1   **Estimating the Scale-Dependent Influence of Natural Terrestrial Corridors on the Positioning of**

2   **Settlements: A Multi-Scale Study of Roman Forts in Wales**

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6   **Abstract**

7   Natural terrestrial corridors have been shown to have influenced the positioning of past settlements.

8   The scale at which this pattern-process relationship operates is often un-estimated and thus remains

9   unclear. This paper proposes the comparison of multiple point process models as an approach for

10   estimating the optimal scale at which this relationship is strongest. With this approach, it is revealed

11   that the positioning of Roman forts used during the conquest of Wales was most influenced by natural

12   terrestrial corridors at a scale of 1,100m. At this scale, the Roman army stationed at these forts could

13   control natural corridors – both via on-the-ground response as well as through overseeing movements

14   by the native communities of Wales. Comparing multiple scenarios, it is also shown that the control

15   of river-systems did not influence the positioning of Roman forts at the expense of controlling these

16   natural terrestrial corridors used by those on foot. With archaeological interpretations susceptible to

17   change as a result of the scale at which this pattern-process relationship is measured, the estimation of

18   the optimal scale is pivotal for non-biased inferences on the processes thought to have influenced the

19   positioning of settlements in the past.

20   **Introduction**

21   The topography of a landscape and its natural terrestrial corridors influenced both where people in the

22   past moved and where they positioned their settlements. Natural terrestrial corridors facilitated the

23   initial 'Out of Africa' and later dispersals of *Homo Sapiens* (Beyin et al., 2019; Field et al., 2007),

24   defined transcontinental linkages between disparate trade centres, e.g. the 'Silk roads' (Frachetti et al.,

25   2017), and were used during the conquest of new regions by states and empires (Carballo and

26   Pluckhahn, 2007; De Soto and Carreras, 2022).

27   Natural terrestrial corridors within the landscape have frequently been identified using least-

28   cost path analysis. Least-cost paths (LCPs) represent the path of least-resistance from a chosen origin

29   and destination location based on costs associated with traversing from one raster cell to another.

30   With this approach, points denoting origin and destination locations for LCPs are defined either

31   around or within a study area of interest. LCPs are calculated for each pair of origin-destination

32   locations, commonly referred to as the 'From-Everywhere-to-Everywhere' (FETE) method (White

33   and Barber, 2012). Natural corridors related to human mobility are identified by quantifying the

34 number of LCPs that cross each cell of the map; more accessible regions have a greater density of

35 calculated paths (Murrieta-Flores, 2012). Simply, natural terrestrial corridors can be interpreted as

36 routes more preferentially used by humans when traversing the landscape.

37 Using this FETE method, natural terrestrial corridors have been shown to have influenced the

38 positioning of sites in the past. For example, archaeological sites representing the earliest phase of

39 human occupation of Australia and New Guinea (Crabtree et al., 2021); prehistoric settlements in the

40 Iberian Peninsula (Yubero-Gómez et al., 2015); and Bronze Age tombs in Crete (Déderix, 2017,

41 2015). Despite its continued use, an often-overlooked component is the scale-variance of this

42 relationship – the influence of natural terrestrial corridors on the positioning of sites can change as a

43 result of the scale at which the relationship is measured. Thus, changing the scale of analysis can alter

44 the estimation of this relationship and any inferred processes that gave rise to an observed pattern.

45 Notable exceptions that incorporate multiple scales of analysis however include the use of varying-

46 sized buffers (e.g. Rubio-Campillo et al., 2022) or counting the number of least-cost paths within a

47 specified radius (e.g. Murrieta-Flores, 2012). The optimal scale at which this relationship is strongest

48 nevertheless remains un-estimated – either due to limitations in the null-hypothesis framework or the

49 qualitative nature of the comparison.

50 This research proposes the comparison of multiple point process models as an approach for

51 estimating the scale at which natural terrestrial corridors—and covariates more generally—most

52 influence the positioning of settlements in the past. The approach is demonstrated via a case study

53 estimating the scale at which Roman forts used during the conquest of Wales were most influenced by

54 natural terrestrial corridors within the landscape. With the scale of analysis changing the identified

55 relationship between a covariate and settlement positioning, estimating the scale at which this

56 relationship is strongest is a pivotal step before proposing any explanations for observed patterns.

Roman Conquest of Wales

58 Five years after the invasion of Britain in AD 43, the Roman army campaigned against the Deceangli

59 in the north of Wales (Jarrett, 2002; Manning, 2004). Soon after in AD 49-50, Ostorius Scapula, the

60 governor of Roman Britain, led a series of campaigns against the Silures in the south-east. This was

61 followed by campaigns against the Ordovices in mid-Wales. In AD 60, the Roman governor

62 Suetonius Paullinus launched an attack on Anglesey, the last stronghold of native resistance. The final

63 conquest of Wales would be delayed following the rebellion of the Icenian queen Boudicca. By AD

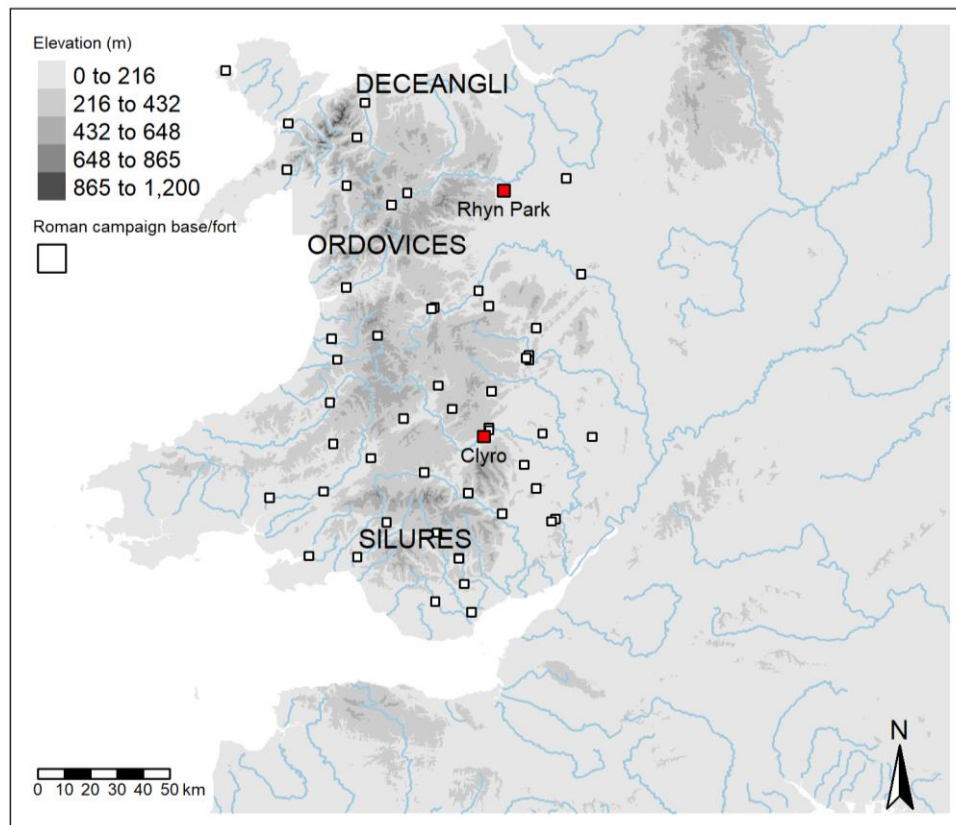64 77, Wales had however become completely subjugated (**Figure 1**).

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 on https://github.com/josephlewis/RW_Natural_Corridors and archived on

Identifying Natural Terrestrial Corridors

84 Natural terrestrial corridors in Wales were calculated using the Ordnance Survey 50 metres resolution

85 Digital Elevation Model (DEM) (Ordnance Survey, 2020). For computational tractability, the DEM

86 was mean aggregated to 100m resolution. The cost of traversing the slope gradient between 8-

87 neighbour adjacent cells within the 100m DEM was calculated using the energy-based sixth-

88 polynomial cost function as proposed by Herzog (2013). The use of an energy-based cost function

89 over a time-based cost function, e.g. Tobler's Hiking Function (1993), reflects the assumption that

90 humans in the past would have optimised for reducing energy-expenditure rather than time-taken

91 when traversing the landscape. In total, three scenarios were assessed: 1) walking-only; 2) walking

92 with rivers acting as barriers; and 3) walking with rivers acting as potential-conduits for movement.

93 The latter scenario applies a riverine travel speed of 2.5km/h and 0.6km/h when travelling upstream

94 and downstream, respectively (Carreras et al., 2019; Carreras and De Soto, 2013). The location of

95 modern-day rivers in Wales was derived from a global rivers dataset (Yan et al., 2022). This resulted

96 in three conductance surfaces (the inverse of the more traditional cost surface) representing the

97 conductance/ease of moving from one cell to all other adjacent cells within the DEM (**Figure 2A**). In

98 total, 629,642 least-cost paths were calculated between 794 points evenly spaced 10 kilometres apart

99 for each of the three scenarios. Conductance surfaces and least-cost paths were calculated using the R

100 packages *leastcostpath* (Lewis, 2023) and *cppRouting* (Larmet, 2022). Natural terrestrial corridors at a

101 100m resolution were identified by quantifying the number of times an LCP crossed a cell within the

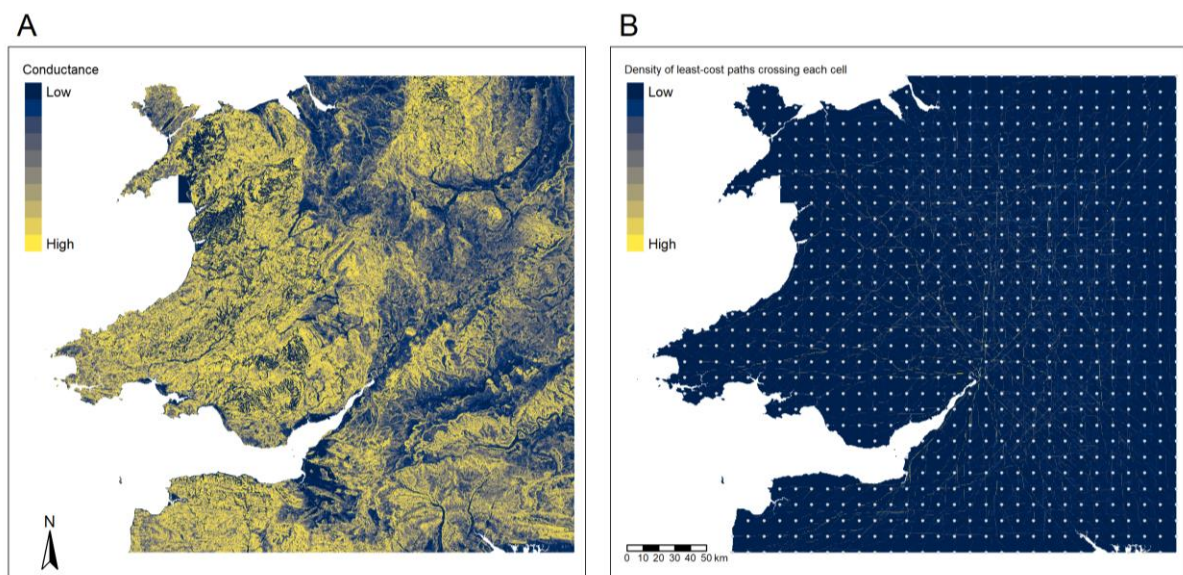102 DEM (**Figure 2B**).

103

104 **Figure 2.** Conductance surface representing the mean conductance of moving to a central cell from-to

105 all other adjacent cells using the energy-based cost function as proposed by Herzog (2013) for the

106 walking-only scenario (**A**). Natural terrestrial corridors in Wales for the walking-only scenario as

107 calculated by quantifying the number of times an LCP crosses a cell within the Digital Elevation

108 Model. The 794 from-to points shown by grey points (**B**)

Calculating Natural Terrestrial Corridors at Multiple Scales

110	The scale at which a covariate most influences the relationship that generated the phenomenon,

111	termed more generally the 'process scale' (Oshan et al., 2022) or 'scale of effect' (Jackson and Fahrig,

112	2015), is often not directly observed and requires estimation from measured data at a specific scale,

113	e.g. the resolution of a DEM. Here the phenomenon of interest is the positioning of Roman forts used

114	during the conquest of Wales with the 'process scale' being the scale at which the influence of natural

115	corridors is strongest. This is predicated on the rationale that the positioning of Roman forts—and

116	settlements more generally— is influenced not only by their specific location but also their

117	surrounding area. Estimating this process scale can reveal important information on the processes that

118	influenced the positioning of settlements in the past. To estimate the optimal scale at which this

119	process operates, the natural terrestrial corridors calculated from the 100m resolution DEM were

120	represented at varying spatial scales. The frequency of LCPs crossing each cell within increasing

121	larger circular windows were summed, with the windows ranging from 300m to 16,100m at intervals

122	at 300m and then increments of 4,000m to 36,100m. In total, 82 different 'scales of window' were

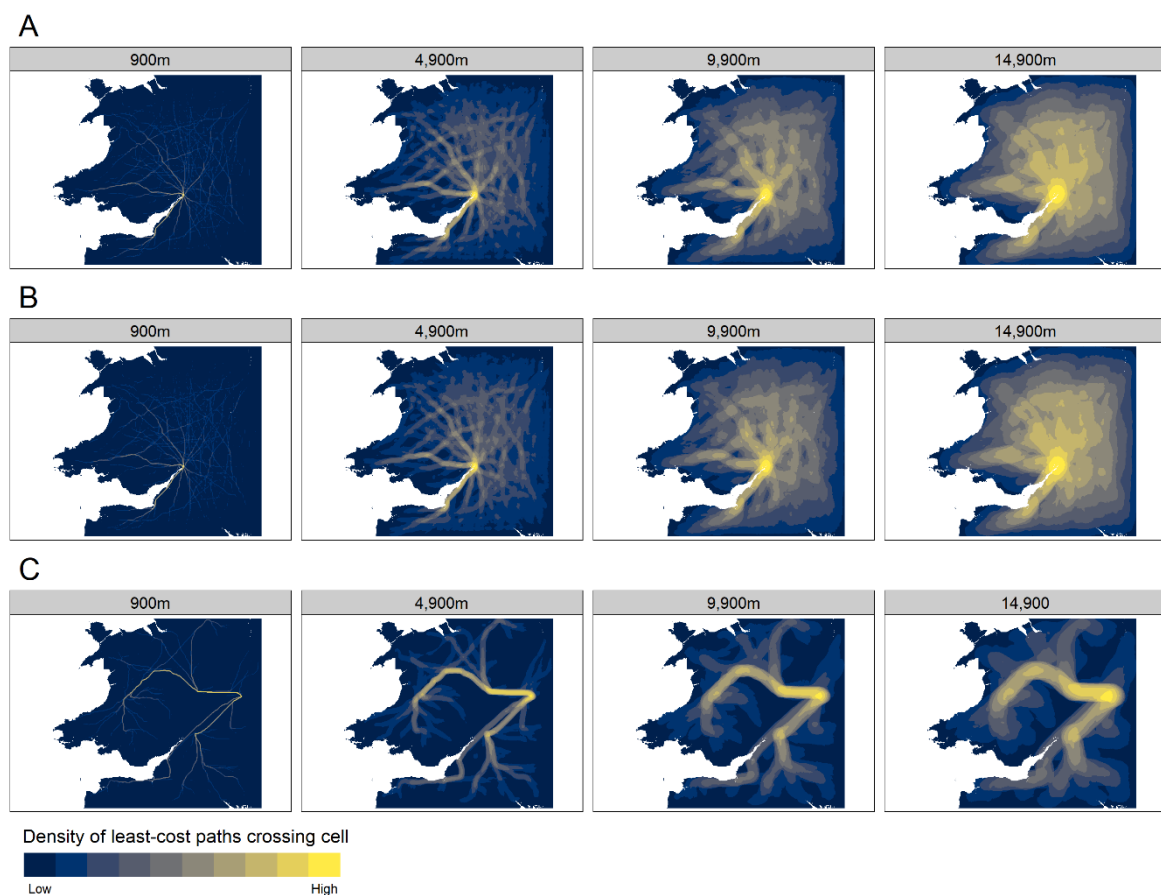123	assessed (**Figure 3**).

124

125	**Figure 3.** Examples of natural terrestrial corridors at four increasingly larger scales for the three

126	tested scenarios: walking-only (**A**); walking with rivers acting as potential conduits for movement (**B**);

127	and walking with rivers acting as barriers to movement (**C**)

128   The rationale to sum the frequency of LCPs crossing each cell within increasingly larger windows

129   reflects that Roman forts were positioned within the landscape to survey surrounding areas and

130   maintain control of the native communities (Bidwell, 2007, pp. 30–37; Jarrett, 2002) Similarly, it is

131   expected that the process scale will be below the distance between contemporaneous Roman forts,

132   c.20km (Jarrett, 1969, p. 145), or that travelled within a single day, c.32km (Kolb, 2001, pp. 310–

133   311). Arnold and Davies (2000, pp. 15–16) for example note that multiple Roman forts in Wales

134   would have been mutually supporting, with regiments from multiple forts working together when

135   responding to trouble.

136   With this approach, a number of assumptions are made. First, it is assumed that the 'process

137   scale' is within the range of evaluated scales. If the 'process scale' is outside this range, the optimal

138   scale at which natural terrestrial corridors most influence the positioning of settlements will be

139   missed, potentially leading to biased estimates. And second, that the spatial resolution of 100m for the

140   original natural terrestrial corridor surface sufficiently captures the main processes influencing

141   movement choice. With the calculation of an LCP being sensitive to the resolution of the DEM

142   (Kantner, 2012), it is worthwhile clarifying this assumption from a pattern-process perspective. The

143   spatial resolution of the DEM denotes the smallest unit of measurement that is recorded, and is often

144   referred to as the observation or measurement scale (Oshan et al., 2022). DEMs with higher spatial

145   resolution capture more information and as a result represent the topographic surface more accurately.

146   When calculating LCPs, the spatial resolution of the DEM provides a lower limit for the processes

147   that can be intentionally represented by the LCP. For example, Branting (2012, p. 217) suggests that

148   movement choices are conducted at the stride-length of an individual, c. 50cm. If an LCP is calculated

149   using a DEM of 100 metre resolution it is therefore assumed that the processes occurring at a scale of

150   50cm are either 1) also operating similarly at a scale of 100m, i.e. scale-invariant between 50cm and

151   100m; or 2) that the processes operating at a scale of 50cm are sufficiently captured within the pattern

152   resultant from processes operating at a scale of 100m, i.e. scale-variant but the calculated LCPs are

153   similar. If either the scale-variant or scale-invariant assumption is deemed justified, the LCP

154   calculated using a DEM of 100m can be used to sufficiently represent movement patterns as a result

155   of processes occurring at a scale of 50cm. If deemed unjustified, a misalignment between the pattern-

156   process relationship may occur, leading to biased results.

157   *Estimating the Process Scale*

158   The influence of natural terrestrial corridors on the positioning of the 53 Roman forts used during the

159   conquest of Wales and the process scale at which this relationship is strongest was estimated using

160   multiple point process models (PPMs). PPMs explicitly model the relationship between covariate and

161   the point process (Illian et al., 2008). The advantages of using PPMs in contrast to other methods that

162   estimate the relationship between covariates and presence/absence data, e.g. logistic regression,

163 include: 1) PPMs model the data-generating mechanism for the original point-events rather than

164 coercing the data into a presence/absence format to fit the model, e.g. gridded data; and 2) unlike

165 logistic regression, inference from PPMs are less sensitive to the number of pseudo-

166 absence/background points chosen or whether their locations change (Baddeley et al., 2010; Warton

167 and Shepherd, 2010).

168 82 PPMs for each of the three scenarios were fitted using the 82 natural terrestrial corridor

169 surfaces at increasingly larger spatial scales. First-order effects—the process which causes the

170 intensity of points, or in this case Roman forts, to vary across a given area—were represented by the

171 natural terrestrial corridor surfaces; routes more preferentially used by humans when traversing the

172 landscape are expected to have had a greater influence on the positioning and number of constructed

173 Roman forts. No second-order effects, i.e. the internal interaction effects between points, were

174 incorporated within the models. To allow for the influence of terrestrial natural corridors on the

175 positioning of Roman forts to be non-linear, the relationship was modelled using a cubic b-spline

176 (Baddeley et al., 2016). 146,876 quadrature points, equivalent to background or pseudo-absence

177 points when conducting logistic regression, were generated at a regular spacing of 500 metres. All

178 PPM steps were conducted using the R package *spatstat* (Baddeley et al., 2016). The process scale at

179 which natural terrestrial corridors most influence the positioning of the 53 Roman forts used during

180 the conquest of Wales was estimated via the Akaike Information Criterion (AIC) score (Burnham and

181 Anderson, 2002).

Results and Discussion

183 Using the proposed point process modelling approach, the positioning of Roman forts in Wales is

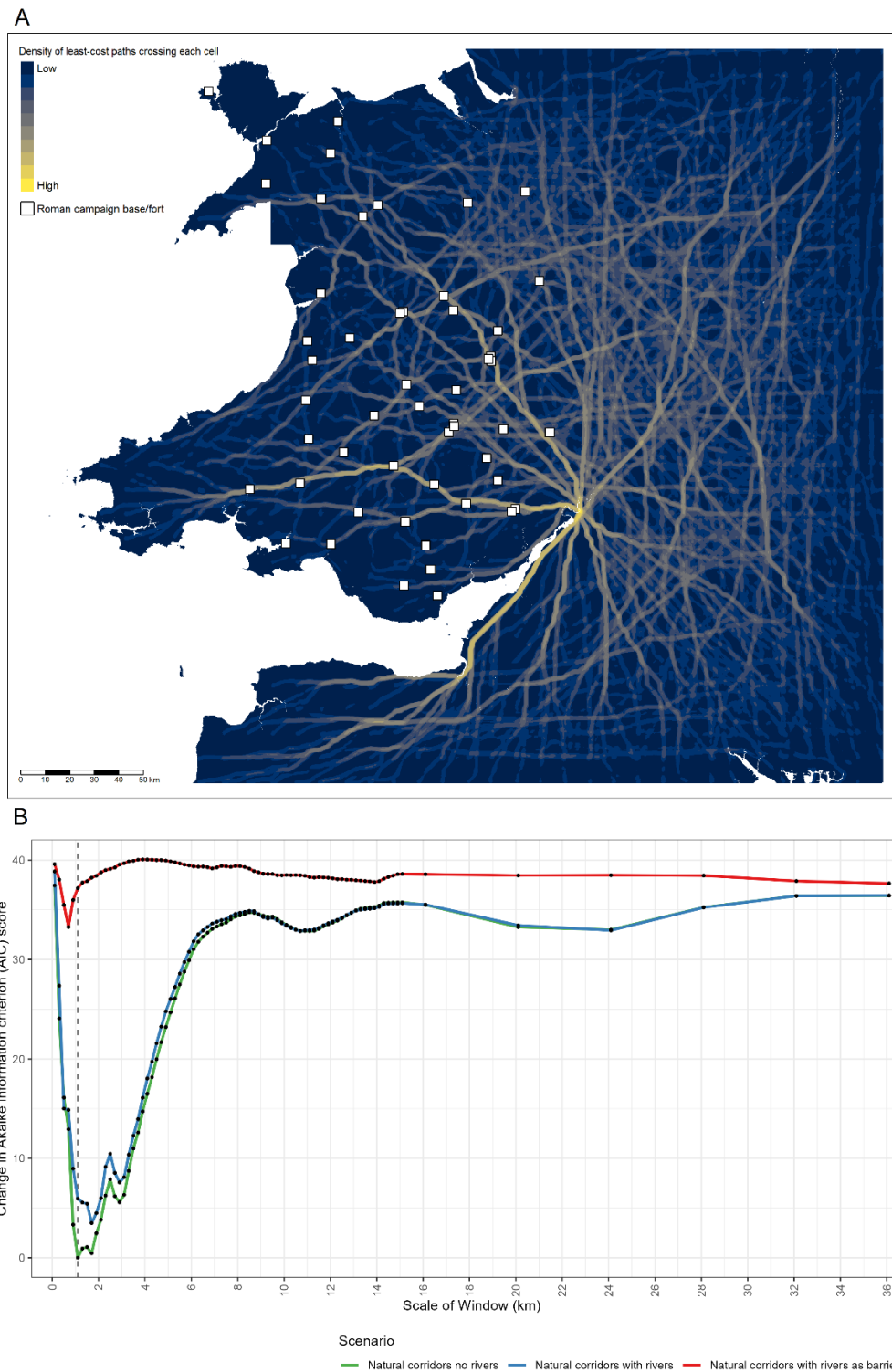184 estimated to be most influenced by natural terrestrial corridors at a process scale of 1,100m (**Figure**

185 **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**)

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

210   The lower predictive power of the walking with rivers as conduits for movement scenario
211   indicates that the control of river-systems by Roman forts was not prioritised at the expense of
212   controlling natural terrestrial corridors used by the native communities within Wales. Of all forts in
213   Wales, approximately 25% were accessible by ship (Burnham and Davies, 2010, p. 48). Those that
214   were, were often located in estuaries, facilitating the transportation of foodstuffs and building
215   materials inland (Burnham and Davies, 2010, p. 68). This is in contrast to pre-Flavian temporary
216   camps, with their position concentrated at major river valleys used during early campaigns (Burnham
217   and Davies, 2010, pp. 37–38). Similarly, fortlets—posts built for a small detachment of a unit—were
218   often positioned to guard where a Roman road crossed a river (e.g. Burnham and Davies, 2010, pp.
219   295–296). Lastly, the lower predictive power of the walking with rivers as barriers to movement
220   suggests that natural corridors within the landscape were not demarcated by the river-systems –
221   movement occurred across rivers.

222   More broadly, this paper has shown the efficacy of comparing multiple PPMs when
223   estimating the optimal scale at which natural terrestrial corridors most influence the positioning of
224   settlements. This PPM approach is not however limited to natural corridors identified using the FETE
225   method, with it also possible to apply this approach to natural corridors identified using other methods
226   that share similar premises, e.g. circuit theory (Howey, 2011; McLean and Rubio-Campillo, 2022)
227   and focal mobility networks (Fábrega-Álvarez, 2006; Llobera et al., 2011). Similarly, the multi-scale

228   approach using point process models as presented here is not limited to a single covariate only, with it

229   also possible to estimate the optimal scale of multiple covariates. The estimation of the optimal scale

230   is nevertheless fundamental for understanding the processes that influenced the positioning of

231   settlements in the past. Measuring this relationship at the incorrect scale can bias inferred

232   relationships and any resultant conclusions. For non-biased archaeological interpretations, it is

233   imperative that pattern-process relationships are measured at the optimal scale.

234 **References**

235 Arnold, C.J., Davies, J.L., 2000. Roman and Early Medieval Wales. Sutton, Stroud.
236 Baddeley, A., Berman, M., Fisher, N.I., Hardegen, A., Milne, R.K., Schuhmacher, D., Shah, R., Turner,
237   R., 2010. Spatial logistic regression and change-of-support in Poisson point processes.
238   Electron. J. Statist. 4. https://doi.org/10.1214/10-EJS581
239 Baddeley, A., Rubak, E., Turner, R., 2016. Spatial point patterns: methodology and applications with
240   R, Champan & Hall/CRC Interdisciplinary Statistics Series. Taylor & Francis Group, London.
241 Beyin, A., Hall, J., Day, C.A., 2019. A Least Cost Path Model for hominin dispersal routes out of the
242   East African Rift region (Ethiopia) into the Levant. Journal of Archaeological Science: Reports
243   23, 763–772. https://doi.org/10.1016/j.jasrep.2018.11.024
244 Bidwell, P.T., 2007. Roman forts in Britain. Tempus, Stroud.
245 Branting, S., 2012. Seven Solutions for Seven Problems with Least Cost Pathways, in: White, D.A.,
246   Surface-Evans, S.L. (Eds.), Least Cost Analysis of Social Landscapes: Archaeological Case
247   Studies. University of Utah Press, Salt Lake City, pp. 209–224.
248 Burnham, B.C., Davies, J.L. (Eds.), 2010. Roman Frontiers in Wales and the Marches. Royal
249   Commission on the Ancient and Historical Monuments of Wales, Aberystwyth.
250 Burnham, K.P., Anderson, D.R., 2002. Model selection and multimodel inference: a practical
251   information-theoretic approach, 2nd ed. ed. Springer, New York.
252 Carballo, D.M., Pluckhahn, T., 2007. Transportation corridors and political evolution in highland
253   Mesoamerica: Settlement analyses incorporating GIS for northern Tlaxcala, Mexico. Journal
254   of Anthropological Archaeology 26, 607–629. https://doi.org/10.1016/j.jaa.2007.05.001
255 Carreras, C., De Soto, P., 2013. The Roman Transport Network: A Precedent for the Integration of the
256   European Mobility. Historical Methods: A Journal of Quantitative and Interdisciplinary
257   History 46, 117–133. https://doi.org/10.1080/01615440.2013.803403
258 Carreras, C., De Soto, P., Muñoz, A., 2019. Land transport in mountainous regions in the Roman
259   Empire: Network analysis in the case of the Alps and Pyrenees. Journal of Archaeological
260   Science: Reports 25, 280–293. https://doi.org/10.1016/j.jasrep.2019.04.011
261 Crabtree, S.A., White, D.A., Bradshaw, C.J.A., Saltré, F., Williams, A.N., Beaman, R.J., Bird, M.I., Ulm,
262   S., 2021. Landscape rules predict optimal superhighways for the first peopling of Sahul. Nat
263   Hum Behav 5, 1303–1313. https://doi.org/10.1038/s41562-021-01106-8
264 De Soto, P., Carreras, C., 2022. The Economic and Social Evolution of the Iberian Peninsula as
265   Revealed through Analysis of Roman Transport Infrastructure, in: Brughmans, T., Wilson, A.
266   (Eds.), Simulating Roman Economies. Oxford University PressOxford, pp. 226–253.
267   https://doi.org/10.1093/oso/9780192857828.003.0008
268 Déderix, S., 2017. Communication Networks, Interactions, and Social Negotiation in Prepalatial
269   South-Central Crete. American Journal of Archaeology 121, 5–37.
270   https://doi.org/10.3764/aja.121.1.0005
271 Déderix, S., 2015. More than Line of Sight and Least Cost Path: An Application of GIS to the Study of
272   the Circular Tombs of South-Central Crete, in: Sarris, A. (Ed.), Best Practices of GeoInformatic
273   Technologies for the Mapping of Archaeolandscapes. Archaeopress, Oxford, pp. 137–147.
274 Fábrega-Álvarez, P., 2006. Moving without destination. A theoretical GIS-based determination of
275   movement from a given origin. Archaeological Computing Newsletter 64, 7–11.
276 Fábrega-Álvarez, P., Parcero-Oubiña, C., 2019. Now you see me. An assessment of the visual
277   recognition and control of individuals in archaeological landscapes. Journal of Archaeological
278   Science 104, 56–74. https://doi.org/10.1016/j.jas.2019.02.002
279 Field, J.S., Petraglia, M.D., Lahr, M.M., 2007. The southern dispersal hypothesis and the South Asian
280   archaeological record: Examination of dispersal routes through GIS analysis. Journal of
281   Anthropological Archaeology 26, 88–108. https://doi.org/10.1016/j.jaa.2006.06.001
282 Fisher, P., 1994. Probable and fuzzy models of the viewshed operation, in: Worboys, M.F. (Ed.),
283   Innovations in GIS. Taylor & Francis, London, pp. 161–175.

284   Frachetti, M.D., Smith, C.E., Traub, C.M., Williams, T., 2017. Nomadic ecology shaped the highland
285   geography of Asia's Silk Roads. Nature 543, 193–198. https://doi.org/10.1038/nature21696
286   Herzog, I., 2013. Theory and practice of cost functions, in: Fusion of Cultures: Abstracts of the XXXVIII
287   Conference on Computer Applications and Quantitative Methods in Archaeology. CAA 2010,
288   Granada, pp. 431–434.
289   Howey, M.C.L., 2011. Multiple pathways across past landscapes: circuit theory as a complementary
290   geospatial method to least cost path for modeling past movement. Journal of Archaeological
291   Science 38, 2523–2535. https://doi.org/10.1016/j.jas.2011.03.024
292   Illian, J., Penttinen, A., Stoyan, H., Stoyan, D., 2008. Statistical analysis and modelling of spatial point
293   patterns, Statistics in practice. John Wiley, Chichester, England.
294   Jackson, H.B., Fahrig, L., 2015. Are ecologists conducting research at the optimal scale? Global
295   Ecology and Biogeography 24, 52–63. https://doi.org/10.1111/geb.12233
296   Jarrett, M.G., 2002. Early Roman campaigns in Wales, in: Brewer, R.J. (Ed.), The Second Augustan
297   Legion and the Roman Military Machine. National Museums & Galleries of Wales, Cardiff,
298   pp. 45–66.
299   Jarrett, M.G., 1969. The Roman Frontier in Wales. Presented at the International Congress of Roman
300   Frontier Studies, 8th, University of Wales Press, Cardiff.
301   Kantner, J., 2012. Realism, Reality, and Routes, in: White, D.A., Surface-Evans, S.L. (Eds.), Least Cost
302   Analysis of Social Landscapes: Archaeological Case Studies. The University of Utah Press, Salt
303   Lake City, pp. 225–238.
304   Kolb, A., 2001. Transport und Nachrichtentransfer im Römischen Reich. Akademie Verlag.
305   https://doi.org/10.1524/9783050048246
306   Larmet, V., 2022. cppRouting: Algorithms for Routing and Solving the Traffic Assignment Problem.
307   Lewis, J., 2023. leastcostpath: Modelling Pathways and Movement Potential Within a Landscape.
308   Llobera, M., Fábrega-Álvarez, P., Parcero-Oubiña, C., 2011. Order in movement: a GIS approach to
309   accessibility. Journal of Archaeological Science 38, 843–851.
310   https://doi.org/10.1016/j.jas.2010.11.006
311   Manning, W., 2004. The Conquest of Wales, in: Todd, M. (Ed.), A Companion to Roman Britain.
312   Blackwell Publishing Ltd, Oxford, pp. 60–74.
313   McLean, A., Rubio-Campillo, X., 2022. Beyond Least Cost Paths: Circuit theory, maritime mobility and
314   patterns of urbanism in the Roman Adriatic. Journal of Archaeological Science 138, 105534.
315   https://doi.org/10.1016/j.jas.2021.105534
316   Murrieta-Flores, P., 2012. Understanding human movement through spatial technologies. The role of
317   natural areas of transit in the Late Prehistory of South-western Iberia. Trabajos de
318   Prehistoria 69, 103–122.
319   Ordnance Survey, 2020. OS Terrain 50m DTM.
320   Oshan, T.M., Wolf, L.J., Sachdeva, M., Bardin, S., Fotheringham, A.S., 2022. A scoping review on the
321   multiplicity of scale in spatial analysis. J Geogr Syst 24, 293–324.
322   https://doi.org/10.1007/s10109-022-00384-8
323   Rubio-Campillo, X., Ble, E., Pujol, À., Sala, R., Tamba, R., 2022. A Spatial Connectivity Approach to
324   Landscapes of Conflict: Julius Caesar and the Assault to Puig Ciutat (NE Iberian Peninsula). J
325   Archaeol Method Theory 29, 1059–1089. https://doi.org/10.1007/s10816-022-09549-7
326   Tobler, W., 1993. Three Presentations on Geographical Analysis and Modeling. Technical Report 93-
327   1. National Center for Geographic Information and Analysis, Santa Barbara, CA.
328   Warton, D.I., Shepherd, L.C., 2010. Poisson point process models solve the "pseudo-absence
329   problem" for presence-only data in ecology. Ann. Appl. Stat. 4. https://doi.org/10.1214/10-
330   AOAS331
331   White, D.A., Barber, S., 2012. Geospatial modeling of pedestrian transportation networks: a case
332   study from precolumbian Oaxaca, Mexico. Journal of Archaeological Science 39, 2684–2696.
333   https://doi.org/10.1016/j.jas.2012.04.017

334   Yan, D., Li, C., Zhang, X., Wang, J., Feng, J., Dong, B., Fan, J., Wang, K., Zhang, C., Wang, H., Zhang, J.,
335   Qin, T., 2022. A data set of global river networks and corresponding water resources zones
336   divisions v2. Sci Data 9, 770. https://doi.org/10.1038/s41597-022-01888-0
337   Yubero-Gómez, M., Rubio-Campillo, X., López-Cachero, F.J., Esteve-Gràcia, X., 2015. Mapping
338   changes in late prehistoric landscapes: A case study in the Northeastern Iberian Peninsula.
339   Journal of Anthropological Archaeology 40, 123–134.
340   https://doi.org/10.1016/j.jaa.2015.07.002
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