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RESEARCH

An Approach from Networks Science to Bronze Age Archaeology in Southeast Iberia

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Abstract

This paper applies networks science to the archaeology of the Bronze Age in southern Iberia, with the aim of extrapolating large-scale social, economic and productive dynamics from artefactual, topographical and architectural data gathered during more than a century of archaeological research. We compare three different networks of archaeological settlements connected through shared economic categories, integrating for the first time the diachronic dimension: Early Bronze Age (EBA) for sites dated between ~ 2200–1800 BCE, Middle Bronze Age (MBA) for sites dated between ~ 1800–1550 BCE, and Early and Middle Bronze Age (EMBA) for sites that persist across both chronologies. Although all networks align closely with a random graph structure, the MBA network stands out for its different values in degree centrality, betweenness centrality and modularity, compared to EBA and EMBA. When the interpretation of the archaeological context is considered in the analysis, MBA appears characterised by extensive procurement and distribution networks compared to EBA, implying a more integrated web of inter-community interaction.

Keywords Bronze Age Iberia · Network analysis · Settlement and economic networks · Bipartite networks · Weighted networks · Graph theory

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Introduction

Archaeology has advanced considerably in recent decades as a scientific discipline, making major contributions to the broader social sciences (Smith *et al*., 2012). In reconstructing past human activities and interactions from material remains, archaeologists now rely not only on traditional analytical tools but also on a wide range of conceptual and methodological frameworks derived from disciplines such as geology (Delgado-Raack *et al*., 2020; Moník *et al*., 2021), biology (Risch *et al*., 2023; Rohrlach *et al*., 2024), chemistry (Ache *et al*., 2017; Breu *et al*., 2024; Guerra-Doce *et al*., 2023), and mathematical and statistical modelling (Barcelo & Bogdanovic, 2015). Among these, complex network science—rooted in graph theory—has emerged as a powerful approach for analysing relational structures in archaeological data (Newman, 2010). Supported by increasing computational capacity and a growing transdisciplinary framework, network-based methods have notably improved our ability to model and interpret ancient social and economic systems (Brughmans, 2013; Brughmans & Peeples, 2023; Collar *et al*., 2015; Knappett, 2013; Monforte-Barberán, 2025; Peeples, 2019).

In this paper, we apply concepts from complex network science (Boccaletti *et al*., 2006; Newman, 2010) with the aim of exploring the socio-economic organisation and potential hierarchical relationships between communities during the Early and Middle Bronze Age in the central-eastern quadrant of the Iberian Peninsula. The study area, covering approximately 177,000 km^2, including the southern Meseta plateau and the Spanish Levante, contains an exceptionally dense record of 1,445 documented Bronze Age settlements (Fig. 1). What distinguishes this region from most of Bronze Age Europe (Fokkens & Harding, 2013; Meller *et al*., 2019; Risch *et al*., 2022) is not only the density of sites, but also their extremely small size and relatively short duration of occupation, probably ranging between 100–200 years. The extraordinary abundance of settlements smaller than 0.02 hectares reflects a marked pattern of community *atomisation*, characterised by the distribution of population among many small, spatially dispersed communities rather than in large nucleated centres, resulting in a fragmented social landscape. A second feature is the placement of dwelling places on elevated and naturally protected positions and/or their delimitation by defensive perimeter structures. This cost-intensive settlement strategy has been described as *enrockment* (Moreno Gil *et al*., 2023; Peres & Risch, 2022), referring to the systematic use of topography and architecture for defensive purposes. Most communities, the majority formed by less than 50–75 inhabitants, were located on average around 100 m above the surrounding arable land and often incorporated substantial defensive features, as exemplified by the *motillas* of La Mancha and fortified hilltop settlements in the Levante.

This pattern of settlement atomisation and enrockment contrasts not only with the more sparsely distributed evidence in western and northern Iberia, but also with the large, long-lived settlements of the El Argar polity in southeastern Iberia, which developed between ca. 2200 and 1550 BCE into a highly centralised and possibly state-level form of organisation (Lull & Micó Pérez, 2011; Peres

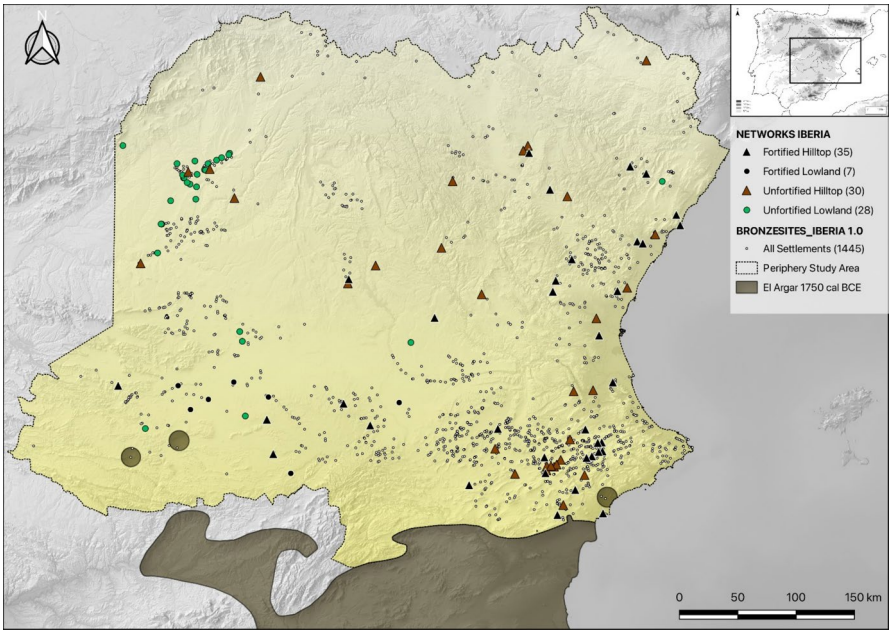


Fig. 1 The central-eastern quadrant of the Iberian Peninsula and the maximum El Argar territory during the Early and Middle Bronze Age

& Risch, 2026). El Argar takes its name from the eponymous site in Almería, excavated by Louis and Henry Siret at the end of the nineteenth century (Siret & Siret, 1887) and is the most intensively studied and best-defined archaeological entity in this region. Although debate continues regarding the extent to which El Argar may be characterised as a state (Aranda Jiménez, 2023; Gilman, 2023), there is broad agreement that it represents the most politically and economically centralised society of Bronze Age Iberia. Archaeologically, it is characterised by a hierarchical settlement system dominated by large and permanently occupied centres, marked social differentiation expressed in standardised intramural burials with highly unequal grave assemblages, specialised craft production, large-scale storage and processing of cereals, extensive metallurgical production, monumental defensive architecture, and a distinctive repertoire of specialised weapons such as halberds and swords, reflecting pronounced social stratification and the concentration of economic, political, and military power (Chapman, 1990, 2008; Lull, 1983; Lull *et al*., 2005, 2010, 2013, 2017, 2018, 2021; Risch, 2002). Between 2200 and 1750 BCE, its territory expanded from a core of ca. 5,500 km^2 to approximately 34,000 km^2 (Fig. 1, coloured in brown), bringing El Argar into sustained and often conflictual interaction with a mosaic of neighbouring communities, particularly along its north-eastern frontier. This expansion created a dynamic and contested frontier in which armed conflict and resistance coexisted with selective cooperation and exchange (Moreno Gil *et al*., 2025; Peres & Risch, 2026).

In particular, proximity to the El Argar territory has been proposed as a key factor underlying the pronounced pattern of settlement *atomisation* and *enrockment*, as both strategies become increasingly pronounced from north to south, towards the El Argar border in the southeast (Moreno Gil *et al*., 2023; Peres & Risch, 2022, 2023a). The scale of economic and political development documented in El Argar –particularly during the Middle Bronze Age between 1800 and 1550 BCE– likely entailed substantial demands for external resources, including agricultural surplus and workforce, obtained through exchange or coercion (Peres & Risch, 2023b, 2026). In order to maintain a degree of autonomy from centralised political structures (Angelbeck & Grier, 2012; Clastres, 1987) peripheral communities appear to have developed "escape strategies" *sensu* Scott (2009), characterised by settlement dispersal, reduced community size, defensive positioning, a strong emphasis on local food self-sufficiency, and with no apparent reliance on centralised networks (Peres & Risch, 2026).

At the same time, however, resistance did not necessarily entail isolation. The circulation of socially high-value Argaric materials, such as metal and ivory, and the selective adoption of Argaric pottery forms along the frontier indicate that economic interaction and cultural influence could persist alongside defensive autonomy and armed conflict (Moreno Gil *et al*., 2025; Peres & Risch, 2026). These interactions may have shaped not only relations between El Argar and its neighbours, but also processes of transformation within the peripheral communities themselves, potentially affecting their internal economic organisation and patterns of interaction.

Alternative interpretations have framed these settlement patterns as the outcome of segmented or "tribal" social organisation (Jover Maestre, 1999), in which communities invested in durable architecture to ensure continuity of residence and intergenerational transmission of property (Cabezas Romero & Jover Maestre, 2024). While such models may partly account for processes of fission and territorial expansion, they do not adequately explain the marked increase in defensive strategies, the short occupation spans, the small size of the communities, or the widespread evidence of destruction episodes. These features instead point to a context of sustained socio-political tension and instability. Moreover, segmentation models have also been applied to settlement systems lacking defensive concerns, such as the central Iberian pit fields, known as *campos de fosos* (Díaz-del-Río, 2001), suggesting that segmentation alone cannot account for the combined pattern of reduced settlement size and intensified defensive investment observed near the El Argar frontier.

Rather than treating these communities simply as a passive periphery of El Argar, it is therefore important to consider how their interactions with this expanding polity may have contributed to internal processes of social and economic differentiation and reorganisation. In this regard, interpretations of hierarchical organisation in these peripheral regions based solely on settlement size or spatial patterning (e.g. Brodsky *et al*., 2013, or Cabezas Romero & Jover Maestre, 2024) remain insufficient without a systematic integration of artefactual and economic data. A relational approach is therefore needed to assess whether patterns of economic interaction were associated with broader changes in the organisation of these communities.

In this context, network science offers a particularly suitable framework for analysing the structure and complexity of these settlement systems. Unlike multivariate

methods, which are useful for dimensionality reduction, network science is useful when the pattern of connections (i.e. the topology) or system robustness are more relevant than variance. By modelling relationships between sites based on shared economic and material characteristics, network analysis allows us to move beyond purely descriptive or spatial approaches and to explore patterns of connectivity, centrality, and clustering within large archaeological datasets. This provides an opportunity to examine whether the economic interactions documented across this region were associated with broader changes in the internal organisation and connectivity of peripheral communities. The database assembled for this study, comprising settlement and artefactual evidence accumulated over more than a century of research, provides a unique opportunity to investigate the underlying structure of economic and social interactions in the region (Peres & Risch, 2022, 2023a).

The study addresses the following research questions:

- To what extent can relational structures be inferred from the archaeological record when analysed through network-based approaches?
- Are there significant differences between the Early and the Middle Bronze Age networks in terms of economic categories and structural measures?
- Are there spatial correlations between network properties, economic variables, and settlement characteristics across different chronological phases?

The paper is organised as follows. The "Materials and Methods" section presents the database and analytical procedures, including the construction of settlement networks based on shared economic attributes and the calculation of centrality and global network measures. The "Results" section presents correlation and structural analyses, including a fragility assessment of network metrics. The "Discussion" interprets these results in socio-economic terms, and the "Conclusions" summarise the main findings and outline future research directions.

Materials and Methods

The present study is grounded in the largest database ever created on Bronze Age settlements in the Iberian Peninsula: BRONZESITES_IBERIA 1.0 (Peres, 2026). This archaeological inventory platform was created between 2016 and 2021 by one of the authors as part of his doctoral thesis (Peres, 2021), and was later expanded and upgraded in the context of studies on settlement patterns and productive forces (Peres & Risch, 2022, 2023a). The current version of this database includes 1,445 Early and Middle Bronze Age (henceforth, EBA and MBA respectively) sites with a total of 123,840 data entries and an average of 86 completed informational fields per site. The original objective of BRONZESITES_IBERIA 1.0 was to observe on a macro-scale the entirety of surveyed and/or excavated sites within a large territory of 117,444 km^2, which currently includes 11 Spanish provinces (Madrid, Guadalajara, Toledo, Cuenca, Ciudad Real, Albacete, northern Murcia, Alicante, Valencia, Castellón and Teruel). During the EBA and MBA (2200–1550 BCE), this region was located just north of El Argar, probably one of

the earliest States in Western Europe (Lull & Risch, 1995; Lull *et al*., 2011), and was inhabited by archaeological communities traditionally known as *campos de hoyos* (pit fields) in the centre of the peninsula (Díaz-del-Río, 2001), *poblados de altura* (hilltop settlements) in the Toledo Mountains (Ruiz Taboada, 1998), *cultura de Las Motillas* in the La Mancha plain (Lenguazco González, 2015; Nájera, 1984), *morras y castellones* in the eastern La Mancha (Fernández-Posse *et al*., 2008) and *Bronce Valenciano* in the coastal Levante (Fernández Vega, 1985; Jover Maestre, 1999).

Regarding the reliability of the data, the initial inclusion of 1,445 surveyed and excavated settlements has been crucial to take advantage of a large dataset and to archaeologically define the social and economic resistance strategies of the peripheries in response to the expansive and centralising shockwave of a surplus focused economic organisation such as El Argar (Moreno Gil *et al*., 2023; Peres & Risch, 2026). The regression analysis between the data obtained from surveyed and excavated settlements showed that the survey evidence recorded an identical proportion of means of production to those found in the excavations, but a smaller quantity and variety of those (Peres & Risch, 2023a, Fig. 4). In other words, the surveys provided a substantial, though incomplete, representation of what might have been uncovered if all sites had been excavated. Another underlying issue with the surveyed sites is that chronology is often based on a small number of ceramic fragments and, in several cases, publications do not specify whether these sites belong to EBA, MBA, or to both. For this reason, in all the aforementioned studies, which include both surveyed and excavated sites, all sites were synchronically analysed within the 2200–1550 BCE period.

With the aim of enhancing the quality and richness of the data, minimise the "noise" produced by limited survey data alone, highlighting meaningful network connections, and conducting a diachronic study between the EBA and MBA, the present study has reduced the number of analysed sites by applying the following filters:

(1) Surveyed settlements have been excluded, due to the limited quantity and variety of their artefactual evidence.
(2) Cave settlements have been excluded, due to the unstable or intermittent nature of their occupations.
(3) All excavated sites have been reviewed, and their chronology has been established based on the published archaeological materials, mostly pottery, and ^{14}C dates.

The resulting 100 high-quality and chronologically reliable settlements include data on chronological, topographical and architectural variables (Bronze Age phases, UTM coordinates, height above mean sea level, relative altitude, topographical location, natural environment, perimeter structures, and settlement size) and artefactual evidence. The combination of topographical location, natural environment and perimeter structures defines settlements as either unfortified or fortified, and as situated in lowland areas or on hilltops, resulting in four distinct

forms of settlement. On the other hand, the combination of artefact evidence, according to their economic and productive implications, has been translated into twelve main economic categories. Unfortunately, artefactual evidence from multilayered settlements, including EBA as well as MBA occupations, lack internal phasing due to the partial nature of some publications, making it impossible to conduct an internal diachronic analysis. Consequently, diachronic interpretations must be restricted exclusively to EBA and MBA settlements. As we will see, the structural results coming from Early as well as Middle Bronze Age sites (henceforth, EMBA) network analysis, which stand between EBA and MBA networks results, could be explained by this fact.

The structure of this smaller database has been conceptually organised as a bipartite (i.e. two-mode) network, with settlements as the first-mode (often referred to as "primary actors" or "rows") and economic categories as the second mode (often referred to as the "events," "groups," or "columns"), and where settlements can be connected by means of any of their shared attributes (Brughmans, 2013). This linking process generates a unipartite (i.e. one-mode) network where (a) only sites are present and (b) edges are weighted with values corresponding to similar attributes between them. Once this network is obtained, we can calculate[1]:

(a) centrality measures to characterise the importance of the nodes (i.e. sites),[2] and
(b) overall statistical signatures to characterise the network dependence on the weights of the edges (i.e. corresponding to the similarity of attributes between sites).

An important attribute here is location (i.e. UTM coordinates), that allows us to correlate economic affinity between sites and Euclidean distances. Although our network is spatial, and thus weighted by definition (Barthélemy, 2011), the centrality measures are obtained for a non-weighted (and non-directed) network.[3]

Site Characterisation by Attribute Categories

The two fundamental attribute categories considered in this paper are settlement form and economic materiality. Form is based on the topographic and architectural variables, which shape the settlement pattern and allow their classification into four main subcategories: fortified hilltop settlements (FH), unfortified hilltop settlements (UH), fortified lowland settlements (FL) and unfortified lowland settlements (UL). The main difference between these categories lies in the presence or absence of stone wall structures within the settlements, as well as in their location, either on rugged promontories and

[1] Centrality and network structural measures have been obtained with NodeXL software (https://smrfoundation.org).

[2] In this paper, the terms 'node' and 'archaeological site/settlement' are equivalent.

[3] In our networks, edge weight cannot be interpreted in terms of a physical measurable magnitude (i.e. longitude, energy or information flow, etc.) for it quantifies economic affinity between sites. This is the reason why centrality measures have been obtained for a non-weighted network.

Table 1 Absolute number of sites distributed by chronology (i.e. Early Bronze Age—EBA, Middle Bronze Age – MBA, and Early-Middle Bronze Age – EMBA) and form (i.e. un/fortified hilltop settlement – U/FH, and un/fortified lowland settlement U/FL)

	Fortified		Unfortified		Total
	Hilltop (FH)	Lowland (FL)	Hilltop (UH)	Lowland (UL)	
EBA	7	0	8	5	**20**
MBA	20	0	13	12	**45**
EMBA	8	7	9	11	**35**
Total	**35**	**7**	**30**	**28**	**100**

steep hills or on plains and gentle slopes. Table 1 shows the absolute number of sites distributed by chronology and form.

The economic materiality includes the different materials found in a site, quantified in twelve economic categories with their corresponding items (Table 2). Categories have been characterised in a dichotomous way: the presence of just one item in the category classifies that category as existing (i.e. with a 1), whereas only the complete absence of items in one category classifies that category as non-existent (i.e. with a 0). Binary coding is used to avoid biases and heterogeneity in preservation, excavation scales, recovery methods and unsystematic surface collections. Transforming data into binary matrices helps neutralise these distortions, allowing to focus on the compositional repertoire and qualitative overlap (i.e. shared traits) of a site, rather than skewed absolute quantities or volume. Thus, each site has its own numerical signature, formed by a twelve binary digit number. This number is used to establish the similarity between sites (see next section).

Unipartite Network

The obtention of unipartite (i.e. one-mode) networks from bipartite (i.e. two-mode) ones follows well stablished procedures that come from the bibliometric field, such as co-citation (Small, 1973) and bibliographic coupling (Kessler, 1963). Both methodologies use a paper's bibliography to assess its similarity with another paper: two papers will be more similar, the more items they share in their corresponding bibliographies. In mathematical terms, the rectangular matrix A, known as incidence matrix, with elements $A_{i,j}$ where i is the number of tuples (i.e. papers in bibliographic terms) and j is the number of attributes (i.e. references in that paper, in bibliographic terms) is defined as $A_{i,j} = 1$ if there exist a relation between tuple i and attribute j, and $A_{i,j} = 0$ otherwise. Then, a co-citation matrix C is a symmetric one and given by

$$C = A \cdot A^T \tag{1}$$

where A^T is the transpose of A. C contains the information needed to generate a weighted (co-citation) network in which there is an edge, if it exists, with weight $C_{i,j} > 0$ between i and j, for $i \neq j$. In this paper we will work with C, the symmetric matrix with size i x i (where i is the number of sites for each chronology) which

Table 2 Production grouping criteria and bibliographic references for economic and similarity analysis. We use economic contiguity to sort economic categories top – down in the following order: agriculture (AGR), storage (STO), hunting (HUN), bladed flint use (BLF), bevelled stone use (BES), macrolithic use (MAC), diary production (DIP), textile production (TEX), metallurgy production (MET), bevelled metal use (BEM), bladed metal use (BLM) and exchange practice (EXC). Violence is included in parentheses because it is not considered a productive activity in itself, but a transversal mechanism underlying the control and appropriation of productive activities and their outputs throughout human history

Archaeological evidence		Socio-economic sphere	
Artefact categories	Raw Materials	Activities	Economic categories (Acronym)
- Sickle elements (Jover Maestre *et al.*, 2019)	Flint, quartz, and related materials	Food harvesting and processing	**Agriculture (AGR)**
- Grinding stones (Risch, 2002)	Coarse grained rocks		
- Underground storage pits (Díaz-del-Río, 2001)	Negative features	Food storage	**Storage (STO)**
- Masonry storage structures (López Sáez *et al.*, 2014)	Stone & mortar		
- Storage vessels (Soler García, 1987)	Pottery		
- Arrowheads (Juan Cabanilles, 2008; López Padilla, 2011)	Bone Flint, quartz, and related materials	Food acquisition (Violence)	**Hunting (HUN)**
- Flakes (Juan Cabanilles, 2008) - Blades (Juan Cabanilles, 2008) - Knifes (Juan Cabanilles, 2008) - Cutting edges (Juan Cabanilles, 2008)	Flint, quartz, and related materials	Processing of various materials, mainly food (Violence)	**Productions performed with bladed flint tools (BLF)**
- Axe heads (Risch, 2002) - Adze heads (Risch, 2002)	Tough & fine-grained rocks	Agriculture Carpentry Butchering (Violence)	**Productions performed with bevelled stone tools (BES)**
- Percussion tools (Delgado-Raack, 2008) - Abraders (Delgado-Raack, 2008) - Specialised abraders (Ache *et al.*, 2017) - Grooved hammers (Delgado-Raack & Risch, 2017)	Coarse-grained rocks	Stone & woodwork, pottery finishing, beeswax & honey production, construction & mining	**Productions requiring macrolithic tools (MAC)**

Table 2 (continued)

Archaeological evidence		Socio-economic sphere	
Artefact categories	Raw Materials	Activities	Economic categories (Acronym)
- Sieves (Peres, 2021)	Pottery	Food (milk derivatives)	**Dairy production (DIP)**
- Spindle whorls (Basso Rial, 2022)	Fired clay	Clothing	**Textile production (TEX)**
- Loom weights (Basso Rial, 2022)	Fired clay or bone		
- Mineral/slag/drops (Simón García, 1998)	Copper waste	Smelting and plastic shaping of metallic objects	**Metallurgy (implies exchange) (MET)**
- Crucibles (Simón García, 1998)	Pottery		
- Casting moulds (Peres *et al*., 2024)	Sandstones		
- Forging hammers (Delgado-Raack and Risch, 2008)	Tough & fine-grained rocks		
- Axe heads (Peres *et al*., 2024) - Chisels (Simón García, 1998) - Adze heads (Simón García, 1998)	Copper	Agriculture Carpentry Butchering (Violence)	**Productions performed with bevelled metal artefacts (BEM)**
- Arrowheads (Kaiser, 2003) - Knives/daggers (Lull, 1983) - Halberds (Lull *et al*., 2017) - Swords (Lull *et al*., 2013)	Copper	Cutting of various materials (Violence)	**Productions performed with bladed metal artefacts (BLM)**
- Ivory objects (Schuhmacher, 2012)	Ivory	Clothing Adornment Social status	**Exchange (EXC)**

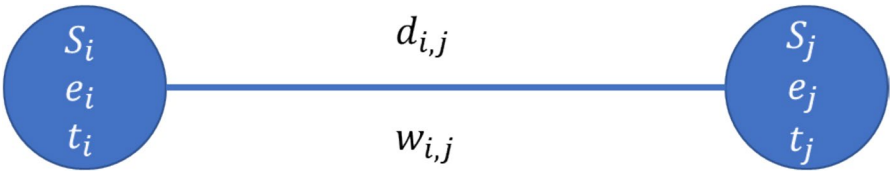


Fig. 2 Two sites S_i (characterised by economic categories e_i and form t_i) connected by an edge (characterised by distance $d_{i,j}$ and weight $w_{i,j}$)

gives the information needed to build a weighted network where $C_{i,j} > 0$ for $i \neq j$ corresponds to the number of shared economic categories, if they exist, between sites i and j. The definition of $C_{i,j}$ is equivalent to the *common neighbour similarity index* which offers much more stability than the rest of the similarity measurements used in the bibliography so far (Liu *et al*., 2015). It should be noted that a similarity index is merely a measure of affinity, in our case *economic affinity*. Thus, a network with edges built in this way, *per se*, does not necessarily imply interaction, contact, shared productive practices or any other dynamic association between nodes. Rather, they reflect convergent subsistence practices, productive activities, and technological repertoires. Nevertheless, some material categories have a different interpretive significance. The presence of non-local raw materials or technologies dependent on external resources, such as copper metallurgy or ivory, may constitute a stronger indicator of inter-settlement interaction. Because these resources were not locally available, their occurrence implies access to broader networks through which raw materials, finished objects, technical knowledge, and/or social information circulated. In such cases, similarity may reflect not only economic affinity but also participation in supra-local interaction networks.

In summary, each affinity network (i.e. EBA, MBA and EMBA) contains S_i sites, where $i = 1 \ldots n$, characterised by economic categories e_i and form t_i, and edges characterised by distance $d_{i,j}$ and weight $w_{i,j}$ (Fig. 2).

Structural Network Analysis

Several measures, both local and global, can be used to characterise the structure of a network (Collar *et al*., 2015; Newman, 2010). Local measures, also known as centrality measures, characterise the individual importance of a node. Local measures can be averaged over the whole network. In this paper we use the average value of the following centrality measures:

- Betweenness b_i: number of shortest paths[4] that contain node i. Quantifies a node's influence based on how often it falls on the shortest paths between other nodes in a network.

[4] A path is a sequence of connected nodes and edges within a network, where each node is linked to the next by an edge.

- Closeness c_i: the inverse of the sum of the shortest paths of node i to all other nodes. In our context, it gives an indication of how close, in terms of economic affinity, one site is to all other sites in the network.
- Clustering coefficient cc_i: number of closed triplets existing among node i and its neighbours. It indicates how likely two neighbours of a node are to also being neighbours of each other.
- Degree k_i: number of edges incident to a node i. Quantifies the number of connections a node has to other nodes within a network, and it is a fundamental measure to describe the structure of networks.

One additional centrality measure used in our analysis is the strength s_i, defined as the degree of a node i assessed by the weight of its edges (Barrat *et al.*, 2004). It quantifies its importance in terms of global connectivity but adding the weights of the edges to the final number of links.

Global measures, on the contrary, do not derive from individual node's ones but depend solely on the size of the network and the number of edges present. In this paper, we use the following global measures:

- Average path length or average shortest path length $< d >$: is the average number of steps along the shortest paths for all pairs of network nodes. It is a measure of the efficiency of transport (i.e. information, mass, etc.) on a network.
- Graph density δ: the ratio between the edges in a graph and the maximum number of edges that the graph can contain. It provides an idea of how dense a graph is in terms of edge connectivity.

We have chosen this battery of local and global measures for both, their widespread and long history utilisation in networks analysis (Wasserman & Faust, 1994) and with the sole objective of characterising and finding differences between the topological structures of our networks. Consequently, our structural measures are designed to capture purely topological and structural shifts across fragility stages, without requiring a conceptual interpretation for every metric. As shown in the following section, some of these measures prove significant in the process of analysing and comparing EBA, MBA, and EMBA networks, whereas others lack the ability to distinguish between different topologies.

Finally, we apply modularity as a foundational quantitative metric in complex network analysis (Newman, 2006) to evaluate the degree to which our networks can be partitioned into distinct communities or clusters. Within a modular structure, nodes exhibit high density and frequent internal connections, whereas ties between separate modules remain sparse. When applied to archaeological datasets (such as site-similarity matrices, artefact co-presence distributions, or exchange networks) modularity allows detecting tightly integrated communities of sites or material culture without imposing arbitrary boundaries.

Results

We have analysed three unipartite networks:

- Early Bronze Age (EBA), with 20 sites chronologically identified between ca. 2200 BCE to 1800 BCE, connected by 180 edges ($\delta = 0.95$).
- Middle Bronze Age (MBA), with 45 sites, chronologically identified between ca. 1800 BCE to 1550 BCE, connected by 912 edges ($\delta = 0.92$).
- Early and Middle Age (EMBA), with 35 sites corresponding to settlements that have endured from Early to Middle Bronze Age, connected by 561 edges ($\delta = 0.94$).

Weights range from $0 \leq w_{i,j} \leq 12$, the maximum value corresponding to edges that connect sites with complete economic affinity: all twelve economic categories listed in Table 2 present in both sites (Fig. 3). While EMBA distribution is monotonically decreasing as weight increases, EBA and MBA networks show two peaks, for $w_{i,j} = 2$ and $w_{i,j} = 3$ respectively.

Distances and Weights

One important aspect to detect is the existence of correlation between (Euclidean) distance $d_{i,j}$ (km between sites) and weight $w_{i,j}$ (shared attributes/economic categories between sites). Table 3 shows the percentage of edges according to their weight (rows) that appear at a given distance (columns) for EBA, MBA and

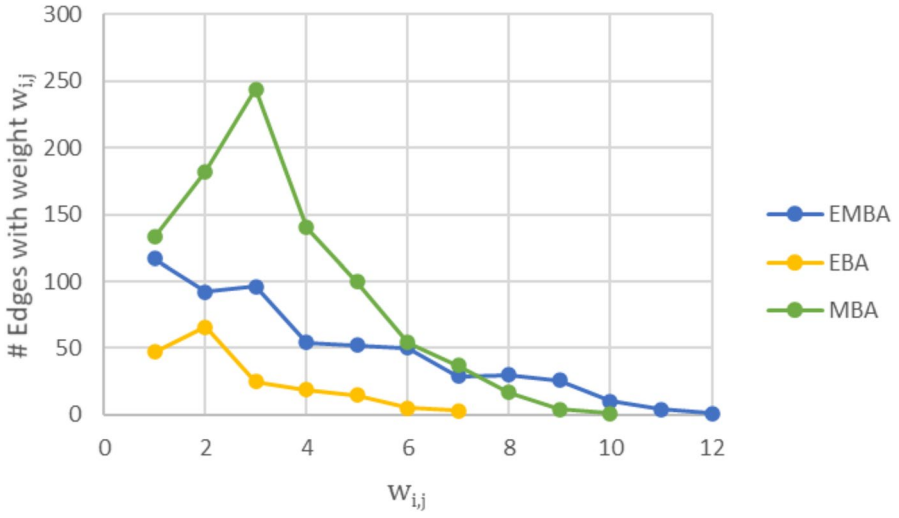


Fig. 3 Absolute distribution of weights. EBA and MBA networks show a peak for $w_{i,j} = 2$ and $w_{i,j} = 3$ respectively, while EMBA distribution is monotonically decreasing as weight increases

Table 3 Percentage of edges with one particular weight that appear at a given distance (percentages for individual weights – last column—and binned distances – uncoloured rows—also given) for EBA, MBA and EMBA networks

		Distance (km)										
	$w_{i,j}$	25	75	125	175	225	275	325	375	425	475	
EBA	1	1.7%	0.6%	2.2%	6.1%	5.6%	3.9%	3.9%	1.1%	1.1%	0.0%	26%
	2	5.6%	3.3%	3.3%	5.6%	6.1%	3.9%	2.8%	6.1%	0.0%	0.0%	37%
	3	2.2%	0.6%	3.3%	2.8%	2.2%	0.6%	0.6%	1.7%	0.0%	0.0%	14%
	4	2.2%	1.1%	0.0%	1.1%	1.7%	0.6%	1.1%	2.2%	0.6%	0.0%	11%
	5	1.1%	0.0%	0.6%	1.7%	1.7%	0.0%	0.0%	2.2%	1.1%	0.0%	8%
	6	1.1%	0.0%	0.0%	0.6%	0.6%	0.6%	0.0%	0.0%	0.0%	0.0%	3%
	7	0.0%	0.0%	0.6%	0.0%	0.6%	0.6%	0.0%	0.0%	0.0%	0.0%	2%
		14%	6%	10%	18%	18%	10%	8%	13%	3%	0%	100%
MBA	1	1.1%	2.1%	2.1%	1.5%	0.5%	0.4%	1.2%	3.5%	2.0%	0.1%	15%
	2	2.4%	2.0%	3.2%	2.4%	1.1%	0.8%	2.0%	5.3%	0.8%	0.1%	20%
	3	4.2%	3.1%	2.4%	3.3%	2.2%	2.1%	3.1%	5.8%	0.5%	0.1%	27%
	4	2.1%	1.4%	2.6%	1.4%	1.0%	1.2%	2.1%	2.9%	0.4%	0.2%	15%
	5	1.4%	1.8%	1.6%	1.4%	0.5%	0.5%	1.0%	1.6%	1.0%	0.0%	11%
	6	0.4%	1.6%	0.8%	0.7%	0.5%	0.7%	0.3%	0.8%	0.1%	0.0%	6%
	7	0.5%	1.0%	0.5%	0.8%	0.3%	0.0%	0.3%	0.5%	0.0%	0.0%	4%
	8	0.5%	0.2%	0.8%	0.1%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	2%
	9	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0%
	10	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0%
		13%	13%	14%	12%	6%	6%	10%	20%	5%	1%	100%
EMBA	1	2.7%	1.2%	1.8%	3.9%	3.2%	2.7%	2.1%	2.9%	0.4%	0.0%	21%
	2	1.8%	1.1%	2.3%	2.1%	2.1%	1.8%	1.6%	2.3%	1.2%	0.0%	16%
	3	2.0%	2.0%	2.5%	2.5%	2.0%	1.2%	1.4%	2.7%	0.9%	0.0%	17%
	4	1.1%	0.9%	0.9%	2.1%	1.1%	0.7%	1.1%	1.6%	0.2%	0.0%	10%
	5	0.9%	0.7%	1.6%	2.1%	0.9%	1.1%	0.7%	0.7%	0.4%	0.2%	9%
	6	1.4%	0.9%	1.2%	1.4%	0.9%	0.7%	1.1%	1.2%	0.0%	0.0%	9%
	7	0.4%	0.5%	0.5%	0.9%	1.2%	0.2%	0.4%	0.7%	0.4%	0.0%	5%
	8	0.7%	0.2%	0.9%	0.9%	2.1%	0.2%	0.0%	0.2%	0.2%	0.0%	5%
	9	0.4%	0.5%	0.5%	0.5%	0.7%	1.2%	0.0%	0.5%	0.2%	0.0%	5%
	10	0.0%	0.4%	0.4%	0.2%	0.0%	0.4%	0.2%	0.2%	0.2%	0.0%	2%
	11	0.0%	0.2%	0.2%	0.2%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	1%
	12	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0%
		11%	9%	13%	17%	14%	10%	9%	13%	4%	0%	100%

EMBA networks. The table also gives the cumulated percentages for individual weights (last column, uncoloured) and binned distances (last row for every network, uncoloured).

The EBA network is characterised by most edges of low weight (63% of edges with weights 1 and 2) and has 3 edges of maximum weight (2% with weight 7). Regarding the distribution by distance, there is an accumulation at 175 km (18%) and 225 km (18%). The MBA network is characterised by a generalised increase in weights (62% of edges with weights 1, 2 and 3) and one edge reaches weight ten. Regarding the distribution by distance, the distance 375 km stands out, with 20% of the edges included in this bin. Finally, the EMBA network is characterised by an even higher increase in weights (64% of edges with weights between 1 and 4) and is the one that contains the heaviest edges (8% of edges with weights between 9 and 12). Like EBA network, the maximum accumulation of edges occurs at 175 km (17%) and 225 km (14%).

Economic Categories and Connectivity Between Settlement Forms

Settlement form and economic materiality can be related by the number of times an edge connects these categories for all weights and for each chronology (Table 4). Our database includes four site forms t_i: fortified hilltop (FH), unfortified hilltop (UH), fortified lowland (FL) and unfortified lowland (UL). Edge characterisation for site form uses all combinations of form. For example: an edge that connects site S_1 characterised by t_1 as FH and site S_2 characterised by t_2 as UH, is characterised as "FH (connected) with UH". Edge characterisation for site economic materiality considers whether the two connected sites contain this materiality m_i. Only when both sites share a particular materiality, is this materiality considered. For example: an edge that connects site S_1, characterised by the presence of *hunting* and *flint* in its materiality m_1, and site S_2, characterised by the presence of *hunting* in its materiality m_2, will add one unit to economic materiality *Hunting* in the Table 4 below, but will add no unit to economic materiality *Flint*. Values are given as percentage, normalised by the accumulated weights of all edges for each chronology, independent of the number of sites.

According to these relations between settlement form and economic materiality, the EBA network is characterised by a concentration of economic categories agriculture (23%), storage (26%) and bladed flint tools (20%). Predominant edge forms are FH – UH (30%), UH – UL (22%), and FH – UL (18%). The MBA network is characterised by the same economic categories as EBA: agriculture (23%), storage (16%) and bladed flint tools (23%). Two predominant edge forms are coincident with EBA: FH – UH (32%) and FH – UL (19%). But in this case, it is the edge form FH – FH (23%) that appears significant, at the cost of UH – UL (which decreases to 12% compared to 22% in the EBA). This result is meaningful for our structural network analysis (see next sections). For both, EBA and MBA networks, there is an absolute absence of FL sites, which all correspond to the EMBA chronology (see Table 1). In fact, FL sites dominate the connectivity of this last chronology, with forms FL-FH (15%), FL-UH (14%), and FL-UL (13%) being the most common.

Table 4 Percentage of shared economic categories between sites of different form (i.e. fortified hilltop – FH, unfortified hilltop – UH, fortified lowland – FL and unfortified lowland – UL) and chronologies. FL sites are non-existent in the MBA and EBA chronologies and corresponding networks

		UL with	UH with		FL with			FH with				
		UL	UL	UH	UL	UH	FL	UL	UH	FL	FH	
EBA	Agriculture (AGR)	0.7%	3.9%	3.3%	0.0%	0.0%	0.0%	3.9%	7.9%	0.0%	3.3%	23%
	Storage (STO)	2.2%	6.6%	3.3%	0.0%	0.0%	0.0%	5.5%	6.6%	0.0%	2.2%	26%
	Hunting (HUN)	0.7%	2.6%	1.3%	0.0%	0.0%	0.0%	2.0%	2.6%	0.0%	0.7%	10%
	Bladed flint (BLF)	1.3%	6.1%	4.6%	0.0%	0.0%	0.0%	2.6%	4.6%	0.0%	0.7%	20%
	Bevelled stone (BES)	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.7%	0.7%	0.0%	0.7%	2%
	Macrolithic (MAC)	0.0%	0.7%	0.7%	0.0%	0.0%	0.0%	0.4%	1.3%	0.0%	0.2%	3%
	Dairy production (DIP)	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.2%	0.2%	0.0%	0.0%	1%
	Textile (TEX)	0.0%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%	2.0%	0.0%	0.7%	3%
	Metallurgy (MET)	0.7%	0.7%	0.0%	0.0%	0.0%	0.0%	2.0%	0.7%	0.0%	0.7%	5%
	Beveled metal (BEM)	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.9%	0.0%	0.2%	1%
	Bladed metal (BLM)	0.0%	0.4%	0.2%	0.0%	0.0%	0.0%	0.7%	1.3%	0.0%	0.7%	3%
	Exchange (EXC)	0.0%	0.4%	0.2%	0.0%	0.0%	0.0%	0.4%	0.9%	0.0%	0.2%	2%
		5%	22%	14%	0%	0%	0%	18%	30%	0%	10%	100%
MBA	Agriculture (AGR)	0.9%	3.4%	2.6%	0.0%	0.0%	0.0%	4.5%	7.2%	0.0%	4.5%	23%
	Storage (STO)	1.5%	2.6%	0.9%	0.0%	0.0%	0.0%	4.6%	3.7%	0.0%	3.0%	16%
	Hunting (HUN)	0.0%	0.5%	0.9%	0.0%	0.0%	0.0%	0.6%	2.4%	0.0%	1.2%	6%
	Bladed flint (BLF)	1.2%	3.2%	1.8%	0.0%	0.0%	0.0%	5.3%	6.5%	0.0%	5.0%	23%
	Beveled stone (BES)	0.0%	0.3%	0.2%	0.0%	0.0%	0.0%	1.0%	2.0%	0.0%	3.4%	7%
	Macrolithic (MAC)	0.0%	0.6%	1.2%	0.0%	0.0%	0.0%	0.6%	2.7%	0.0%	1.2%	6%
	Dairy production (DIP)	0.3%	0.5%	0.1%	0.0%	0.0%	0.0%	0.8%	0.5%	0.0%	0.3%	3%
	Textile (TEX)	0.0%	0.2%	0.7%	0.0%	0.0%	0.0%	0.2%	1.4%	0.0%	0.5%	3%
	Metallurgy (MET)	0.0%	0.2%	0.7%	0.0%	0.0%	0.0%	0.3%	2.3%	0.0%	1.5%	5%
	Beveled metal (BEM)	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%	0.2%	1%
	Bladed metal (BLM)	0.1%	0.7%	0.7%	0.0%	0.0%	0.0%	1.1%	2.5%	0.0%	1.8%	7%
	Exchange (EXC)	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.3%	1%
		4%	12%	10%	0%	0%	0%	19%	32%	0%	23%	100%
EMBA	Agriculture (AGR)	0.7%	1.6%	0.7%	1.9%	1.9%	1.0%	2.2%	2.2%	2.5%	1.3%	16%
	Storage (STO)	2.0%	2.3%	0.5%	3.2%	1.6%	1.0%	2.3%	1.1%	1.6%	0.5%	16%
	Hunting (HUN)	0.1%	0.5%	0.3%	0.5%	0.7%	0.3%	0.8%	1.1%	1.1%	0.7%	6%
	Bladed flint (BLF)	1.6%	3.3%	1.3%	2.9%	2.5%	1.0%	2.0%	1.8%	1.6%	0.5%	18%
	Beveled stone (BES)	0.3%	0.9%	0.5%	1.3%	1.6%	1.0%	0.9%	1.1%	1.6%	0.5%	10%
	Macrolithic (MAC)	0.1%	0.7%	0.5%	0.8%	1.4%	0.7%	0.7%	1.1%	1.4%	0.5%	8%
	Dairy production (DIP)	0.3%	0.7%	0.3%	0.7%	0.7%	0.3%	0.5%	0.5%	0.5%	0.1%	5%
	Textile (TEX)	0.1%	0.4%	0.1%	0.7%	0.7%	0.5%	0.7%	0.7%	1.1%	0.5%	5%
	Metallurgy (MET)	0.0%	0.2%	0.0%	0.4%	0.4%	0.3%	0.6%	0.6%	1.3%	1.0%	5%
	Beveled metal (BEM)	0.0%	0.1%	0.1%	0.1%	0.4%	0.1%	0.1%	0.4%	0.4%	0.1%	2%
	Bladed metal (BLM)	0.0%	0.3%	0.7%	0.2%	1.4%	0.5%	0.3%	1.6%	1.4%	0.7%	7%
	Exchange (EXC)	0.0%	0.0%	0.0%	0.0%	0.4%	0.3%	0.0%	0.4%	0.7%	0.3%	2%
		5%	11%	5%	13%	14%	7%	11%	13%	15%	6%	100%

The EMBA network is characterised also by a concentration of economic categories agriculture (23%), storage (16%) and bladed flint tools (18%), but with a slight increase in the rest of economic categories.

Structural Network Analysis

Our assessment of local and global structural measures for EBA, MBA and EMBA networks is conducted using a dynamic, incremental approach comparable to a fragility (or robustness) analysis, in which network properties are evaluated across successive stages of edge addition or removal (Albert *et al*., 2000; Rosas-Casals *et al*., 2007; Watts & Strogatz, 1998). In this case, we analyse the evolution of network measures as edges are progressively added in decreasing order of weight (Fig. 4). At each stage, a new network is constructed by including all edges above a given weight threshold. The initial network (corresponding to the first data point on the left of each subfigure in Fig. 4) consists only of edges with maximum weight (i.e. $w_{max}^{EBA} = 7$, $w_{max}^{MBA} = 10$ and $w_{max}^{EMBA} = 12$). For this network, we calculate the proportion of nodes included, $n(\%)$, which is used as the x-axis variable.[5] In subsequent steps, edges are added according to decreasing weight values. At each step, the network is expanded to include all edges with weights equal to or greater than the current threshold, thereby incorporating additional nodes and connections. The corresponding value of $n(\%)$, which increases monotonically with each step, is recalculated and used to track network growth. This procedure allows us to examine how network structure evolves from highly selective configurations, defined by strong affinities between sites, to increasingly inclusive networks that capture weaker connections. By monitoring changes in average centrality and global structural measures at each step, we assess how the progressive integration of less affinitive sites affect the overall network organisation. The process continues until the full network is obtained, when all edges are included and $n(\%) = 100$. Expressing network growth in percentage terms enables a normalised comparison across the three chronological phases.

The findings demonstrate that for every centrality measure analysed, the EBA or MBA network diverges in behaviour from the EMBA network. It is important to note that these metrics illustrate structural configurations derived from economic affinity and projection methods. Notably, this pattern remains consistent regardless of the edge weight threshold applied (i.e. $n(\%)$ value). To quantify these differences, we employ the mean squared error (MSE) as a measure of distance between the values obtained for each dataset (Table 5). MSE values are of the same order of magnitude, with the exception of betweenness and degree. In the case of betweenness, the MSE between the EBA and EMBA networks is one order of magnitude lower than that observed for the EBA–MBA and MBA–EMBA comparisons, indicating a markedly distinct behaviour of the MBA network for this centrality measure. Conversely, for

[5] The relationship between $n(\%)$ and the percentage of edges included at each step, $m(\%)$ is slightly nonlinear but exhibits a smooth and consistent trend across all three networks (results not shown in the text), thereby supporting the robustness and comparability of the analytical procedure.

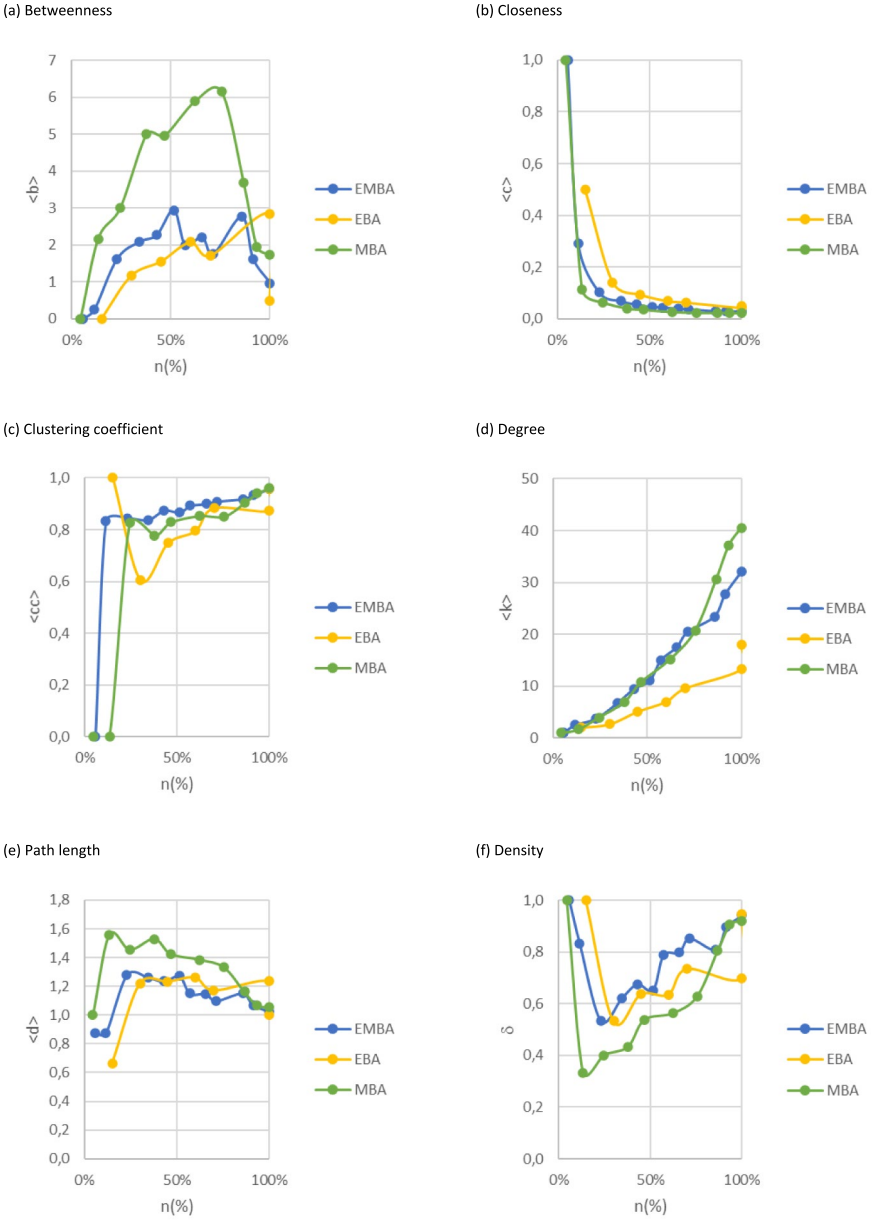


Fig. 4 Evolution of average local (betweenness, closeness, clustering coefficient and degree) and global (average path length and graph density) network structural measures as a function of the percentage of nodes $n(\%)$ present in the networks

Table 5 Mean squared error (MSE) values for local and global structural measures (Fig. 3) obtained for each network combination: EBA – MBA, EBA – EMBA and MBA – EMBA. In bold, significantly lower values for betweenness (0.63) in the case of EBA – EMBA comparison, and degree (9.56) in the case of MBA – EMBA comparison

MSE		EBA—MBA	EBA—EMBA	MBA—EMBA
Local	**Betweenness**$\langle b \rangle$	9.65	**0.63**	6.58
	Closeness$\langle c \rangle$	0.014	0.008	0.002
	Clustering coefficient$\langle cc \rangle$	0.04	0.01	0.08
	Degree$\langle k \rangle$	112.61	66.35	**9.56**
Global	**Average path length**$\langle d \rangle$	0.08	0.02	0.07
	Densityδ	0.04	0.01	0.04

degree, the MSE between the MBA and EMBA networks is one order of magnitude lower than that of the EBA–MBA and EBA–EMBA comparisons, pointing to a distinctive behaviour of the EBA network in terms of connectivity.[6] In summary:

- The EBA network is characterised by comparatively low degree values relative to the MBA and EMBA networks.
- The MBA network stands out for its high betweenness, compared to EBA and EMBA networks.
- The EMBA network combines features of both, displaying degree values similar to the MBA network while maintaining betweenness levels closer to those of the EBA network.

In networks science, assessing the significance of the different local and/or global structural measures in absolute terms is counterproductive at best, if not useless at worst. Empirical results alone admit multiple interpretations; therefore, it is necessary to operate across different levels of abstraction to better understand real–world phenomena. To this end, network models are used to abstract empirical reality and to compare observed measures with those derived from simulated systems. One of the oldest and most extensively studied models is the random graph model (Bollobás, 2001; Newman *et al.*, 2002). It is widely employed as a baseline for comparison for two main reasons: (1) it relies on randomness as its fundamental assumption, thus representing a minimal level of structural complexity, and (2) many of its average properties can be derived analytically. In this study, we use the random graph model $G(n, p)$, where n is the size of the network (i.e. number of nodes) and p the probability of an edge appearing between any pair of vertices, to generate synthetic networks. These are then used to compute the same local and global structural measures as those obtained for the real ones.[7]

[6] Closeness centrality shows also a one order of magnitude difference in MSE values between EBA and MBA networks (i.e. 0.014 vs. 0.008 and 0.002), but they are not significant in absolute terms.

[7] Although the standard random graph model is not a suitable null model for the unipartite projections of bipartite networks, we are analysing small subsets of the global network that do not contain the full information of the unipartite projection. In this regard, and despite not being entirely suitable for all stages of our fragility analysis, it has been chosen as a reference for the reasons outlined in the text.

Table 6 Mean squared error (MSE) values for local and global structural measures (Fig. 3) obtained for real (EBA, MBA and EMBA) and random model (EBA_{rnd}, MBA_{rnd} and $EMBA_{rnd}$) networks. In bold, significantly higher deviation values for MBA and EMBA. Density is used as input parameter

MSE		EBA – EBA_{rnd}	MBA – MBA_{rnd}	EMBA – $EMBA_{rnd}$
Local	**Betweenness**$\langle b \rangle$	0.002	0.14	0.004
	$\sigma(\langle b \rangle)$	2.59	**18.57**	2.34
	Closeness$\langle c \rangle$	0.0003	0.0009	0.0035
	Clustering coefficient$\langle cc \rangle$	0.02	0.07	0.03
	Degree$\langle k \rangle$	0.0003	**1.69**	**6.29**
	$\sigma(\langle k \rangle)$	1.75	**12.26**	4.29
Global	**Average path length**$\langle d \rangle$	0.02	0.02	0.04

In this model, the two only input parameters are n and p, the latter being equivalent to the network density δ at each step of fragility analysis described above (Fig. 4). While the model allows analytical derivation of average properties, our interest also lies in the associated probability distributions of centrality measures, particularly degree $p(k)$ and betweenness $p(b)$. As before, we use the mean squared error (MSE) to quantify the differences between empirical and random networks (Table 6).[8]

The results presented in Table 6 highlight several important aspects of the comparison with the random network model:

- The model reproduces closeness, clustering coefficient and average path length with a high degree of agreement across all three networks, as indicated by consistently low MSE values.
- The EBA network also has a high degree of agreement with a random model. MSE values are the lowest among the three networks for nearly all measures except one: the standard deviation for betweenness $\sigma(\langle b \rangle)$, reaches 2.59, which is remarkably close to the EMBA value (2.34). Particularly noteworthy is the value of $MSE_{\langle k \rangle} = 0.0003$, which is four orders of magnitude lower than those observed for the MBA and EMBA networks.
- In contrast, the model does not reproduce with the same level of accuracy the standard deviations of betweenness $\sigma(\langle b \rangle)$ and degree $\sigma(\langle k \rangle)$, especially for the MBA network. In this case, the deviations are substantial (18.57 and 12.26

[8] As far as we know, exactly solvable expressions for average betweenness and corresponding probability distributions do not exist for $G(n, p)$. These have been obtained numerically, averaging over 10^4 simulations and with values for n and p (equivalent to density δ) corresponding to each $n(\%)$ step of analysis.

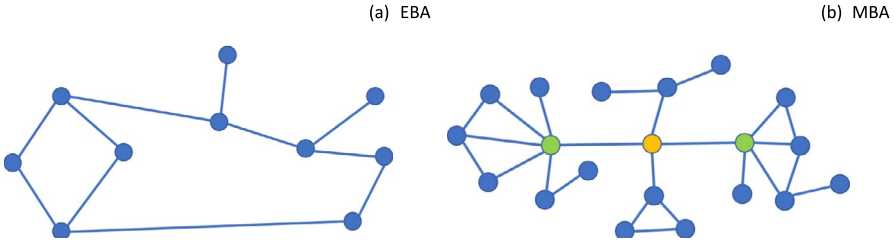


Fig. 5 Synthetic illustrative topologies for EBA and MBA networks. Green nodes highlighted by their high degree. Yellow nodes highlighted by their low degree but high betweenness

respectively), with values one order of magnitude higher than those for the EBA (2.59 and 1.75 respectively) and EMBA (2.34 and 4.29 respectively) networks. This discrepancy indicates that the empirical MBA network exhibits probability distributions of $\langle k \rangle$ and $\langle b \rangle$ with significantly higher variance (i.e. low kurtosis) than those predicted by the random model.[9] In other words, the MBA network displays greater structural heterogeneity, reflected in a wider dispersion of node degree and betweenness values.

In summary, although EBA and EMBA networks are well explained by a random graph structure, the MBA network emerges as a more heterogenous, with sites connected in a less random way. This results in an increased prominence of nodes with high betweenness, reflecting their role as intermediaries along paths linking other nodes within the network. It is important to emphasise that these results come from normalised procedures and are therefore independent of variations in the number of sites or edges. To further illustrate these differences, the observed centrality and global measures can be translated into synthetic networks, allowing the distinct topological configurations of each period to be visualised in an intuitive—albeit deliberately accentuated—manner (Fig. 5).

Modularity

The higher variance observed in $\langle b \rangle$ and $\langle k \rangle$ for the MBA network also suggests a more pronounced modular structure (i.e. a greater number of clusters, groups, or

[9] In all three networks we observe a positive and non-linear correlation between degree and betweenness. In complex networks, degree centrality and betweenness centrality are often correlated (Meghanathan, 2015): nodes with high degree centrality (many connections) tend to have higher betweenness centrality (more shortest paths pass through them).

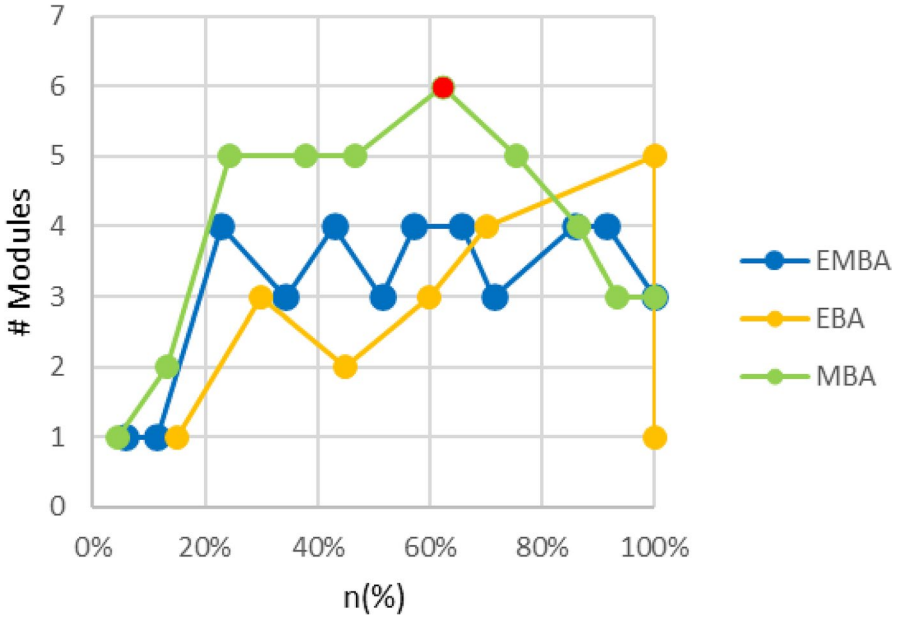


Fig. 6 Number of modules as a function of the percentage of nodes $n(\%)$ present in the networks. MBA network accumulates the highest number of modules at almost each step of analysis. At the point of maximum modularity (highlighted in red), the MBA network has 6 modules which include 28 settlements (62% of the total number, 45) connected by 213 edges (23% of the total number, 912) with $5 \leq w_{i,j} \leq 10$

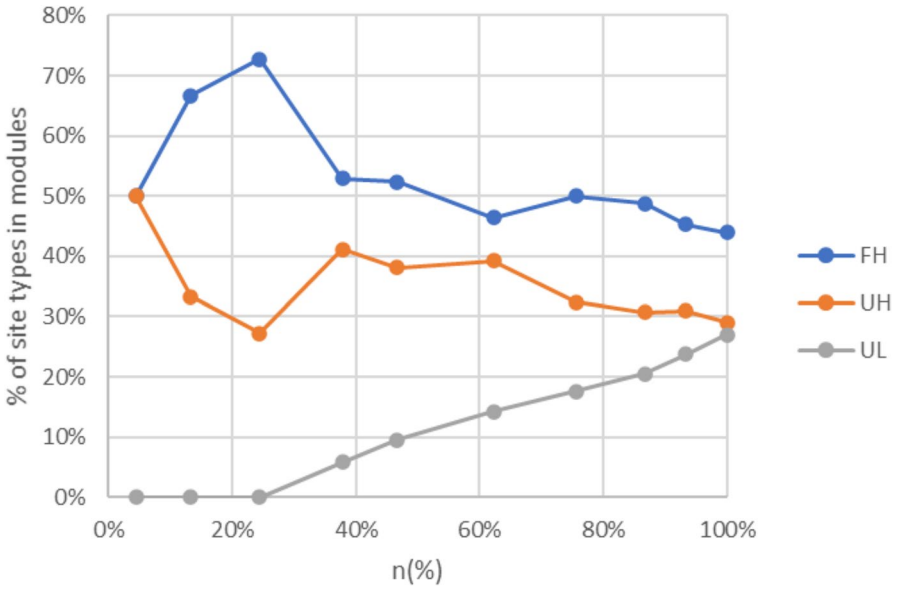


Fig. 7 Presence of site forms FH, UH and UL in MBA modules as percentage and as a function of the percentage of nodes $n(\%)$ present in the network. Hilltop sites (both fortified, FH, and unfortified, UH) decrease in the different modules, while unfortified lowland site form increases

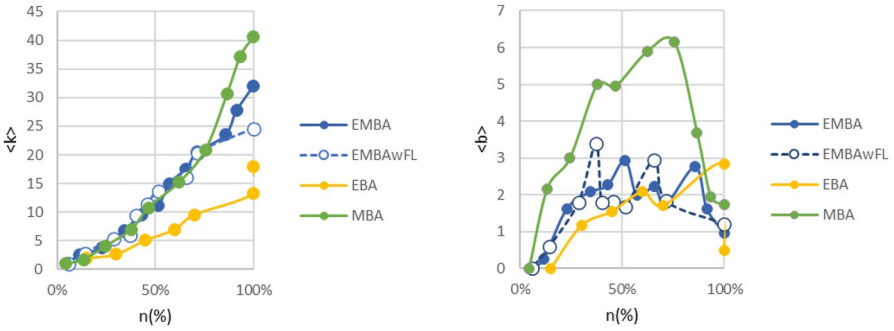


Fig. 8 The effect of removing all (and unique in the EMBA network) FL sites does not change the overall structural behaviour (average degree and betweenness centrality measures shown) of the $EMBA_{wFL}$ network, compared to the original EMBA one

communities).[10] Modularity measures the strength of the division of a network into modules and is defined as the fraction of the edges falling within a given group minus the expected fraction if edges were distributed at random. Networks with high modularity have dense connections within modules and comparatively sparse connections between them (Girvan & Newman, 2001). In this study, modularity is assessed using the Wakita-Tsurumi algorithm (Wakita & Tsurumi, 2007).[11] The results indicate that the MBA network consistently exhibits a higher number of clusters than the EBA and EMBA ones, and this pattern holds across almost all steps of the analysis (Fig. 6).

In light of these results, an important question concerns the relationship between network modularity and settlement forms. This can be explored by analysing the relative presence of settlement forms (i.e. fortified (FH) and unfortified (UH) hilltop and lowland (UL) sites) within the identified clusters, expressed as percentages and as a function of the proportion of nodes *n*(%) present in the MBA network (Fig. 7). It is worth recalling that the MBA dataset comprises 45 sites (Table 1), of which 20 of them of FH form (44%), 13 of them of UH form (29%) and the other 12 of UL form (27%). Across the identified modules, hilltop settlements (both FH and UH) tend to decrease in relative frequency—albeit with inverse symmetry, while UL sites show a corresponding increase. These patterns indicate that the modular structure of the MBA network is primarily driven by hilltop settlements, whereas unfortified lowland sites play a more marginal role. In other words, UL settlements do not contribute to the formation of similarity (or affinity) modules, despite their comparable proportional presence in the network relative to UH sites (29% for UH and 27% for UL). This observation is consistent with the statistical results presented in Table 4 for the MBA network, where FH – FH connections (23%) appear particularly significant, while UH–UL connections decrease notably (from 22% in the EBA to 12% in

[10] "Cluster" should not be confused here with "clustering coefficient", being the latter a node centrality measure.

[11] Other algorithms, like the Clauset-Newman-Moore (Clauset *et al*., 2004) have given equivalent results (not shown in the text).

the MBA). Together, these results point to a reorganisation of settlement interactions in which hilltop locations—especially fortified ones—become the primary structuring elements of network cohesion.

The Case of Fortified Lowland Settlements in the EMBA Network

The EMBA network is the only one that includes sites classified as fortified lowland settlements (FL). These are 7 sites separated by an average distance of 80 ±50 km. To assess their structural significance within the network, we performed an additional fragility analysis excluding these seven sites. The resulting network, labelled $EMBA_{wFL}$ (i.e. EMBA *without* FL sites) is 20% smaller (28 nodes compared to the original 35) and nearly 40% less connected (344 edges compared to the original 561). Given this substantial reduction in size and connectivity, a corresponding shift in centrality measures would be expected. However, the EMBA and $EMBA_{wFL}$ networks display remarkably similar behaviour across all measures (Fig. 8). In other words, from a structural perspective, fortified lowland settlements do not play a decisive role in shaping the overall topology of the EMBA network, despite exhibiting the highest levels of economic affinity (i.e. $10 \leq w \leq 12$).

Economic Power and Settlement Size

Finally, one question that can be approached through networks science concerns the possible relationship between economic power and settlement size. To address this, we cross-correlated settlement area (in hectares) against node strength, s_i, used

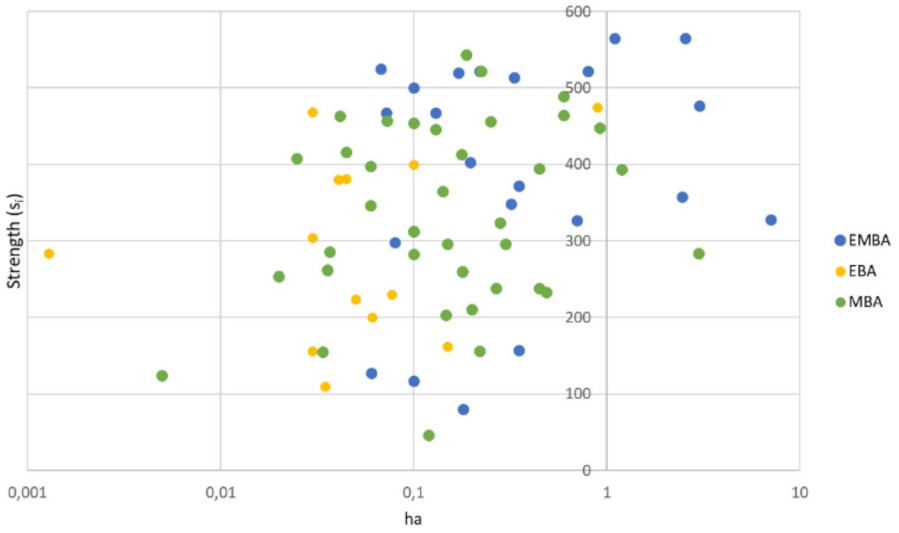


Fig. 9 Cross-correlation between settlement size (logarithmic scale) and strength (used as a proxy for economic power) for each chronology

Table 7 Relative importance of economic categories for each weight of the edges, and for the EBA (left) and the MBA (right) networks. The most regular (i.e. similar percentages for all weights) productive activities are those related to agriculture, storage and bladed flint tools

	EBA						
$w_{i,j}$ =	7	6	5	4	3	2	1
Agriculture (AGR)	14%	17%	20%	24%	21%	22%	40%
Storage (STO)	14%	13%	17%	18%	21%	39%	40%
Hunting (HUN)	5%	7%	13%	17%	12%	6%	4%
Bladed flint (BLF)	14%	17%	20%	22%	15%	26%	13%
Beveled stone (BES)	5%	10%	5%	3%	0%	0%	0%
Macrolithic (MAC)	14%	0%	4%	1%	9%	1%	0%
Dairy production (DIP)	0%	0%	1%	0%	0%	2%	0%
Textile (TEX)	14%	17%	5%	4%	0%	0%	0%
Metallurgy (MET)	0%	7%	9%	3%	8%	3%	0%
Beveled metal (BEM)	5%	0%	1%	4%	1%	0%	0%
Bladed metal (BLM)	14%	3%	3%	3%	5%	2%	2%
Exchange (EXC)	0%	10%	0%	1%	7%	1%	0%
	100%	100%	100%	100%	100%	100%	100%

	MBA									
	10	9	8	7	6	5	4	3	2	1
Agriculture (AGR)	10%	11%	13%	14%	17%	20%	24%	27%	30%	35%
Storage (STO)	10%	11%	11%	12%	13%	11%	14%	20%	24%	26%
Hunting (HUN)	10%	6%	8%	8%	6%	6%	8%	5%	2%	0%
Bladed flint (BLF)	10%	11%	13%	14%	17%	20%	24%	31%	31%	15%
Beveled stone (BES)	10%	6%	10%	9%	10%	10%	6%	4%	1%	15%
Macrolithic (MAC)	10%	6%	7%	5%	5%	8%	9%	5%	7%	0%
Dairy production (DIP)	10%	6%	4%	3%	2%	4%	2%	2%	0%	9%
Textile (TEX)	10%	8%	5%	6%	4%	4%	3%	2%	1%	0%
Metallurgy (MET)	10%	11%	13%	12%	10%	5%	2%	2%	3%	0%
Beveled metal (BEM)	0%	11%	4%	2%	0%	0%	1%	0%	0%	0%
Bladed metal (BLM)	10%	11%	13%	14%	14%	9%	6%	4%	1%	0%
Exchange (EXC)	0%	3%	1%	1%	2%	2%	1%	0%	0%	0%
	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

here as a proxy for economic power (Fig. 9). Strength is defined as the weighted degree of a node i that is, the sum of the weights of its edges (Barrat *et al*., 2004). In this framework, economic power is operationalized through connectivity: a settlement with high strength is linked to many other sites and/or shares a large number of economic categories with them. Since edge weights represent the number of shared economic traits, higher strength values indicate a greater level of economic integration and structural relevance within the network. As shown in Fig. 9, the results do not suggest any positive correlation between settlement size and economic power as measured by node strength. These findings indicate that if hierarchical control by larger settlements over smaller sites existed, it is not manifested within this economic similarity network, given the current dataset and methodological parameters.

Discussion

It is important to emphasise that in this paleo-economic evaluation of the Bronze Age networks, the identified edges do not necessarily represent active inter-community relationships. Indeed, our results show no correlation between physical distance and other variables, such as artefactual evidence or network structural measures. Instead, edges reflect varying degrees of technological, socioeconomic, and productive *affinity* among communities that inhabited the plains and mountains of east-central Iberia during the Early and Middle Bronze Age. This pattern applies to most of the economic categories considered in this study (i.e. agriculture, hunting, flint and macrolithic tools, textile, storage, and everyday production). However, certain categories, particularly those involving non-local raw materials such as metal or ivory, are plausibly interpreted as the result of inter-community interactions.

Our results show that most average centrality and global measures are not significant to detect structural differences between EBA, MBA and EMBA networks. Only *average degree* $\langle k \rangle$ and *betweenness* $\langle b \rangle$ centralities exhibit sufficient discriminant

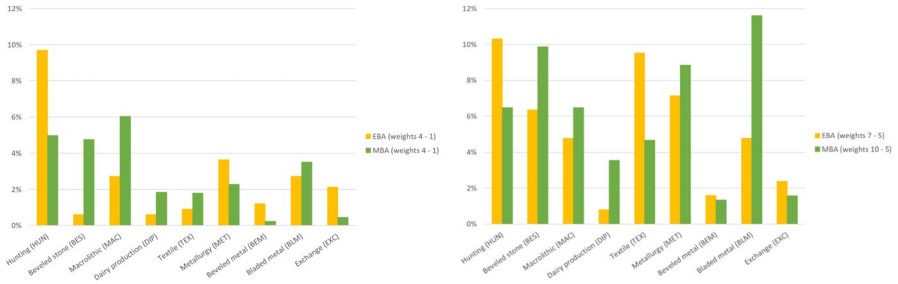


Fig. 10 Relative importance of economic categories based on synthetic groups of economic affinities built with the highest (10–5, right) and the lowest (4–1, left) weights. Economic categories of agriculture (AGR), storage (STO) and bladed flint tools (BLF) have been excluded, given that their importance is evenly distributed throughout all weights

capacity to distinguish among these three topologies.[12] All economic structures except the MBA network align closely with a random graph structure.. In fact, the deviation of MBA from the random graph framework accounts for its distinct behaviour in terms of $\langle k \rangle$ and $\langle b \rangle$: the standard deviations of the probability distributions of both average *degree* and *betweenness* in the MBA are considerably higher than those in the equivalent random graph. This increased heterogeneity results in a more modular network (i.e. with a higher number of clusters) across all $n(\%)$ values compared to EBA and EMBA networks. The settlements forming these clusters are predominantly hillforts (FH) and upland sites (UH), while lowland unfortified settlements (UL) are largely absent. This suggests that the modularization process was driven primarily by hilltop sites, which we know from previous studies were mainly located towards the southeast and east, closer to the El Argar border (Peres & Risch, 2022, Fig. 6). Instead, unfortified lowland settlements, mostly located in central Iberia, followed a different economic dynamic.

The specific economic patterns underlying this modularity can be examined by considering the relative importance of economic categories for each weight (Table 7). In all three networks (EBA, MBA, and EMBA), the artefactual evidence is dominated by agriculture (AGR), storage (STO), and productions performed with bladed flint tools (BLF). These can be described as *stable production* categories, as they consistently dominate *affinity* patterns across all weight classes. All these three economic categories are evenly distributed across edge weights, albeit with a significant increase in the lowest weight class (i.e. $1 \leq w_i \leq 2$).

The differences between EBA and MBA networks arise when edge weight increases: we observe how the relative importance of economic categories for each weight is more evenly distributed for the MBA case, especially for bevelled stone (BES), macrolithic (MAC), dairy production (DIP), metallurgy (MET), bladed metals (BLM), and exchange (EXC). This feature can also be observed when we

[12] Unlike degree centrality, betweenness centrality is exceptionally sensitive to sampling biases. Although assessing the robustness of our results against, for example, a controlled node-removal routine would have been methodologically appropriate, formal subsampling in small networks artificially fragments the graph into disconnected components and overestimates instability.

group the economic categories to the highest and lowest edge weights, and exclude subsistence activities (i.e. AGR, STO and BLF). Figure 10 illustrates the relative importance of economic categories based on synthetic groups of economic affinities. In one group (Fig. 10, right) we aggregate edges with the highest weights (i.e. $5 \leq w_i \leq 10$ for the MBA network, which corresponds to $n(\%) \cong 0.6$ and the highest number of modules shown in Fig. 6; and $5 \leq w_i \leq 7$ for the EBA network). In another group (Fig. 10, left), we aggregate the remaining weights (i.e. the most common edge weights, $1 \leq w_i \leq 4$ for both networks). In this latter group percentages are similar and correlate across all categories: the most important economic categories for the EBA network with the highest weights are hunting (10.3%) and textile production (9.5%). In contrast, the high-weight group reveals major differences: the economic categories that define the strongest affinities in the MBA are bevelled stone artefacts (9.9%), metallurgy (8.9%) and bladed metal artefacts (11.6%), all of these materials associated with extensive distribution networks, implying a more integrated web of inter-community connections and the existence of different types of economic networks between EBA and MBA. Importantly, these differences do not correlate with settlement location or type. The distribution of sites is broadly comparable in both periods, with roughly 75% located in elevated areas outside the valley and only 25% in lowland contexts (Table 1). This suggests that the identified trends were driven primarily by changing socio-economic and socio-political dynamics rather than by variations in settlement geography or environmental change.

An additional issue here is the spatial distribution of the settlements connected with the highest-weight edges (i.e. settlements with highest economic affinity). In the EBA network, the strongest edges ($6 \leq w_i \leq 7$) are spread between 125 and 275 km, while in the MBA network the strongest edges ($8 \leq w_i \leq 10$) occur at shorter distances, between 25 and 175 km. By contrast, the EMBA network presents a more homogeneous distribution of edges across distances, with the strongest edges ($10 \leq w_i \leq 12$) spanning between 75 and 425 km. As already noted, this may be a result of the insufficient precision in the dating of the sites.

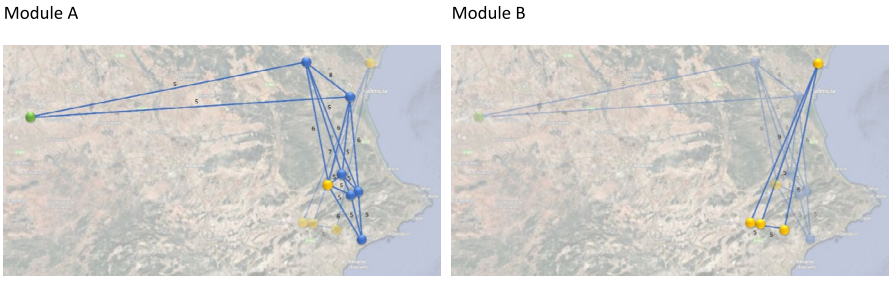


Fig. 11 Spatial location of MBA settlements included in two modules that show economic affinity and spatial proximity (out of 6 modules at the point of maximum modularity) and settlement forms: fortified hilltop (FH, blue), unfortified hilltop (UH, yellow) and unfortified lowland (UL, green). The label in an edge indicates its weight (only edges connecting settlements belonging to the same module are shown)

Our results above would suggest that MBA communities sharing similar economic forms tended to be located closer to each other compared to their EBA counterparts. This fact could be explained by the higher settlement density in the MBA (45 MBA against 20 EBA settlements). But from the overall network perspective, when modularity analysis is considered, economic affinity does not show a significant correlation with distance. At the point of maximum modularity for the MBA, there exist six modules which arise from a network of 28 settlements (62% of the total 45), connected by edges with weights ranging from 5 to 10 (see Fig. 6, point highlighted in red). At this stage, the distribution of settlement forms is as follows: 65% FH (13/20), 85% UH (11/13) and 33% UL (4/12). This pattern again indicates that modularity, in terms of economic affinity identified by edges with the highest weights, is driven by hilltop-form sites, especially unfortified ones, while lowland settlements (which in the MBA are exclusively unfortified, as all *motillas* belong to EMBA) play a lesser role in structuring the network. Spatial relative proximity is somehow relevant in only two of the six modules, which group settlements located near or along the eastern coastline. Module A (Fig. 11, left) comprises eight settlements (the largest number of them in any of the six clusters), six of which are FH, one UL, and one UH. Module B consists of four settlements, all being UH (Fig. 11, right). The remaining modules do not show a clear spatial clustering or a dominant settlement form.[13]

Another complementary perspective emerges when we analyse the economic affinities between settlement forms (see Table 4). The main difference between EBA and MBA networks lies in the change in UH – UL and FH – FH connections: UH–UL edges decrease from 22% (EBA) to 12% (MBA), whereas FH–FH edges increase from 10% (EBA) to 23% (MBA). With the remaining percentages broadly stable, this pattern indicates a decline in economic affinity among lowland sites, alongside an increase in affinity between fortified hilltop sites (FH).

Additionally, storage activities decline significantly across all settlement forms during the MBA (from 26 to 16%), with the sole exception of fortified hilltop settlements (FH), which show a slight increase (from 2.2% to 3.0%). During the Middle Bronze Age, FH settlements were the only form experiencing economic growth across nearly all productive domains analysed (10 out of 12). This pattern coincides chronologically with the territorial and economic peak of the Argaric State (ca. 1800–1550 BCE), a phase characterised by the consolidation of its borders and the strengthening of its economic control mechanisms (Moreno Gil, 2026).

These observations are consistent with previous studies suggesting that, under increasing sociopolitical pressure, peripheral communities might have adopted a strategy of physical protection of production, relocating key resources to highland and fortified settlements (Peres & Risch, 2022, 2023a). The novelty of the present results lies in showing that this dynamic was particularly pronounced during the Middle Bronze Age (1800–1550 BCE).

A special case is represented by fortified lowland (FL) sites, which are present exclusively in the EMBA network. Counterintuitively, our analysis shows that these

[13] The number and type of sites in the remaining four modules are 5 (4 FH/1 UH), 4 (2 FH/2 UH), 4 (1 FH/2 UL/1 UH) and 3 (2 UH/1 UL).

settlements, despite exhibiting complete similarity in terms of form and economic categories (i.e. edges that connect them have weights between 12 and 10), were not important in terms of overall network topology. In other words, the structure of the network is not sensitive to their presence or absence, despite the substantial investment in defensive architecture and the construction of central wells. This apparent economic un-specificity of the FL communities within the EMBA network is consistent with our broader analysis of the productive forces and relations of production (Peres & Risch, 2023a).

Regarding the economic power of settlements, it is noteworthy that our analysis shows absolutely no correlation between economic centrality and settlement size, contrary to some theories (Chapman, 1990; Johnson, 1999). Even the few settlements exceeding one hectare do not stand out in terms of economic interaction or affinity. This suggest that, in the peripheral regions north of El Argar, larger settlements did not dominate or exert control over smaller ones, at least in terms of relations of production.

Conclusions

Addressing the research questions posed at the outset of this study, network analysis reveals the existence of large-scale economic affinity among EBA settlements in central-eastern Iberia. The communities analysed shared similar means of production and a broadly comparable economic organisation, confirming the results of previous paleo-economic studies (Peres & Risch, 2023a). This relative technological and productive uniformity, extending across an area of at least 177.000 km^2, indicates the presence of analogous economic patterns among settlements separated by several hundred kilometres. Archaeologically, this suggests that the pronounced atomisation of settlement during the EBA did not correspond to a highly differentiated economic landscape. Instead, numerous small and spatially dispersed communities appear to have participated in a broadly shared productive framework.

The underlying economic basis of this shared system was agriculture, and more specifically cereal cultivation, storage, and processing. This common economic strategy contrasts sharply with the situation observed during the Copper Age, when marked differences between settlements are evident not only in lithic assemblages but also in botanical and faunal remains (Eguíluz *et al*., 2023). Regardless of the specific combination of climatic, epidemiological, or migratory factors associated with the 4.2 ka event in the Iberian Peninsula, the results of the network analysis suggest that communities converged economically towards a cereal-based subsistence strategy while simultaneously becoming more spatially dispersed, in a clear process of atomisation into smaller settlement units compared to the Copper Age. Additionally, the low weights and limited number of edges, together with the high frequency of zero values in several economic indicators (Tables 3 and 7)—with the mentioned exception of those related to cereal agriculture—suggest a context of relative economic scarcity. This pattern contrasts with the situation of both material and symbolic abundance that characterises the Chalcolithic period (Bueno Ramírez & Soler Díaz, 2011; Eguíluz *et al*., 2023). Taken together, these observations are

consistent with a phase of reduced economic diversity and intensity after 2300–2200 BCE, lasting until approximately 1800 cal BCE, compared to the preceding Chalcolithic period. The combination of economic convergence, low diversity, and settlement atomisation is therefore important: rather than indicating the emergence of increasingly specialised or economically competitive communities, the EBA appears to have been characterised by a relatively homogeneous and decentralised economic system.

By contrast, and somewhat unexpectedly, the network analysis does not account for the process of settlement enrockment observed in the southern sector of central-eastern Iberia, north of the El Argar territory (Martínez Monleón, 2014; Moreno Gil, 2026). This distinction is archaeologically important because it suggests that the increasing preference for elevated and defensible locations after 2300–2200 BCE was not primarily driven by economic factors, but rather reflects broader socio-political, territorial, or conflict-related dynamics that may have been associated with the expansion of El Argar, among other factors, and are not directly captured by economic connectivity.

Our study also reveals the existence of significant structural differences between the EBA and MBA networks, as reflected in the network measures analysed. From a network science perspective, the fact that only two centrality measures (i.e. average degree and betweenness) among all those used in this analysis, are able to discern structural differences is a relevant outcome for establishing a systematic approach to network analysis of archaeological data. In the Middle Bronze Age (MBA), a substantial transformation of the network is observed. Productive and technological homogeneity extends now to the rest of economic categories, mainly stone and metal axes, metal knifes, metallurgy, dairy production, and exchange values. This pattern is especially associated with hilltop settlements, which dominate the modules (i.e. clusters) composed of economically similar sites. Although the general orientation towards subsistence remains, the data indicate an increase in the availability and circulation of metal, possibly linked to the intensification of mining exploitation in the Argaric territory around 1850 BCE and the peak of the metallurgical settlement of Peñalosa (Arboledas Martínez *et al*., 2014; Delgado-Raack *et al*., 2026; Moreno Onorato & Contreras Cortés, 2010; Murillo-Barroso *et al*., 2025). We could hypothesise that El Argar increased, directly or indirectly, the supply of metals in peripheral communities during the Middle Bronze Age, fostering a dynamic of transformation in their internal social relations. It is precisely during the MBA that we observe an increasing economic disparity between the settlements in central Iberia — particularly the unfortified lowland sites around the Madrid area — and those in the Levante and La Mancha, in proximity to the El Argar territory. Our analysis suggests that the modularization process during the Middle Bronze Age was led by hilltop settlements, with more bladed metal artefacts and more metallurgy, emerging as the most decisive economic categories. In summary, from the MBA onwards, the fortified and small peripheral settlements in the southeast appear to have increased their productive and exchange capacity, configuring a different and significantly open economic model, in contrast to the EBA system, more characterised by self-sufficiency. Importantly, however, this increasing differentiation does not appear to have produced a clear economic hierarchy. Rather, it suggests a process of internal

reorganisation within a still broadly decentralised settlement system. This interpretation is consistent with the absence of prominent economic centres in terms of specialisation or functional differentiation in our analysis.

The activities most shared among different forms of settlements, across all chronological phases, are agriculture, storage and flint cutting, indicating the persistence of a common economic substrate in the central-eastern Iberian Peninsula during the Bronze Age. Likewise, the correlation between settlement strength, used here as a proxy for economic power, and size (in hectares) is not significant in any of the three periods analysed. Consequently, settlement size cannot be considered a reliable indicator of hierarchy or economic centrality. Not even the *Motillas* group, with their extensive extramural settlements and high internal economic affinity, stands out for structurally differentiated behaviour compared to other settlements. This reinforces the broader conclusion that spatial scale, settlement size, or architectural investment alone are insufficient to reconstruct patterns of socio-political organisation without considering the productive forces and means of production.

In summary, the connectivity patterns identified through our network science approach, expressed in terms of economic affinity between Bronze Age settlements, provide a new perspective for analysing socio-economic structures and potential hierarchical relationships in central-eastern Iberia. Taken together, the results reveal a transition from a broadly homogeneous and relatively low-diversity EBA economic system towards a more differentiated and modular MBA structure, while providing no evidence for clearly dominant economic centres. This transformation suggests that peripheral communities were not simply a passive periphery of El Argar, but active participants in changing regional networks whose internal economic organisation and connectivity were themselves transformed during the period of increasing interaction with the Argaric polity. The contrasts, as well as the interactions, between Copper Age, peripheral Bronze Age, and El Argar socio-economic systems will be explored in future research, once more comprehensive and comparable datasets become available.

Network analysis thus offers an additional analytical layer for examining artefact categories, their interrelationships, and their spatial distribution, yielding valuable insights into the economic organisation of prehistoric societies. More broadly, the study demonstrates that network approaches can help distinguish between processes that are often conflated in archaeological interpretation—such as economic differentiation, connectivity, and hierarchy—and can therefore contribute to a more nuanced reconstruction of how Bronze Age Iberian communities reorganised themselves within a context of structural changes in political and economic landscapes.

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Author Contributions MRC: Conceptualization, investigation, methodology, software, formal analysis, and writing (original draft).

MP: Conceptualization, data curation, investigation, formal analysis, and writing (review & editing).

SDR: Conceptualization, investigation, formal analysis, and writing (review & editing).

RR: Conceptualization, funding acquisition, data curation, investigation, formal analysis, supervision, and writing (review & editing).

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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