Estimating the Scale-Dependent Influence of Natural Terrestrial Corridors on the Positioning of Settlements: A Multi-Scale Study of Roman Forts in Wales

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Abstract

Natural terrestrial corridors have been shown to have influenced the positioning of past settlements. The scale at which this pattern-process relationship operates is often un-estimated and thus remains unclear. This paper proposes the comparison of multiple point process models as an approach for estimating the optimal scale at which this relationship is strongest. With this approach, it is revealed that the positioning of Roman forts used during the conquest of Wales was most influenced by natural terrestrial corridors at a scale of 1,100m. At this scale, the Roman army stationed at these forts could control natural corridors – both via on-the-ground response as well as through overseeing movements by the native communities of Wales. Comparing multiple scenarios, it is also shown that the control of river-systems did not influence the positioning of Roman forts at the expense of controlling these natural terrestrial corridors used by those on foot. With archaeological interpretations susceptible to change as a result of the scale at which this pattern-process relationship is measured, the estimation of the optimal scale is pivotal for non-biased inferences on the processes thought to have influenced the positioning of settlements in the past.

Introduction

The topography of a landscape and its natural terrestrial corridors influenced both where people in the past moved and where they positioned their settlements. Natural terrestrial corridors facilitated the initial 'Out of Africa' and later dispersals of *Homo Sapiens* (Beyin et al., 2019; Field et al., 2007), defined transcontinental linkages between disparate trade centres, e.g. the 'Silk roads' (Frachetti et al., 2017), and were used during the conquest of new regions by states and empires (Carballo and Pluckhahn, 2007; De Soto and Carreras, 2022).

Natural terrestrial corridors within the landscape have frequently been identified using least-cost path analysis. Least-cost paths (LCPs) represent the path of least-resistance from a chosen origin and destination location based on costs associated with traversing from one raster cell to another. With this approach, points denoting origin and destination locations for LCPs are defined either around or within a study area of interest. LCPs are calculated for each pair of origin-destination locations, commonly referred to as the 'From-Everywhere-to-Everywhere' (FETE) method (White and Barber, 2012). Natural corridors related to human mobility are identified by quantifying the number of LCPs that cross each cell of the map; more accessible regions have a greater density of calculated paths (Murrieta-Flores, 2012). Simply, natural terrestrial corridors can be interpreted as routes more preferentially used by humans when traversing the landscape.

Using this FETE method, natural terrestrial corridors have been shown to have influenced the positioning of sites in the past. For example, archaeological sites representing the earliest phase of human occupation of Australia and New Guinea (Crabtree et al., 2021); prehistoric settlements in the Iberian Peninsula (Yubero-Gómez et al., 2015); and Bronze Age tombs in Crete (Déderix, 2017, 2015). Despite its continued use, an often-overlooked component is the scale-variance of this relationship – the influence of natural terrestrial corridors on the positioning of sites can change as a result of the scale at which the relationship is measured. Thus, changing the scale of analysis can alter the estimation of this relationship and any inferred processes that gave rise to an observed pattern. Notable exceptions that incorporate multiple scales of analysis however include the use of varying-sized buffers (e.g. Rubio-Campillo et al., 2022) or counting the number of least-cost paths within a specified radius (e.g. Murrieta-Flores, 2012). The optimal scale at which this relationship is strongest nevertheless remains un-estimated – either due to limitations in the null-hypothesis framework or the qualitative nature of the comparison.

This research proposes the comparison of multiple point process models as an approach for estimating the scale at which natural terrestrial corridors—and covariates more generally—most influence the positioning of settlements in the past. The approach is demonstrated via a case study estimating the scale at which Roman forts used during the conquest of Wales were most influenced by natural terrestrial corridors within the landscape. With the scale of analysis changing the identified relationship between a covariate and settlement positioning, estimating the scale at which this relationship is strongest is a pivotal step before proposing any explanations for observed patterns.

Roman Conquest of Wales

Five years after the invasion of Britain in AD 43, the Roman army campaigned against the Deceangli in the north of Wales (Jarrett, 2002; Manning, 2004). Soon after in AD 49-50, Ostorius Scapula, the governor of Roman Britain, led a series of campaigns against the Silures in the south-east. This was followed by campaigns against the Ordovices in mid-Wales. In AD 60, the Roman governor Suetonius Paullinus launched an attack on Anglesey, the last stronghold of native resistance. The final conquest of Wales would be delayed following the rebellion of the Icenian queen Boudicca. By AD 77, Wales had however become completely subjugated (**Figure 1**).

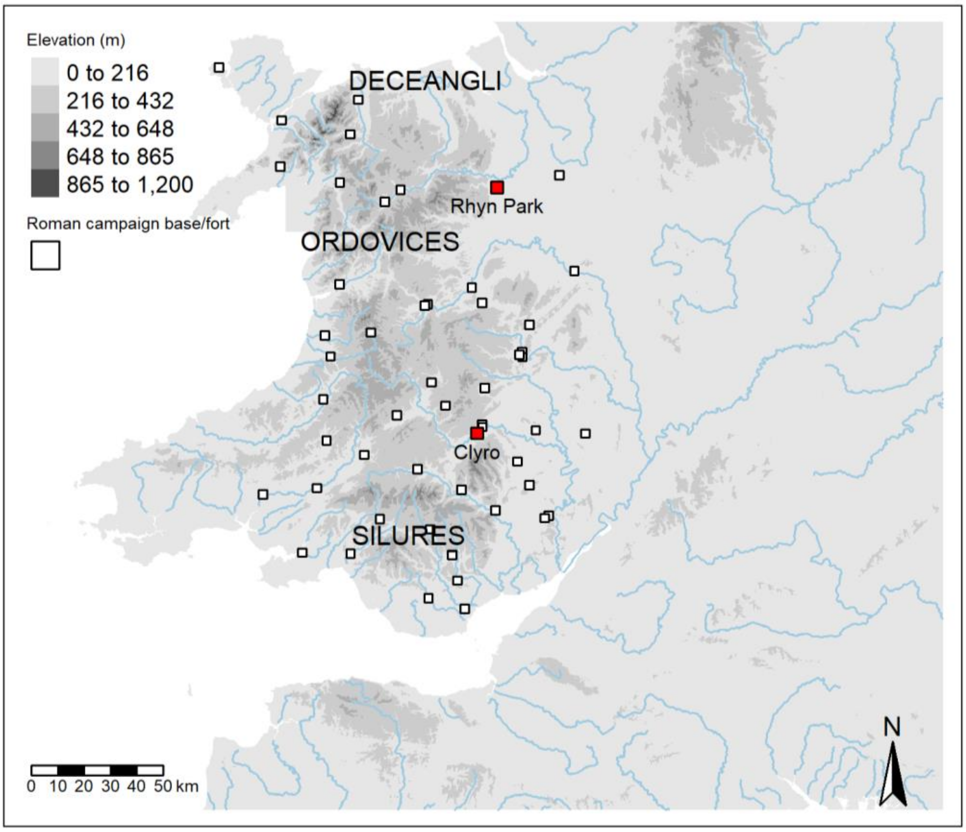

Figure 1. 50 metre resolution Digital Elevation Model derived from Ordnance Survey (2020). Roman campaign bases/forts (squares) derived from Burnham and Davies (2010). Campaign bases mentioned in text are shown in red. Mentioned pre-Roman tribes in pre-Roman Wales based on Burnham and Davies (2010, p. 21). Modern-day river systems derived from Yan et al. (2022)

During its initial conquest, a number of pre-Flavian period (AD 48-69) campaign bases/forts were established across Wales (Jarrett, 2002; Manning, 2004). Clusters of forts such as at Rhyn Park and Clyro were positioned on the interface between the uplands and the lowlands (Arnold and Davies, 2000, pp. 8–10). From these locations, hostiles moving towards the lowlands could be monitored and blocked; the number of hillforts and settlements in the uplands indicate that this is where the majority of the native population lived. By controlling the major valleys to the uplands, the ability for native communities to resist was significantly reduced. By the Flavian period (AD 74-96), the movement of the native population was controlled via a network of Roman forts—with many positioned in valley-bottoms—connected by a developing all-weather road system (Arnold and Davies, 2000, pp. 15–24; Burnham and Davies, 2010, pp. 67–68).

Methods and Theory

All data and R scripts are available at https://github.com/josephlewis/RW_Natural_Corridors and permanently archived on https://zenodo.org/doi/10.5281/zenodo.11067177.

Identifying Natural Terrestrial Corridors

Natural terrestrial corridors in Wales were calculated using the Ordnance Survey 50 metres resolution Digital Elevation Model (DEM) (Ordnance Survey, 2020). For computational tractability, the DEM was mean aggregated to 100m resolution. The cost of traversing the slope gradient between 8-neighbour adjacent cells within the 100m DEM was calculated using the energy-based sixth-polynomial cost function as proposed by Herzog (2013). The use of an energy-based cost function over a time-based cost function, e.g. Tobler's Hiking Function (1993), reflects the assumption that humans in the past would have optimised for reducing energy-expenditure rather than time-taken when traversing the landscape. In total, three scenarios were assessed: 1) walking-only; 2) walking with rivers acting as barriers; and 3) walking with rivers acting as potential-conduits for movement. The latter scenario applies a riverine travel speed of 2.5km/h and 0.6km/h when travelling upstream and downstream, respectively (Carreras et al., 2019; Carreras and De Soto, 2013). The location of modern-day rivers in Wales was derived from a global rivers dataset (Yan et al., 2022). This resulted in three conductance surfaces (the inverse of the more traditional cost surface) representing the conductance/ease of moving from one cell to all other adjacent cells within the DEM (**Figure 2A**). In total, 629,642 least-cost paths were calculated between 794 points evenly spaced 10 kilometres apart for each of the three scenarios. Conductance surfaces and least-cost paths were calculated using the R packages *leastcostpath* (Lewis, 2023) and *cppRouting* (Larmet, 2022). Natural terrestrial corridors at a 100m resolution were identified by quantifying the number of times an LCP crossed a cell within the DEM (**Figure 2B**).

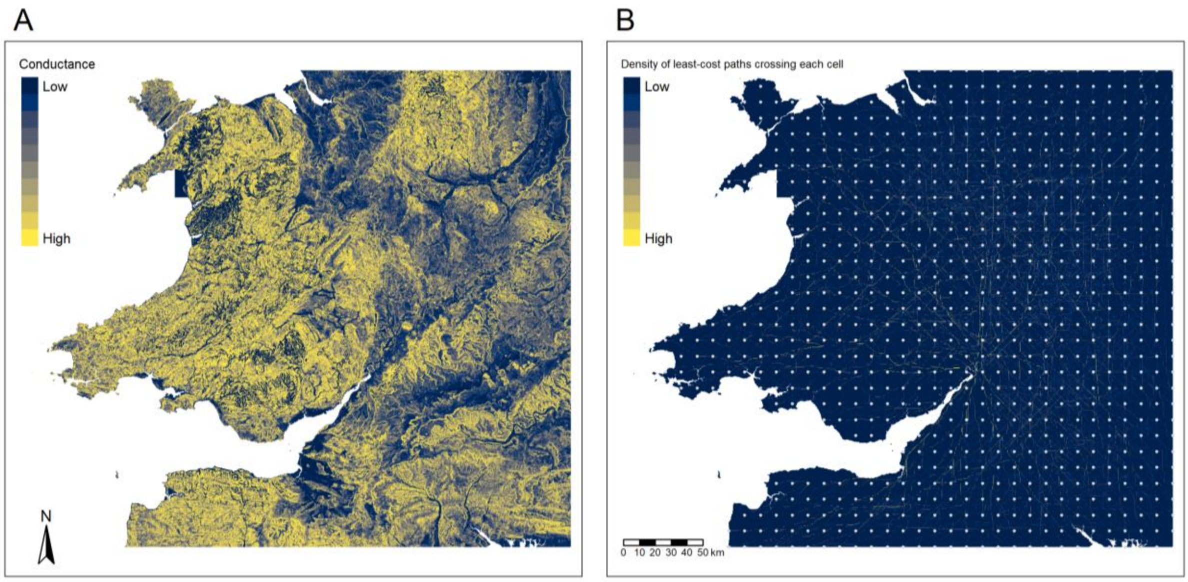

Figure 2. Conductance surface representing the mean conductance of moving to a central cell from-to all other adjacent cells using the energy-based cost function as proposed by Herzog (2013) for the walking-only scenario (**A**). Natural terrestrial corridors in Wales for the walking-only scenario as calculated by quantifying the number of times an LCP crosses a cell within the Digital Elevation Model. The 794 from-to points shown by grey points (**B**)

Calculating Natural Terrestrial Corridors at Multiple Scales

The scale at which a covariate most influences the relationship that generated the phenomenon, termed more generally the ‘process scale’ (Oshan et al., 2022) or ‘scale of effect’ (Jackson and Fahrig, 2015), is often not directly observed and requires estimation from measured data at a specific scale, e.g. the resolution of a DEM. Here the phenomenon of interest is the positioning of Roman forts used during the conquest of Wales with the ‘process scale’ being the scale at which the influence of natural corridors is strongest. This is predicated on the rationale that the positioning of Roman forts—and settlements more generally— is influenced not only by their specific location but also their surrounding area. Estimating this process scale can reveal important information on the processes that influenced the positioning of settlements in the past. To estimate the optimal scale at which this process operates, the natural terrestrial corridors calculated from the 100m resolution DEM were represented at varying spatial scales. The frequency of LCPs crossing each cell within increasing larger circular windows were summed, with the windows ranging from 300m to 16,100m at intervals at 300m and then increments of 4,000m to 36,100m. In total, 82 different ‘scales of window’ were assessed (**Figure 3**).

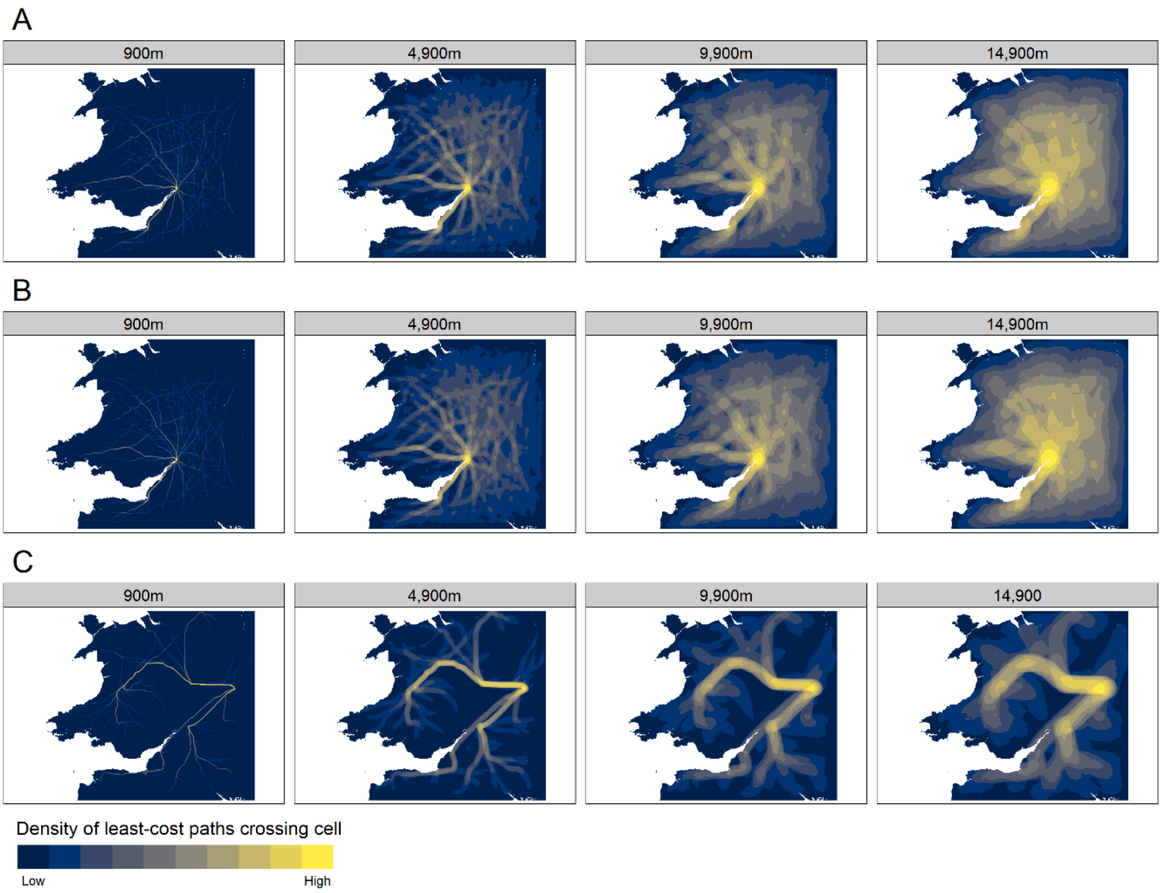

Figure 3. Examples of natural terrestrial corridors at four increasingly larger scales for the three tested scenarios: walking-only (**A**); walking with rivers acting as potential conduits for movement (**B**); and walking with rivers acting as barriers to movement (**C**)

The rationale to sum the frequency of LCPs crossing each cell within increasingly larger windows reflects that Roman forts were positioned within the landscape to survey surrounding areas and maintain control of the native communities (Bidwell, 2007, pp. 30–37; Jarrett, 2002) Similarly, it is expected that the process scale will be below the distance between contemporaneous Roman forts, c.20km (Jarrett, 1969, p. 145), or that travelled within a single day, c.32km (Kolb, 2001, pp. 310–311). Arnold and Davies (2000, pp. 15–16) for example note that multiple Roman forts in Wales would have been mutually supporting, with regiments from multiple forts working together when responding to trouble.

With this approach, a number of assumptions are made. First, it is assumed that the 'process scale' is within the range of evaluated scales. If the 'process scale' is outside this range, the optimal scale at which natural terrestrial corridors most influence the positioning of settlements will be missed, potentially leading to biased estimates. And second, that the spatial resolution of 100m for the original natural terrestrial corridor surface sufficiently captures the main processes influencing movement choice. With the calculation of an LCP being sensitive to the resolution of the DEM (Kantner, 2012), it is worthwhile clarifying this assumption from a pattern-process perspective. The spatial resolution of the DEM denotes the smallest unit of measurement that is recorded, and is often referred to as the observation or measurement scale (Oshan et al., 2022). DEMs with higher spatial resolution capture more information and as a result represent the topographic surface more accurately. When calculating LCPs, the spatial resolution of the DEM provides a lower limit for the processes that can be intentionally represented by the LCP. For example, Branting (2012, p. 217) suggests that movement choices are conducted at the stride-length of an individual, c. 50cm. If an LCP is calculated using a DEM of 100 metre resolution it is therefore assumed that the processes occurring at a scale of 50cm are either 1) also operating similarly at a scale of 100m, i.e. scale-invariant between 50cm and 100m; or 2) that the processes operating at a scale of 50cm are sufficiently captured within the pattern resultant from processes operating at a scale of 100m, i.e. scale-variant but the calculated LCPs are similar. If either the scale-variant or scale-invariant assumption is deemed justified, the LCP calculated using a DEM of 100m can be used to sufficiently represent movement patterns as a result of processes occurring at a scale of 50cm. If deemed unjustified, a misalignment between the pattern-process relationship may occur, leading to biased results.

Estimating the Process Scale

The influence of natural terrestrial corridors on the positioning of the 53 Roman forts used during the conquest of Wales and the process scale at which this relationship is strongest was estimated using multiple point process models (PPMs). PPMs explicitly model the relationship between covariate and the point process (Illian et al., 2008). The advantages of using PPMs in contrast to other methods that estimate the relationship between covariates and presence/absence data, e.g. logistic regression, include: 1) PPMs model the data-generating mechanism for the original point-events rather than coercing the data into a presence/absence format to fit the model, e.g. gridded data; and 2) unlike logistic regression, inference from PPMs are less sensitive to the number of pseudo-absence/background points chosen or whether their locations change (Baddeley et al., 2010; Warton and Shepherd, 2010).

82 PPMs for each of the three scenarios were fitted using the 82 natural terrestrial corridor surfaces at increasingly larger spatial scales. First-order effects—the process which causes the intensity of points, or in this case Roman forts, to vary across a given area—were represented by the natural terrestrial corridor surfaces; routes more preferentially used by humans when traversing the landscape are expected to have had a greater influence on the positioning and number of constructed Roman forts. No second-order effects, i.e. the internal interaction effects between points, were incorporated within the models. To allow for the influence of terrestrial natural corridors on the positioning of Roman forts to be non-linear, the relationship was modelled using a cubic b-spline (Baddeley et al., 2016). 146,876 quadrature points, equivalent to background or pseudo-absence points when conducting logistic regression, were generated at a regular spacing of 500 metres. All PPM steps were conducted using the R package *spatstat* (Baddeley et al., 2016). The process scale at which natural terrestrial corridors most influence the positioning of the 53 Roman forts used during the conquest of Wales was estimated via the Akaike Information Criterion (AIC) score (Burnham and Anderson, 2002).

Results and Discussion

Using the proposed point process modelling approach, the positioning of Roman forts in Wales is estimated to be most influenced by natural terrestrial corridors at a process scale of 1,100m (**Figure 4B**).

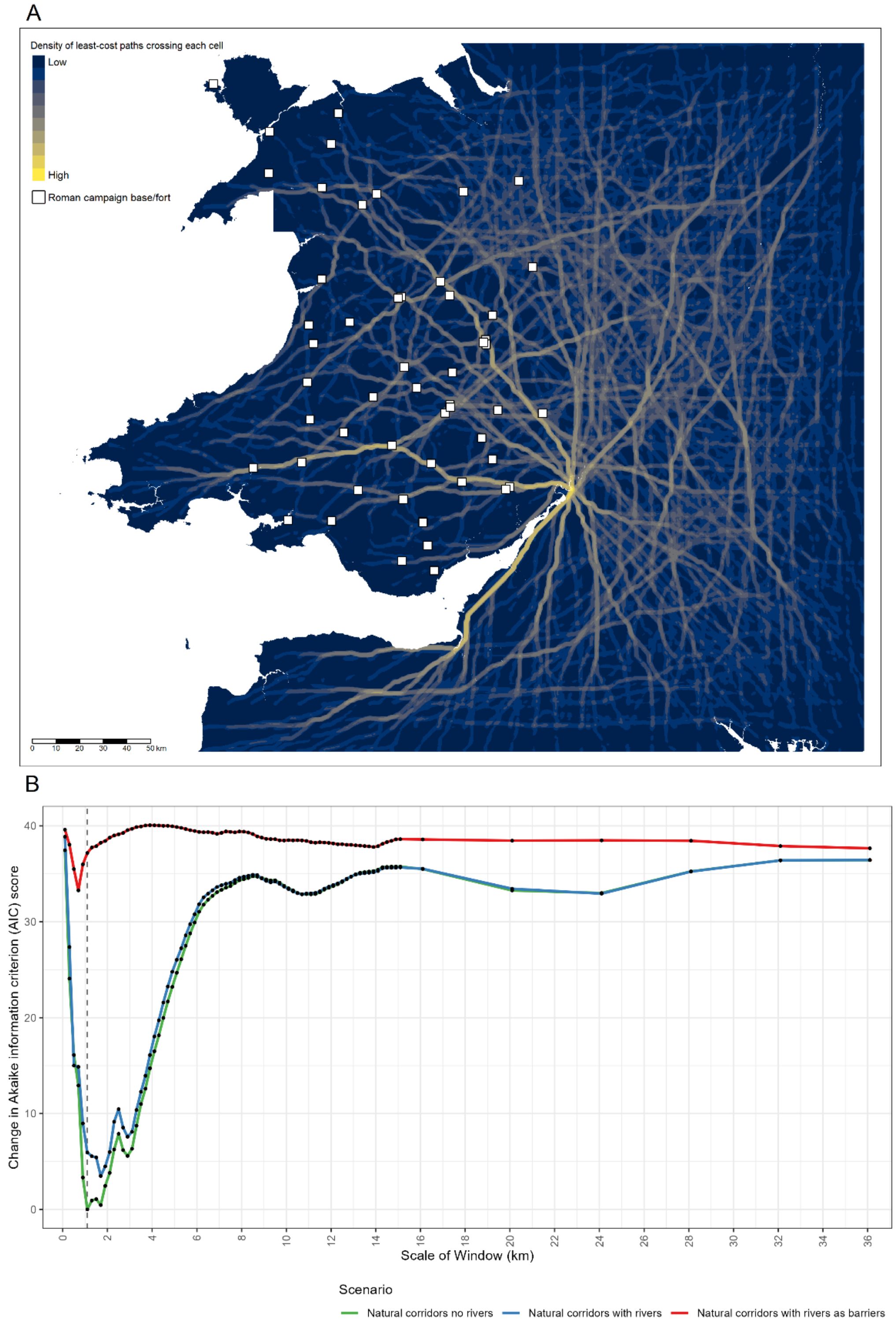

Figure 4. Natural terrestrial corridors at process scale of 1,100m for the walking-only scenario (**A**). Relative change in Akaike Information Criterion (AIC) scores for point process models estimating the process scale at which the influence of natural terrestrial corridors on the positioning of Roman forts in Wales is strongest. Estimated process scale of 1,100m (lowest AIC) is highlighted with a dashed, horizontal line (**B**)

Specifically, the walking-only scenario resulted in the highest predictive power, compared to both the walking with rivers as conduits for movement and rivers as barriers to movement. As predicted, the process scale of 1,100m is also below the distance between contemporaneous Roman forts (c.20km) or that travelled within a single day's march by the Roman army (c.32km). With the process scale identifying the scale at which natural terrestrial corridors influenced the positioning of Roman forts, the estimated scale can be related to both the movement and visibility of the area around each fort. Assuming a movement speed of 6km/h, the distance of 1,100m can be covered in ~11 minutes. Furthermore, Fisher (1994) suggests that visibility of an area does not decay until a distance of c.1km from an observer; it is not until over this 1km distance that visibility begins to degrade. More recently, Fábrega-Álvarez and Parcero-Oubiña (2019) also suggested 1,250-975m as the maximum distance at which an individual can be recognised as a human being. With surrounding natural corridors overseen by each fort both accessible and within the distance of potential visibility, the Roman army could control the same corridors used by native communities that were being conquered. This locally-defined process of control via the construction of forts is suggested to have been modulated by the topographic complexity of Wales, with its valleys and coastal plains. Burnham and Davies (2010, p. 45) for example note that many forts founded in the Flavian period were positioned in major river valleys and coastal plains – both of which facilitate movement due to their less mountainous terrain.

The lower predictive power of the walking with rivers as conduits for movement scenario indicates that the control of river-systems by Roman forts was not prioritised at the expense of controlling natural terrestrial corridors used by the native communities within Wales. Of all forts in Wales, approximately 25% were accessible by ship (Burnham and Davies, 2010, p. 48). Those that were, were often located in estuaries, facilitating the transportation of foodstuffs and building materials inland (Burnham and Davies, 2010, p. 68). This is in contrast to pre-Flavian temporary camps, with their position concentrated at major river valleys used during early campaigns (Burnham and Davies, 2010, pp. 37–38). Similarly, fortlets—posts built for a small detachment of a unit—were often positioned to guard where a Roman road crossed a river (e.g. Burnham and Davies, 2010, pp. 295–296). Lastly, the lower predictive power of the walking with rivers as barriers to movement suggests that natural corridors within the landscape were not demarcated by the river-systems – movement occurred across rivers.

More broadly, this paper has shown the efficacy of comparing multiple PPMs when estimating the optimal scale at which natural terrestrial corridors most influence the positioning of settlements. This PPM approach is not however limited to natural corridors identified using the FETE method, with it also possible to apply this approach to natural corridors identified using other methods that share similar premises, e.g. circuit theory (Howey, 2011; McLean and Rubio-Campillo, 2022) and focal mobility networks (Fábrega-Álvarez, 2006; Llobera et al., 2011). Similarly, the multi-scale approach using point process models as presented here is not limited to a single covariate only, with it also possible to estimate the optimal scale of multiple covariates. The estimation of the optimal scale is nevertheless fundamental for understanding the processes that influenced the positioning of settlements in the past. Measuring this relationship at the incorrect scale can bias inferred relationships and any resultant conclusions. For non-biased archaeological interpretations, it is imperative that pattern-process relationships are measured at the optimal scale.

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