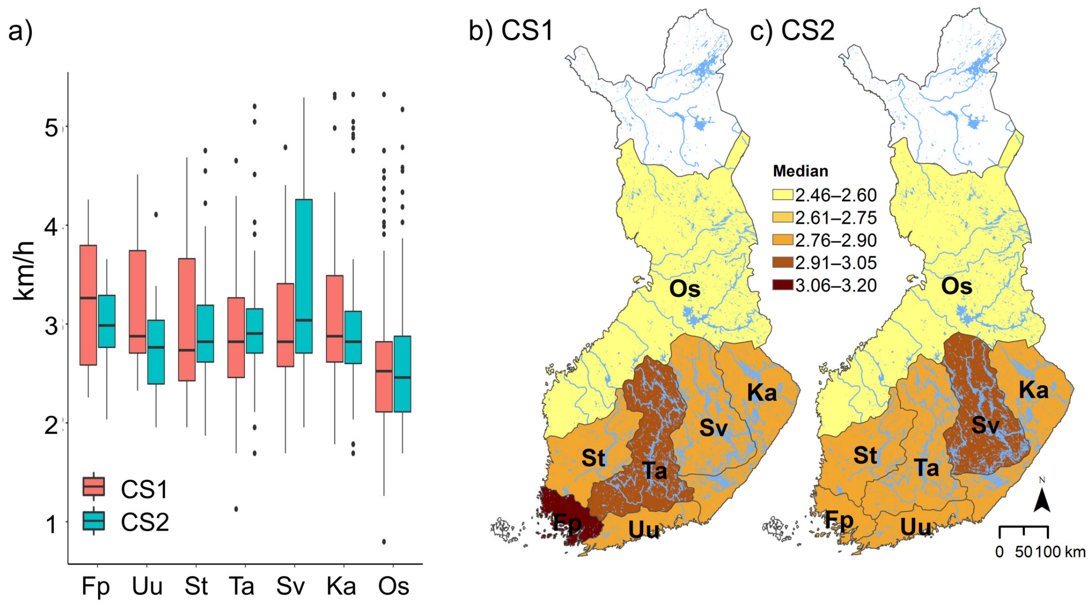

Fig. 7. a) Travel speed variation of the historical provinces between the cost surfaces CS1 (Environment and human) and CS2 (Early environment) as median, interquartile range and 1,5x interquartile range, b) historical provinces classified according to the median travel speed for CS1, and c) for CS2. Provinces of Laponia and Åland and all sea points are excluded (n=711). See labels of historical provinces in Figure 6.

The travel times, distances and travel speeds using the least-cost path for each transect on each cost surface (see Table 4) show notable variation (Table 5, Appendix 2). To highlight the differences, the transect pair with the lowest (transect pair 12) and highest (transect pair 1) travel efforts are plotted on the map in Figure 8. We also analyzed the differences within each transect pair between the travel directions: the values for traveling N-S versus E-W show only minor variation on the different cost surfaces (Table 6).

Table 5. Time, length, and average speed of transect pairs with most travel effort (1), and least travel effort (12) for each cost surface combinations divided in N-S and E-W directions. Transect pair number 1 is located in Northern Finland and 12 is in Southern Finland. See values for all transect pairs (1–15) in Appendix 2.

Transect pair no.	Cost surface	N-S			E-W		
		Time (h)	Length (km)	Average speed (km/h)	Time (h)	Length (km)	Average speed (km/h)
1	CS1	34.02	114.08	3.35	32.01	106.63	3.33
	CS2	34.02	114.08	3.35	32.01	106.63	3.33
	CS3	34.46	111.60	3.24	33.18	111.36	3.36
	CS4	34.92	105.80	3.03	33.47	105.80	3.16
	CS5	37.12	101.66	2.74	37.26	102.49	2.75
12	CS1	20.18	127.05	6.29	25.62	147.20	5.75
	CS2	28.33	116.33	4.11	30.83	109.70	3.56
	CS3	35.26	116.08	3.29	34.18	116.57	3.41
	CS4	36.75	114.08	3.10	35.88	112.43	3.13
	CS5	38.42	103.31	2.69	38.31	100.83	2.63

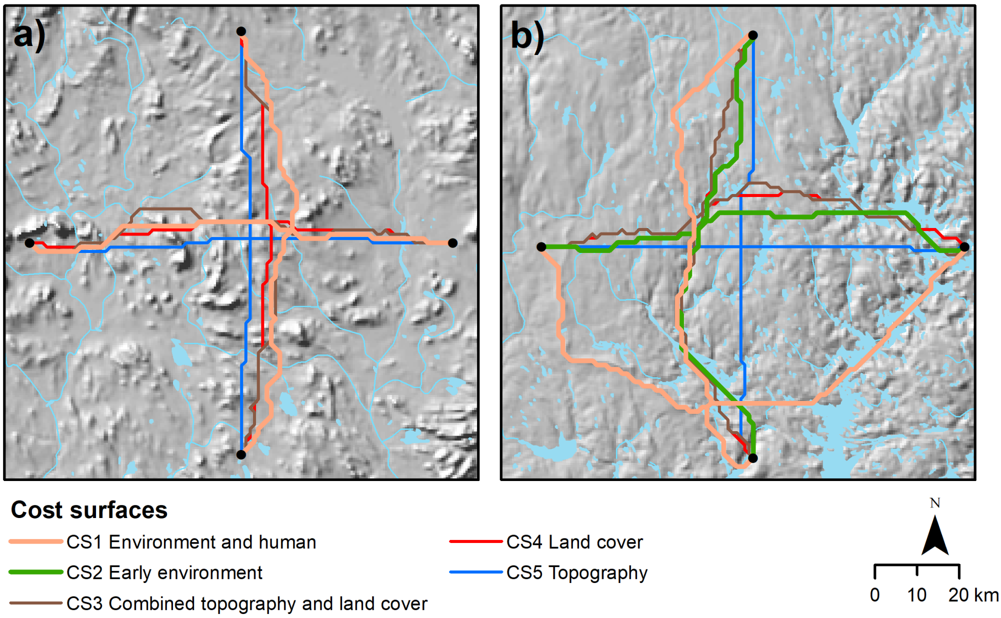

Fig. 8. Transect pairs with a) the most travel effort (transect pair 1), and b) the least travel effort (transect pair 12) with least-cost paths for each cost surface (see Figure 4 for the location of the transect pairs). Shorter routes between pairs correspond to lower average speed and longer total time (Table 5). In a), CS1 and CS2 routes are completely overlapping. Using the CS1 surface, there are 10 changes of travel mode in a) in N-S direction and 12 in E-W direction. Corresponding values for b) are 12 and 12. The base map indicates terrain topography and surface water formations for reference.

Table 6. Least-cost routes in hours in north-south, east-west and all transects (n=30) together based on all cost surfaces (CS1–CS5).

Surface / direction		Average	Median	Min	Max	Range
CS1	N-S	26.77	26.99	17.54	34.02	16.48
	E-W	28.07	29.52	14.58	36.28	21.71
	All	27.42	28.31	14.58	36.28	21.71
CS2	N-S	29.59	29.82	23.76	34.02	10.26
	E-W	30.49	30.83	22.72	36.28	13.57
	All	30.04	30.34	22.72	36.28	13.57
CS3	N-S	34.81	35.26	28.27	38.78	10.51
	E-W	34.69	34.18	32.28	38.62	6.34
	All	34.75	34.39	28.27	38.78	10.51
CS4	N-S	35.13	35.53	30.59	37.54	6.95
	E-W	35.36	34.93	33.19	38.92	5.73
	All	35.25	35.04	30.59	38.92	8.34
CS5	N-S	38.74	38.70	35.53	41.85	6.32
	E-W	38.99	38.94	35.62	42.20	6.58
	All	38.86	38.88	35.53	42.20	6.67

Discussion

The results indicate that travel speed variation, and thus the required travel effort, varies notably within the country (Fig. 5, 6, 7), despite the lack of major hindrances such as mountain ranges. As a general trend, traveling in southern Finland, where almost all areas have average travel speeds above 3 km/h, has been significantly easier than in the north, where vast areas with average travel speeds below 2.5 km/h occur. This is also observed in the sub-regional classification among the historical provinces (Fig. 6, 7). The modeled travel speeds in the landscape range from 0.6 km/h to 5.3 km/h, which covers a range with nearly a tenfold difference between lowest and highest speeds.

The overall traveling speeds within the country were calculated separately for the *Environment and human* (CS1) and *Early environment* (CS2) cost surfaces to differentiate between travel environments with and without impact of road networks (since the 16th century) and administrative borders. Practically CS2 reflects the Pre-Medieval and CS1 reflects the Post-Medieval travel environment. We do not implicitly study here the impacts of different travelling means to the travel effort, but differences between the two cost surfaces hint towards some trends to be further studied elsewhere. We assume that water bodies and water routes made a difference for Pre- and Post-Medieval travelers as the lake district of southeastern Finland and the Baltic Sea coast appear as regions of lower travel effort (Fig. 5, 6b, 7bc). Instead, variable topography, boulder fields, and large forested wetlands are unfavorable for human travel even in the generalized scale, as seen in the northern parts of the country, where these features prevail. In this scale, many facilitating factors, such as the major rivers in northern Finland, have little or no impact on the regional travel speed values. Further, Post-Medieval traveling in South-West Finland was easier than Pre-Medieval traveling (Fig. 5, 7ab), likely because of expansion of road networks. However, traveling in Savonia needed more effort in the Post-Medieval environment (Fig. 7ab). The increased travel effort probably was caused by addition of administrative borders as road networks unlikely would have increased the travel effort.

The analysis based on the randomly selected 100 km transects highlights the variability in the least-cost routes in different landscapes and, importantly, in relation to the combination of the source data used for each cost surface (Fig. 8, Table 5, 6). In a homogeneous environment, the least-cost routes closely follow a straight line transect, which is exemplified in Figure 8a (transect pair number 1, northern Finland). Often only patches of significantly lower travel speeds in the cost surface cause the least-cost routes to diverge from a straight line transect. Longer and more winding least-cost routes, such as many that occurred in transect pair 12 (Fig. 8b) in southwestern Finland, indicate the presence of roads or waterways which promote significantly higher travel speeds, and thereby justify longer optimal routes in kilometers.

The 15 north-south and 15 east-west transects indicate minor differences in travel effort between the directions. East-west travel was, on average, slightly more demanding than traveling north-south, but E-W also shows greater variation in travel effort (Table 6). The differences are likely related to the landscape structure, which is formed by recent glacial flow directions that shaped lakes and the overall topography. However, the landscape orientation is related to the glacial flow directions, which themselves are subject to significant local variation across the country.

This study produced a comprehensive digital spatial travel environment model for Finland. The primary objective was to study the overall accessibility within the country by looking at travel effort. For this, we compiled all features into one surface, and analyzed the whole traveling environment using maximum cell values simultaneously. We also studied the impact that different landscape feature compositions in model creation had on the least-cost routes (see Fig. 8); this in turn sheds light on the role of facilitating/hindering feature parameterization, and serves as an evaluation of the model's functionality.

It should be noted that best available spatial data must be used in building the cost surfaces, even though it is clear that optimal data is not always available. While using modern day topographical data to portray historical topography is likely very close to the truth, for example spatial data about land use patterns in the medieval time simply do not exist. However, the modern-day data can be modified according to historical maps and documents to provide better accuracy.

The determination of cost values for different environmental parameters adds a subjective sensitivity element to the cost-distance analysis (e.g. Seifried & Gardner 2019). For example, assigning a speed value (in km/h) for a pathway or for forested land, or quantifying the impact of barriers (watersheds or administrative borders) on travel speed, is ultimately a subjective decision. However, the element of subjectivity remained minimal because we used documented descriptions of historical travel and combined these with documented travel speeds for different means of travel. By using the average travel speed as a basis, all classes were assigned values comparable to each other. In addition, the spatial generalization in the overall travel effort computation (Fig. 5) averaged out possible inaccuracies of individual cost values on individual landscape features.

While the results are reported in 0.01 km/h accuracy, which is quite detailed in relation to the source data and modeling parameters, it should be noted that this is to better illustrate the differences between the sub-regions rather than to indicate very accurate local values. Further, even though the statistical testing of the travel effort among the provinces provides very accurate numerical results, the inherent uncertainties of the underlying data, must be considered when drawing conclusions.

Our model parameterization incorporates three alternative means of travel (on foot, by horse or by watercraft), and the ability to change freely between these means en route. In the exemplary 100 km transects in Figure 8 (*Environment and human*, CS1), the least-cost route allows for 8–12 travel method changes en route.

The spatial travel effort model is not an indication of actual realized travel, but rather it reflects the potential for human movement in a certain area. While the ease of travel is one factor, often other reasons, such as travelers' motivations, needs or compulsions are at least as important (Masonen 1999a; Salminen 2006). In addition, travelers should know the environment thoroughly to be fully able to optimize routes.

The cost-distance approach can be used to reconstruct the physical surroundings where travelling decisions were made in the past. However, it does not provide insights into how the landscape is experienced mentally. Salminen (2006) mentions that travelling during the late medieval period may have required plenty of patience from a traveler, with longer distances forcing people to stay overnight along the way, but if there was a need to travel, even long distance journeys were feasible. Factors related to safety and administrative control also had an impact on travel (e.g. Salminen 2013), as did the length of any given journey and the frequency with which it was repeated. People might have felt insecure when traveling, and therefore favored certain routes over others. For example, forests might have been avoided because of the threat posed by predators. Furthermore, administrative decisions related to warfare, taxes, and trade (e.g. Masonen 1999a; Salminen 2013) all had an impact on life at both individual and community levels. All people traveled during their lives, but the overall duration of journeys varied (Salminen 2006) from local movement for everyday interaction within the community to long distance journeys, due for instance to trade or exploration.

Our cost surfaces are scalable in spatial, temporal, and thematic dimensions, as far as applicable source data are available. More detailed parameterization of seasonality (particularly winter conditions), or the season-dependent possibility of changing the travel method en route, would enable more precision in the modeling of historical human movement. In addition, future developments of this model could include different corridors within the landscape, such as rivers, roads, and eskers, in more detail (Pinto & Keitt 2009). The model can be applied when examining specific study questions such as those related to spatial patterns found in archaeological, genetic, or linguistic data, and it is readily applicable in other areas as well.

Our methodological analysis chain was used to extract information from digital and analogue sources, to construct a cost-distance model for historical travel landscapes applicable when describing archeological, linguistic, or genetic variation for instance. All analyses were carried out using stock tools that are available in any geographical information system (GIS) software, and only basic GIS skills are required. However, as the process includes the interpretation of various source information types (e.g. spatial resolution, travel speed definitions, data generalization into scale, different means of travel), a robust understanding of human environment characteristics and interactions is required to create sophisticated, comprehensive spatial models of travel environments.

The results of our study based on the spatial travel environment model indicate significant spatial variability in past human movement in Finland. This variation cannot be discarded when studying historical human or cultural spread in Finland. This study also demonstrates how historical information and current day spatial data can successfully be combined to study past travel efforts spatially.

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Appendix 2. Time, length, and average speed of transect pairs for each cost surface combinations divided in N-S and E-W directions.

Transect pair no.	Cost surface	N-S			E-W		
		Time (h)	Length (km)	Average speed (km/h)	Time (h)	Length (km)	Average speed (km/h)
1	CS1	34.02	114.08	3.35	32.01	106.63	3.33
	CS2	34.02	114.08	3.35	32.01	106.63	3.33
	CS3	34.46	111.60	3.24	33.18	111.36	3.36
	CS4	34.92	105.80	3.03	33.47	105.80	3.16
	CS5	37.12	101.66	2.74	37.26	102.49	2.75
2	CS1	27.60	116.08	4.21	29.61	109.70	3.70
	CS2	26.96	115.26	4.27	29.37	110.53	3.76
	CS3	36.26	113.84	3.14	37.81	109.11	2.89
	CS4	36.29	107.46	2.96	35.15	104.97	2.99
	CS5	38.70	103.31	2.67	41.36	106.63	2.58
3	CS1	33.83	108.28	3.20	36.28	111.60	3.08
	CS2	33.83	108.28	3.20	36.28	111.60	3.08
	CS3	35.46	109.94	3.10	37.83	114.67	3.03
	CS4	35.53	108.28	3.05	38.92	115.50	2.97
	CS5	36.40	101.66	2.79	35.62	100.00	2.81
4	CS1	30.80	111.94	3.63	28.89	136.71	4.73
	CS2	30.80	111.94	3.63	28.89	136.71	4.73
	CS3	38.78	110.77	2.86	38.62	124.71	3.23
	CS4	36.03	104.97	2.91	38.91	111.60	2.87
	CS5	39.38	104.97	2.67	38.29	104.14	2.72
5	CS1	30.22	141.78	4.69	22.72	122.18	5.38
	CS2	29.82	141.78	4.75	22.72	122.18	5.38
	CS3	36.65	109.11	2.98	33.00	112.43	3.41
	CS4	36.84	106.63	2.89	34.93	112.43	3.22
	CS5	37.81	102.49	2.71	37.39	105.80	2.83
6	CS1	32.69	114.08	3.49	32.60	104.97	3.22
	CS2	32.31	114.08	3.53	31.71	104.97	3.31
	CS3	35.94	113.26	3.15	35.03	111.94	3.20
	CS4	37.54	112.43	2.99	37.23	110.28	2.96
	CS5	35.53	100.83	2.84	37.13	102.49	2.76
7	CS1	23.76	117.15	4.93	32.90	137.30	4.17
	CS2	23.76	117.15	4.93	32.22	113.25	3.52
	CS3	32.28	113.01	3.50	32.28	113.01	3.34
	CS4	33.96	112.43	3.31	37.01	110.53	2.99
	CS5	40.12	110.77	2.76	38.94	103.31	2.65
8	CS1	24.07	126.95	5.27	31.66	106.63	3.37
	CS2	24.07	126.95	5.27	31.66	106.63	3.37
	CS3	28.27	107.46	3.80	34.31	107.21	3.12

	CS4	30.59	107.46	3.51	34.56	105.80	3.06
	CS5	35.97	103.31	2.87	39.49	106.63	2.70
9	CS1	31.40	121.88	3.88	27.74	116.33	4.19
	CS2	32.91	113.60	3.45	30.07	112.47	3.74
	CS3	37.59	110.77	2.95	33.76	115.74	3.43
	CS4	36.81	105.80	2.87	34.71	107.46	3.10
	CS5	38.54	102.49	2.66	38.98	101.66	2.61
10	CS1	26.99	131.10	4.86	29.52	135.88	4.60
	CS2	26.87	131.10	4.88	29.19	134.71	4.61
	CS3	31.54	110.77	3.51	32.97	109.94	3.33
	CS4	32.53	109.94	3.38	33.57	107.46	3.20
	CS5	41.12	108.28	2.63	41.00	106.63	2.60
11	CS1	23.74	144.71	6.09	30.01	136.85	4.56
	CS2	29.58	127.54	4.31	29.78	104.14	3.50
	CS3	35.09	109.11	3.11	34.27	107.46	3.14
	CS4	34.54	107.46	3.11	33.77	103.31	3.06
	CS5	41.81	105.80	2.53	40.20	104.14	2.59
12	CS1	20.18	127.05	6.29	25.62	147.20	5.75
	CS2	28.33	116.33	4.11	30.83	109.70	3.56
	CS3	35.26	116.08	3.29	34.18	116.57	3.41
	CS4	36.75	114.08	3.10	35.88	112.43	3.13
	CS5	38.42	103.31	2.69	38.31	100.83	2.63
13	CS1	26.88	126.57	4.71	26.53	132.13	4.98
	CS2	29.30	105.80	3.61	32.18	107.46	3.34
	CS3	32.52	111.60	3.43	33.51	109.94	3.28
	CS4	33.55	110.77	3.30	33.82	105.80	3.13
	CS5	39.46	102.49	2.60	39.75	103.31	2.60
14	CS1	17.54	129.30	7.37	20.44	126.61	6.19
	CS2	30.60	104.97	3.43	29.58	104.14	3.52
	CS3	33.66	109.94	3.27	32.54	110.77	3.40
	CS4	34.04	104.97	3.08	33.19	105.80	3.19
	CS5	38.86	104.14	2.68	38.90	104.14	2.68
15	CS1	17.88	121.05	6.77	14.58	126.47	8.68
	CS2	30.64	118.57	3.87	30.89	106.63	3.45
	CS3	38.42	119.15	3.10	37.00	111.59	3.02
	CS4	37.06	102.49	2.77	35.30	104.97	2.97
	CS5	41.85	104.97	2.51	42.20	108.28	2.57