



# Remote Sensing and GIS Modelling of Roman Roads in South West Britain

CASE STUDY

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## ABSTRACT

The recent availability of a systematic airborne LiDAR coverage for England in the scope of the Environment Agency's 'National LiDAR Programme' has enabled the mapping of a new Roman road network system in South West Britain, an area where there was little solid evidence for a system of long-distance roads. To understand the rationale behind their construction, a GIS spatial analysis approach to model movement was developed, which included not just straightforward Least Cost Paths, but also other methods, such as MADDO and CMTC, to overcome some of the common limitations of Least Cost Paths and produce a more reliable prediction of the likely layout of the Roman road network in the area. The results indicate that this network privileged the movement of animal-drawn wheel vehicles, avoiding where possible areas subject to flooding risks. This road network is possibly the result of an evolutionary model, integrating pre-existing Prehistoric routeways with Roman military and civilian roads, most of which were probably still in use in Medieval times.

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## KEYWORDS:

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# 1. INTRODUCTION

This paper aims to demonstrate the presence of an extensive and coherent road network of probable Roman date in South West Britain and to reveal its most probable layout using a combination of mapping from LiDAR data and GIS spatial analysis. As will be shown, our GIS modelling complements the most obvious use of straightforward Least Cost Paths with a creative use of two additional methods, MADO (Focal Mobility Networks, Fábrega-Álvarez 2006; Llobera et al. 2011) and CMTC (Conditional Minimum Transit Corridors, Pinto & Keitt 2009), to overcome some of the common limitations of Least Cost Paths.

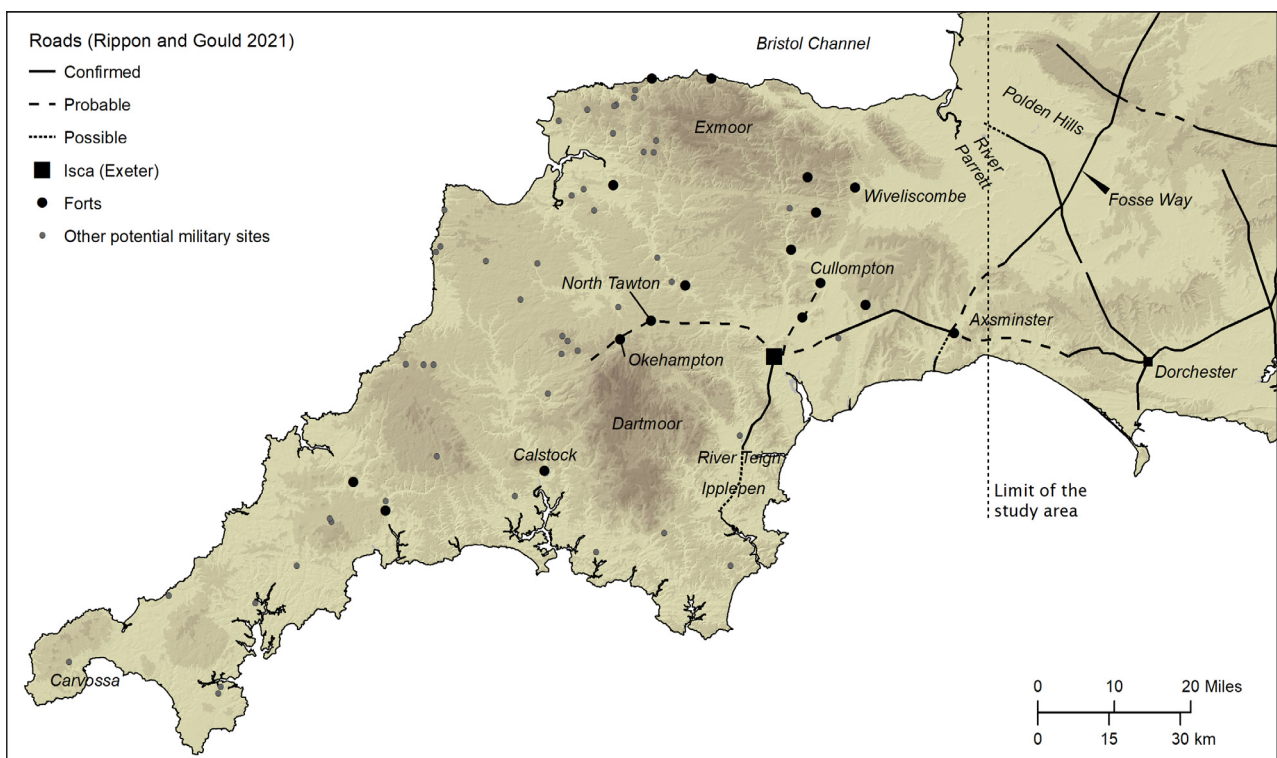
The purpose of this is to, first, show that the counties of Devon and Cornwall as well as western parts of Somerset developed infrastructure in the Roman period that connected them with the wider province of *Britannia*. Second, to illustrate how the phased approach taken to mapping of LiDAR anomalies, along with the GIS spatial analysis, enabled mutual corroboration of the proposals made. And third, it aims to describe a combination of modelling methods that can be applied to the modelling of networks of paths in other contexts.

The recent availability of seamless LiDAR coverage for Britain, collected as part of the Environment Agency’s ‘National LiDAR Programme’ and made available via the DEFRA Data Services Platform,<sup>1</sup> has provided the means to transform our understanding of the Roman road network that developed within the province, and nowhere more so than in the far south western counties, in the territory

of the *Dumnonii*. Despite more than seventy years of scholarship, published maps of the Roman road network in southern Britain (Figure 1) have remained largely unchanged and all are consistent in showing that west of Exeter, Roman *Isca*, there was little solid evidence for a system of long-distance roads (for a recent review see Rippon and Gould 2021, 50–53, Figure 3.4 and 3.5).

# 2. THE ROMAN ROADS OF SOUTH WEST BRITAIN

In what remains the most definitive volume on the subject, Ivan Margary’s ‘Roman Roads in Britain’ (1967), it is shown that a principal road linked Exeter with Dorchester, with the Fosse Way connecting to this road near Axminster. Communication with the Bristol Channel, via ports on the River Parrett, was enabled by a road branching from the Fosse Way and running along the south side of the Polden Ridge. Beyond Exeter, a road to the south around the east side of Dartmoor, was attested by ground observations in the 1950s (Woolner and Woolner 1954), but had not been followed further than the River Teign at modern-day Newton Abbot. To the west of Exeter, a route to the north of Dartmoor, was proposed as far as North Tawton, where an extensive complex of Roman activity is found, beginning in the military period (c. AD 50–85) (Rivet 1953; Smart and Fonte *in prep.*). The character and construction of that road has been confirmed through its recording where it is



**Figure 1** Study area, showing the location of the Roman roads known or hypothesized before the beginning of this study, alongside Roman towns, forts and other potential military sites. Places mentioned in the text are also shown.

cut by the Den Brook, first in 1992 (Salvatore and Knight 1991) and subsequently in 2012 (Brennan and Leivers 2013), and it was shown to comprise a c. 5 m to 7 m-wide stone *agger* with flanking ditches. Other roads have been proposed, predominantly based on the alignments of historical roads along logical topographic routes (e.g. Margary 1967, map 3), but while these were recently reviewed by Rippon and Gould as part of the ‘Exeter: A Place in Time project’ (2021) they remain speculative.

Roads within Roman-period sites, military and civilian, have been excavated in a number of places, for instance:

- a road exiting the west gate of the 1<sup>st</sup>-century auxiliary fort at Calstock, Cornwall (Smart 2014),
- a similar one exiting the east gate of the fort at Okehampton, Devon (Rainbird and Caine, forthcoming),
- a road running through the long-lived Iron Age to early medieval settlement at Ipplepen, Devon (Rippon, forthcoming),
- and one within the enclosed settlement at Carvossa, in West Cornwall (Douch and Beard 1970).

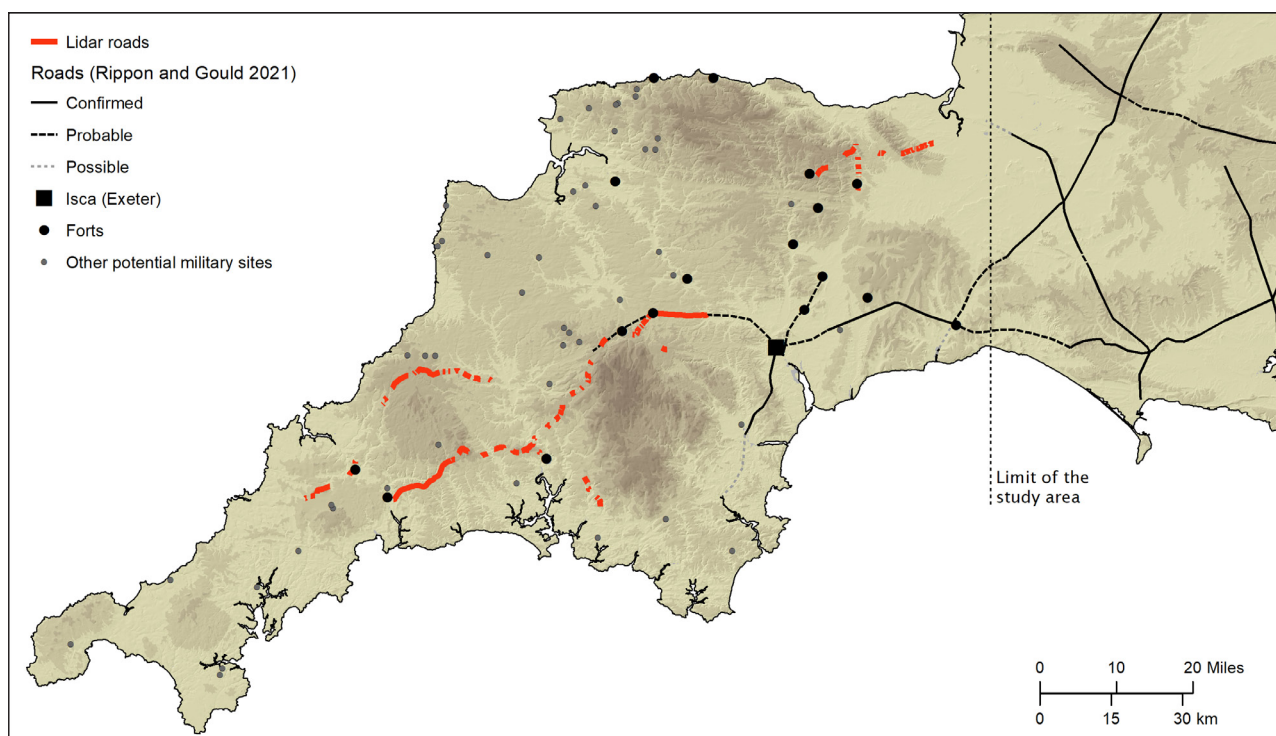
However, no long-distance routes running through open country have been confirmed through excavation. Despite what follows here, this remains the case.

In the past decade, an increased availability and use of open-source LiDAR data has provided researchers a new means by which to prospect for traces of lost roads, and in South West Britain its early use enabled a better understanding of the Exeter – North Tawton road, and mapping of it for an additional six km almost as far as

Okehampton (Salvatore *et al.* 2019). North of Exeter, discontinuous earthwork remains indicated a road running through the Culm and Exe Valleys, toward Exmoor and the coastline in West Somerset (Devon Monument MDV 125780, 124645, Somerset Monument 39966) variously mapped by Steve Kaye, Bryn Gethin and the late Hugh Toller. This route, at least superficially, appears to link Exeter with the Roman auxiliary forts at Cullompton and Wiveliscombe, and beyond, perhaps to iron-rich districts, coastal ports, and South Wales via the Bristol Channel/ Severn Estuary nexus. These additions to the Roman road network take us as far as 2019, with the most recent published map integrating these observations appearing in 2021 (Rippon and Gould 2021, Figure 3.5).

### 3. REMOTE SENSING OF ROMAN ROADS IN SOUTH WEST BRITAIN

Between 2019 and 2022, the UK Environment Agency completed seamless coverage of LiDAR data for South West Britain as part of the National LiDAR Programme, made freely available under Open Government Licence. Before this date, LiDAR data existed but was patchy in extent, covering only ca. 11% of the study area. Smart and Fonte, leading a team of public volunteers as part of two National Lottery Heritage Fund projects ‘Understanding Landscapes’ and ‘Unlocking Landscapes’ as well as independent research by Steve Kaye and Mike Haken, have now mapped an additional c. 100 km of probable Roman roads over the whole study area (Figure 2).



**Figure 2** New sections of Roman roads in South West Britain identified through the 2022 National LiDAR Programme data, which covers the whole study area.

The one-meter Digital Terrain Model (DTM) tiles from the Environment Agency National LiDAR Programme<sup>2</sup> were used for the mapping of Roman roads in South West Britain.<sup>3</sup> Systematic coverage is available for the whole of England. From the mosaicked DTM tiles, a local relief model (LRM) (Hesse 2010) was generated using planlauf/TERRAIN software to enhance the visualization of the Roman roads earthworks, in particular the associated *agger* and quarry pits (Figure 3). The mapping of Roman roads was done manually through systematic visual inspection of the LiDAR-derived terrain models in a GIS environment (ArcGIS Desktop 10.8.1).

#### 4. A FIRST APPROACH TO A PREDICTIVE MODEL FOR THE NETWORK OF ROMAN ROADS

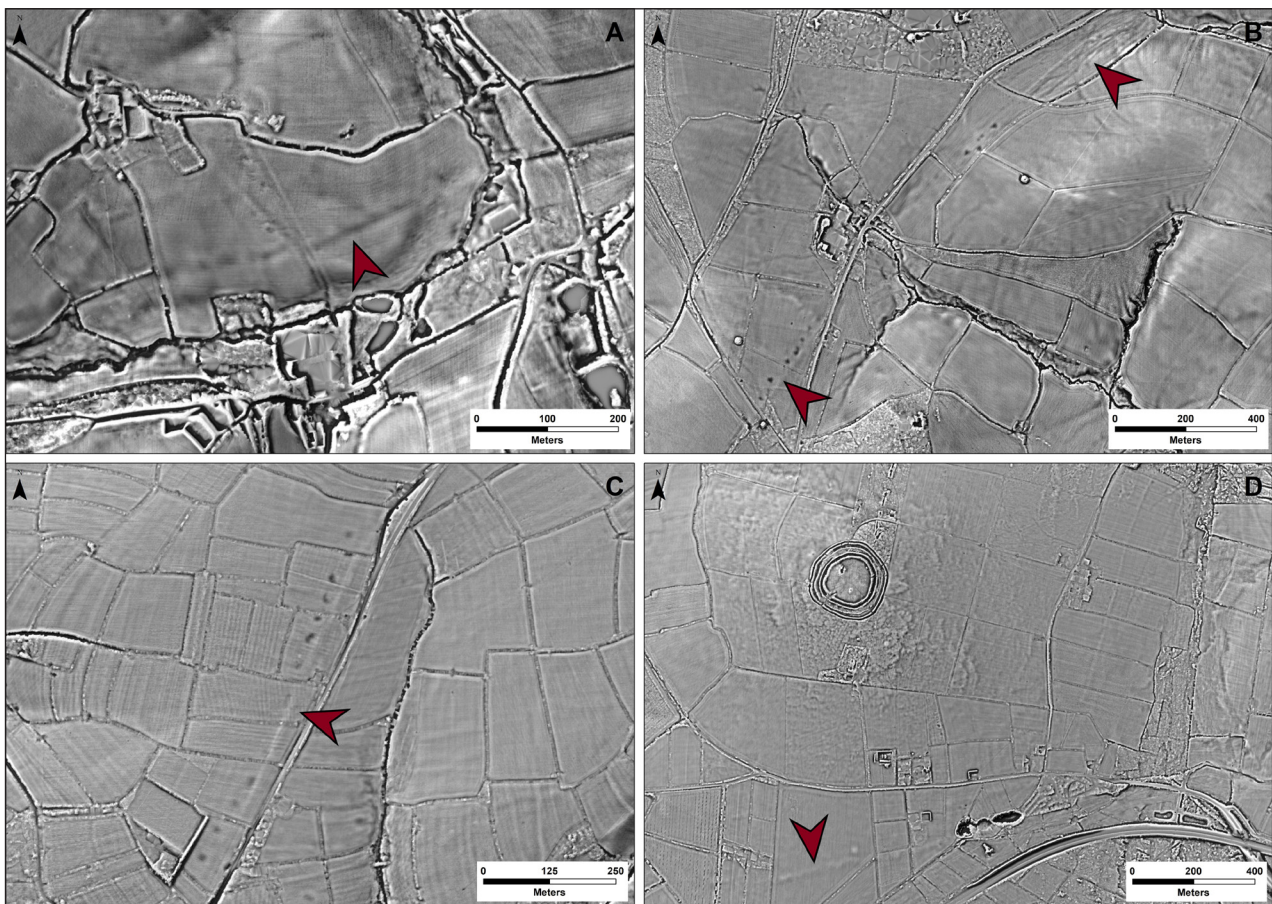
Although this is a significant advance with respect to the previous state of the art, there still remain large portions of the area with no evidence of Roman roads and the picture is still fragmentary and patchy. In order to complete the map, we proposed to develop a GIS-based predictive model of the likely layout of the road network, aimed also at providing a baseline to guide

future attempts at detecting new traces both through remote sensing and in the field.

##### 4.1. DATA PREPARATION: DTM

The Ordnance Survey (OS) 5-meter DTM (OS Terrain 5) was used as a topographic base for the GIS modelling.<sup>4</sup> The tiles were downloaded and mosaicked in order to build a single DTM for the entire Southwest England region. This DTM was then resampled to a 25-meter spatial resolution. The main modern roads were still visible in this DTM, something that can influence the outcome of the analysis in those areas (e.g. Verhagen and Jeneson, 2012; Herzog, 2021). It actually did, as proved by some tests we made. It was then decided that a refined DTM should be produced, one that would blur those topographic alterations. After testing various methods, the one that best worked was:

1. Extracting the shapefile of the routes of the A30 and A38 in Devon and Cornwall from the OS Open Roads dataset;<sup>5</sup>
2. Extending them (buffer) to cover an area that would include (and exceed a bit) all the terrain modified by the road (50 m to each side of the centre of the road, 100 m in total);



**Figure 3** Examples of segments of Roman roads identified from the LiDAR-derived terrain models provided by Environment Agency's 'National LiDAR Programme'.

3. Clipping the pixels in the DEM inside this area;
4. Producing a contour map for the remaining DEM (that is, the original DEM without the buffered area around the roads);
5. Interpolating a new DEM for the whole area based on those contours (using Topo to Raster tool in ArcGIS);
6. Figure 4 shows a comparison of the original and final DEM in three random sectors (the motorways always run across the centre of the maps).

As can be seen, the scars of the motorway are no longer there. As a side effect, the new topography is less detailed and more blurred, although it retains the basic forms of the terrain (similarly to previous approaches, such as Verhagen and Jensen, 2012). The accuracy of the new topography was measured using 100 points randomly extracted from the original LiDAR point cloud data.

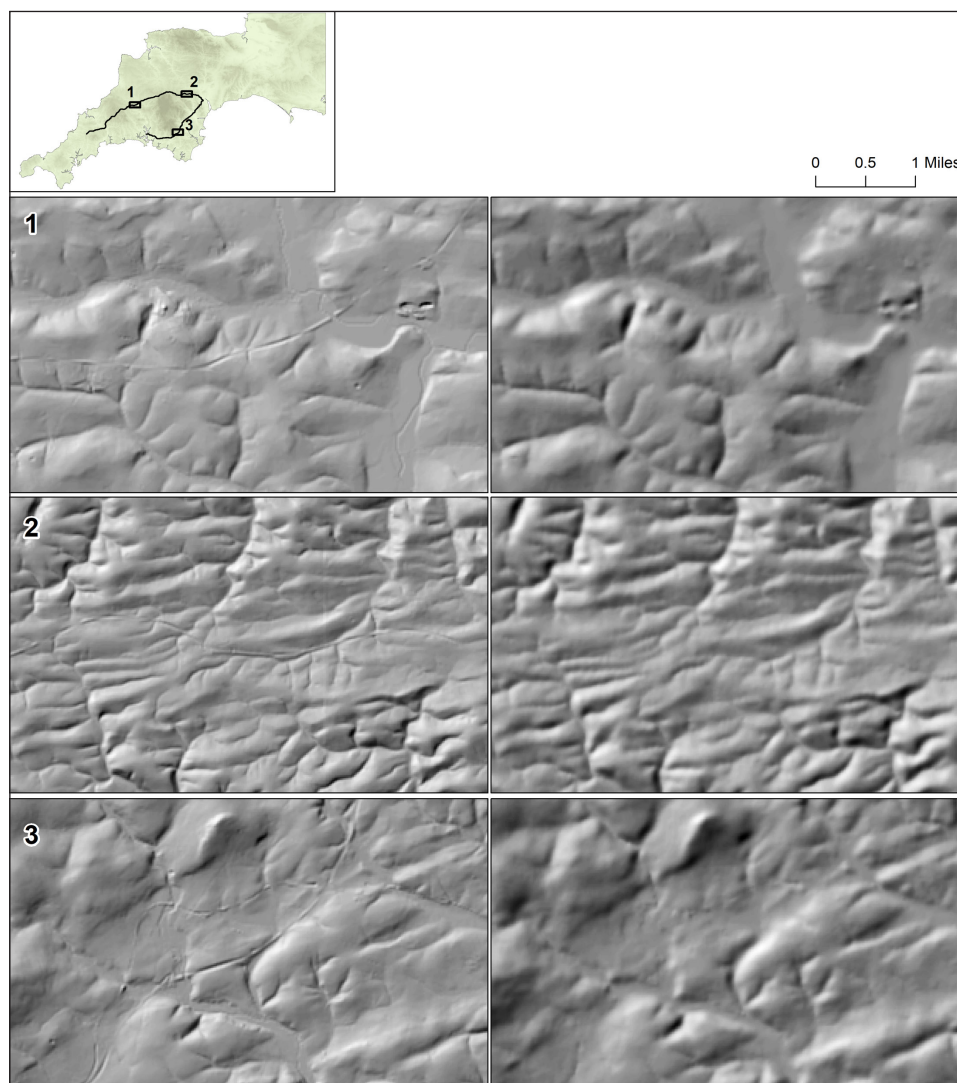
- RMSE: 3.38 m.
- Mean absolute error: 2.21 m.
- SD absolute error: 2.55 m.

#### 4.2. GIS MODELLING: THE STRAIGHTFORWARD APPROACH

Digital modelling of movement involves different approaches, methods, and tools (Verhagen et al., 2019; Herzog, 2020, 2021). In this case, where the objective is to predict the most probable route of largely unknown ancient roads, the most obvious approach is using so-called Least Cost Paths (LCPs onwards). LCPs are the optimal connections between two or more points, under some predefined circumstances. LCPs are calculated with two basic inputs:

1. The location of the points that are to be connected (nodes onwards);
2. The criteria that were considered when those paths were established.

In archaeology, typically we only have educated guesses about both criteria. The first is usually less problematic, since we might know what places are to be connected. In our case, this would imply knowing, or guessing, what



**Figure 4** Comparison of original (left) and refined DEM for three sectors, showing how the routes of modern motorways have been smoothed out.

were the main Roman settlements in the region, around which the network of Roads was established.

The second point is far less obvious. There are many examples in the literature addressing this issue for Roman roads elsewhere in Europe (Bödöcs, 2011; Carreras and de Soto, 2013; Fonte et al., 2017; Güimil-Fariña and Parcero-Oubiña, 2015; Lewis, 2021; Parcero-Oubiña et al., 2019; Verbrugge et al., 2017). Two main issues need to be considered here: first, what factors (physical and/or cultural) will be considered as affecting the decisions behind the layout of the roads. Second, how these factors can be quantified.

In the following sections we will describe the decisions taken with respect to these two points.

#### 4.2.1. Nodes of the network

The network was divided into primary and secondary nodes (Figure 5). A primary node is one that precedes the construction of the network, a place that is to be connected with other equivalent primary nodes. Exeter and North Tawton were considered as primary nodes since they are the main Roman settlements currently known in Southwest England. North Tawton is quite close to Exeter, which might limit a bit the usefulness of this second primary node. Despite this proximity, North Tawton is located in a position that is geographically more central than Exeter, and this is interesting since its position might suggest that it acted as the basic organizer of internal mobility in this region.

In addition to Exeter and North Tawton, Roman permanent military fortifications (not temporary camps), including the known forts and the fortlets of Old Burrow and The Beacon, Martinhoe (Symonds, 2018), constitute the most obvious candidates to be considered as relevant nodes in the network, assuming that these permanent military sites were linked by the Roman road system. In order to simplify the analysis, we checked to what extent all these fortifications should be considered as equally relevant inputs, since some of them might be located along LCPs connecting other sites. This was done by connecting the two main nodes of the area (Exeter and North Tawton) and those fortifications located further away from them (connections were done with the cost factors detailed in the next section). Some sites happened to be indeed located along those long-distance paths, so they were considered secondary nodes for the purpose of this analysis and removed from this first step. The fortifications at Ide and Stoke Hill were also excluded due to their close proximity to Exeter.

#### 4.2.2. Criteria considered for the construction of the network

There are many different forms of digitally modelling human movement across the landscape, of predicting how people would move and following what routes. Most of them are based on measuring the effect of terrain slope in human movement. The measure of that effect is made through different cost functions, which transform

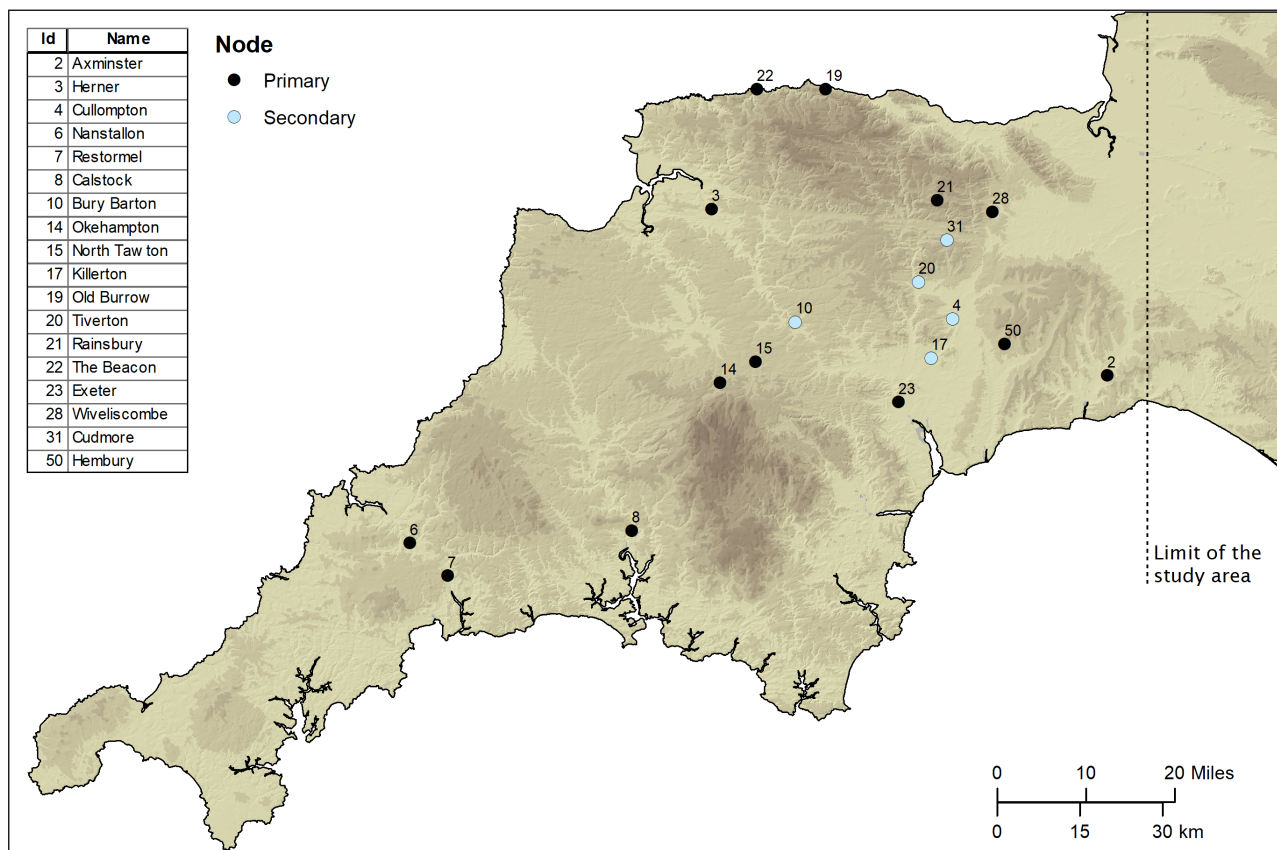


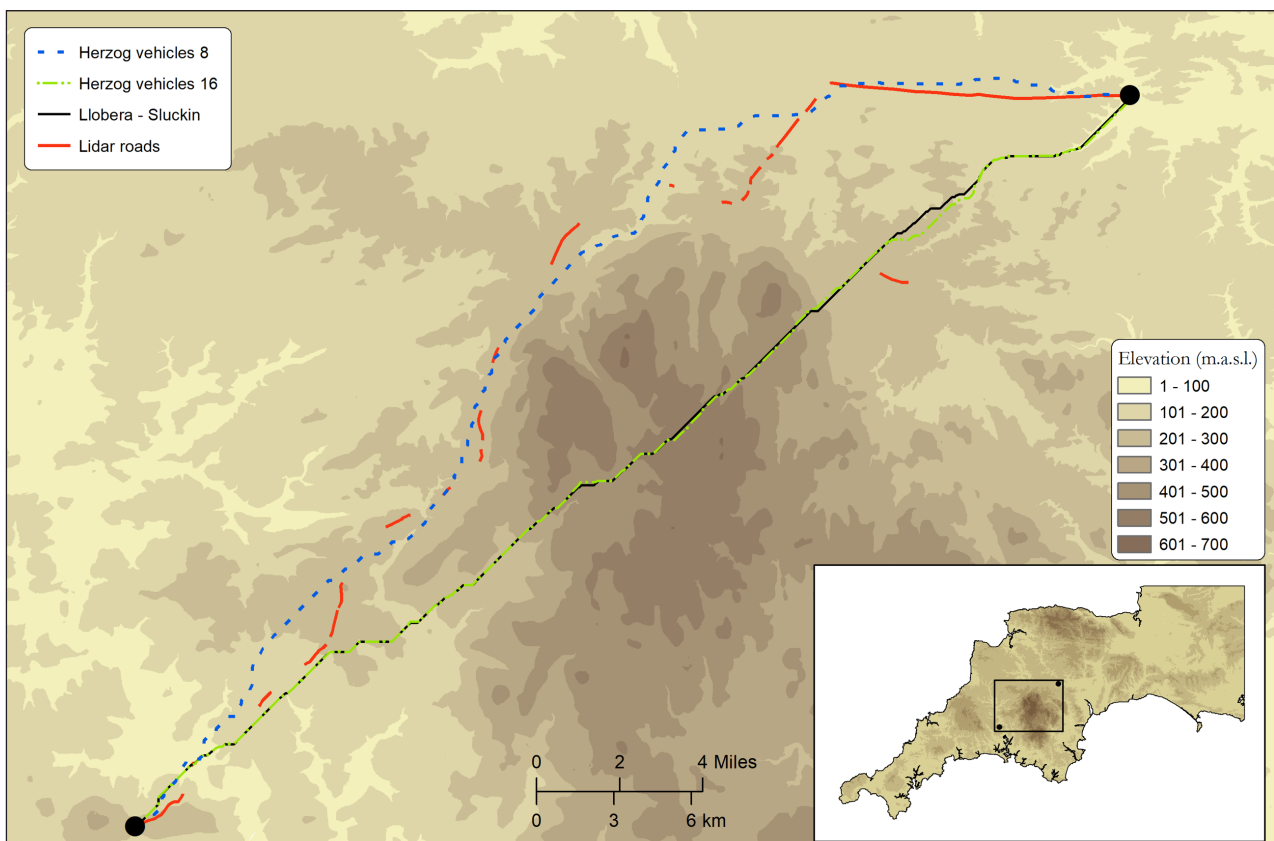
Figure 5 Primary and secondary nodes in the study area.

terrain slope (something we can directly measure) into movement costs (something we cannot). In most cases, there are no big differences in the outcomes of those different functions, but that is not always the case (e.g., Herzog 2013, 2014, 2021; Kantner 2012; Güimil-Fariña and Parcero-Oubiña, 2015). It depends basically on (a) the topography of the area and (b) the type of movement to be modelled (e.g., human pedestrian vs. wheeled vehicles).

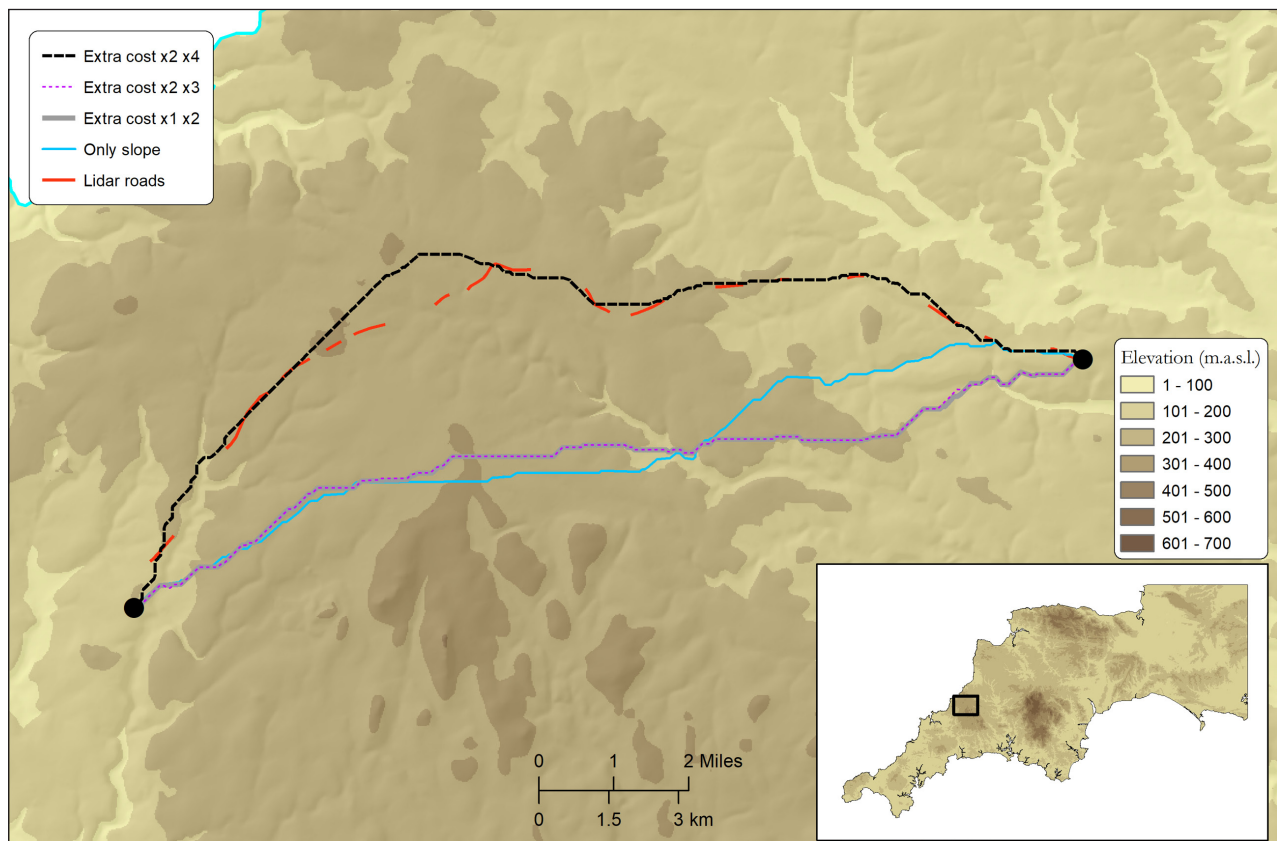
One typical procedure to justify the selection is to test different cost functions in an area where positive evidence exists of the routes we want to model. In our case, we have used some of the newly LiDAR mapped sections of Roman roads as a training area. Here, different cost functions were tested to see which one better matched the documented layout of the Roman roads. Basically, we considered cost functions designed for pedestrian movement (by Llobera and Sluckin, 2007, that has given good results in Northwest Iberia: Güimil-Fariña and Parcero-Oubiña, 2015; Fonte et al., 2017; Parcero-Oubiña et al., 2019), and for animal-drawn vehicles (proposed by Herzog, 2013). The one that better matched the layout of the Roman roads is Herzog's, with a critical slope of 8, so we decided to proceed with this one (Figure 6). Although the goodness of fit between two linear features can be quantified in different ways (e.g. Goodchild and Hunter 1997), we believe that in this particular case the difference is obvious enough just on visual inspection. It is worth mentioning that this function is isotropic, direction of movement is not relevant, meaning

that the least-cost path from origin to destination will be the same as from destination to origin.

Despite the generally good agreement that was obtained, there remained some sectors where a difference still existed between the modelled routes and the actual roads (Figure 7). This suggested that some other factors could be influencing the layout of the roads. In this particular region, where rivers extend almost from coast to coast, we thought of riverine/estuarine flooding as a potentially relevant factor due to its influence on where rivers had to be crossed by roads. To test its influence on theoretical mobility, the British Geological Survey database of geological indicators of flooding<sup>6</sup> was used. It includes two types of flooding risks: river and coastal, and two levels of risk: higher and lower. The relevant field is the level of risk, so different costs were tested to areas with lower and higher risks, using the same procedure of selecting a test area where slope-based costs produced routes that did not match the known roads. Eventually,  $\times 2$  costs for lower potential areas and  $\times 4$  for higher potential areas were used. Note that these are extra costs, on top of those of the slope. This means that the cost of movement caused by the slope increases by a factor of 2 in areas of lower flooding potential and 4 in those of higher potential. The results show some improvements in the similarity between the theoretical paths and the actual sections of Roman roads (Figure 7). This suggests that this weighting ( $\times 2$  and  $\times 4$ ) works well in modelling the influence of flooding areas in the layout of Roman roads in this particular area.



**Figure 6** Comparison of the outcomes of different cost functions in an area where direct evidence of Roman roads is known.



**Figure 7** Comparison of LCPs with and without considering flooding areas as extra costs, with different weightings tested for low and high potential flooding areas. Note how only  $\times 2$  and  $\times 4$  values produce a significant modification (higher extra costs, not shown here, do not add any further difference).

#### 4.2.3. Creating a network

The obvious first step of our analysis was connecting all the primary nodes with LCP. In doing so, not all the potential connections between pairs of points were used: we assumed that the underlying logic of this road network is connecting the area with two central nodes (Exeter and North Tawton), instead of directly connecting all Roman forts with each other, so those connections that did not follow this “radial” logic were discarded. As can be seen and was already explained, all the “secondary” forts are located along paths connecting other pairs of forts (Figure 8).<sup>7</sup>

This gives us a first approach to a predictive model of the layout of the Roman road network in this area, but it is still too schematic. Besides that, this approach has all the shortcomings related with the exclusive use of LCP:

1. It only considers the first best route between two points, while in many cases the second or third might be as good alternatives as the first;
2. It is based only on directly connecting pairs of points, which impedes the identification of potential junctions;
3. It stops at the limit of the input nodes, which leaves a substantial portion of the area out of consideration;
4. It gives a discrete prediction (routes as lines), without accounting for spatial imprecision.

In the following section we will describe the methods we devised to overcome these limitations and produce a far-reaching model.

## 5. OVERCOMING THE LIMITATIONS OF LEAST COST PATHS

### 5.1. EXTENDING BEYOND THE FIRST OPTIMAL PATH AND OVER THE WHOLE REGION

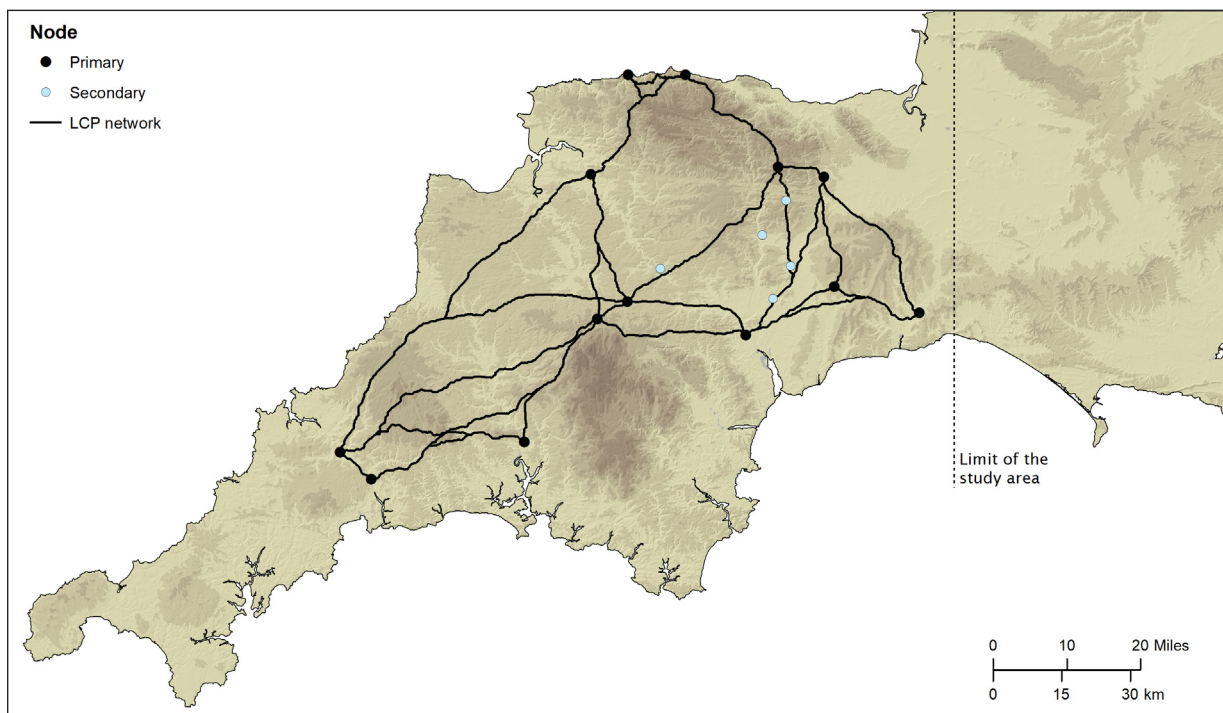
A first approach to address some of these shortcomings (in particular, one and three in the list above) was relying on MADO or Focal Mobility Networks (as in Parcero-Oubiña et al. 2019). This is a calculation that obtains all the naturally optimal routes approaching one single destination (Fábrega-Álvarez 2006; Llobera et al. 2011). The idea is to explore how movement extends beyond the current limits of our network using just one single criterion: following the naturally easiest corridors (for the specific conditions of movement that were chosen).

We used the MADO method (1) to extend the network beyond the known nodes (forts) and (2) to extract other alternate routes that complement the narrow limits of the LCP. Calculating the MADO for all forts will produce a massive number of potential paths, so we designed an alternate approach: we established an exclusive area

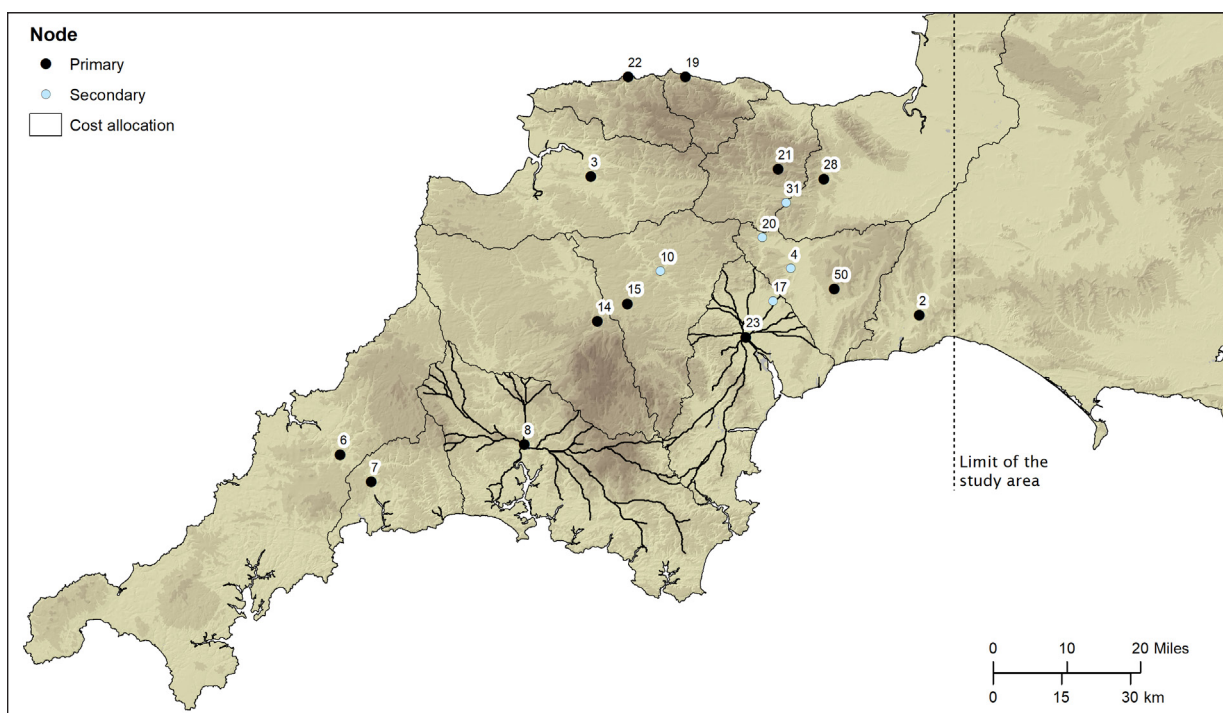


of influence for each node and used those polygons to clip the respective MADO paths (Figure 9). The area of influence was calculated with a cost allocation analysis that delineates the portion of terrain where mobility gravitates around each input node (the area where each node is more easily accessible than any other fort). Cost allocation was calculated with the same parameters used for the calculation of LCPs (i.e., slope and flooding risk).

After doing that, we selected those paths that (1) connected across two neighbour areas or extended towards the edges of the study area and (2) did not coincide with already existing LCPs (Figure 10). As was expected, we obtained in some cases more than one single connection between nodes, different potential alternatives to cross the study area. This is evident, for instance, in the area between nodes 8 and 23, among



**Figure 8** Network resulting from the direct connection (LCP) of all primary nodes. The location of secondary nodes (Roman forts not used in the calculation) is shown.



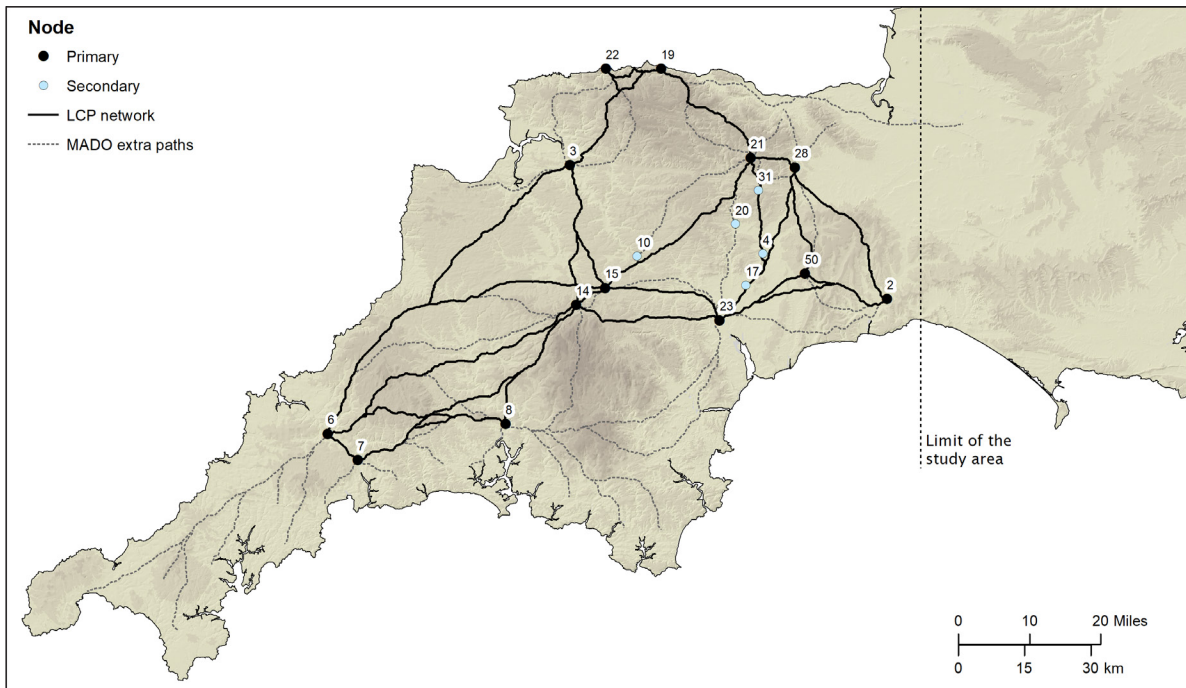
**Figure 9** Cost allocation polygons (areas of movement influence) for all primary nodes and example of MADO paths for nodes n. 8 and 23, showing paths that connect across the respective areas of influence.

others. Besides that, we were able to extend the network beyond the strict limits of the sector where the Roman sites are distributed. This is mostly visible towards the SW area, where the MADDO paths radiating from nodes n. 6 and 7 allow extending the network significantly.

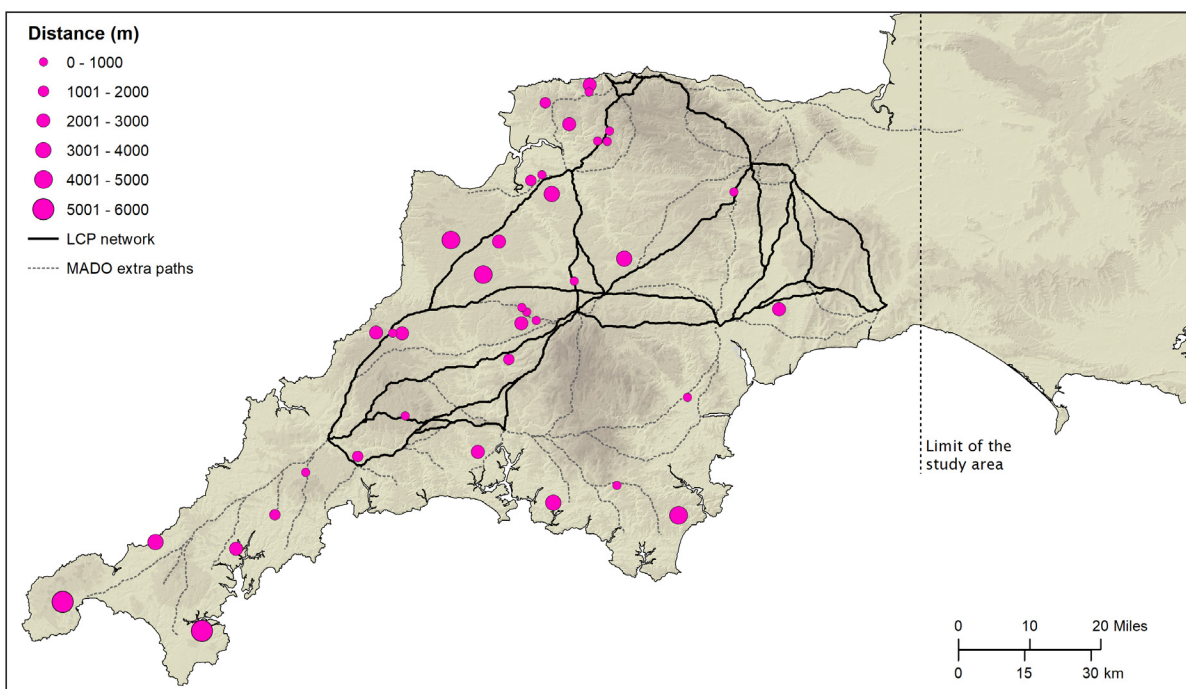
**5.2. ASSESSING THE RESULTS**

Some measurements to test the goodness of fit of this prediction when compared with the direct evidence available were performed. The first dataset used was the

other potential Roman military sites in the South West (n = 47), primarily mapped via remote sensing based on their morphology of earthwork. These earthworks have typical Roman geometry – square or rectangular, with straight sides and rounded corners – but of course might originate from a different time period or have a non-military function. The following map (Figure 11) shows these sites mapped as points whose size is proportional to the distance to the closest part of the network. As it can be seen, most of them, even the most distant ones



**Figure 10** Multiple LCPs connecting all primary nodes and radiating from them towards the limits of the study area.



**Figure 11** Distance of other possible Roman military sites to the network.

(e.g., sites at the SW), seem to be located in relation to the network, a visual impression that is reinforced by the measurement of the distances between the sites and the network (Table 1): almost all sites are located within six km from the network, and most significantly almost 50% of them within just two km.

Regarding the correspondence with the sections of roads documented with LiDAR, the following map already suggests a good match (Figure 12), that is again supported by the measurement of distances (Table 2): almost 90% of the known roads are within just 1.5 km of the modelled network, with almost 70% within just 500

DISTANCE TO NETWORK (m)	N. SITES	%
500	11	23.4
1,000	18	38.3
1,500	21	44.7
2,000	23	48.9
2,500	29	61.7
3,000	32	68.1
3,500	34	72.3
4,000	36	76.6
4,500	37	78.7
5,000	39	83.0
5,500	39	83.0
>6,000	47	100

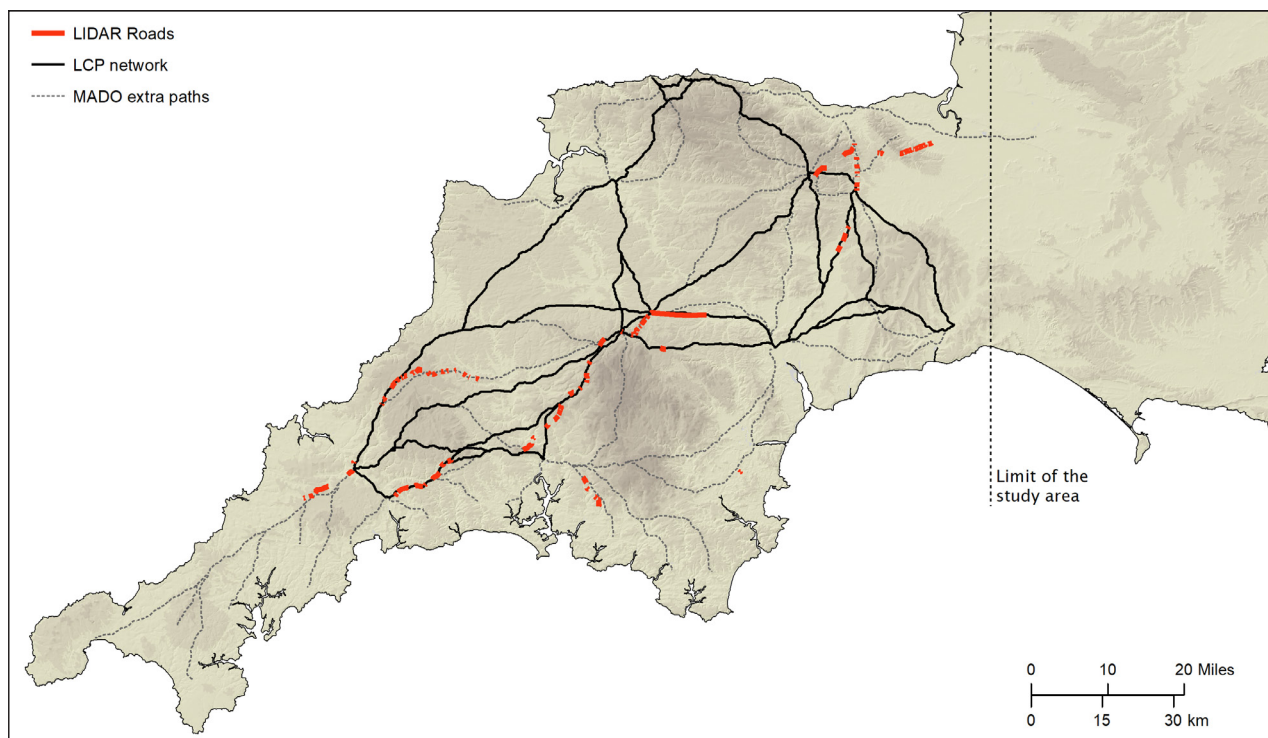
**Table 1** Distance of other Roman military sites to the network.

m. It must be noted that the section of roads extending NE of fort n. 28 (Wiveliscombe), where this particular analysis is most limited (a possible case of “border effect”, due to the terminal character of this fort within the study area), is responsible for most of the poorer values. This sector accounts for most of the 19% of the total roads that is beyond one km. It is worth noting how not all sections of LiDAR-derived roads correspond with LCPs between nodes and how the inclusion of MADO increases the similarity between the roads and the model.

While this looks like a good match, there is obviously a limit to the precision (i.e., level of detail) with which LCPs and MADO paths can represent the most likely route of actual roads. As was said, they give a discrete result (routes as lines), without accounting for spatial imprecision. A fuzzy approach would represent much better the practical utility of this modelling.

DISTANCE TO NETWORK (m)	% OF LIDAR ROADS
250	49.49
500	67.25
750	75.17
1,000	81.15
1,250	86.03
1,500	89.02
>1,500	100

**Table 2** Distance of known remains of Roman roads sites to the network.



**Figure 12** Network compared with the known remains of Roman roads.

### 5.3. INCORPORATING FUZZINESS

Digital modelling of movement is in many cases far from a completely precise prediction. LCPs and MADO, that take the shape of lines, can give the impression of a highly detailed map of paths, although it is implicit in how they are calculated that they rather represent broad corridors. The remains of actual roads could be located around these lines, at variable distances. If the prediction is good, those distances should not be very high, but in any case, there is always a buffer zone where the actual remains of paths could be found.

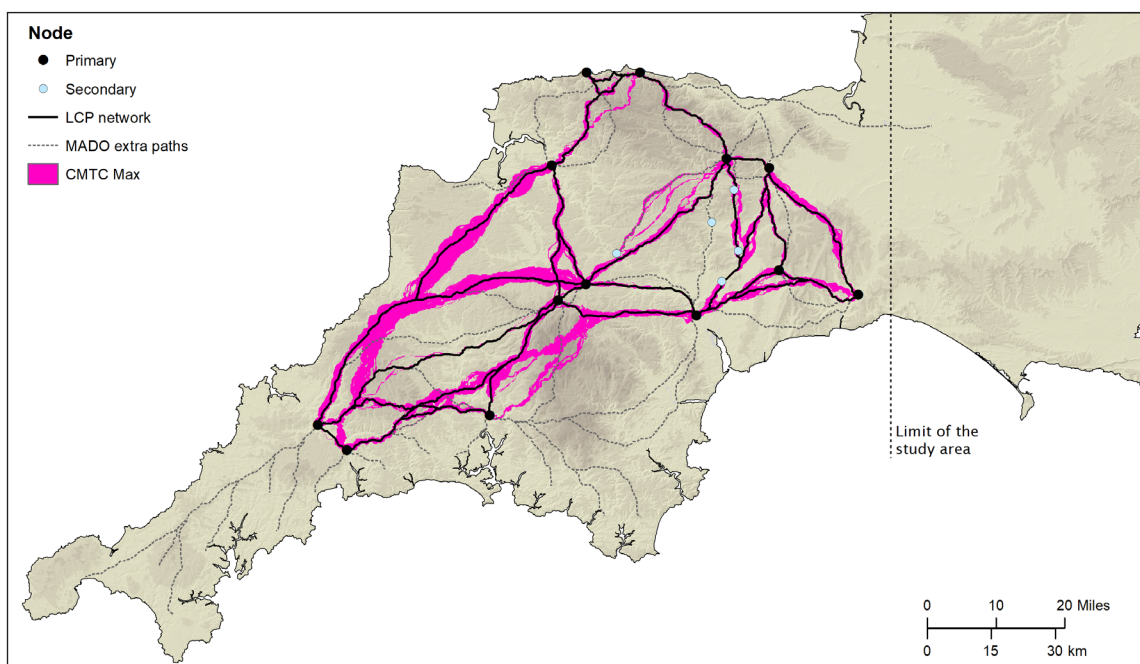
A simple solution is just to set a fixed distance buffer around these LCPs (e.g., one km). However, there are better ways to approach this, since not all areas are equal in that respect. Think for instance of a narrow pass between high mountains and of a flat, open plain. In the first case, the actual possibilities for movement are highly restricted and any LCPs or MADO will be probably very close to the real-world paths, whereas in the case of a plain, distances between prediction and reality can be much higher. Using a fixed distance buffer does not account for that.

Alternatively, buffer areas adapted to the conditions of the terrain were calculated. For that, the conditional minimum transit cost (CMTC) technique was used, which was originally created in the field of ecology (Pinto & Keitt 2009) and has been recently used for the analysis of ancient roads in Italy (Hodza & Butler 2022). It allows creating “least-cost travel corridors that convey mapping uncertainty, which degrades with distance from the optimal path” (Hodza & Butler 2022: 51). This method produces buffer areas connecting pairs of points whose width is directly related with the conditions of terrain for mobility. Besides that, it can also uncover alternative routes to the single best least cost path.

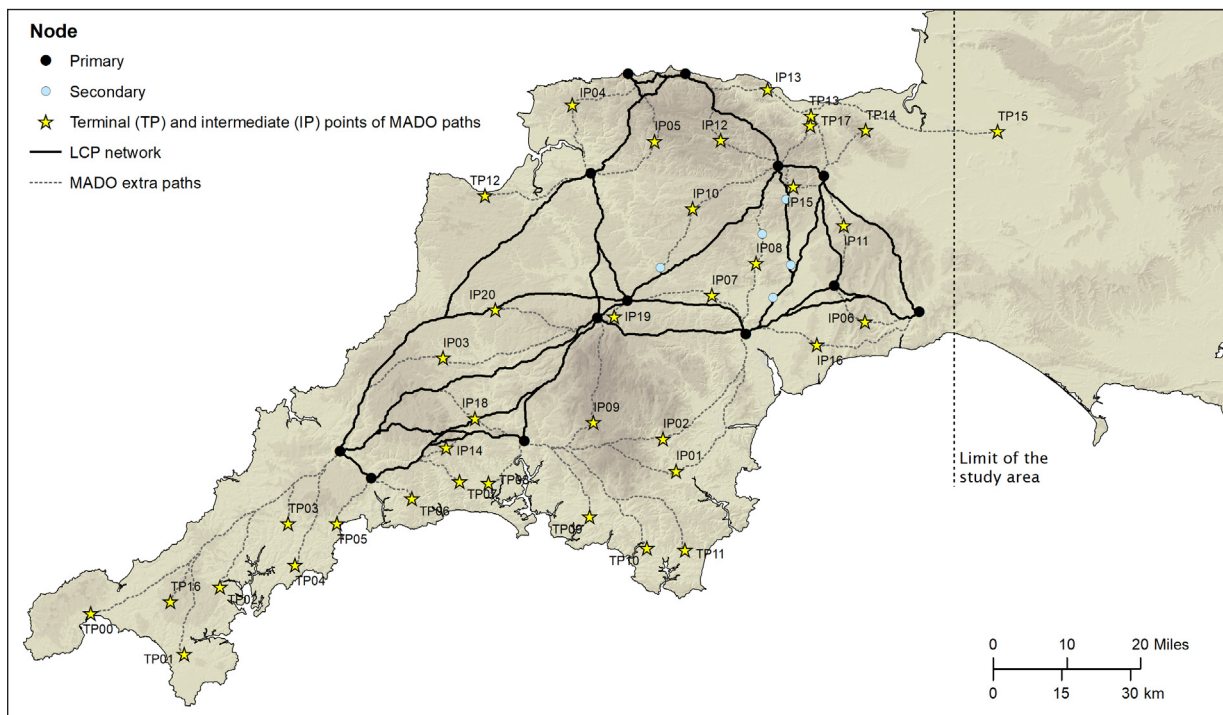
Figure 13 shows the combination of all CMTC pairs used in the calculation of the first stage of the network (LCPs directly connecting the primary nodes). This is the easiest part, since nodes define points of origin and destination, necessary inputs in the CTMC analysis. How can we extend that network to create also buffer areas around the MADO-generated paths that extend beyond the primary nodes? The CTMC method needs pairs of points for calculation, and by definition MADO paths are based on just one focal point. To allow creating CTMC areas, points were manually placed at the end of the MADO lines or, in those cases where terminal points do not exist, at the midpoint of MADO paths (where MADO lines cross the cost allocation-based areas of influence). Figure 14 shows the map of these new points.

This produces a large number of new points (a total of 495 potential pairs of connections between all Roman primary sites and all these new terminal/mid points, if all pairs were to be computed). Besides overflowing the analysis, this would produce a high number of redundant and unwarranted connections. The obvious solution was to compute only the connections that correspond with the underlying logic of the network: for instance, CTMC for IP02 was only computed with relations to Exeter and Calstock (Sites 8 and 23). This reduced the number of pairs to be computed to 55.

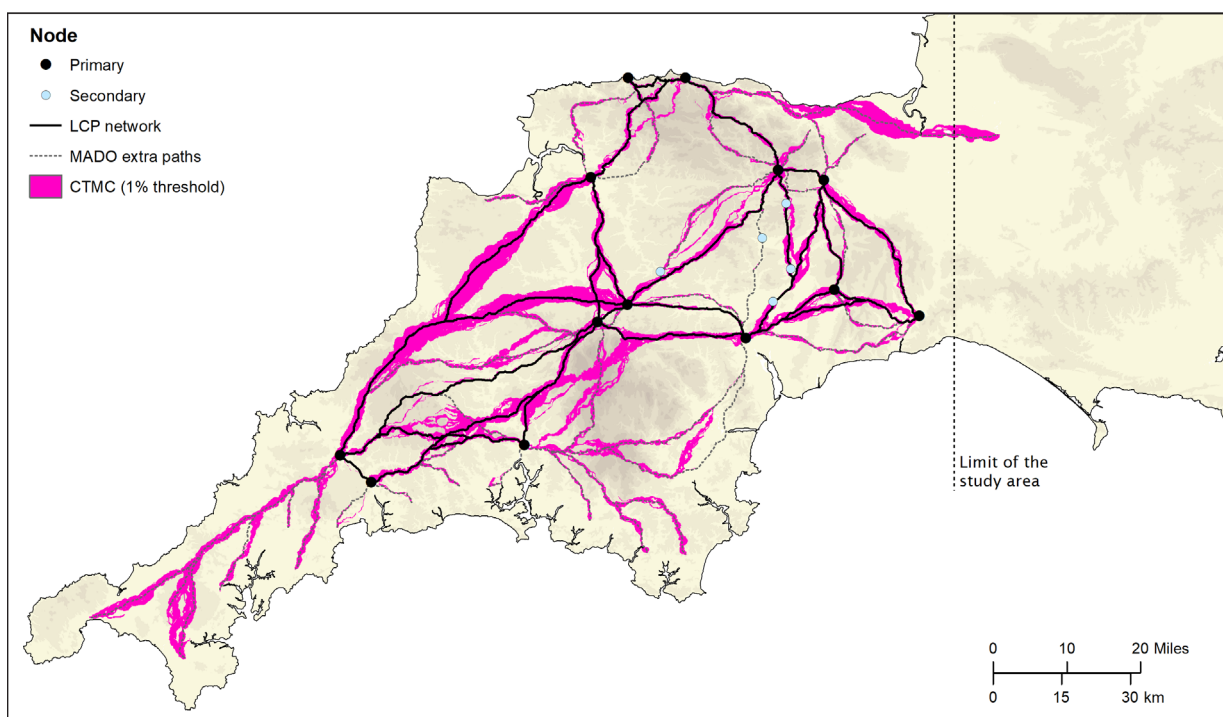
A combination of all these CTMC gives a full map of buffer zones around the whole network (Figure 15). As previously explained, CMTC calculation is about probability, so different thresholds might be used that will produce wider or narrower buffer areas. In the map below only areas with a highest probability are showed (threshold = 1%, see Pinto and Keitt, 2009 for more details).



**Figure 13** CMTC for the direct connections between primary nodes.



**Figure 14** Points created at the end or along MADO paths to allow a CMTC analysis.



**Figure 15** Full network incorporating fuzziness around paths.

If we include the buffer areas obtained with the CMTC analysis, the results improve significantly. First, we can compare the shortest distance between military sites other than forts ( $n = 47$ ) and the nearest features in both the linear network and the CTMC areas (Table 3). As it can be seen, almost all of them (38 out of 47) are within 3.5 km from the CTMC corridors, and even a substantial 49% of the sites are just within 500 m. While this may still be seen as a relatively poor match, it must be considered that proximity to paths cannot be assumed as the only,

or even the main, location factor for these sites. Their military quality implies that in some cases perhaps other factors were also at play when selecting their location (e.g., visual command, proximity to strategic places...). It is in this light that these figures should be seen.

For that reason, proximity to actual remains of roads is a much better measure (Table 4). The improvements are noticeable: ca. 76% of the LiDAR-derived roads are within just 250 m of the CTMC corridors, with no less than 90% within one km.

DISTANCE TO NETWORK AND CTMC (m)	N. SITES	%
0	13	27.7
500	23	48.9
1,000	26	55.3
1,500	29	61.7
2,000	32	68.1
2,500	34	72.3
3,000	37	78.7
3,500	38	80.9
4,000	39	83.0
4,500	39	83.0
5,000	39	83.0
5,500	42	89.4
>6,000	47	100

**Table 3** N. of Roman sites, other than forts, at a distance from the network of paths and the fuzzy CTMC areas around them.

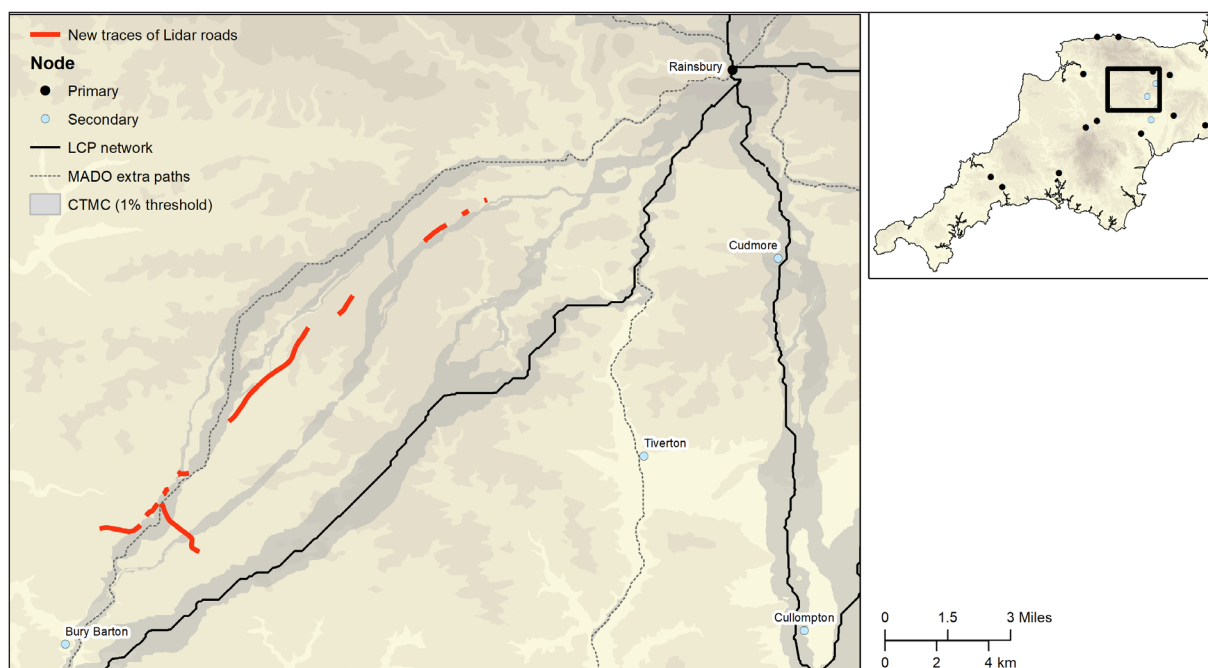
DISTANCE (m)	% OF LIDAR ROADS TO LINEAR NETWORK	% OF LIDAR ROADS TO NETWORK AND CTMC
250	49.49	75.76
500	67.25	75.76
750	75.17	84.85
1,000	81.15	90.91
1,250	86.03	90.91
1,500	89.02	90.91
>1,500	100	100

**Table 4** Distance of known remains of Roman roads to the modelled network, with and without fuzzy areas.

Actually, after completing the modelling process, we returned to the LiDAR data to try to find new traces of the roads in the areas pointed by the prediction. After all, this was one of the main objectives for the modelling. In an exploratory revision of the LiDAR-derived terrain models between the sites of Bury Barton and Rainsbury (n. 10 and 21 in Figure 5), the results were highly positive: some 13 new km of likely Roman roads were identified, within or at short distance from the areas predicted by the model (Figure 16).

## 6. DISCUSSION AND CONCLUSIONS

The availability of seamless LiDAR data for South West Britain has enabled the mapping of a wide-reaching, convincing network of Roman roads across the counties of Devon and Cornwall, linking with the adjacent counties of Somerset and Dorset. Furthermore, GIS-enabled modelling based on early identifications of roads, and nodal places, corroborates the network and allows the suggestion that further lengths of road are yet to be identified on the ground. Although it could be argued that roads no longer in use and visible as earthworks might be of pre-Roman, or medieval date, the combination of 1) the consistency in construction practice (*agger*, quarry pits, terracing), 2) the coherency of the road pattern, and 3) in places the stratigraphic relationship with medieval field systems, argues for it being of Roman origin. The network presented here is only that which has been mapped as an archaeological earthwork visible on LiDAR data and, for example, there are gaps between those segments connected by historic tracks, lanes and roads which are likely to have fossilised the Roman route.



**Figure 16** New traces of roads documented between Bury Barton and Rainsbury, following the areas predicted by the model.

In terms of chronology, it is likely that the proposed network is an amalgam of pre-existing Prehistoric routeways and Roman military campaign roads (“tactical roads”), formally adopted into the provincial communications system, and of those constructed during peacetime (“permanent roads”), in a wholly civilian context (Gethin and Toller, 2014). This evolutionary model is supported by the fact that the network does not solely connect Roman forts and their hinterlands directly, which are often connected by branch roads, but instead appears to serve a broader purpose than required by military supply. Mapping suggests that Exeter was not the sole nodal point in the region – not all roads led there – and instead we see connections with tidal estuaries north and south of Bodmin and Dartmoor, with the major settlement at North Tawton, with Exmoor (and possibly its iron mines), and the Parrett Estuary. Crucially, the latter appears to have served as a major shipment route, one which we now can see accessed from a southwest direction, and not just from Exeter northwards, or from within Somerset.

GIS modelling allowed us to propose a prediction of the possible layout of the Roman roads in the region, besides the specific sections that have been documented so far. Testing different cost factors and functions in a couple of well-documented areas allowed suggesting that the main rationale behind Roman roads in this region might have been using routes that privilege the movement of animal-drawn wheel vehicles, avoiding where possible areas subject to flooding risks. However, there remain some sections of the study area that show a poorer match between the model and the available evidence; in particular, the zone to the NE of Wiveliscombe (fort 28). As we already commented, this might just be a case of “border effect”: due to the terminal character of this fort within the study area, there are no further nodes to the NE that can guide the extension of the model in that direction. But we must also bear in mind the possibility that not all the all roads are dictated by the same factors influencing their location (e.g. Herzog 2021). Our analysis used a selection of specific cost factors based on the analyses made in two test areas. The future remote-sensing detection of new sections of roads will allow to explore whether this is applicable over the whole area.

Due to the relatively small number of input data available for the analysis (primary nodes of the network), we have been forced to use an approach that complements the most obvious use of straightforward Least Cost Paths. A creative use of MADON (Focal Mobility Networks) has allowed us extending the model to areas that lie beyond the main Roman sites known in the region, and also suggesting some secondary or tertiary routes alternative to the single best optimal path. Besides, the use of the CMTC method has allowed injecting some fuzziness into the prediction, which may greatly increase the usefulness of the proposal for guiding future prospection.

That South West Britain was served by a road network like any other part of Roman Britain brings with it considerations for the future of Roman archaeology in the region. We considered North Tawton to be a primary node and new archaeological evidence (Smart and Fonte in prep) suggests that it was extensive and perhaps had an urban character, and thus we might expect other important nodal places at junctions within the road network, or at its terminal points, as elsewhere in Roman Britain (Smith and Fulford, 2019; Lewis, 2022). In this regard, the recognised network, and the GIS-enabled modelling, may serve to predict the location of settlements that are as yet unknown to us.

New archaeological evidence, including that proposed here for the existence of a wide-reaching Roman road network, urges for a reconsideration of the degree of capital investment in infrastructure and the development of a more complex settlement network hierarchy in the Roman South West Britain. The physical connections with the remainder of the Roman province are now clear.

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## NOTES

- 1 <https://environment.data.gov.uk/>.
- 2 More info at: <https://www.data.gov.uk/dataset/f0db0249-f17b-4036-9e65-309148c97ce4/national-lidar-programme>.
- 3 Data available from the Defra Survey Data Download geoportal: <https://environment.data.gov.uk/DefraDataDownload/?Mode=survey>.
- 4 Available at: <https://www.ordnancesurvey.co.uk/business-government/products/terrain-5>.
- 5 Available at: <https://data.gov.uk/dataset/65bf62c8-eae0-4475-9c16-a2e81afcbdb0/os-open-roads>.
- 6 Available at: <https://www.bgs.ac.uk/datasets/geological-indicators-of-flooding/>.
- 7 Although fort n. 20 is not along any LCP here, it is considered secondary since later in the analysis we found that it is located along an alternate optimal path between nodes 21 and 23 (see section 5 and Figure 10).

## REPRODUCIBILITY

The data used in this research are available at: <http://hdl.handle.net/10261/310113>.

## COMPETING INTERESTS

The authors have no competing interests to declare.

## AUTHOR CONTRIBUTIONS

CP-O: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Visualization.

JF: Conceptualization, Validation, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition.

CS: Conceptualization, Validation, Investigation, Resources, Writing – original draft, Writing – review & editing, Funding acquisition.

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