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From dots to dynamics: Searching the complexities of prehistoric mobility in the Lisbon Peninsula

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ABSTRACT

This study explores prehistoric mobility networks in the Lisbon Peninsula, focusing on the Chalcolithic and Late Bronze Age periods. Utilising Least Cost Path (LCP) methodologies and Tobler's Hiking Function, movement patterns and connectivity between settlements were analysed. The research reveals a complex landscape of human interactions and environmental adaptations, highlighting social and economic transformations across these periods. In the Chalcolithic, a dense network of routes was identified, which suggest intense social and trade exchanges. In contrast, the Late Bronze Age (LBA) exhibits a changed mobility landscape, with less dense but more focused routes, reflecting possible socio-economic reorganisations. This study not only sheds light on the territorial dynamics of the Lisbon Peninsula during these critical periods but also contributes to a richer understanding of occupation strategies and the relationship between humans and their environment.

1. Introduction

In prehistoric societies, the connection among communities and their respective settlements is only evidenced indirectly. Mobility is a key component of the economic, social and symbolic dynamics of such communities (Kelly, 1992; Leary, 2014), and the regional circulation of raw materials, people, and livestock (Barnard and Wendrich, 2008; Leary, 2014), along with the diffusion of cultural features, like architecture and pottery, point at the existence of complex social networks. The study of mobility is often associated with the circulation of materials through geochemical analysis and migration models (Olalde et al., 2019; Furholt, 2018) towards long-distance relationships. Short distance mobility is more difficult to assess and is mainly studied through the geographic analysis of the settlement network and in the material culture.

The present paper addresses mobility by focusing on a GIS approach, which follows several key questions: 1) How do the interrelation patterns of Chalcolithic walled enclosures, analysed through Least Cost Path (LCP) and Tobler's Function, reflect the socio-economic dynamics of these societies? 2) What are the changes in movement and connectivity between the Chalcolithic and Late Bronze Age periods, and how do these changes mirror broader shifts in social structures, subsistence practices, and territorial organisation? 3) In what ways did environmental features and human choices shape the landscape and movement patterns, and what do these patterns reveal about the social and economic pathways connecting prehistoric communities?

The subject area is the Lisbon Peninsula, a narrow slit of land nestled between the Lower Tagus River and the Atlantic Ocean (Fig. 1). The region is a rich mosaic of geological features, characterised by a varied substratum, with extensive areas of marls and limestones interspersed with basalt and granite formations, all of which contribute to the area's diverse topographical and ecological landscape. This area is a significant locus of prehistoric activity, as evidenced by the detection of a considerable number of Chalcolithic walled enclosures (20) and Late Bronze Age settlements (16), of which seven are hilltop settlements and nine are low settlements) (Fig. 2).

Furthermore, the Holocene marked a distinct phase in the region's geological history, particularly regarding its coastal configuration. During this period, the coastal line of the Lisbon Peninsula was considerably different than it is today. This would have significantly influenced the settlement patterns, resource distribution, and mobility of the prehistoric communities. The coastal environment, coupled with the varied geological substratum, would have played a crucial role in shaping the socio-economic structures and cultural developments of the

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societies that thrived in this region. Notably, these historical geological conditions have been detailed in studies such as those by Ramos-Pereira and Ramos (2020), providing crucial insights into the environmental backdrop against which these ancient communities lived and interacted.

The Chalcolithic period, in the Lisbon Peninsula's prehistory, is characterised by a flourishing of cultural and economic activities. Walled enclosures are landmarks of the onset of copper metallurgy, *tholos* tombs, and intensified agro-pastoral practices (Sousa, 2021), pivotal for unravelling the socio-economic dynamics that underpinned Chalcolithic societies (Díaz-del-Río et al., 2021). These sites share many architectural features, such as walled and ramparted enclosures, what appear to be defended gates, and semi-circular bastions and towers (Gonçalves et al., 2013; Llull et al., 2018; Kunst, 2021). Walled enclosures usually occupy high and strategically important places, granting control of the surrounding landscape. The establishment and development of these enclosures took place during the third millennium BC in several areas of the Iberian Peninsula, with a special prominence in the Portuguese Estremadura (Lisbon and Setúbal *Peninsulae*) and in the Southeastern part of present-day Spain. However, there is a need to underscore that these areas include some of the best known and well researched sites, such as Los Millares, Zambujal and etc, which might introduce some bias. The analysis of material culture (mainly pottery) during the third millennium BC, seems to point to the development of a strong regional cultural identity (Fig. 3). However, at the same time, relations with wider territories are nonetheless present, proven by the presence of exogenous material and similar symbolic practices to the ones present in Southern Spain (Bueno Ramírez and Soler Díaz, 2021). The cultural landscape, with walled enclosures and other archaeological sites (including several tomb types namely *tholoi*, hypogea, natural caves and dolmens), reflects the complex interplay of human activity and environmental adaptation.

While the Chalcolithic period provides a vivid panorama of the region's social and economic complexity, the subsequent Late Bronze Age era offers an intriguing contrast (Sousa and Sousa, 2018). This phase, marked by an apparent decline in the number and monumentality of settlements and tombs and a reorganisation of pre-existing networks (Blanco-González et al., 2018; Valera, 2021), serves as an important point of comparison for understanding the dynamics of change. Up until the Late Bronze Age (ca 1200–800 BC) (Mataloto et al., 2013) — and the appearance of new hilltop settlements—, the region does not evidence any sign of recovery of the visibility of the settlements and the reestablishment of wider interregional connections (Cardoso, 1999–2000; Vilaça and Cardoso, 2017). From this standpoint, we have chosen to compare these two periods in an attempt to analyse the mechanisms underlying mobility networks and their evolution, while testing the methodology used in two different case studies. In spite of the focus on features of the Chalcolithic and Bronze Ages such as monumental structures and material culture, there is a dearth in the research into movement patterns and connectivity between sites in this specific region. Our study aims to bridge this gap, and make a contribution to the long-term chronology of the Lisbon Peninsula during the Third and the second millennia. By studying mobility, and the placement of redistribution hubs within the landscape (Manière et al., 2021), this research aims for a new perspective on the ancient movement of people, which undoubtedly shaped the region's history, thereby highlighting the convergence of influences and peoples in northern Estremadura during the third millennium B.C.

2. Methodology

The surveyed area includes 20 walled Chalcolithic enclosures. We have selected the sites which offer accurate chrono-cultural information, extracted from archaeological fieldwork. The "open" sites have not been considered, as they are mainly characterised by finds in plough-soil, which do not include many sites with structures and C14 analysis. In addition, we must consider walled enclosures as central nodes in chalcolithic networks, featuring long-term occupations and frequent presence of «ideo-technic » materials (Andrade et al., 2020).

The methodology employed follows the analysis of three primary environmental parameters: orography, hydrography, and land use, using paleoenvironmental data from the 3rd millennium BC (García-Artola et al.,2018; Ramos-Pereira and Ramos, 2020; Schirrmacher et al., 2024). The weighing of each parameter was carefully adjusted according to its impact on prehistoric human mobility. Specifically.

- Orography: The terrain slope was calculated using the digital elevation model (DEM), applying the anisotropic values proposed by Llobera (1999), which reflect increasing mobility costs with higher inclinations. The slope's influence was critical in determining the

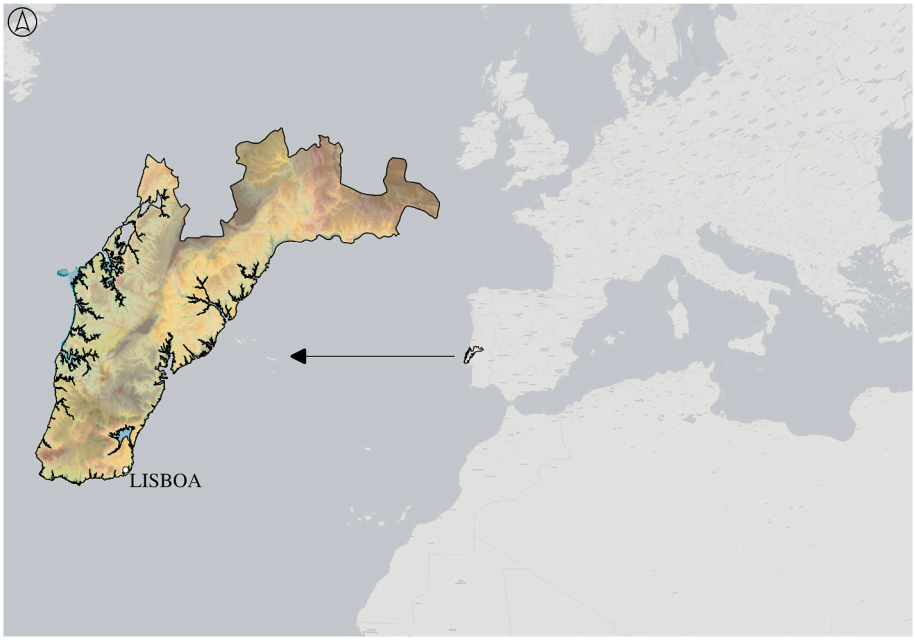


Fig. 1. Contextualising the study area within Europe by authors.

paths taken by prehistoric populations, making this variable essential in our analysis.

- Hydrography: Rivers and estuaries are considered natural barriers. River crossings, particularly in regions with wider bodies of water, implicate higher mobility costs. However, in areas near estuaries where fluvial movement could facilitate displacement, the cost was considered lower, in order to reflect their potential role as transport corridors.
- Land Use: Areas with fertile soils, such as alluvial soils near watercourses, were rated as having lower mobility costs, given their attractiveness for human settlement. In contrast, rocky or less arable soils were assigned higher costs.

These parameters were integrated through rasterization of the environmental layers, with different cost values assigned to each terrain type. The final output was a unified cost mesh that served as the foundation for the Least Cost Path (LCP) calculations between Chalcolithic and Bronze Age settlements. The proposed 380 trajectories were arrived at by considering all possible routes between the 20 Chalcolithic walled enclosures and the 16 Bronze Age settlements analysed, which generate multiple paths between nodes, and represent the complexity of the mobility network.

The distribution of the Late Bronze Age sites (LBA) exhibits a notable shift in settlement patterns when compared to the Chalcolithic ones. These sites, 16 in total, include both hilltop and walled enclosures, as well as open settlements in flat areas. In the LBA, hill settlements are often found at higher altitudes, as exemplified by significant sites like Cabeço de Alcainça, Serra do Socorro in Mafra, Castelo dos Mouros in Sintra, and Castelo da Amoreira in Odivelas (Sousa and Sousa, 2018) (Fig. 4). At these locations, preliminary surveys and small-scale excavations have provided hints at possible walled structures, which could be embankments or remnants of more substantial constructions. This variation in settlement altitude and structure in the LBA provides a contrasting dynamic to the Chalcolithic period, enriching our understanding of societal changes across these periods.

In this study, we applied the Least Cost Path (LCP) methodology to investigate the dynamics of movement during the Chalcolithic period and Late Bronze Age in the northern Portuguese Estremadura. Recognising the crucial role of environmental elements in shaping human mobility, our approach is rooted in the analysis of the intricate relationship between natural landscapes and the archaeological record, including monuments and settlements (Fábrega Álvares and Parcero-Oubiña, 2007; Howey, 2011). Our primary aim with LCP was not to delineate precise historical routes, but rather to explore the broader network of connectivity between settlements, offering insights into the ways in which movement was facilitated within these landscapes (Fábrega Álvarez, 2006; Caseldine, 2021).

This methodology entailed an in-depth analysis of three environmental parameters: orography, hydrography, and soil use. In order to reach a more realistic approximation, we have performed this exercise based on the paleo coastline of the third millennium BC (Ramos-Pereira and Ramos, 2020). Each of these elements was meticulously examined to generate individual cost meshes, which were subsequently merged into a comprehensive layer representing the overall mobility cost across the terrain (Safi, 2014; Becker et al., 2017; Gowen y de Smet, 2020; Caseldine, 2021; Lewis, 2021; Manière et al., 2021). Rivers and estuaries played a crucial role in defining mobility costs. During the Chalcolithic, river crossings were modelled as significant natural barriers, raising the cost of mobility in regions where crossings would require substantial logistical effort. Conversely, areas near estuaries, which facilitated displacement and access to resources, were modelled with lower mobility costs, reflecting their potential as transport corridors. This treatment of hydrographic features allowed us to capture the complexity of human movement within the landscape of the Lisbon Peninsula. The high-resolution data, essential for the accuracy of our model, was sourced from the Copernicus Land Monitoring Service and Copernicus-EU, with a specific focus on the DEM layer, characterised by a 30m mesh size, the most detailed available for our study area in

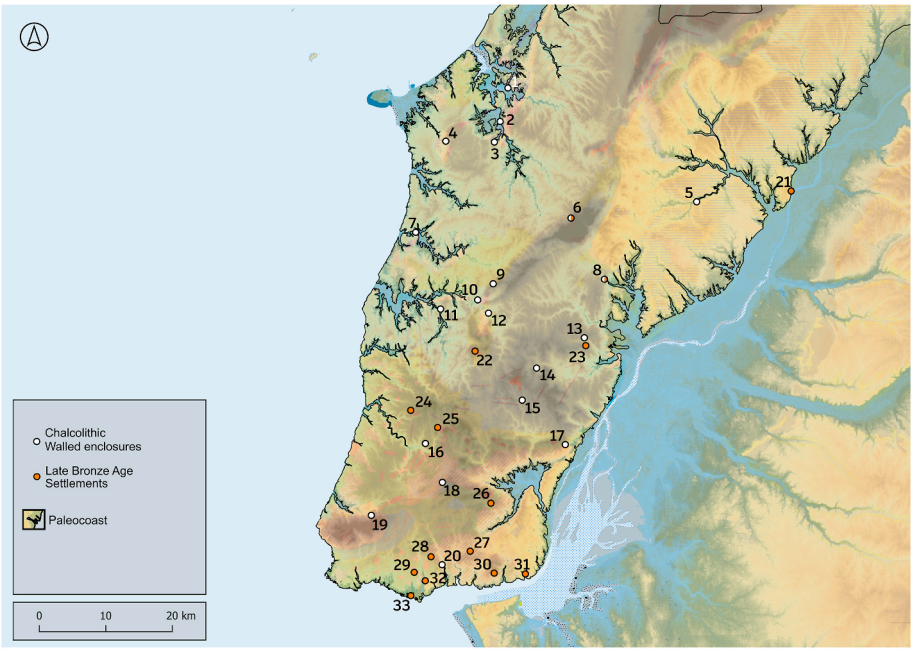


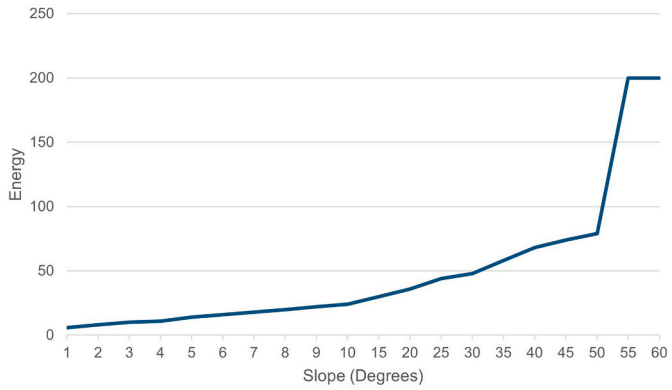
Fig. 2. The archaeological sites under study – 1: Outeiro da Assenta (Óbidos); 2: Outeiro de São Mamede (Bombarral); 3: Columbeira (Bombarral); 4: Paço (Peniche); 5: Vila Nova de São Pedro (Azambuja); 6: Pragança (Cadaval); 7: Pico Agudo (Torres Vedras); 8 - Ota (Alenquer); 9: Achada (Torres Vedras); 10: Fórnea (Torres Vedras); 11: Zambujal (Torres Vedras); 12: Penedo (Torres Vedras); 13: Pedra de Ouro (Alenquer); 14: Castelo (Arruda dos Vinhos); 15: Moinho do Custódio (Arruda dos Vinhos); 16: Penedo do Lexim (Mafra); 17: Moita da Ladra (Vila Franca de Xira); 18: Olelas (Sintra); 19: Penha Verde (Sintra); 20: Leceia (Oeiras); 21: Santarém; 22: Serra do Socorro; 23: Amaral (Alenquer); 24: Quinta da Cerca 2 (Mafra); 25: Cabeço de Alcainça (Mafra); 26: Castelo da Amoreira (Odivelas); 27: Moinho da Atalaia (Amadora); 28: Alto das Cabeças (Oeiras); 29: Cabeço do Mouro (Cascais); 30: Tapada da Ajuda (Lisbon); 31: Encosta de Santana (Lisbon); 32: Abrunheiro (Oeiras); 33: Quinta Nova de Santo António (Cascais) by authors.

Fig. 3. Local materials of the Lisbon Peninsula. A) Grooved cup (copo canelado) from Penedo do Lexim (Sousa, 2021); b) "Acacia leaf" decorative style from Penedo do Lexim (Sousa, 2021) by Victor Gonçalves; c) and d) Globular pot and drawing from Zambujal (Kunst, 2010).

Fig. 4. Comparative landscapes illustrating – walled enclosures (a,b,c) and hilltops settlements (d,e,f). by authors.

Portugal (Lewis, 2021).

In executing the GIS analysis using GRASS in QGIS (3.10), our process involved the importation and integration of various environmental layers, followed by their rasterization and slope calculation. The data underwent reclassification to achieve anisotropic values based on established scales by Llobera (1999) for slopes and López Romero (2005) for hydrography and soils, thereby facilitating a dynamic and directionally sensitive cost analysis (see Graph 1). The culmination of this phase was the creation of a unified cost map, which served as the foundation for the LCP route calculations between the Chalcolithic settlements. To further refine our analysis, we conducted 380 route calculations, resulting in a heatmap visualisation to emphasise movement avenues between sites. However, more often than not, these routes highlighted the archaeological sites as primary hotspots. Therefore, in order to focus on the mobility networks between sites, we implemented a 1 km buffer around each site, removing all intersections within this



Graph 1. Relationship between terrain slope and mobility cost based on Llobera (1999).

zone. This approach successfully revealed the principal movement corridors, and provided a clearer depiction of the inter-site mobility networks in the Lisbon Peninsula, during both the Chalcolithic and Late Bronze Age periods (Fig. 5).

Further enhancing the depth of our analysis, we incorporated Tobler's hiking function into the recalculation of the LCP to estimate the time required for travel between points, thus adding a critical temporal dimension to our spatial analysis (Tobler, 1993; Pingel, 2009).

It is, however, imperative to acknowledge the inherent limitations of the LCP methodology. The primary limitation stems from the presumption that ancient travellers possessed optimal knowledge of the landscape, consequently selecting the most efficient routes. This assumption often results in the generation of a singular, optimal route for each analysis, which potentially does not reflect the true historical complexity of human movement (White, 2015). Moreover, the LCP analysis does not account for the mobility constraints faced by large groups, or individuals burdened with loads, factors which would significantly impact real-world travel dynamics. As such, the paths identified through our analysis are best regarded as approximations of potential historical routes, rather than definitive reconstructions (Caseldine, 2021).

In short, our methodology combines advanced GIS techniques with archaeological and environmental data, offering a nuanced exploration of movement patterns and connectivity within Chalcolithic societies in Lisbon Peninsula. While acknowledging its limitations, this approach strives to provide a richer and more holistic understanding of the interplay between humans and their environment during this

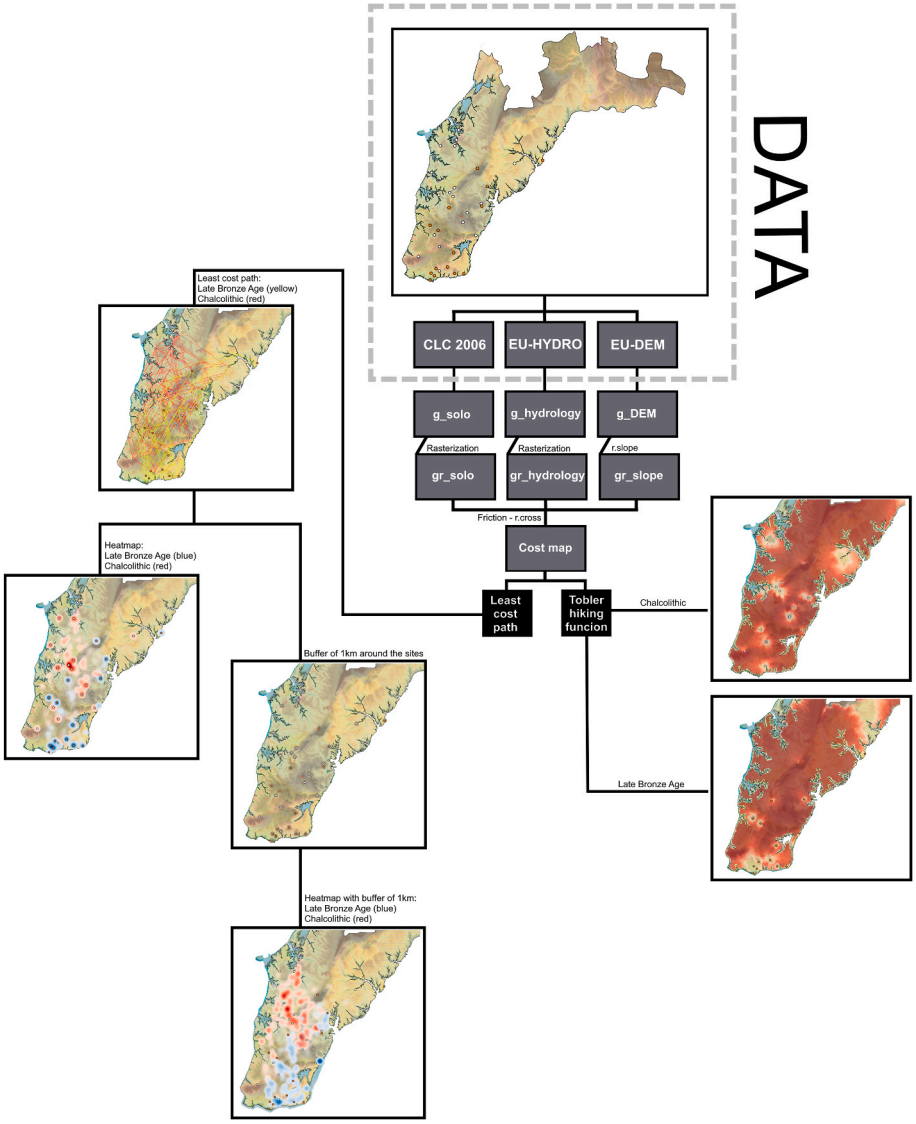


Fig. 5. Workflow followed in the creation of final products.

archaeological period.

3. Results

The analysis of mobility networks in prehistoric societies of the Lisbon Peninsula, during the Chalcolithic and Late Bronze Age, reveals a complex landscape of human interactions and environmental adaptations. The use of LCP methodologies and Tobler's hiking function allowed for a quantitative approach to potential travel routes, offering new insights into settlement patterns and regional connection networks.

The results from the LCP application (380 routes) indicate that during the Chalcolithic, communities established an intersecting network of routes, reflecting a complex system of territorial movement. The most densely used routes suggest the existence of main corridors that facilitated mobility between walled enclosures which would be fundamental for social interaction and trade. This pattern is reinforced by the presence of nodal points, understood as locations where several routes converge, which may have functioned as nerve centres for cultural and economic activity. Contrasting with the Chalcolithic, the Late Bronze Age evidence reveals a transformed mobility landscape, mainly attested by a decrease in the number of settlements (16). These routes (208) are less dense but more focused, suggesting a possible reorganisation of activity centres and socioeconomic dynamics. This shift may reflect adaptations to environmental variations, new social structures, and/or changes in subsistence strategies and trade.

This in-depth spatial analysis, illustrated through heatmaps (Fig. 6), allows us to visualize of the distribution of route intersections. In the Chalcolithic, intersections are widely spread, suggesting an extensive and well-distributed use of the territory, even though the main axes of movement are somewhat clearer in the relations between the current territories of Torres Vedras and Arruda dos Vinhos/Alenquer, Torres Vedras and Mafra, or Torres Vedras, and the areas around the Óbidos Lagoon. However, in the Late Bronze Age, these areas seem to be displaced towards the vicinity of present-day Lisbon, on the banks of the Tagus, largely due to the emergence of new sites (see Fig. 2).

The heatmap visualisation revealed areas of greatest density of route intersections, which suggest the existence of priority movement corridors that connected the main settlement centres during the Chalcolithic and Late Bronze Age. While in the Chalcolithic the routes are widely distributed across the territory, reflecting an intensive and diffused use of the landscape, in the Bronze Age the routes became less dense and more focused on specific areas, suggesting a reorganisation of socio-economic activity centres.

The analysis of the primary mobility axes and nodal points identified priority corridors connecting the main settlement centres during the Chalcolithic and Late Bronze Age. These corridors were fundamental in facilitating trade and communication, reflecting the socio-economic complexity of these societies. In the Chalcolithic, the axes connecting Torres Vedras to Alenquer and Arruda dos Vinhos, as well as Torres Vedras to Mafra, stand out as key routes with numerous intersections, indicative of a widely distributed and interconnected use of the territory. By contrast, in the Late Bronze Age, these main axes shifted towards the Tagus estuary region, with the emergence of new focal points near present-day Lisbon. This reorganisation suggests significant changes in socio-economic structures, potentially reflecting a more centralised mode of interaction.

By incorporating a temporal dimension with Tobler's hiking function (Fig. 7), the results highlight the immediate territories of Chalcolithic and Late Bronze Age sites, providing a sense of territories accessible within 2 h and 30 min, or less, of walking. This data underscores the efficiency of mobility networks, and their ability to maintain social and economic cohesion throughout a diverse landscape. Furthermore, the integration of Tobler's hiking function into the analysis provided a temporal dimension to the connectivity networks. The Chalcolithic routes demonstrated travel times of less than 2 h between major settlements, highlighting the efficiency of the mobility system. In contrast, Late Bronze Age routes, while fewer in number, exhibited longer travel times, reflecting the spatial reorganisation and increased focus on strategic nodes along the Tagus estuary.

The quantitative results derived from the LCP and Tobler's hiking exercises, complemented by graphical visualisations, not only highlight the main routes and interaction points but also pave the way for a deeper understanding of strategies of territorial occupation. These strategies appear to be guided both by physical geography and by the needs and choices of the communities that shaped the landscape. In particular, the analysis of routes from the Chalcolithic and Late Bronze Age reveals a mosaic of paths intertwining across the landscape, cutting through valleys and hills, following watercourses, and circumventing natural

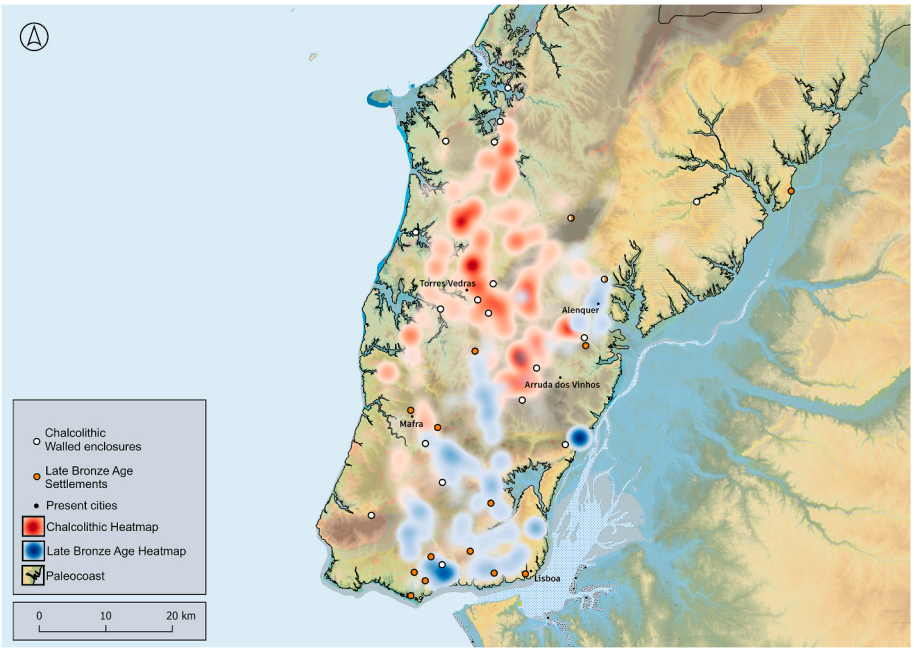


Fig. 6. Heatmaps of the interceptions of the Chalcolithic and Late Bronze Age routes by authors.

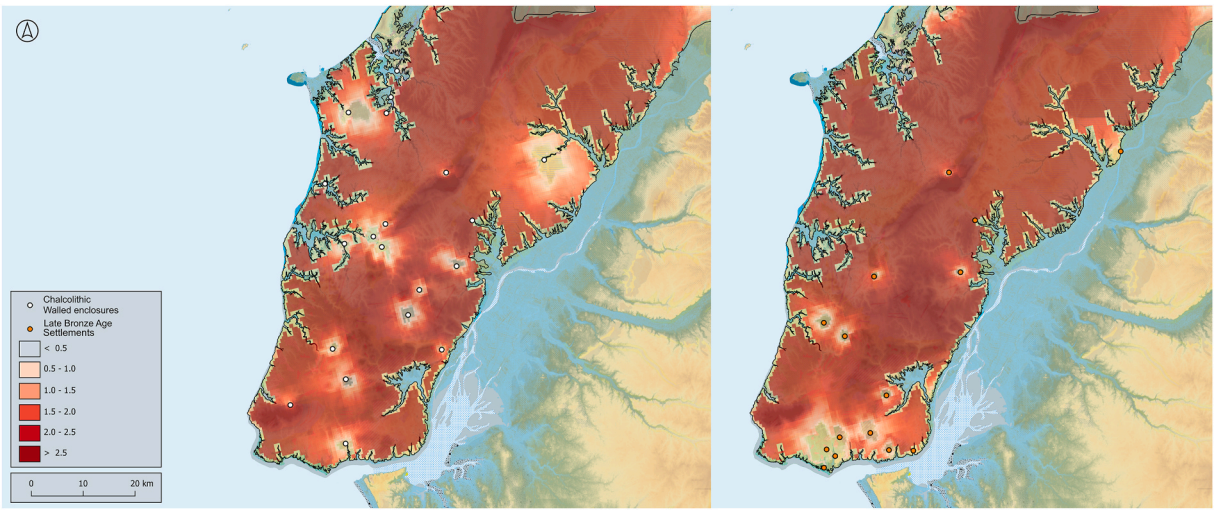


Fig. 7. Results of the Tobler Hiking Function exercise for the walled enclosures (Chalcolithic) and for the settlements (Late Bronze Age) by authors.

obstacles. This analysis, based on geomorphology, rivers, and soils, makes it clear that the routes taken by these populations are not mere lines drawn on a map, but rather the reflection of choices made by moving populations, seeking to optimise their journeys in terms of effort and available resources.

4. Discussion

The analysis of mobility patterns in the Lisbon Peninsula, particularly during the Chalcolithic period, provides profound insights into the region's complex prehistoric networks. This intricate interplay of pathways, settlements, and material culture not only reflects adaptations to environmental and social changes but also underpins the cultural and historical development of the region.

It is important to note that similar GIS-based mobility analyses have been applied in other regions of the Iberian Peninsula, providing valuable comparative data. Recent studies conducted in the central-eastern part of the Peninsula, such as those by Peres and Risch (2022, 2023) and Moreno et al. (2023), provide a foundation for drawing comparisons with the settlement networks identified in the Portuguese Estremadura. Although the geographic and cultural contexts differ, these comparisons demonstrate the existence of similar mobility patterns, where the density of routes is influenced by environmental variables and available resources. Such analyses underscore the complexity of human-environment interactions across various regions during the Chalcolithic and Bronze Age.

Following the spatial study of the distribution of Chalcolithic enclosures, several key themes have emerged that warrant deeper research.

a) Maritime and Riverine Connectivity:

The positioning of Chalcolithic enclosures, typically distanced from the seashore in spite of the Lisbon Peninsula's coastal geography (Fig. 2), warrants a re-evaluation of maritime and riverine roles in these societies. Contrary to an anticipated reliance on coastal and riverine routes, our findings point towards a nuanced relationship with these natural features. The Chalcolithic enclosures' locations, often near tributary streams of the Tagus or directly connected to the Atlantic, indicate an intricate balance between accessibility and strategic settlement. The scarcity of aquatic resources in the diet of these populations, as evidenced by faunal (Carvalho et al., 2019) and isotopic analyses (Guiry et al., 2016; Cubas et al., 2020), further supports this interpretation. This inland preference contrasts with the Late Bronze Age (Fig. 2), when a clear shift towards the Tagus valley is observed, suggesting a reorientation of settlement strategies, possibly under the influence of climatic or socio-political changes. This transition can be related to the settlement model developed during the Early Iron Age (Arruda et al., 2017). Beyond the strategic placement of these enclosures, the delineation of principal trafficability axes and nodal points, further illuminates the intricate nature of mobility networks within the Lisbon Peninsula.

b) Main Trafficability Axes and Nodal Points:

The identification of major routes and nodal points underscores the complexity of Chalcolithic and Late Bronze Age mobility. These axes likely served as conduits for trade, communication, and cultural exchange, playing a crucial role in the socio-economic fabric of these societies. The distribution of materials, particularly in the Chalcolithic period, paints a picture of a society deeply engaged in a network of exchange and interaction. The contrast between the decentralised Chalcolithic mobility system and the Late Bronze Age's focus on estuarine hubs highlights broader socio-economic and environmental adaptations. The Chalcolithic networks facilitated widespread interaction and resource distribution, supporting a dynamic and interconnected society. By the Late Bronze Age, these networks became more hierarchical, aligning with a strategic shift in settlement patterns, possibly driven by changes in subsistence strategies, resource availability, or emerging socio-political structures.The presence of exotic materials at nodal points, such as variscite, amber, and ivory, indicates that these locations were more than mere convergence points; they were likely central to the socio-economic and cultural dynamics of the time. The significance of these mobility axes and nodal points extends beyond facilitating trade and communication, and possibly reflects the hierarchical structure of settlements across the region.

c) Settlement Hierarchization

Variations in size and material culture in different settlements might suggests a hierarchical structure within these societies. Large enclosures, often well supplied with exotic materials, may have functioned as key social, economic, and possibly religious centres. In contrast, smaller settlements, while less rich in exotic materials, were integral to the broader network, serving as vital nodes in the exchange of goods and ideas. This hierarchy is further evidenced by the isotopic studies of human and animal remains, indicating varying degrees of mobility and trade relations across different settlements (Guiry et al., 2016; Wright

et al., 2019).

d) Evidence of mobility

Advancing from the structural dynamics of settlement hierarchization, a detailed examination of the correlation between mobility patterns and material culture in this era provides a critical lens through which to interpret trade mechanisms and cultural interconnectivity.

The isotope analyses of Chalcolithic human and faunal remains from the Estremadura region, particularly around Torres Vedras, reveal significant insights into the mobility of these ancient populations. The analyses indicate limited migration among human populations, with only a small percentage of migrant individuals identified (Waterman et al., 2014). In contrast, the mobility of animals was much more pronounced, suggesting extensive animal trade within the Lisbon Peninsula and beyond, including connections to areas such as Ossa-Morena (Spain) (Wright et al., 2019). This disparity in human and animal movement patterns underscores the complexity of mobility in these societies, where trade and resource exchange played crucial roles.

The material culture of the region during the Chalcolithic, particularly pottery, demonstrates a strong local specificity. The unique styles and decorations, such as the "copos canelados" (grooved cups) and "acacia leaf" motifs (Fig. 3), indicate a rich cultural identity within the Lisbon Peninsula, distinct from the decorative styles found in the Southern Iberian Peninsula (Kunst, 1996; Gonçalves, 2003; Cardoso, 2006; Sousa and Gonçalves, 2012; Sousa, 2021). This local uniqueness in pottery styles suggests a tight-knit network among the communities of the territory.

However, the presence of imported materials alongside these local items points to a dual nature of mobility and trade. Materials such as amphibolite, copper, variscite, amber, and ivory played different roles in these societies (Fig. 8). Amphibolite and copper, vital for daily activities, were predominantly sourced from Central Alentejo, particularly the Ossa-Morena strip (Cardoso and Barros e Carvalhosa, 1995; Lillios, 1997; Valério et al., 2016; Kunst, 2021). Their widespread recovery in the Lisbon Peninsula suggests efficient trade networks crossing the Tagus, with sites like Moita da Ladra and Penedo possibly serving as redistribution centres.

On the other hand, exotic materials such as variscite, amber, and ivory were potentially symbols of prestige and social differentiation. Variscite, for instance, is primarily found in large and small enclosure settlements and necropoles throughout Portuguese Estremadura. Its primary source appears to be the mines of Palazuelo de las Cuevas in Zamora (Spain) (Odriozola et al., 2010, 2012; 2013b; 2016). The presence of ivory and amber, with extra-peninsular origins, in settlements and necropoles further illustrates the extensive reach of trade networks during this period. The presence of ivory is limited, for the moment, to the sites of Leceia (Schumacher and Cardoso, 2007), Zambujal (Schumacher, 2017), and Penedo do Lexim. Studies of amber include wider samples on which *FTIR* analyses have been applied (Odriozola et al., 2017). Through these analyses, a chronology was proposed for the circulation of these materials, with an initial moment in the fifth millennium BC, and a final one at some point in the second millennium BC. During the Neolithic and Chalcolithic, amber came mainly from Sicily, and can be associated with the ivory originary from North Africa (Odriozola et al., 2017).

In the Late Bronze Age, however, there is a noticeable divergence in mobility and material culture patterns. The data becomes more fragmented, with a lack of comprehensive analyses on human and faunal remains. The established metallurgical routes, particularly those related to copper and, later, to tin, likely continued, but with notable changes. The circulation of materials like variscite and ivory declines significantly, while amber sources shift from Sicily to the Baltic Sea (Odriozola et al., 2017). This change suggests a reorientation of trade networks, potentially influenced by broader socio-economic and environmental factors. The circulation of amber from the Baltic to the Mediterranean and then to the Lisbon Peninsula encapsulates the dynamic nature of trade and cultural exchange during this period. Its recovery in various contexts, from settlements to votive sites, illustrates the adaptability and resilience of these ancient trade networks (Sousa et al., 2022).

The study of mobility and material culture in the Chalcolithic and Late Bronze Age societies of the Lisbon Peninsula paints a complex picture of these ancient communities. The intricate networks of trade and communication, the strategic placement of settlements in relation to natural resources and topography, and the dynamic interplay between local and imported materials all contribute to a deeper understanding of these societies. This research not only enriches our knowledge of prehistoric communities in the Lisbon Peninsula but also offers valuable perspectives on the broader patterns of human mobility, trade, and cultural interaction in ancient Europe.

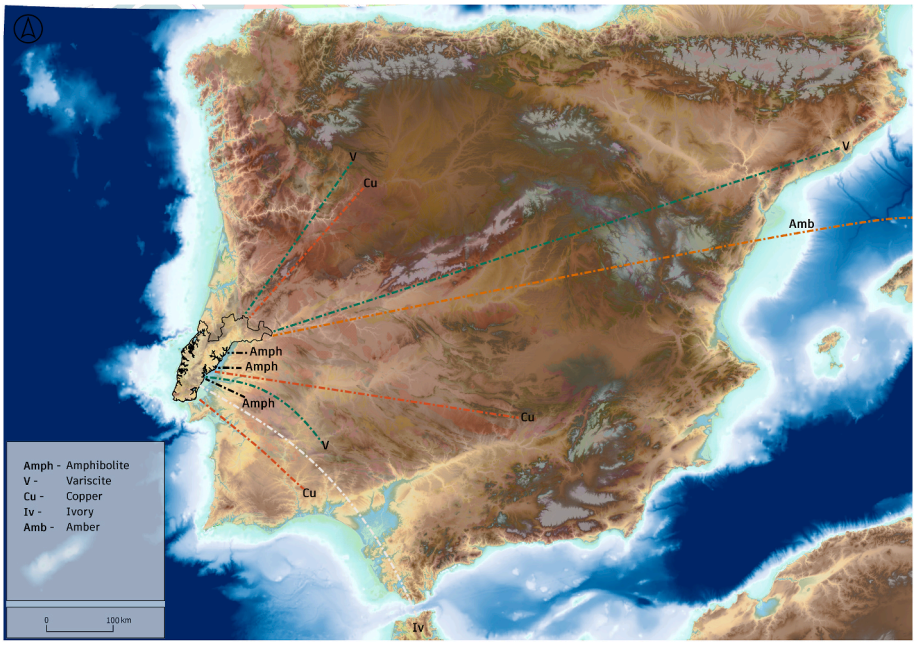


Fig. 8. Imports from the "Lisbon Peninsula" and their origins by authors.

5. Conclusions

The variable of territorial connection between settlements -mainly the ones which acted as hubs is crucial to the study of mobility in prehistoric societies. The methodology used approaches this variable from the highest possible number of elements; i.e. the material record, raw materials, biochemical markers, settlement patterns, routes and paths.

The comparison between the Chalcolithic and Bronze Age periods reveals a change in the mobility patterns, with a particularly visible transition from a dispersed to a more centralised network evidencing an answer to shifting environmental and social conditions. On the one hand, the Chalcolithic evidence shows a greater dispersion in routes and intersection points across the territory, suggesting a pattern of broad and integrated territorial occupation. This likely highlighting the existence of hubs for the exchange of raw and processed materials (e.g. copper elements), but also of ideas and information. On the other hand, the Late Bronze Age routes and intersections are concentrated around key areas, possibly revealing a more focused and strategic occupation pattern. This shift may indicate changes in subsistence practices, long-distance trade networks, and social structure, resulting in a greater focus on coastal and estuarine regions.During the Chalcolithic, human groups seem to be organised communities with a high regional interaction, as indicated by the unique pottery styles, as well as by the low mobility indicated by the isotope analyses. In the construction of this cultural identity, routes between settlements highlight the Torres Vedras-Alenquer-Arruda dos Vinhos axis, as a central area in the Lisbon peninsula, even though it did not occupy a central position in relation to the Tagus estuary. By analysing the settlements, it is possible to establish differences in size and shape; however, there seems to be little evidence of hierarchization, as daily-use imported materials (i.e. copper and amphibolite) are widely

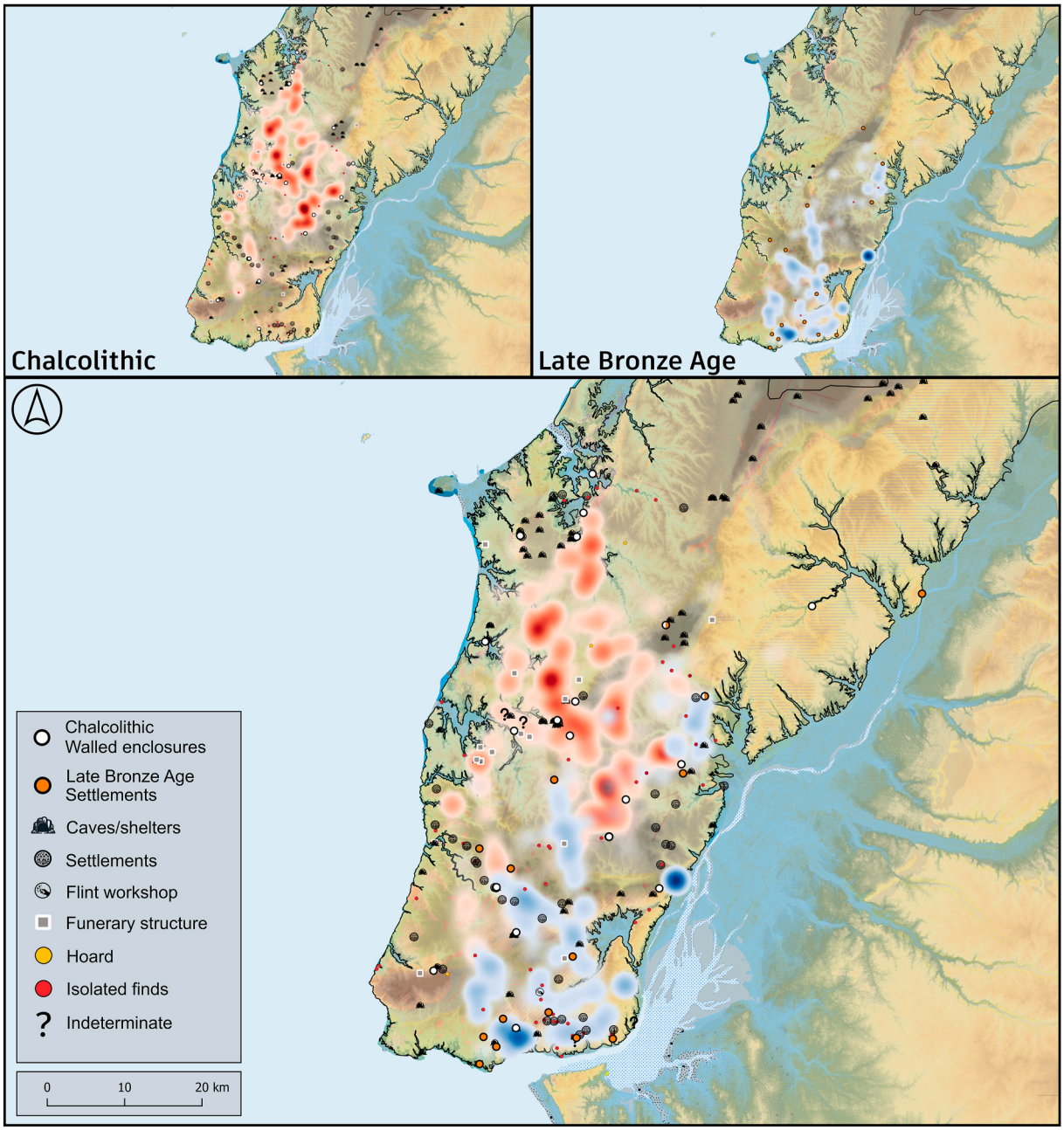


Fig. 9. The combination of results obtained from the route heatmaps created by LCP and the potential "cultural" landscapes of the Chalcolithic, Late Bronze Age and aggregate periods by authors.

dispersed. In contrast, exotic imported materials (i.e. ivory and variscite) present a more unequal distribution pattern.

In the Late Bronze Age, the settlement pattern shifts towards the estuary areas in the Tagus' banks. The hinterland occupation is maintained mainly in the hilltop settlements. By analysing distribution of materials, increasingly hierarchised mobility networks seem to emerge.

The image in Fig. 9 strikingly illustrates the shift in the interaction of prehistoric populations with the landscape of the Lisbon Peninsula, from the Chalcolithic to the Late Bronze Age. The juxtaposition of the heatmaps, with various archaeological sites suggests a nuanced narrative of socio-cultural evolution. In the Chalcolithic heatmap, a dispersed pattern of walled enclosures, settlements, and specialised sites suggests a society engaged in a widespread network of production and exchange. Conversely, the concentration of heat (sites and paths) in specific Late Bronze Age areas implies a potential shift towards more centralised or specialised economic and social activities. Notably, the funerary structures remain consistently peripheral across both periods, possibly indicating longstanding cultural traditions related to burial practices. Hoards and isolated finds are sparse, but where they coincide with areas of intense heat map activity, they could indicate zones of wealth accumulation and trade. The indeterminate sites prompt a reflection on the unknown aspects of these societies and highlight the potential for further discovery.

This visual synthesis of mobility and settlement patterns underscores a millennium of transformation, raising questions about the driving forces behind these changes, be it environmental pressures, resource distribution, or shifts in social organisation.

CRediT authorship contribution statement

André Texugo: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Pablo Sánchez de Oro:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ana Catarina Sousa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Data availability

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.10870751.

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Declaration of competing interest

The authors wish to declare that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

The research and preparation of the manuscript were conducted independently and impartially. The findings and views expressed in the manuscript are solely those of the authors and do not necessarily reflect those of their affiliated institutions or any funding bodies.

Each author has contributed significantly to the conception, design, execution, or interpretation of the study and the writing of the manuscript. All authors have read and approved the final version of the manuscript to be published.

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