Process-Explicit Hierarchical Model Reveals Structure of Roman Roads in the Roman Empire

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Introduction

Roadways constructed by past societies are routinely characterised by a single defining feature, their straightness. The *Chaco Great North Road* of the American Southwest, the Mayan *Cobá–Yaxuná Sacbe* ('white road'), and the Roman *Via Appia* of the Roman empire crossed mountains, valleys, and marshlands with little deviation[1–4]. At the same time, the position of past roadways was flexible, influenced by topographic constraints such as mountain passes, ravines, and steep gradients[4–7]. Yet our understanding of this variability across past roadway systems is limited. This is despite roadways providing a robust empirical foundation for inferring the socio-political and economic structure and objectives of past societies[8–14], overcoming the scarcity of direct evidence for past decision-making[3,4,15]. A major obstacle is the classification of roadways into typologies based on their construction, proposed function, and the sites that they connect[3,11,12,16–20]. The usefulness of such typologies for understanding variability in archaeological material including roadways is a subject of long debate[8,11,12,20–25].

Here, I use a process-explicit, hierarchical movement model to estimate the variability in the influence of topographic constraints on the position of Roman roadways in Roman Wales and across the Roman empire. Detailed knowledge on the position of multiple road sections[26,27], combined with the mountainous terrain of Wales, make the study of roadways within this region of the Roman empire highly suitable. Roadways in Wales also have two additional advantageous that promote transferability to roadways across the Roman empire: 1) Roman roadways in Wales are thought to have been constructed *de novo*, limiting the impact of pre-existing roadways influencing their position within the landscape; and 2) like other regions of the Roman empire, roadways were constructed or overseen by the Roman army[28]. A larger-scale analysis of roadways across the Roman empire, or other past societies, is prohibited by the often dubious provenance of many reported roadways and the lack of systematic standards when recording their position within the landscape[29,30].

Results

Results reveal substantial variability in the influence of topographic constraints on the position of the 62 known Roman roadways in Wales (**Fig. 1**). Median posterior estimates for the rate of incline from the minimum influence of topographic constraints across individual roadways (parameter b) ranges between 0.25 and 35.69. The majority of these roadways (74%, 46 out of 62) are more influenced by topographic constraints than expected when minimising time while hiking (Tobler's Hiking Function, parameter b = 3.5)[31]. Roman roadways also possess shallower slope gradients at a rate higher than expected while hiking (**Extended Data Fig. 1**). Median posterior estimate ($\bar{b}$) for roadways across the Roman empire is 6.31 [0.27-35.60, 95% Credible Interval] with a standard deviation (σ) of 0.76 [0.03-3.86]. Like the majority of roadways in Wales, the influence of topographic constraints on roadways across the Roman empire is also greater than expected while hiking.

Maximum slope gradient for individual roadways ranges between 0.03 and 0.44 (**Extended Data Fig. 2**). 55 (88.7%) roadways in Wales are shallower than the maximum slope gradient of 0.25 for roadways in Roman Scotland, a similarly mountainous region of the Roman empire[32]. In contrast, only 29 (46.8%) roadways have a maximum slope gradient shallower than the preferred maximum slope gradient of 0.125 for Roman roadways in Britain[33].

56 roadways (90.3%) have a maximum slope gradient shallower than the 0.29 critical slope gradient—that is, the maximum slope gradient at which an individual can efficiently ascend or descend without slipping or experiencing significant difficulty—while hiking, navigating wooded environments, or participating in hill running races[31,34–38]. 36 roadways (58.1%) also have a maximum slope gradient shallower than the 0.15 critical slope gradient for a fully loaded Roman wheeled vehicle[39]. In comparison, 15 roadways (24.2%) possess maximum slope gradients steeper than 0.20, or that which is deemed too steep to have been traversable by a wheeled vehicle.

For roadways across the Roman empire, 68.63% are estimated to have a critical slope gradient below that while hiking. In contrast, only 46.95% of roadways have critical slope gradients below the critical slope gradient for wheeled vehicles (**Extended Data Fig. 3**).

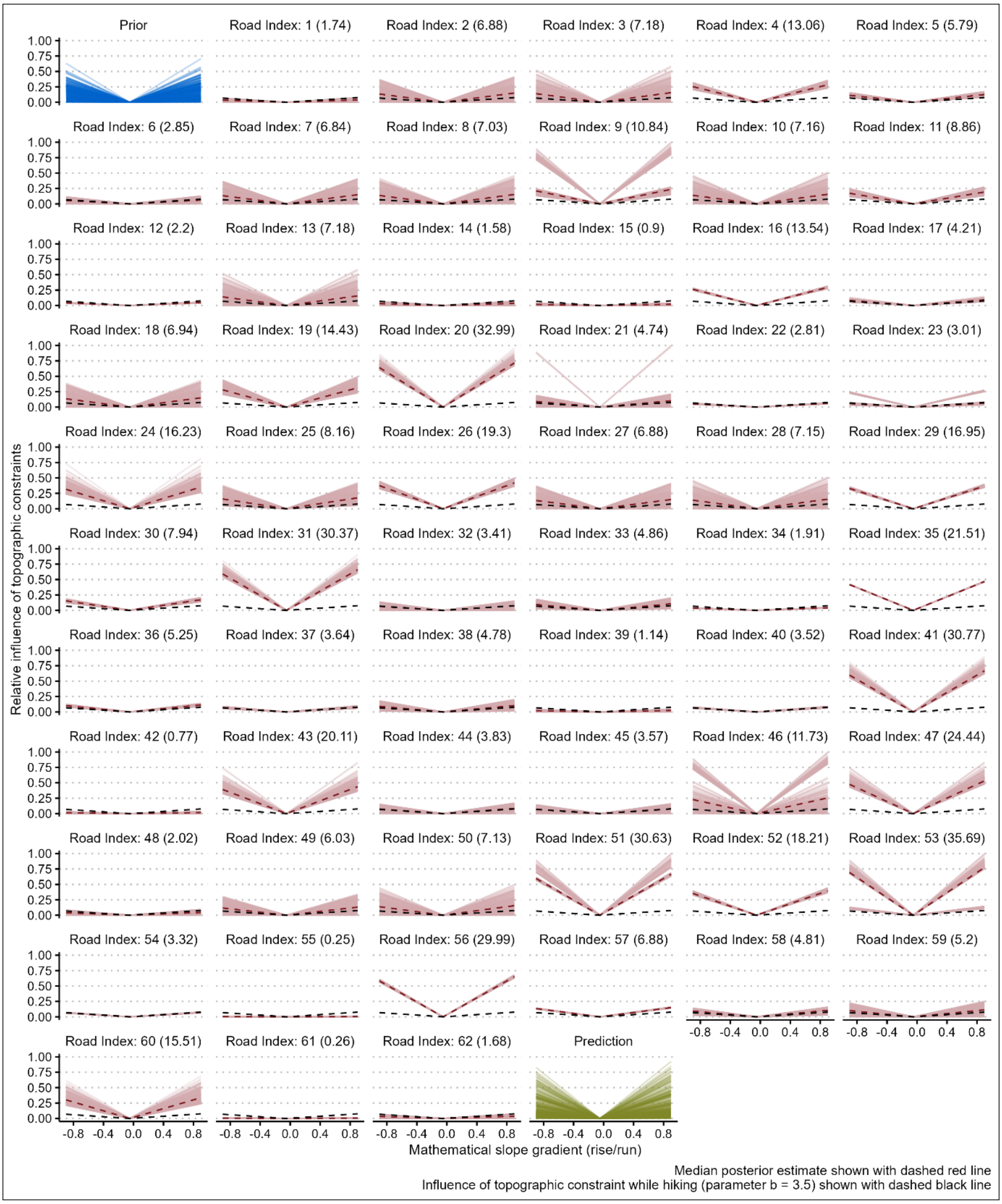

Fig. 1. Estimated relative influence of topographic constraints on the position of Roman roadways. 250 prior estimates drawn from the prior distribution (top left, blue), 250 accepted parameter values for each roadway (red), and 250 predicted estimates drawn from posterior distributions for Roman roadways across the Roman empire (bottom right, green). Median posterior estimates for the rate of incline from the minimum influence of topographic constraints (parameter *b*) shown in brackets

Discussion

The first conclusion we can draw from the results is that the influence of topographic constraints varied across Roman roadways in Wales. Roadways did not conform to a single, unifying principle of straightness but were flexible to the influence of topographic constraints.

The results also show that the majority of roadways in Wales were shallow enough for both traversal when on foot and using a wheeled vehicle. Roman roadways traversable by foot and wheeled vehicles facilitated the movement of armies and their supplies, essential for the conquest and consolidation of the region[28]. Roadways in Wales were however steeper than roadways in Britain, likely reflecting the more mountainous terrain of Wales and its greater influence on the position of roadways. The influence of the terrain on the steepness of roadways is further corroborated by Roman roadways in Scotland also being steeper than roadways in Britain. Nonetheless, the position of roadways in Wales is shown to have been preferentially chosen to minimise the frequency of steep slope gradients, reducing the difficulty of traversal compared to when hiking off-road. The desire to minimise the frequency of steep slope gradients, or 'lost descent', along roadways has been noted previously in Roman Cyprus, also a mountainous region of the Roman empire[30].

The majority of roadways across the Roman empire are likewise estimated to have been traversable by foot. Nearly half of roadways are however estimated to have presented difficulties when using a wheeled vehicle. A number of approaches are known to have been used to ease this difficulty, including the use of steps[6]. The presence of wheel ruts on steps[40] for example indicates that steep roadways were used by wheeled vehicles, despite the difficulty.

Like Wales, Roman roadways in other regions of the Roman empire were pivotal for its initial expansion, consolidation, and political and socio-economic integration. Roadways shallow enough to accommodate wheeled vehicles for example facilitated the political integration of elites during the rise of Rome[41,42]. Throughout the Roman empire, roadways also influenced the founding of new towns and cities, amplified the flow of goods, materials and people, and integrated local communities and their economies into the wider Roman world[43].

Materials and Methods

Roman roadways in Wales

The position of 62 known Roman roadways and Roman garrison posts in Wales (**Extended Data Fig. 4**) were digitised from '*Roman frontiers in Wales and the Marches*'[28].

Hierarchical Movement Model

The influence of topographic constraints on the position of 62 Roman roadways was estimated using a Bayesian hierarchical movement model. This influence was modelled as the reciprocal of an exponential function defined as follows

$$TC_i \sim \frac{1}{\exp\left(-b_i * abs(x + 0.05)\right)}$$

$$b_i \sim TruncNorm(\bar{b}, \sigma)$$

$$\bar{b} \sim TruncNorm(1, 10)$$

$$\sigma \sim Exponential(1)$$

where TC_i is the influence of topographic constraints on the position of individual Roman roadway i in Roman Wales, b_i is the rate of incline from the minimum influence of topographic constraints, $\bar{b}$ is the rate of incline from the minimum influence of topographic constraints on the position of Roman roadways across the Roman empire, and σ is the standard deviation for the rate of incline from the minimum influence of topographic constraints on the position of Roman roadways across the Roman empire.

Priors are weakly informative and informed by realistic ranges. For example, restricting b_i to positive-only values ensures that the influence of topographic constraints on the position of roadways cannot decrease with increasing slope gradient. To establish the robustness of the hierarchical movement model, a dataset of comparable sample size (n = 62) was simulated. The model was able to correctly estimate the majority of parameters within the 95% credible interval (**Extended Data Fig. 5**).

Least-cost path calculation

250,000 b_i parameter values drawn from $\bar{b}$ and σ were used to calculate 250,000 TC_i. Each TC_i was used to calculate 250,000 least-cost paths for each Roman roadway (15,500,000 least-cost paths in total). Least-cost paths represent the optimal path between two locations using a raster surface that quantifies the cost of traversing from one cell to another[44]. The topography of Wales was represented by the Ordnance Survey 50 metre Digital Elevation Model[45]. Least-cost paths were calculated using the *leastcostpath* R package[46].

Parameter inference

b_i, $\bar{b}$, and σ parameter values for each of the 62 Roman roadways were estimated using Approximate Bayesian Computation[47]. Posterior distributions were estimated by accepting 250 (0.1%) parameter values with the lowest Path Deviation Index value[48]. The Path Deviation Index quantifies the deviation between each least-cost path and its associated Roman roadway. Path deviation index is defined as follows

$$path\ deviation\ index = \frac{area\ between\ two\ paths}{Elucidean\ idstance\ of\ the\ shortest\ path}$$

Extended Data Figures

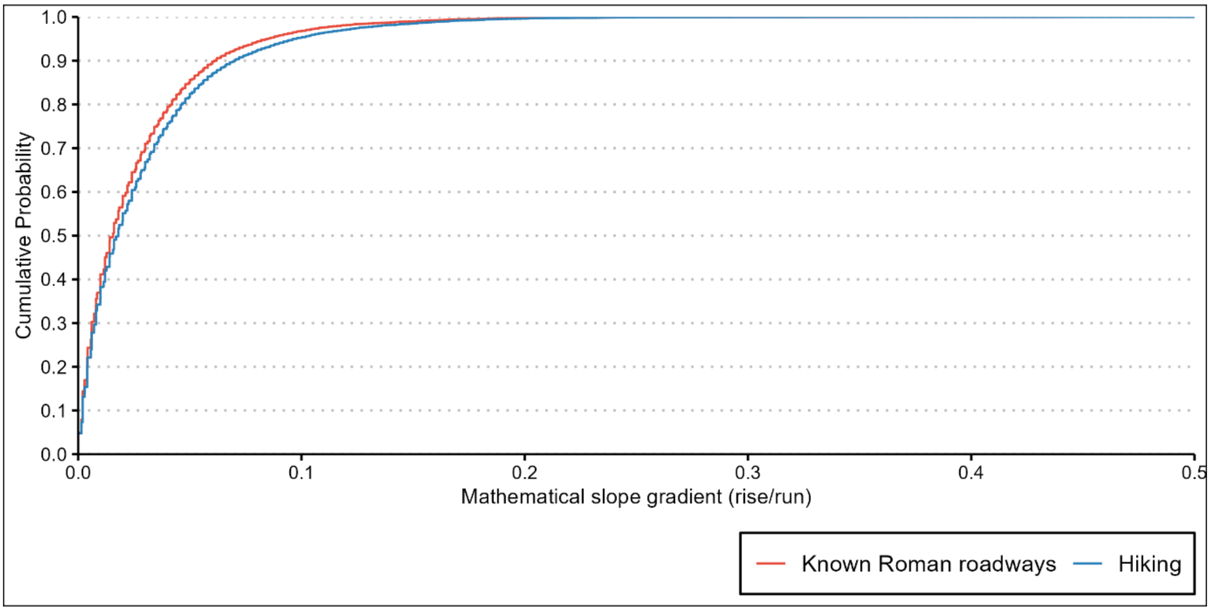

Fig.1. Probability of mathematical slope gradients for Roman roadways and while hiking

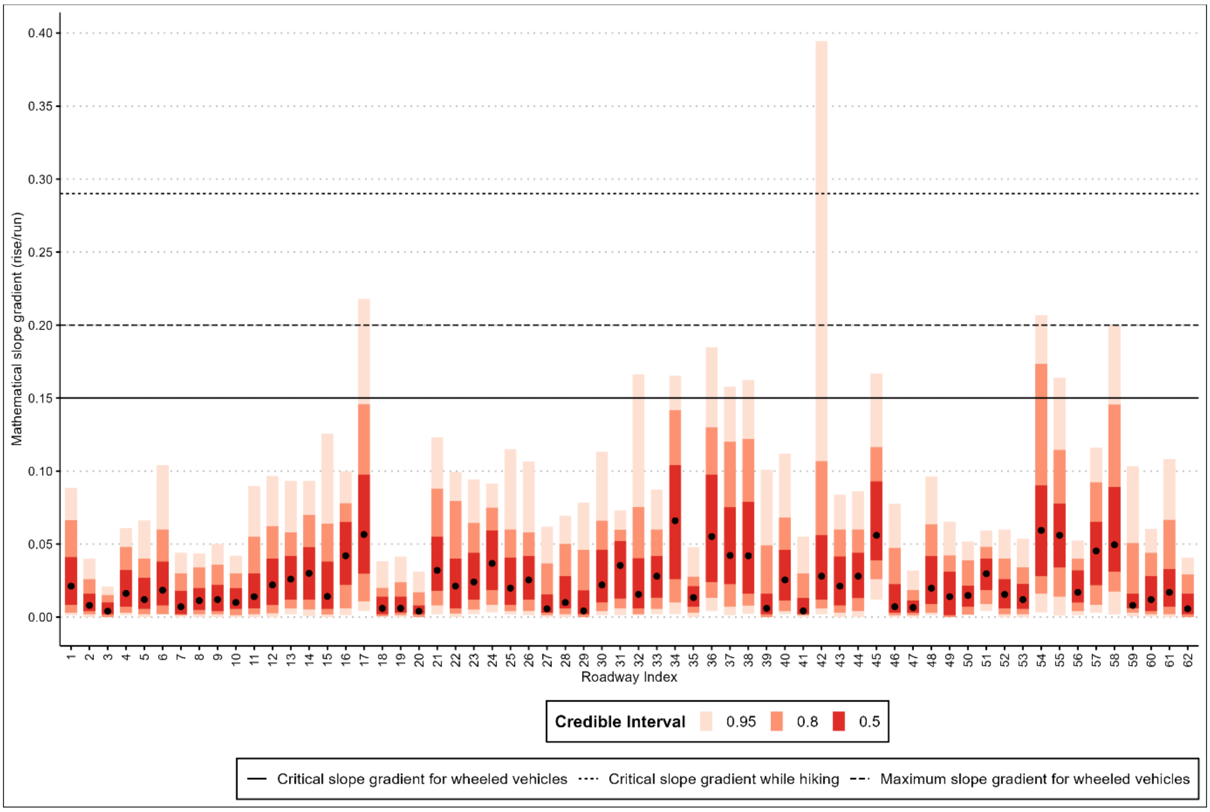

Fig.2. Mathematical slope gradients for Roman roadways in Wales

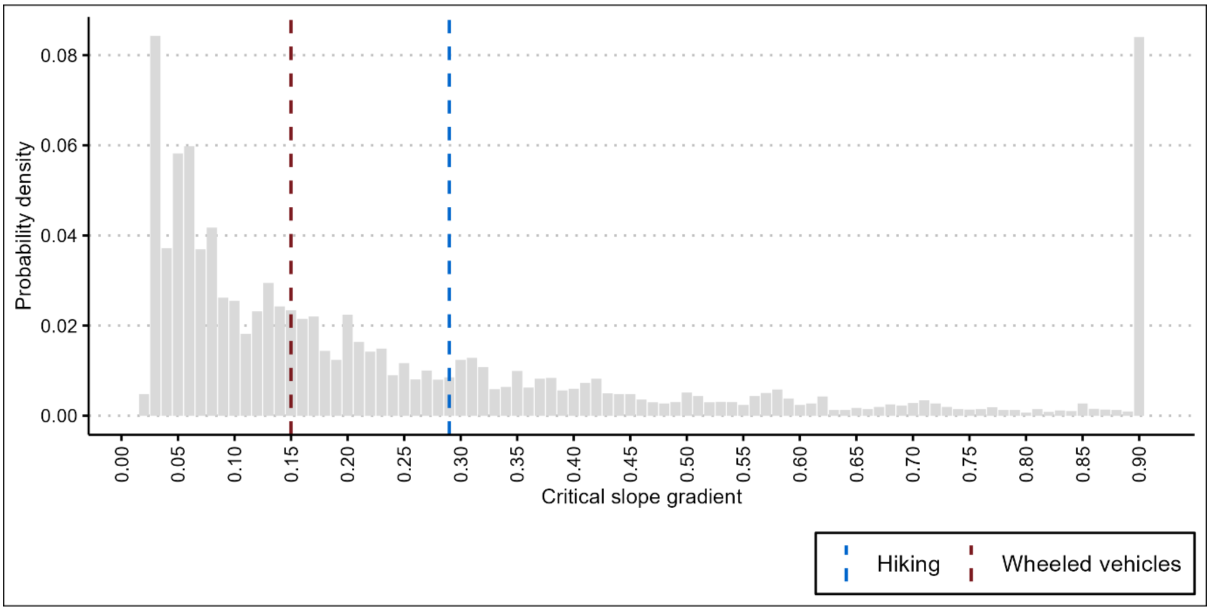

Fig.3. Critical slope gradient for Roman roadways across the Roman Empire

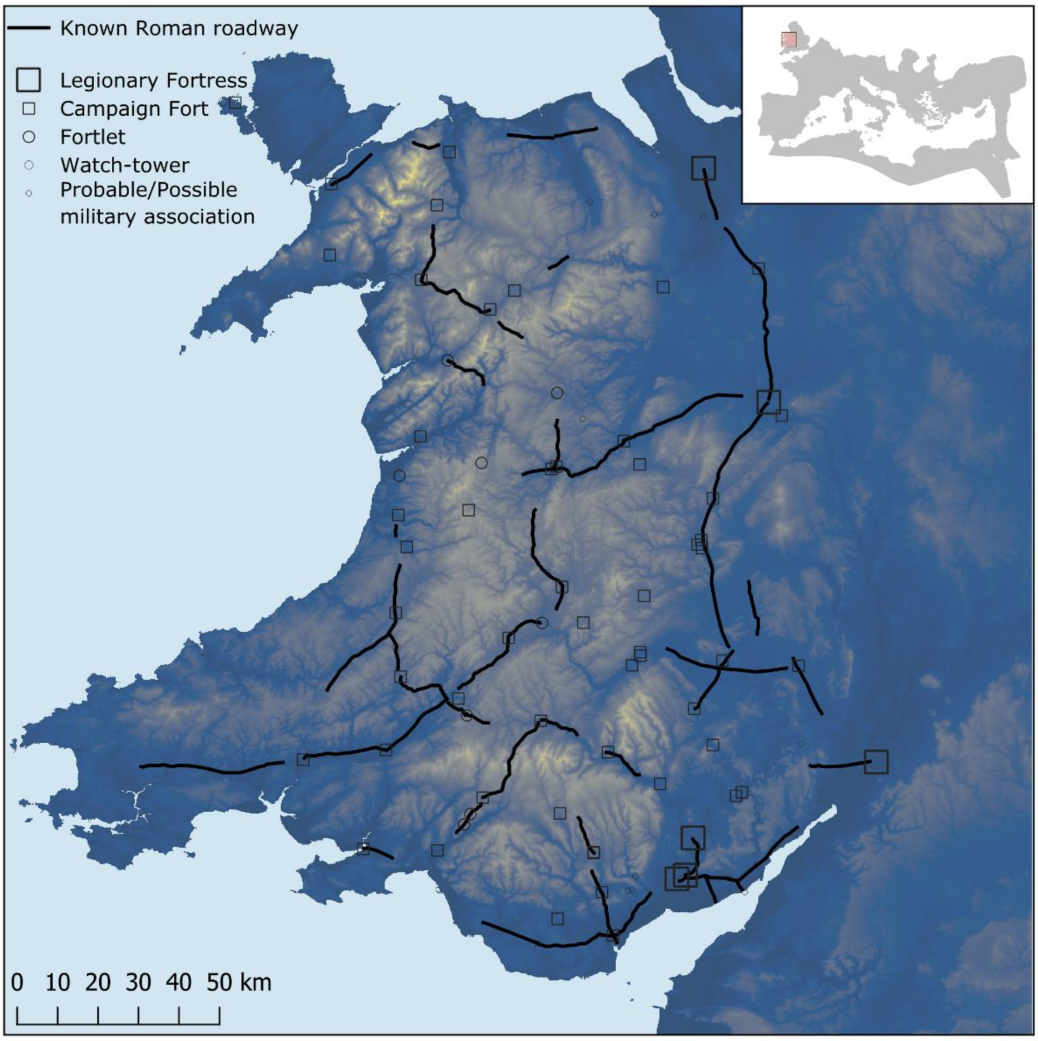

Fig.4. Map of study area. Roman roadways (n = 62) used for analyses and locations of Roman garrison posts

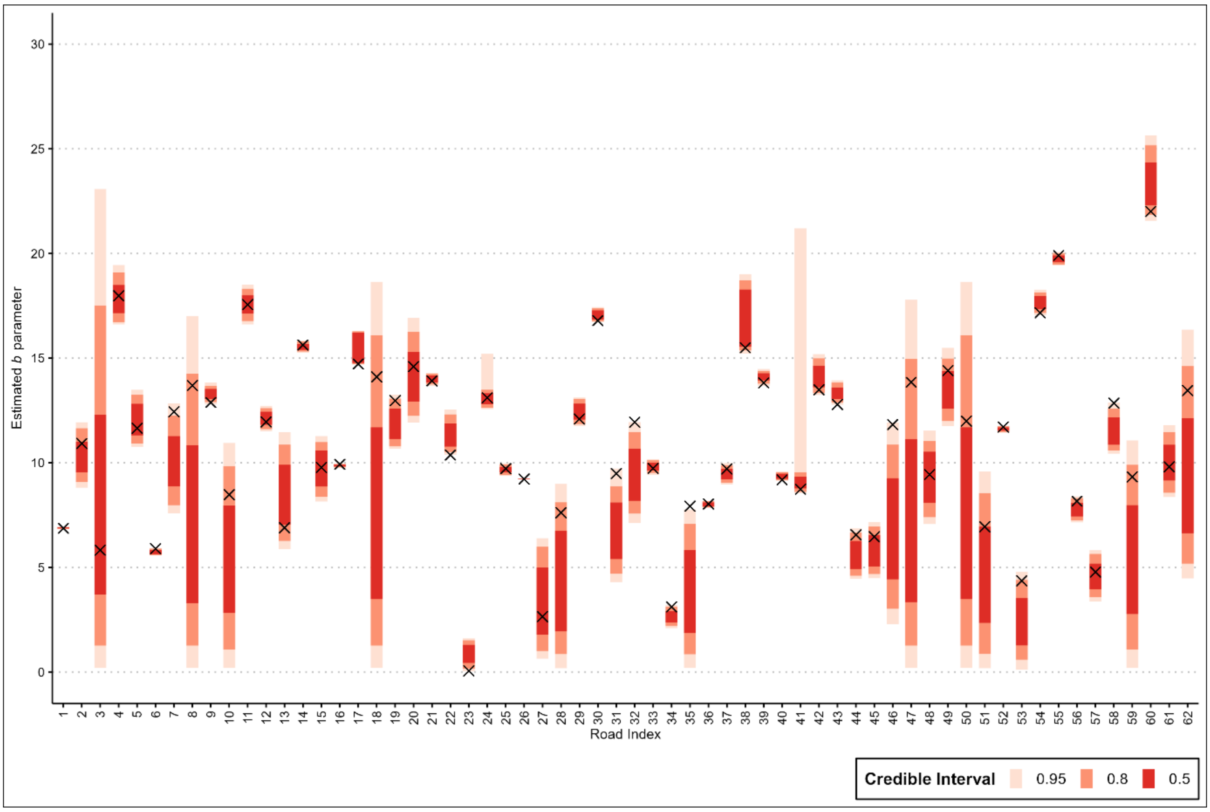

Fig.5. Estimated influence of topographic constraints on the position of simulated routes. known rate of incline from the minimum influence of topographic constraints (parameter b_i) shown with a cross

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