The Emilian Apennines in the 2nd millennium BC: new perspectives on the settlement pattern and trans-Apennine mobility

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Abstract

In the past decades, several works have attempted to reconstruct the Bronze Age settlement pattern in the mountain regions of Emilia (Northern Italy). These studies have provided a fundamental basis for drawing general historical trajectories and highlighted the widespread occupation of the Emilian Apennines. However, as most of these achievements relied on surface finds, chrono-typology of materials, and a limited number of topographic analyses, the results are far from fully satisfactory.

By recalling David Clarke's three analytical scales (1977), we will present the preliminary results of our ongoing research at the micro, semi-micro and macro scales, carried out in the mountain regions of four river valleys (Reno, Panaro, Secchia and Taro). The application of different methods, such as extensive surveys, manual coring, detailed photogrammetric surface modelling from a drone, spatial analyses in a GIS environment and the results of the excavation at Monte della Croce, dated to the 13th-12th century BC, are currently providing new data about the settlement pattern, the internal morphology of the fortified sites and their differentiated territorial functions.

Keywords

Uplands, Bronze Age, GIS, LCPA, Viewshed Analysis

Introduction

The importance of the Emilia-Romagna region in Italian prehistoric studies is closely tied to the earliest discoveries made in the plains of the Parma and Piacenza provinces by Luigi Pigorini and Pellegrino Strobel as early as 1860, soon followed by similar finds documented by Gaetano Chierici in Reggio Emilia and Carlo Boni in Modena.

By contrast, discoveries in the Emilian Apennines were regarded as more problematic (Strobel 1889, 133), raising important questions concerning their social and economic relationship with the Terramare settlements of the lowlands.

Over the last decades, archaeological research in the mountains of Emilia-Romagna has intensified through the increasingly systematic application of established archaeological methods (Putzolu and Cavazzuti 2019). Surveys and occasional, though significant, excavations have progressively enriched a picture that had long relied primarily on sporadic finds.

The Archaeology of the Uplands project aims to expand this body of evidence through a range of analytical approaches, including extensive surveys, manual coring, detailed drone-based photogrammetric surface modelling, and spatial analyses within a GIS environment (density analysis, viewshed analysis, and Least Cost Path Analysis). Together with the new data emerging from the excavation of Monte della Croce — a fortified site in the upper Reno River valley dated to the 13th–12th centuries BC — these methods are substantially improving our understanding of settlement organisation, site morphology, and differentiated territorial functions (Zanotti *et al.* 2023; Cavazzuti *et al.* 2025).

The study area extends, from west to east, across the present-day provinces of Piacenza, Parma, Reggio Emilia, Modena, and Bologna, covering approximately 200 km from north-west to south-east (Fig. 1). Its northern boundary is defined by the River Po, while the southern limit corresponds to the Apennine ridge separating Emilia from Liguria and Tuscany. From north to south, the region can broadly be divided into plains, hilly zones, and mountainous areas.

In the mountainous sector, with altitudes up to 2165 m a.s.l., soils are predominantly clayey and silty, with adequate drainage and slopes generally above 25%. Slopes are frequently stable, except in areas affected by localised landslides. The hydrographic network is largely composed of Apennine streams. Woodland represents the dominant land cover, although meadows and pastures are also widespread. In the hilly areas, soils are mainly silty and sandy, characterised by poor drainage and average slopes between 10% and 25%. Here too, slopes are generally stable and the hydrographic network is dominated by Apennine streams. The land is widely cultivated, with patches of woodland and uncultivated areas concentrated near river courses, and at high altitudes. In the plains, soils range from gravelly to clayey, becoming silty near minor rivers and ancient palaeochannels, and increasingly sandy towards the River Po. Slopes are generally below 10%, with efficient drainage conditions.

Recognising the hermeneutic potential of digital approaches in landscape archaeology, this article focuses on a series of territorial case studies, adopting GIS-based geospatial analyses at different scales in order to develop models capable of informing future research strategies.

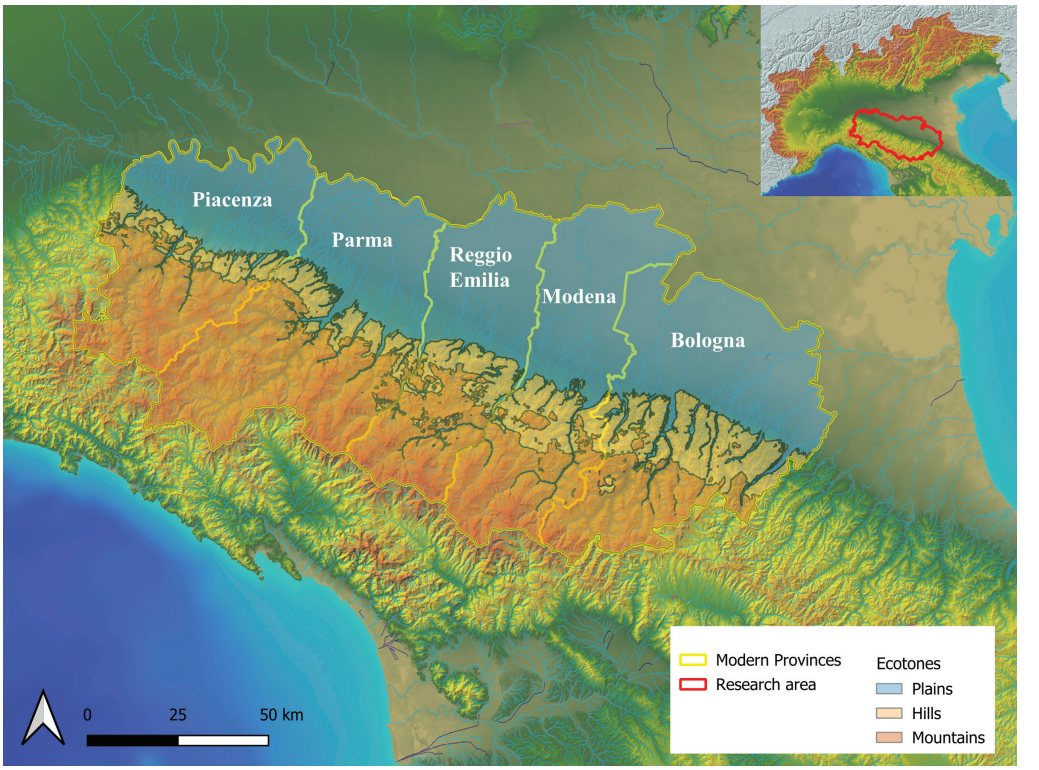


Figure 1. The research area. (CP)

Following Clarke's (1977) three levels of spatial resolution — micro, semi-micro, and macro — we first cross-referenced the distribution of known archaeological sites across the Emilia region with river basins in order to test whether variations in population density reflect broader shifts in settlement patterns (macro scale). At the semi-micro scale, we applied Least Cost Path Analysis (LCPA), Least Cost Path with Visibility (LCPV), and Potential Mobility Hubs Mapping across three sectors of the Tuscan-Emilian Apennines. LCPA was conducted within the central basins of the Secchia, Panaro, and Serchio rivers; LCPV within the western basins of the Taro, Magra, and Vara; and Mobility Hubs Mapping within the eastern Reno basin. These analyses were intended to assess the extent to which such methods can generate meaningful hypotheses regarding mobility and territorial control along trans-Apennine routes. Finally, at the micro scale, we ground-truthed an LCPA-derived route between two Bronze Age sites, identifying in the field the most accessible path connecting them (Fig. 2).

Environmental data and their relevance to the understanding of the historical cycles of the 2nd millennium BC

Compared with earlier periods, the Bronze Age witnessed a marked increase in the number of settlement sites across the Italian peninsula. Mountain regions, and particularly the Emilian Apennines, were fully involved in this process, which appears to have been driven by a combination of climatic, environmental, and socio-demographic factors.

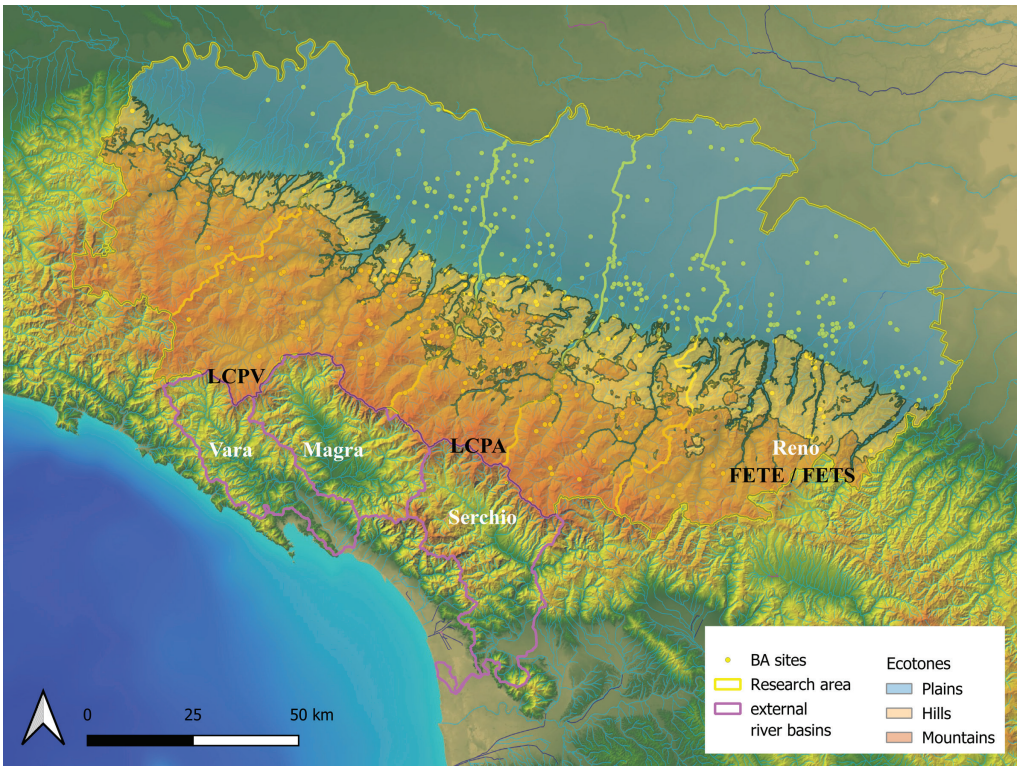


Figure 2. The external geographic windows investigated through spatial analyses. (CP)

The Mid–Late Holocene was characterised by significant changes in the vegetation of the Northern Apennines. Available pollen diagrams indicate a gradual decline of *Abies* in favour of *Quercus* (below 900 m) and *Fagus* (above 900 m), together with a substantial increase in *Poaceae* (grasses), suggesting slightly warmer conditions and a more open landscape (Branch and Marini 2014). At the same time, evidence of human activity increases significantly around 3600 BP (Middle Bronze Age), particularly in relation to charcoal concentrations in sediment cores, clearly pointing to episodes of intense fire-driven deforestation (Vescovi *et al.* 2010). More ephemeral traces of similar land-clearance practices, dating to the end of the Early Bronze Age (1884–1737 cal. BC (2σ); Pini *et al.* 2024), have recently been identified at Ca' Nova di Albareto (c. 700 m a.s.l.) in the western Apennines (Bosi *et al.* 2024).

Human impact has also been documented at higher altitudes, above the present-day tree line (c. 1700 m a.s.l.). A charcoal-enriched soil horizon identified in the Monte Cimone–Monte Cervarola area and dated to the end of the second millennium BC has been interpreted as evidence of high-altitude forest clearance aimed at creating open pastureland (Vittori Antisari *et al.* 2018).

Although the environmental dataset still requires further expansion and refinement, current studies suggest that the Bronze Age landscape — at least in terms of vegetation associated with climatic biozones — was broadly similar to that of today. The principal difference lies

in forest cover, which has expanded continuously over the past century as a consequence of the progressive abandonment and underexploitation of mountain areas, particularly at higher elevations (Fiore *et al.* 2024). This process now conceals a significant proportion of the archaeological evidence visible on the surface. A further issue concerns climate change and the increasing frequency of extreme rainfall events (Luppichini and Bini 2025), which have caused destructive flooding in the Emilian plain — most notably in May 2023 — and major landslides in mountain areas characterised by clay-rich geolithologies, especially where deforestation has occurred (such as at Baiso in May 2023 and Boccassuolo in May 2025; see also Zanotti *et al.* 2023: fig. 2). These phenomena exert a dual impact on slope geomorphology, causing erosion in upper areas and the accumulation of thick sterile deposits towards valley bottoms. Consequently, in addition to the severe effects on mountain communities, many archaeological sites located on hilltops and upper slopes are increasingly threatened by erosion and destruction, while sites closer to valley floors may become buried beneath metres of colluvial deposits.

From this perspective, when both historical and active landslides are taken into account, it becomes evident that our present understanding of Bronze Age occupation in the Apennines is biased towards sites located on mountain tops, whereas settlement patterns in the lower valleys appear much more dispersed.

Land use and subsistence practices represent another area requiring further investigation. Owing to the limited number of excavated sites, archaeobotanical datasets based on macro-remains are still insufficient to reconstruct Bronze Age agricultural strategies in mountain environments with confidence. At Monte della Croce (917 m a.s.l.), for instance, preliminary analyses indicate the presence of wheat, barley, and millet alongside wild fruits such as Cornelian cherry and elderberry (Cavazzuti *et al.* 2025). Nevertheless, significant variations linked to pedology, exposure, climate, and altitude may have existed between different sites. The abundance of faunal remains — mostly attributable to domestic species — at Monte della Croce further suggests that animal husbandry played a central role in the upland economy (Cavazzuti *et al.* 2025). It remains unclear whether domestic herbivores grazed primarily in nearby pastures as part of household husbandry systems, or whether forms of seasonal transhumance were already practised, a question that future isotope analyses may help to clarify. The episodes of forest clearance documented at the end of the second millennium BC (Vittori Antisari *et al.* 2018) may point to the deliberate expansion of high-altitude pastures linked to transhumant practices, likely associated with increased investment in livestock, dairy production, and other secondary products.

Particularly noteworthy is the discovery, in the Corno alle Scale area at approximately 1700 m a.s.l., of a charcoal-production platform (*Fraxinus* sp.) dated to 1131–1008 cal. BC (2σ) (Benatti *et al.* 2019). This evidence suggests that, by the Late Bronze Age, even the highest-altitude zones were being seasonally exploited for a variety of resources. Charcoal was primarily used in metallurgical activities, which are well documented at several sites, including Groppo Predellara (Ghiretti 2003).

Overall, it may be argued that the occupation of the mountain regions south of the Po plain was facilitated by relatively favourable climatic conditions, but also driven by demographic

pressure from the lowlands, alongside the desire to exploit upland resources and establish secure routes connecting Northern Italy with the rest of the peninsula.

Methods

In the first part of this contribution, we present the results of several GIS-based analytical approaches; in the second section, we discuss their significance for the reconstruction of settlement patterns.

Site density

We first assessed the reliability of the boundary hypothesised for the western plain and investigated whether a comparable pattern could also be identified in the eastern sector. To this end, we calculated the density of Bronze Age (BA; c. 2200-950 BC) sites within each river basin, distinguishing between upland areas (mountains and hills) and lowlands (plains). Following earlier approaches (Di Renzoni 2006), which divided the Terramare region into sectors oriented perpendicular to the River Po, we adopted river basins as our primary analytical units.

The river system of Emilia-Romagna consists of a series of approximately parallel watercourses flowing south-west to north-east from the Apennines towards the Po. Building on the observed variability in lowland settlement patterns during the Late Bronze Age, Cardarelli (1997, 656) proposed that such differences may reflect distinct "political systems" organised around the major rivers. Although palaeohydrological studies demonstrate that the principal rivers of the Po Plain shifted both eastwards and westwards over time, complicating the reconstruction of Bronze Age river basins in the plains, the morphology of the Apennines — where ridges clearly separate adjacent catchments — still allows the identification of territorially defined districts structured along trans-Apennine routes leading towards the Tyrrhenian coast.

Given the contrasting settlement patterns characterising the Terramare region and its western neighbour — the former markedly denser, the latter characterised by fewer sites and lower population levels — the sequence of adjacent parallel river basins provides an effective framework for identifying the discontinuities expected at the boundary between distinct cultural areas.

This approach allowed us to test the prevailing model of Terramare distribution south of the Po, which proposes a continuous occupation of the lowlands from Piacenza in the west to Bologna in the east, alongside a more concentrated settlement pattern in the uplands between Parma and Modena.

Given the limited chronological and functional resolution of many sites, the dataset was analysed as a whole, without separating Middle Bronze Age and Late Bronze Age phases. Although this approach requires caution — particularly in light of demographic growth across the Po Plain (Cardarelli 2009) — it nevertheless provides an effective basis for assessing relative differences in settlement density between individual districts.

The dataset builds upon a comprehensive bibliographic survey compiled for a previous study (Putzolu and Cavazzuti 2019, with contributions by Iames Tirabassi and Roberto Maggi),

supplemented by Bronze Age sites recorded in the Province of Bologna through the Po-BaSyN project (Cattani and Debandi 2015), and includes all categories of archaeological evidence currently known within the study area. Since most of these sites are identified only through sparse surface ceramic finds and often lack stratigraphic evidence capable of clarifying their function, all available evidence was cautiously included in the dataset.

All spatial analyses were carried out using QGIS[1].

Calculating the number of sites per 100 km² within the plains, hills, and mountain sectors of each river basin from west to east allowed us to compare areas affected by broadly similar post-depositional processes, which may equally have hindered the identification of archaeological sites. This approach therefore helped to minimise biases resulting from uneven archaeological visibility and research intensity.

Least Cost Path Analysis (LCPA)

To investigate mobility across the Northern Apennines during the Bronze Age, we applied Least Cost Path Analysis (LCPA), a GIS-based method designed to model energetically optimal routes. The analysis aimed to assess whether the distribution of sites within the Secchia, Panaro, and Serchio basins reflects settlement patterns structured along natural corridors, and to test possible correspondences with historically documented medieval routes (e.g., the *via Bibulca* and *via Matildica*).

Pathways were calculated from Digital Terrain Models (30–90 m resolution) using native QGIS tools. Basemaps at higher resolution (e.g., TINITALY 10 m) were not employed, since the primary objective of the analysis was to identify potential routes connecting sites located on the northern and southern sides of the Apennine chain, thus covering a broad territorial scale. Under these conditions, the difference between routes generated from higher-resolution datasets and those produced using the selected basemap proved negligible (approximately ±100 m). Moreover, the adopted resolution ensured greater computational efficiency when conducting analyses across such extensive spatial units (Bilotti *et al.* 2024).

The cost surface was primarily defined by slope, using Tobler's hiking function (Tobler 1993; Pingel 2010), which models walking speed in relation to gradient and is particularly well suited to mountainous landscapes. Least-cost routes between coeval sites dating to MBA 2 (c. 1650-1550 BC) were then calculated using Dijkstra's algorithm (Korte and Vygen 2018) in order to assess plausible connections and estimated travel times. The selected start and end points — Castellarano (RE) and Fossa Nera di Porcari (LU), respectively — were chosen because, among the currently available evidence, they best fulfil the requirements of this study: (1) they are broadly contemporary, implying the possibility of movement between them; (2) both have yielded diagnostically significant ceramic assemblages; and (3) the starting site lies at the edge of the Po Plain, whereas the end site is located within the Lucca plain, thereby encompassing the entire geographical extent of the study area.

For each route, total travel duration was estimated assuming an average speed of 2 km/h under mountain conditions while carrying loads, together with intermediate distances

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between sites, in order to evaluate the possible existence of regular stopping points suitable for multi-day journeys. The resulting paths were subsequently compared with medieval trans-Apennine routes in order to investigate potential long-term continuities in mobility networks. More specifically, the analysis sought to determine whether the routes linking known Bronze Age sites correspond to pathways documented in later periods, particularly medieval trans-Apennine routes such as the Via *Bibulca*–Nonantolana. Such comparisons allow us to hypothesise a degree of continuity in mobility patterns through time, suggesting that some of these routes may already have been in use during prehistory. Where significant correspondences emerged, historical sources were consulted to reconstruct the medieval itineraries and systematically compare them with the modelled routes.

A further noteworthy aspect is that the identified 'hot spots' tend to coincide with medieval and modern trans-Apennine routes. Particularly significant is the Via *Bibulca*, which follows the middle Secchia Valley, crosses the Apennines at the Passo di San Pellegrino, and descends into the Serchio Valley towards Lucca — a city founded in 180 BC following the Roman defeat of the Ligurian populations. This route provides an especially relevant case study for comparison (Cavalieri 1991; Sabbatini 2019).

Field Test of LCPA Path: From Monte della Croce to Rocchetta Mattei

Although most GIS-based analyses can be carried out entirely within a digital environment, archaeological research ultimately requires verification in the field through ground truthing. With this aim, a least-cost path model generated in QGIS was tested during the Experimental Archaeology Lab at the University of Bologna. The resulting vector, produced through LCPA, extended over approximately 7 km and connected the two Recent Bronze Age sites of Monte della Croce and Rocchetta Mattei, both located in the eastern Apennines within the province of Bologna.

As demonstrated by similar experimental studies (e.g. Cabras *et al.* 2023), the practical viability of modelled routes may be affected by modern obstacles such as fences, dense vegetation, and private property boundaries. For this reason, a tolerance of approximately 100 m on either side of the LCPA-derived route was considered acceptable when evaluating the correspondence between the modelled pathway and actual mobility conditions in the field.

Least Cost Path with Visibility (LCPV)

The integration of movement and visibility analysis has become a central aspect of archaeological applications of GIS. Traditionally, mobility has been modelled through friction surfaces and visibility through viewshed analysis; however, landscapes are not only traversed but also perceived. Least Cost Path with Visibility (LCPV) combines Least Cost Path Analysis (LCPA) with visibility modelling, enabling a shift from a detached "look-to" perspective towards a more embodied "look-from" approach (Llobera 2003). This method highlights the ways in which individuals navigated, oriented themselves, and structured their interaction with the surrounding landscape. Concepts such as the *visualscape* (Llobera 2003), together with broader debates concerning scale (Lock and Pouncett 2017), further emphasise the importance of linking analytical modelling with lived experience. Within this framework, visibility is treated not merely as a descriptive variable, but as a factor capable of influencing

movement itself, since routes that maintain visual references and facilitate orientation are likely to have been preferentially selected. Accordingly, areas characterised by lower visibility were incorporated into the friction surface as higher-cost zones, reflecting the potential constraints that limited visual exposure may impose on navigation and situational awareness.

The analysis focused on a 12.5 km² area surrounding Ca' Nova di Albareto, in the upper Taro River basin of the western Emilian Apennines. To ensure systematic spatial coverage, three grids of destination points were generated at intervals of 500 m, 1 km, and 2.5 km. This design made it possible to model movement towards evenly distributed points across the landscape, thereby reducing bias in destination selection.

Three variables were incorporated into the friction model. Slope was derived from the DTM and converted into travel times using Tobler's Hiking Function, ensuring methodological continuity with the previous LCPA analysis and reflecting the primary constraint on movement in mountainous terrain. Visibility was modelled through: (1) binary viewsheds generated from five accessible vantage points; (2) cumulative viewsheds (CVA) derived from 150 × 150 m grids of observer points; and (3) Individual Distance Viewsheds (IDV), which applied perceptual thresholds for detection and recognition (Fábrega-Álvarez and Parcero-Oubiña 2019). The observer grid was subsequently filtered in order to retain only points situated at higher elevations relative to Ca' Nova and located within an estimated walking distance of one to two hours, ensuring that the selected viewpoints reflected both topographic prominence and a plausible spatial range of local mobility. While binary and IDV approaches were employed to investigate different dimensions of visibility and local visual control, the cumulative viewshed (CVA) was ultimately selected as the operative variable within the friction model, since it provides a continuous representation of visual prominence across the landscape.

Flow accumulation was calculated using the deterministic D8 algorithm in SAGA and subsequently reclassified into ten categories. Lower values correspond to areas with limited drainage that are relatively easy to cross, whereas higher values represent progressively larger and more significant watercourses. A threshold of 750,000 cells was used to identify major watercourses, which were treated as non-traversable and therefore assigned the highest movement cost within the friction surface.

The three rasters were then combined into a composite friction surface. Weighting was established through the Analytic Hierarchy Process (AHP), assigning greater importance to slope (0.7) than to visibility (0.22) and hydrological flow (0.08). This approach builds upon previous studies (e.g. Fovet and Zakšek 2014) that explored the relative influence of slope and visibility within least-cost modelling frameworks.

The weighting scheme was further refined through iterative testing. Initial models employing more balanced weight distributions produced unrealistic results, with least-cost paths frequently following riverbeds because of their high visibility values. Such outputs were considered implausible within a mountainous context, where movement is constrained primarily by slope rather than by visual exposure alone. The final weighting system therefore reflects a calibrated adjustment intended to prioritise slope reduction while still preserving the influence of visibility and hydrological variables.

The weighted rasters were integrated multiplicatively rather than additively in order to preserve the interaction between variables. This approach ensures that overlapping constraints — such as steep terrain combined with poor visibility — are jointly penalised, thereby producing more coherent pathway distributions. Least-cost paths were calculated from Ca' Nova to the destination grids using both QGIS and GRASS GIS, and the resulting outputs were cross-checked to ensure consistency.

Mapping Potential Mobility Hubs: FETE and FETS

The final method employed aimed to model potential mobility and identify high-density movement corridors within the study area. To achieve this, two complementary forms of Least Cost Path Analysis were applied: the From Everywhere To Everywhere (FETE) and From Everywhere To Somewhere (FETS) approaches. These analyses were conducted through a combined use of the *movenetw* R script (Alberti 2019) and QGIS.

The FETE approach (O'Sullivan 2019) is designed to generate a probabilistic travel network in which neither origins nor destinations are predefined. This is achieved by overlaying the cost-surface raster with a regularly spaced vector grid, whose nodes function simultaneously as both origins and destinations for path calculations. The resulting network of interconnected routes constitutes a synthetic simulation of potential movement across the landscape, highlighting areas with a higher probability of traversal.

Building upon these results, the FETS analysis employs the same cost surface but introduces known archaeological locations as fixed destinations, while maintaining the grid nodes as origins. This procedure makes it possible to identify the routes most likely to have connected known sites with the surrounding landscape. The FETS output is subsequently transformed into a new cost surface by subtracting the frequency value of each cell from the maximum recorded frequency, thereby converting areas of higher movement frequency into lower-cost zones. In this way, the FETS-derived corridors of intensified movement function as a weighting mechanism capable of refining the broader FETE network.

The originality of the present approach lies in the use of FETS results not simply as a visualisation tool, but as an active filtering layer for rationalising the FETE network. Rather than relying exclusively on colour-coded density maps to identify possible traffic corridors (cf. Branting 2004), redundant paths within the FETE network were systematically reduced through the application of FETS-derived buffer zones. These buffers, tested at different distances (50 and 100 m), define the spatial extent within which superfluous FETE routes overlap areas already characterised by high connectivity. The simplification of the residual FETE network was then achieved through the Douglas-Peucker algorithm (Douglas and Peucker 1973), which reduces the number of vertices composing each polyline by minimising geometric dissimilarity between the original and simplified curves (Fig. 3).

The resulting rationalised network provides a balanced representation of both high-probability mobility corridors and alternative pathways that may reflect less structured or still undocumented trajectories. The integrated FETE–FETS approach therefore refines probabilistic LCPA modelling while preserving the capacity to detect previously unrecognised movement zones and simultaneously reducing redundancy in areas already associated with

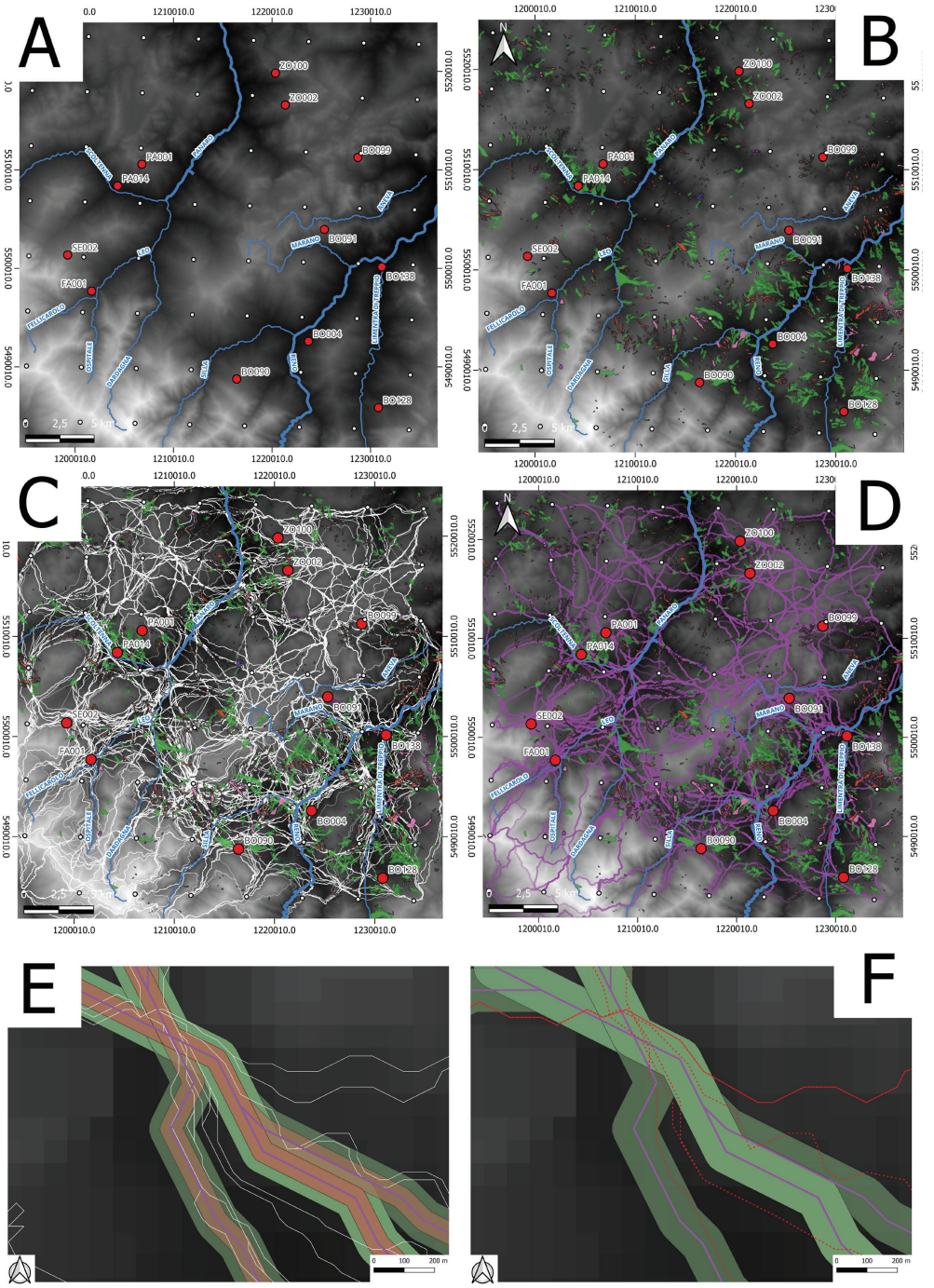


Figure 3. The various steps of FETE and FETS approach: A) the research area between the Reno (east) and Panaro (west) river valleys; B) in green and pink the landslides within the territory; C) FETE white LCPs vectors; D) FETS purple LCPs; E) the skimming 100 and 50 m buffers around the FETS paths and F) after filtering the redundancies, the red polylines represent the alternative paths. (EZ)

known traffic patterns. As such, the method offers a flexible analytical framework applicable to a variety of landscapes and may serve as an effective guide for targeted ground-truthing and future studies of mobility.

In order to test this approach effectively, it was necessary to employ the largest possible number of origin points (i.e. archaeological sites) within the FETS network so as to maximise the filtering of redundancies. For this reason, we selected the Recent Bronze Age 1 phase (*Bronzo Recente 1*, c. 1450–1350 BC), which, in the Apennines, represents the period characterised by the highest concentration of Bronze Age evidence currently known (Cardarelli and Malnati 2006; Guerra 2015; Zanotti *et al.* 2023).

Results

Site density

Using the "countpointsinpolygon" function from the Vector Analysis Processing Toolbox, the number of sites falling within the boundaries of each river-basin sector was calculated.

The resulting density values were subsequently classified into four ordinal categories — low, medium, high, and very high — through application of the Jenks natural breaks algorithm (Jenks 1967). This method is specifically designed to partition bimodal or multimodal datasets by minimising variance within classes while maximising differentiation between them (Francisci 2021).

Given the marked heterogeneity in density distributions across the three geomorphological zones — shaped by differing landscape formation processes, post-depositional dynamics, and uneven histories of archaeological investigation — the Jenks classification was applied separately to the plain, hilly, and mountain sectors of the Emilian river basins. The results of these independent classifications are presented in Figures 4–6.

Within the plains (Fig. 4), the most striking feature is the exceptionally high concentration of sites in the Enza River Basin (9.00 sites per 100 km²), located between the modern provinces of Parma and Reggio Emilia. This pattern reflects the long-standing intensity of archaeological research in the area, particularly since the earliest investigations into the Terramare culture. Beyond this core zone, the eastern portion of the plain — including the Crostolo (5.15 sites per 100 km²), Secchia (2.70 sites per 100 km²), Panaro (5.40 sites per 100 km²), and Reno (4.79 sites per 100 km²) basins — consistently falls within the "high-density" category, suggesting a broadly continuous and uninterrupted pattern of occupation across the region.

By contrast, the western sector displays a markedly different configuration. Here, only the Parma Basin reaches high-density values (5.32 sites per 100 km²), whereas the adjacent Taro (2.47 sites per 100 km²) and Arda (2.12 sites per 100 km²) basins fall within the medium-density category. All remaining basins are characterised by low-density values. This apparent scarcity of sites, however, must be interpreted with caution. Both the Taro and Arda basins have been the subject of sustained archaeological investigation since the formative stages of Italian prehistoric research in the late nineteenth century, including major excavations at Castellazzo di Fontanellato, Castione Marchesi, and Castelnuovo Fogliani. The material

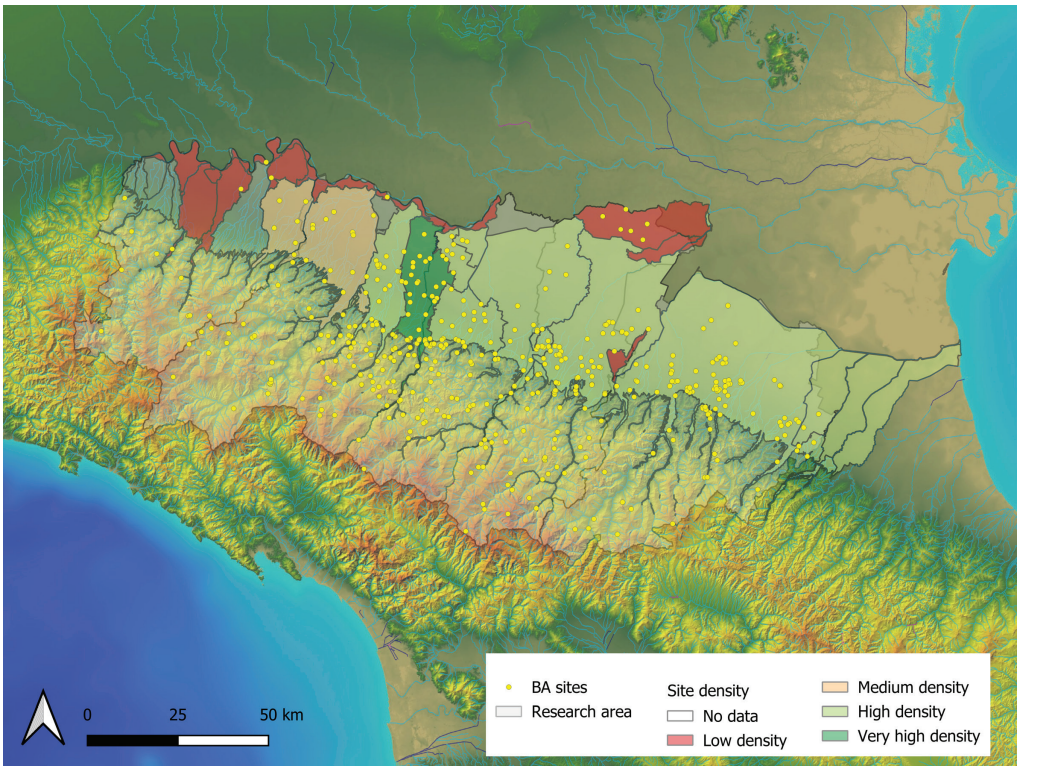


Figure 4. Site density in the plains. (CP)

assemblages recovered from these sites are unequivocally attributable to the Terramare cultural horizon. In contrast, the basins located west of the Arda are not only sparsely represented archaeologically, but also lack diagnostic ceramic assemblages associated with the Terramare tradition.

Building upon patterns already recognised in the uplands — where two distinct areas have previously been identified on the basis of both material culture and settlement strategies (Putzolu and Cavazzuti 2019, 261) — it is possible to tentatively outline a cultural boundary between the Terramare sphere and the Middle Bronze Age Western Culture (BINO, *Bronzo dell'Italia Nord-Occidentale*). This boundary appears broadly to correspond with the transition from medium- to low-density basins, specifically between the Arda and Chiavenna systems. Particularly significant in this context is the site of Rovere di Caorso, situated in the interfluve between these basins near the River Po. First excavated by Luigi Scotti between 1891 and 1896, the site has recently been re-examined through rescue excavations, which yielded ceramic forms and decorative repertoires characteristic of both cultural traditions. These findings suggest the existence of a zone of interaction — if not direct overlap — between the two cultural spheres (Bonometti *et al.* 2024).

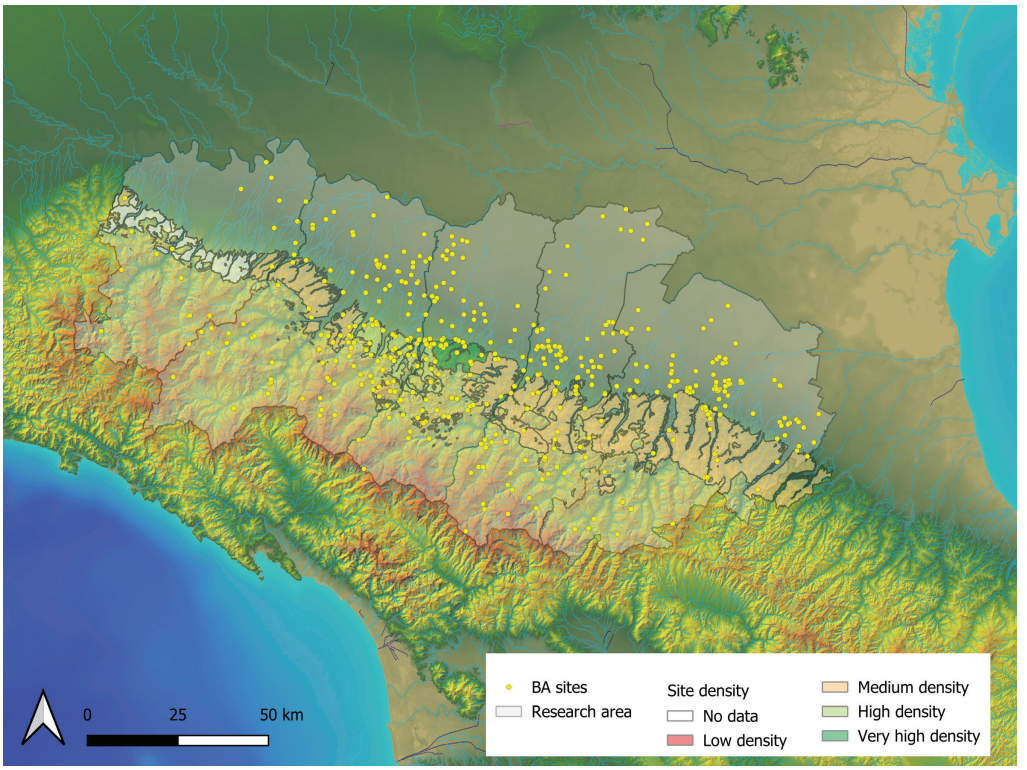


Figure 5. Site density in the hills. (CP)

The hilly sector (Fig. 5) displays a distribution pattern broadly comparable to that observed in the plains, characterised by a pronounced concentration peak in a central basin — the Crostolo (12.14 sites per 100 km²), within the present-day province of Reggio Emilia — followed by a sequence of eastern basins with relatively homogeneous density values (Secchia, Panaro, and Reno, ranging between 2.63 and 2.77 sites per 100 km²). In this case, however, the eastern hilly sectors consistently fall within the medium-density category rather than the high-density values recorded in the plains. Despite this difference in magnitude, the data again suggest a coherent and uninterrupted pattern of occupation, with no clear discontinuities in settlement organisation.

In the western sector, the Enza and Parma basins emerge as relatively high-density areas, followed by the Taro and Arda basins, which fall within the medium-density category. A significant divergence from the pattern observed in the plains is evident in the hilly areas of the province of Piacenza, where sites are not merely underrepresented but appear entirely absent. This apparent void should nevertheless be treated cautiously, as it most likely reflects the near-total absence of systematic landscape archaeological investigations comparable to those undertaken in neighbouring regions (Ghiretti 2000; De Marchi 2003). Even so, both the hilly and plain sectors reveal a clear westward decline in site density, whereas density values

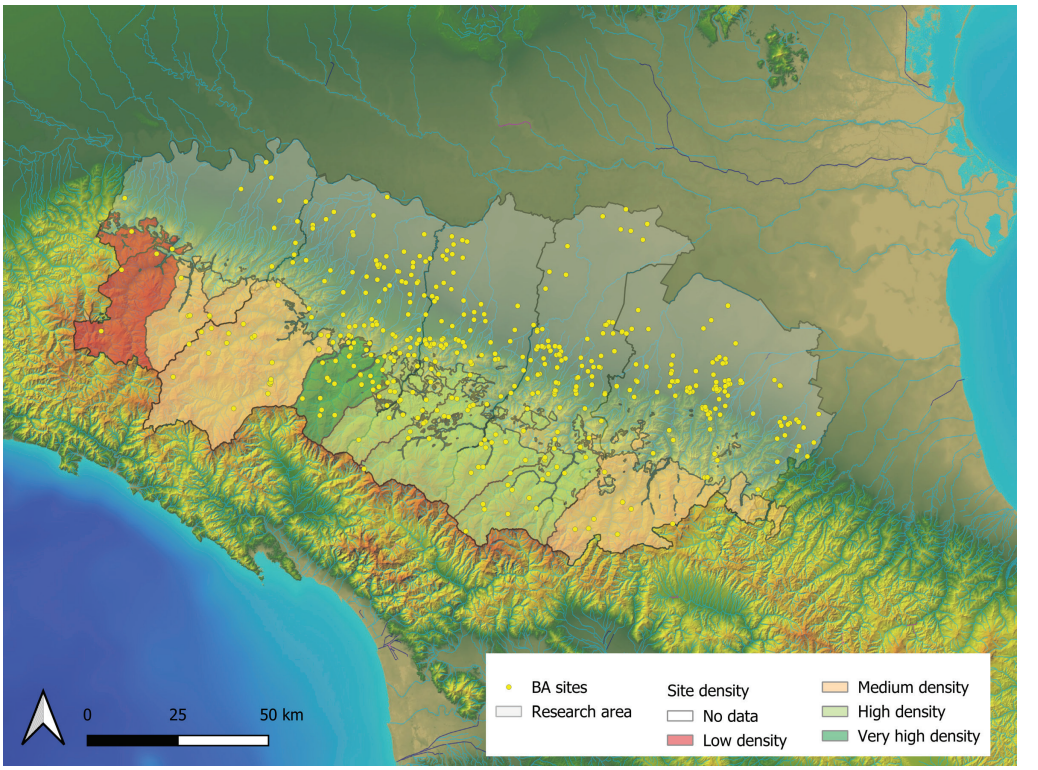


Figure 6. Site density in the mountains. (CP)

remain comparatively stable in the eastern sector, reinforcing the impression of a continuous and structured settlement framework.

Finally, the mountain sector (Fig. 6) presents a distributional pattern that both parallels and diverges from those observed at lower elevations. The highest concentration of sites occurs in the Parma Basin (7.31 sites per 100 km²), while elevated density values are also recorded further east in the Enza (6.24 sites per 100 km²), Crostolo (3.04 sites per 100 km²), Secchia (3.20 sites per 100 km²), and Panaro (2.80 sites per 100 km²) basins. By contrast, the Reno Basin (1.18 sites per 100 km²) falls within the medium-density category. Unlike the plains and hilly sectors — where the Reno Basin displays density values broadly comparable to those of the neighbouring western basins — this continuity is not maintained in the mountain zone. Here, the Reno Basin records substantially lower site density values than the adjacent Panaro Basin, amounting to less than half its density and thus marking a pronounced local decline in site frequency.

This discrepancy must be interpreted within the broader cultural and settlement framework. The strong material-culture affinities between the Reno and Panaro basins, together with the absence of any clear discontinuity in settlement patterns across the plains and hills, suggest that the reduced site density in the mountain sector is unlikely to reflect a genuine

demographic contraction. Rather, it is more plausibly the result of uneven archaeological exploration within these upland environments.

Since the boundary between the Terramare and BINO cultural spheres has already been examined in detail by previous studies employing finer-grained analytical approaches (Putzolu 2024), the present discussion remains intentionally more limited in scope. Within the framework of the density-based analysis adopted here, the most significant trend remains the progressive westward decline in site density beginning from the Taro Basin and extending across the wider study area.

Trans-Apennine Least Cost Path Analysis

In order to evaluate mobility across the Northern Apennines, Least Cost Path Analysis (LCPA) was applied to model routes connecting the Secchia, Panaro, and Serchio basins. Tobler's off-path hiking function was selected, as the routes under investigation traverse steep slopes and challenging terrain, including ridgelines and densely forested areas. An additional reduction factor (0.6) was applied to walking speed in order to approximate more realistic travelling conditions:

$$V=(6\cdot e^{-3.5\cdot|s+0.05|})\cdot 0.6$$

where V represents walking speed (km/h) and s the slope gradient expressed as a decimal value.

The principal test route was calculated between Castellarano (Reggio Emilia) and Fossa Nera di Porcari (Lucca). The resulting pathway measures 270.6 km. Its geometry reveals a marked tendency to maintain elevation once higher ground has been reached, favouring ridge-top trajectories and gradual descents rather than the shortest or most direct routes.

Estimated travel times further highlight the distinction between theoretical and realistic mobility scenarios. Assuming a constant speed on flat terrain (5 km/h), the route could theoretically be completed in approximately 54 hours. However, when corrected for mountain gradients (±20%), carried loads of around 20 kg, and a more realistic average walking speed of 2–3 km/h, the Castellarano–Porcari route would have required approximately 12 effective days of travel, assuming ten hours of movement per day. The use of pack animals would reduce this duration by roughly half, to approximately 6–7 days (Fig. 7).

The archaeological evidence provides further support for the model. Bronze Age sites dated between MBA 1 and MBA 2 tend to cluster along the Castellarano route, frequently within a 4 km buffer zone, suggesting that they may have functioned as intermediate stopping points. In the Secchia Valley, the average distance between sites ranges between 6 and 8 km, corresponding broadly to a day's journey on foot and indicating a settlement configuration compatible with sustained patterns of mobility.

Comparison with the medieval *via Bibulca* (98 km, approximately five days of travel, and +2400 m of elevation gain) also illustrates the limitations of the model. Whereas the historical route follows the valley floor towards the San Pellegrino Pass, the LCPA preferentially

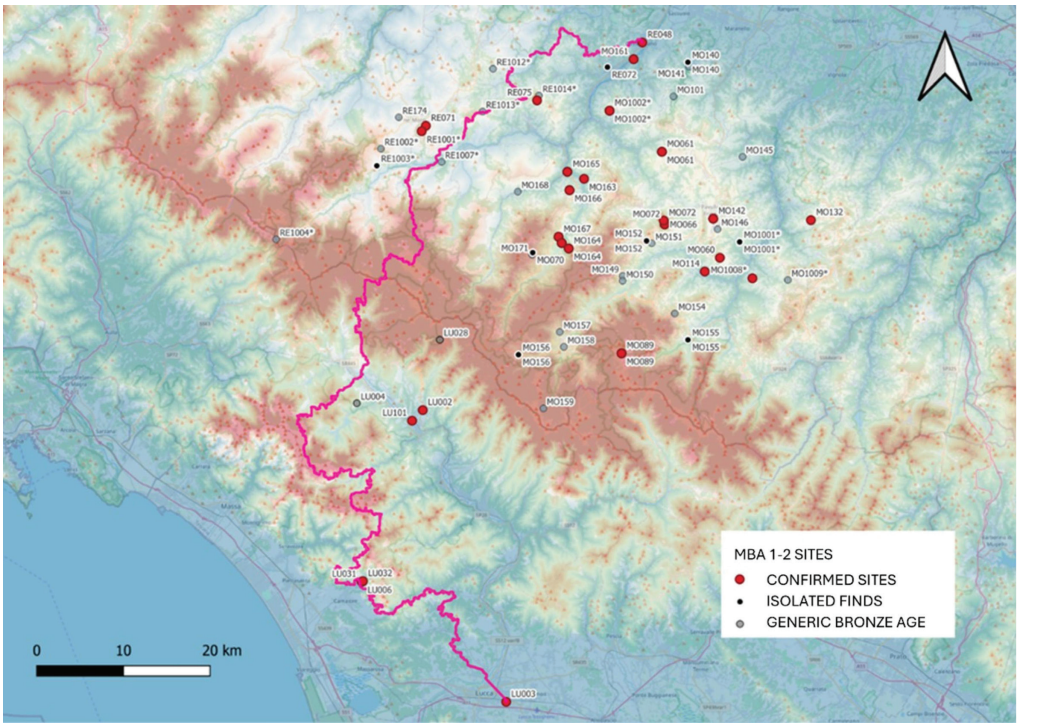


Figure 7. Trans-Apennine route produced with LCPA (in purple) from the site of Castellarano to the site of Fossa Nera di Porcari. (SF)

identifies ridge-based solutions in order to minimise energetic expenditure. This contrast highlights both the heuristic potential and the limitations of LCPA: although the method can effectively identify long-term mobility corridors, its results require critical integration with archaeological and historical evidence in order to avoid overly deterministic interpretations.

Testing the LCP model from Monte della Croce to Rocchetta Mattei

As noted above, a field test was conducted on 30 May 2024 in order to assess the reliability of the LCPA outputs. Starting from the site of Monte della Croce, the route was followed downhill while recording actual travel time and systematically documenting archaeological and environmental features at regular intervals. Observations included pasture and cultivated land, rock shelters, water sources, mineral outcrops, traces of medieval and modern ceramics, and changes in vegetation cover. Visibility checks showed that Rocchetta Mattei first became visible after approximately 50 minutes of walking, while additional Bronze Age sites came into view later along the route. The first water source was reached after approximately one hour.

Some deviations from the modelled pathway proved necessary owing to steep slopes, dense vegetation, fences, private property boundaries, and the crossing of the Reno River, which today requires the use of a bridge situated approximately 300 m away from the LCPA-derived route. To account for such constraints, a tolerance buffer of up to 500 m was applied (Fig. 8).

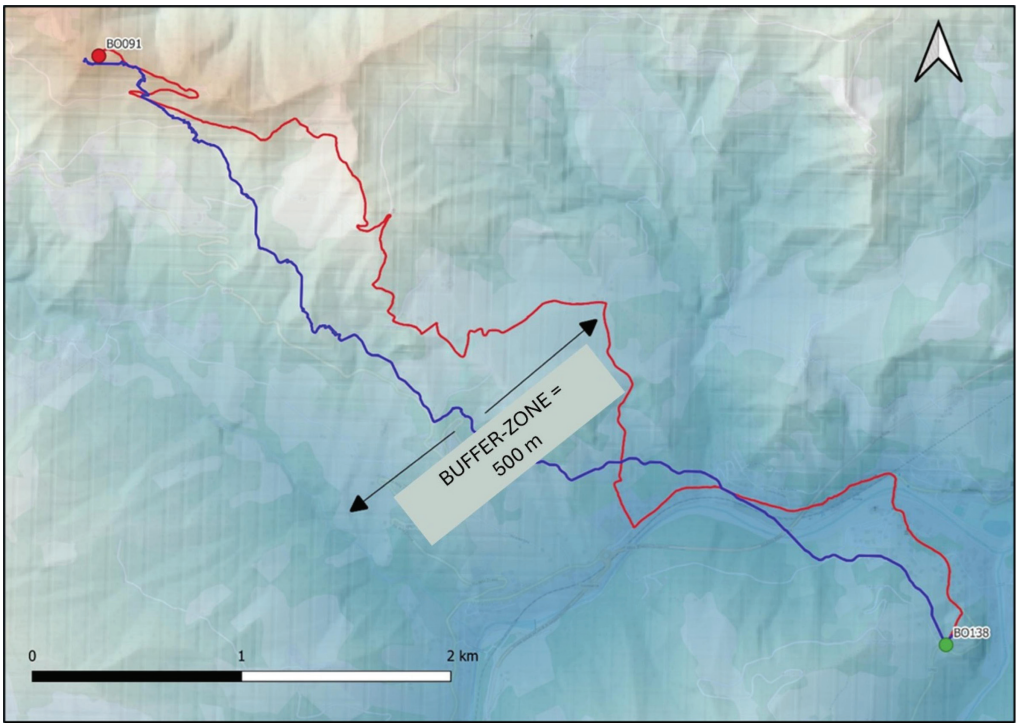


Figure 8. Comparison between the LCPA-generated path vector and the GPX track recorded via GPS during the field test (in red). The tolerance area, or buffer zone, extends c. 500 m on either side of the LCPA path. (SF)

Overall, the observed travel time (2 h 18 min) corresponded closely with the modelled estimate of approximately two hours, and the reconstructed route was considered plausible within the landscape, with deviations largely imposed by modern obstacles. Average walking speed was also calculated in order to further assess the reliability of the model. In this respect, it is important to note that the significance of the spatial tolerance applied to a least-cost path — for example, a 500 m buffer — varies according to the analytical scale considered. In large-scale analyses, such as the Castellarano–Fossa Nera case study, a deviation of this magnitude may be regarded as relatively negligible. At the micro- or semi-micro scale, however, as in the 7 km route tested here, a 500 m offset corresponds to roughly 7% of the total distance and may therefore substantially influence both spatial accuracy and interpretative outcomes.

The field test thus confirmed the heuristic potential of LCPA, while also underscoring the importance of field validation and scale awareness in refining archaeological interpretations of mobility.

Results of LCPV

Turning to the western Apennines, all three visibility approaches described in the methodological section converge on the same overall pattern: Ca' Nova displays extensive long-range visibility over the Taro and Tarodine valleys, while simultaneously presenting

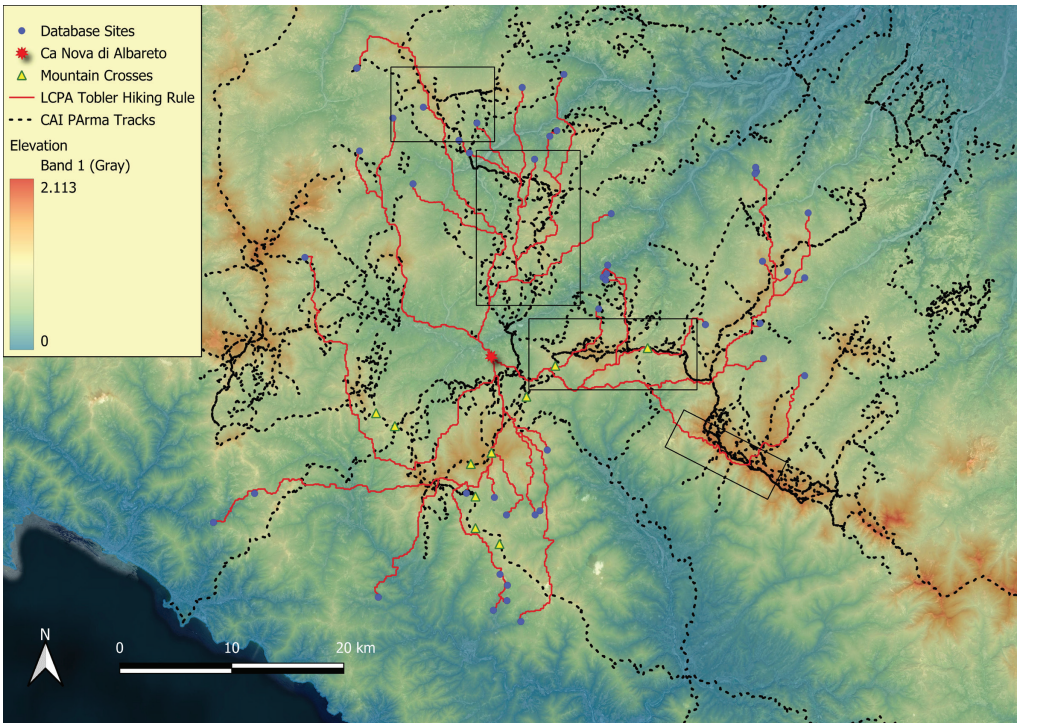


Figure 9. Semi-micro scale visibility. Blind spots around Ca' Nova identified through cumulative viewshed analysis (CVA). (JCA).

persistent blind zones to the north-east and south-west (Fig. 9). This structural duality — combining distal prominence with proximal limitations — remains consistent across binary, cumulative, and distance-weighted analyses, and appears closely related to the local topography, whereby elevated positions favour long-distance visibility while restricting coverage of nearby slopes.

The integration of slope, visibility, and flow accumulation within the LCPV model further refines this pattern. Compared with earlier tests, the adopted weighting scheme reduces the tendency of routes to follow valley bottoms, which are often associated with major watercourses that are difficult or impractical to cross, and instead generates pathways that preferentially follow ridgelines while remaining within visually exposed areas. In this context, the plausibility of the resulting routes is evaluated in relation to their topographic coherence and their consistency with expected movement constraints in mountainous terrain. The multiplicative integration of variables reinforces this effect by penalising areas where constraints overlap, such as sectors characterised by both steep slopes and limited visibility.

Least-cost paths were calculated using both QGIS and GRASS GIS, producing broadly comparable results, although QGIS proved more effective in handling edge destinations. Comparison with the CAI Parma trekking network reveals significant spatial correspondences, particularly when employing the broader 2.5 km destination grid (Fig. 10). This comparison should nevertheless be regarded as heuristic rather than as a form of direct validation: although modern in origin,

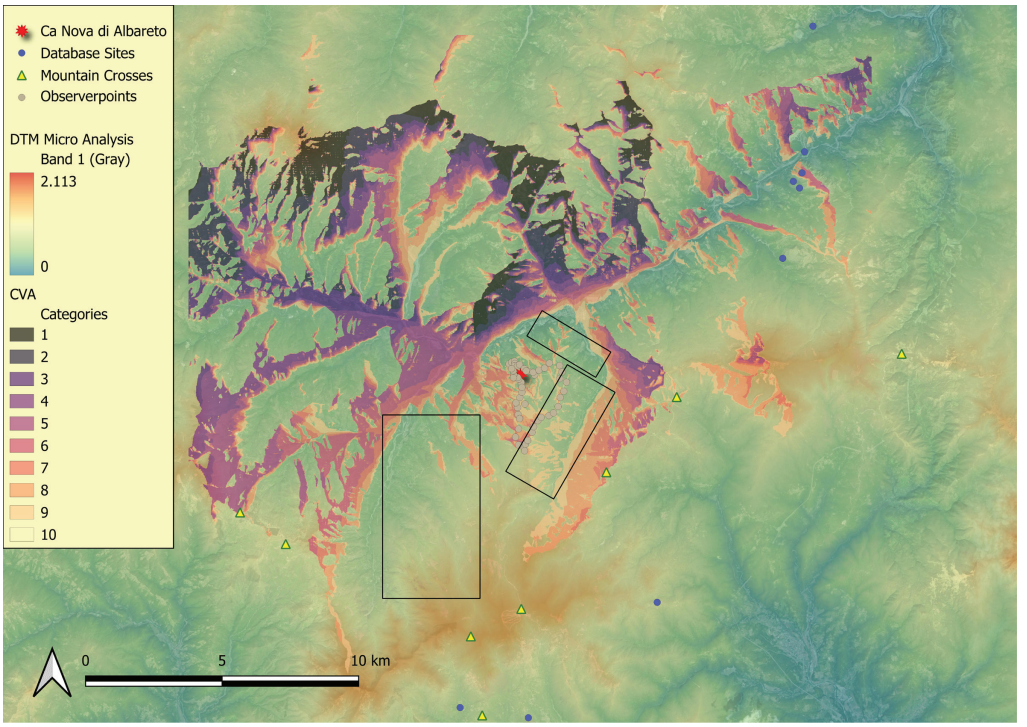


Figure 10. Comparison with CAI Parma trekking routes as a form of "digital ground-truthing" (JCA).

CAI routes reflect the cumulative experiential knowledge of movement across the landscape. Their convergence with the modelled outputs highlights areas of potential correspondence, while divergences help identify parameters requiring refinement and areas warranting further investigation.

Overall, the results indicate that Ca' Nova combined extensive long-range visibility with comparatively restricted local visual control. This configuration suggests that, although the site occupied a visually prominent position within the wider landscape, its capacity to monitor the surrounding area at close range may have been only partial, potentially necessitating complementary vantage points in order to achieve more continuous territorial coverage.

Assessing Potential Site Locations toward Liguria and Tuscany

The integration of LCPV and cumulative viewshed analysis was further developed into a predictive framework aimed at identifying areas where currently undocumented Bronze Age sites may plausibly have complemented the role of Ca' Nova. The objective is not to reconstruct settlement patterns with certainty, but rather to highlight zones where movement efficiency and visual exposure converge.

The identification of these potential locations was guided by a series of spatial criteria derived from the previous analyses, including proximity to least-cost paths and mountain passes,

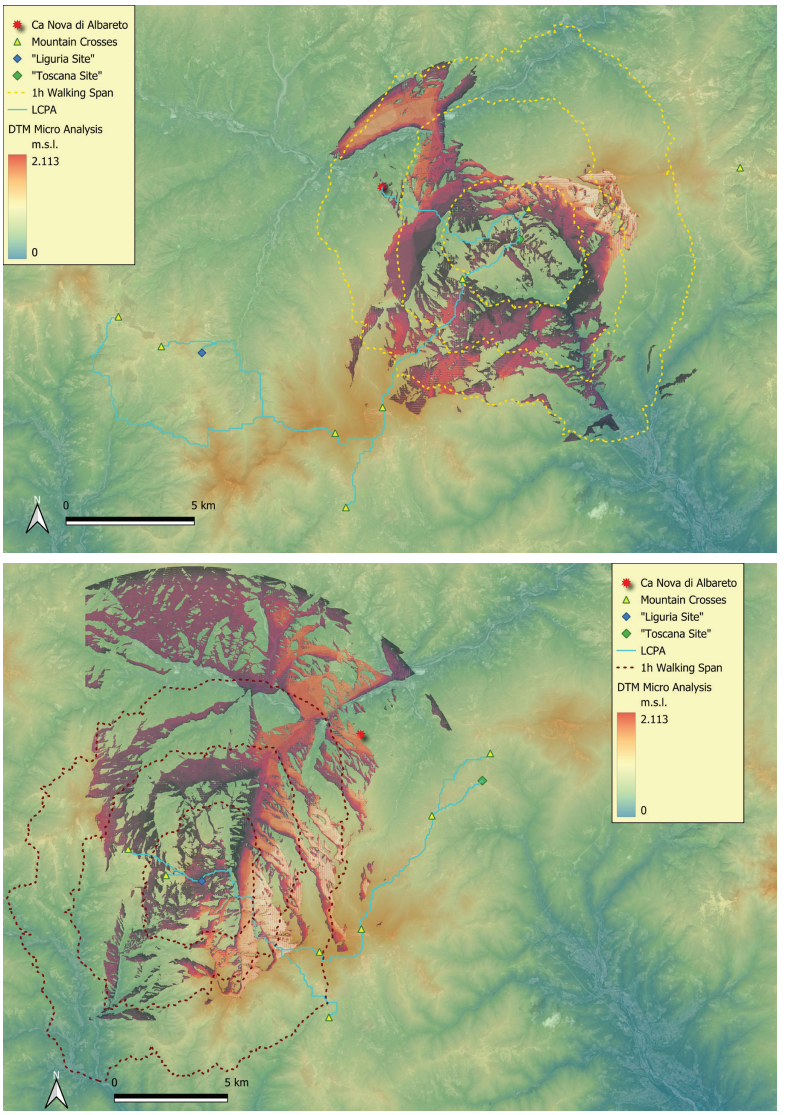


Figure 11. Predictive modelling. Proposed complementary sites toward Tuscany (a - above) and Liguria (b - below), combining viewsheds and LCPA paths. (JCA).

inclusion within the cumulative viewshed (CVA) of Ca' Nova, potential intervisibility, and location on elevated terrain within an estimated walking range of approximately one hour. Taken together, these parameters define areas where mobility and visibility intersect most effectively.

Two locations emerge as particularly significant (Fig. 11). To the south-east, near the Bratello and Borgallo passes leading towards Tuscany, elevated plateaus situated within roughly one hour's walk of the principal movement corridors provide extensive visibility over the routes descending into the Magra Valley. To the west, in the area surrounding the Cento Croci and Scassella passes on the Ligurian frontier, a comparable topographic configuration can be observed, characterised by elevated terrain and broad visibility across the Gotra Valley and

the principal routes traversing the area. In both cases, these locations are intervisible with Monte Chiaro and correspond to areas that help compensate for the north-eastern and south-western blind zones identified in the local-scale analysis.

When cumulative viewshed analyses are recalculated from these proposed locations, a complementary pattern becomes apparent. Areas previously identified as poorly visible from Ca' Nova — particularly within the north-eastern and south-western sectors — become incorporated into the combined visibility field. Although this does not imply complete or continuous visual coverage, the overlapping CVA outputs suggest a more distributed and integrated visibility structure across the landscape.

Least-cost modelling based on Tobler's Hiking Function further indicates that the routes connecting Ca' Nova with the proposed locations tend to follow ridge systems and areas of lower slope, while avoiding valley bottoms associated with major watercourses. This pattern is clearly visible in Figure 11, where the modelled pathways preferentially track elevated terrain and intersect key mountain passes. Their close correspondence with the topographic structure of the landscape supports the interpretation of these areas as potential complementary vantage points within a broader spatial network.

Although necessarily hypothetical, this approach helps address the apparent isolation of Ca' Nova within a regional context otherwise characterised by clusters of intervisible sites. By identifying plausible complementary locations, it generates testable hypotheses capable of guiding future field survey. In this respect, predictive modelling operates both as an analytical tool — exploring the relationship between movement and visibility — and as a heuristic framework for directing future archaeological investigation.

Predictive and postdictive results of the FETE and FETS LCPA

Lastly, the implementation of the FETE and FETS Least Cost Path Analyses yielded particularly interesting outcomes. When tested within a smaller yet significant analytical window centered on the upper valleys of the Reno and Panaro rivers, the method highlighted several areas of potentially high mobility intensity. By applying both predictive and postdictive perspectives to the simulation, two main zones emerged as likely focal points of movement within the reconstructed network.

The first of these areas corresponds to an interfluvial crossroads where southward-oriented paths intersect EW routes linking two of the principal hilltop sites of this period, Monte della Croce (Cavazzuti *et al.* 2025) and Gaiato (Cardarelli, Malnati 2006). Within this sector, the site of Montese (Zanotti *et al.* 2023), currently under reassessment, falls precisely within the area of highest predicted mobility. Although only generic Bronze Age ceramic fragments have been recovered there so far, and the site has not yet been firmly attributed to the LBA 1, its position lends preliminary support to the model's reliability.

The second area of interest lies on the Masera pass, an apparent archaeological void between two of the highest-elevation settlements known for this period, Castelluccio di Porretta (Scarani 1963) and Fanano (Cardarelli, Malnati 2006). Situated along a longitudinal ridge leading toward the main Apennine divide between present-day Tuscany and Emilia-Romagna,

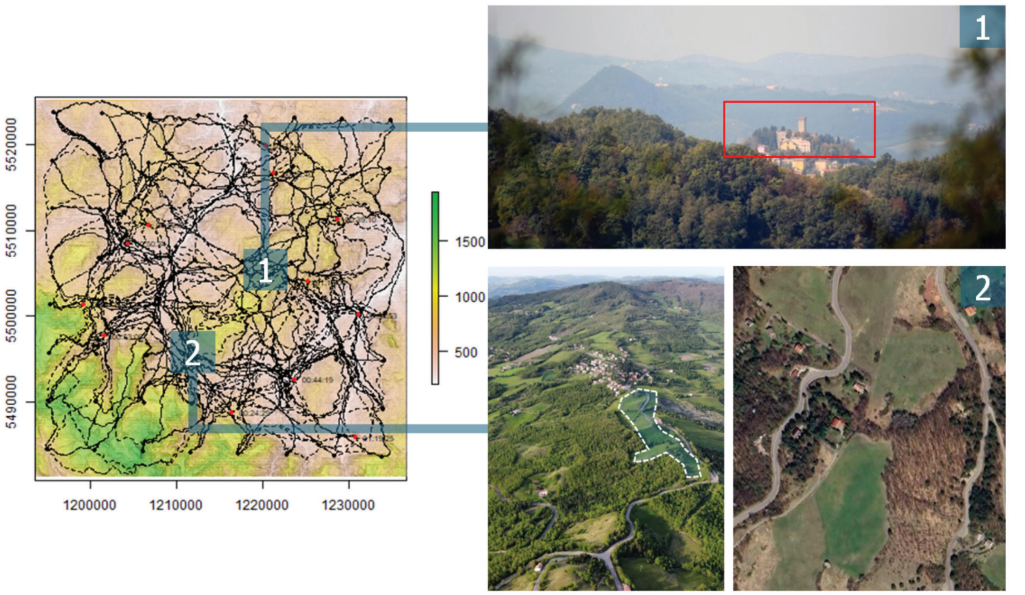


Figure 12. Here highlighted, with the plot produced with movenetw, the two areas with higher mobility outside the FETS network: 1) Montese, in the red square, with the sharp peak on which Gaiato lies, and 2) the Masera pass located in the void area between the two LBA1 sites of Castelluccio and Fanano. (EZ)

this corridor also exhibits a high probability of mobility. Its location, in close proximity to zones that were likely exploited for charcoal production during this phase of the Bronze Age (Benatti *et al.* 2019), further strengthens its interpretive potential (Fig. 12).

Although preliminary, these results underscore the promise of digital modelling techniques such as FETE and FETS LCPA in supporting subsequent stages of research. Ultimately, the patterns identified here will require verification through systematic ground-truthing and targeted field survey to assess the archaeological validity of the proposed mobility routes.

Discussion

The density analysis presented in this paper stems from the assumption that the occupation of the Emilian Apennines was closely connected to the Terramare settlement system of the Po Plain (Putzolu and Cavazzuti 2019, 253), as has likewise been suggested for the same chronological horizon in the central-eastern Alpine region (Carrer and Migliavacca 2019). The uplands likely functioned as a crucial catchment area for a wide range of raw materials and resources, including specific plant taxa, charcoal, steatite, deer antler, and possibly copper minerals. Through the network of routes crossing these territories — largely corresponding to the river corridors of the Apennine system (Putzolu and Cavazzuti 2019, 260) — the uplands facilitated connections between the Po Plain and the Tyrrhenian coast, enabling access to maritime resources, most notably salt.

The settlement pattern identified across most of the Emilian Apennines — extending from the Taro River basin in the west to the Reno basin in the east — is characterised by clusters of sites linked through direct intervisibility and strategically positioned to control the principal trans-Apennine routes. These pathways may also have functioned as short- and medium-distance transhumance routes within an economic system connected to wool production, recently hypothesised for the Middle and Late Bronze Age Emilian plains (Putzolu, Del Fattore, and Tecchiati forthcoming; Sabatini *et al.* 2022). Although Sabatini and colleagues observed that the area surrounding the Terramara of Montale may already have been capable of sustaining large herds, they further suggested that "exploitation of the neighboring mountainous terrains would provide the chance for even larger herds and/or more articulated economic and organisational solutions", implying that "at least part of the herds were mobilized and brought for instance to summer pastures" (Sabatini *et al.* 2022, 1, 9).

The recognition of relatively homogeneous site densities across much of the Emilian Apennines, together with the identification of recurring settlement strategies adapted to a different ecotonal environment yet still reflecting the same logic of village networks exercising local territorial control — the defining feature of the Terramare system in the Po Plain — highlights the importance of a region whose contribution to the success of the Terramare system has often been underestimated. Even the enormous demand for timber generated by the Terramare settlements would alone underline the strategic significance of the uplands for the major lowland centres, particularly with regard to mountain-specific species such as beech, pine, and chestnut. More broadly, however, the importance of the Apennines as a living environment in their own right becomes especially evident when considering that, among the relatively few sites across the entire Terramare cultural sphere yielding material culture attributable to the final stages of the Late Bronze Age (*Bronzo Finale* in Italian chronology), the majority are located in mountain contexts. This pattern may reflect the resilience of an area whose economy was likely more self-sufficient than that of the Po Plain and therefore better able to develop diversified subsistence strategies capable of responding to the twelfth-century BC crisis that led to the collapse of the Terramare system (Cardarelli 2009).

The LCPA results further demonstrate the usefulness of least-cost modelling for identifying mobility patterns in mountainous landscapes. At the same time, the discrepancies observed between the modelled outputs and the actual topographic configuration of the terrain indicate that such models must always be interpreted critically and in relation to the specific constraints imposed by the landscape, rather than treated as direct representations of past movement.

The LCPV results provide a more nuanced understanding of the relationship between movement and visibility at the local scale. In the case of Ca' Nova, their significance lies in the contrast between extensive long-range visibility and more restricted visual control over the immediate surroundings. This pattern reflects the morphology of the terrain itself: elevated locations favour distant visibility, but do not necessarily guarantee comprehensive oversight of nearby areas. Consequently, the site appears visually dominant at a broader territorial scale while remaining comparatively constrained within its immediate environment.

Rather than suggesting a system of continuous or coordinated visual control, these results instead point to a landscape in which visibility was uneven and strongly conditioned by

topography. No single location appears capable of ensuring complete visual coverage. In response to this pattern, the predictive analysis identified two potential areas of archaeological interest — oriented respectively towards Liguria, and thus coastal routes, and towards Tuscany and inland connections — which may have contributed to a more continuous visual presence across this frontier zone.

From a methodological perspective, the integration of slope, visibility, and flow accumulation makes it possible to approach movement as the outcome of interacting constraints rather than isolated variables. In this sense, pathways reflect not only topographic accessibility, but also the distribution of visual exposure across the landscape, particularly where these factors converge.

Finally, the predictive extension of the model demonstrates its value for identifying areas where such variables intersect. The LCPV approach therefore provides a useful framework for investigating how movement and visibility may have shaped the organisation of the landscape, while simultaneously offering a basis for future archaeological exploration.

Conclusion

The data and models presented here suggest that the substantial increase in site density within the mountain regions of Emilia during the Middle Bronze Age (c. 1650-1350 BC), continuing into the Late Bronze Age (c. 1350-950 BC), was associated with settlement strategies oriented both towards the exploitation of land and resources and towards the control of preferential trans-Apennine routes. Further research is particularly needed in the higher-altitude zones (above 1000 m a.s.l.) in order to clarify the role of the Tuscan-Emilian ridge areas, both in terms of resource exploitation — such as vertical transhumance and charcoal production — and as preferential corridors connecting Northern Italy with the rest of the peninsula.

LCPA and intervisibility networks may contribute significantly to the development of predictive models capable of improving both the identification of new archaeological sites and our understanding of human mobility and territorial control. By integrating movement and perception, these approaches provide a heuristic framework for exploring how prehistoric communities experienced and structured their landscapes. Ultimately, such predictive models may guide future research by highlighting areas where archaeological evidence can be used to test and refine these interpretative hypotheses.

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Authors' roles

Conceptualisation: CP, CC; Data curation: CP, SF, JCA, EZ; Formal analysis: CP, SF, JCA, EZ; Investigation: CP, CC, SF, JCA, EZ; Methodology: SF, JCA, EZ; Supervision: CP, CC; Writing: CP, CC, SF, JCA, EZ.

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