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Sanctuaries in the Sardinian Bronze Age and Early Iron Age landscape (1200-700 BC): Network analysis and GIS approach

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Abstract: This paper aims to investigate the role of the Nuragic sanctuaries in regards to the settlement-pattern, control of metal resources and mobility of those resources during the Final Bronze Age (1200-900 BC) and Early Iron Age (900-700 BC) in Sardinia. Prior studies have, in fact, noted the importance of past sacred landscapes not only as ritual and symbolic places, but as deeply embedded in the social-economic structure of a community and ecological space. The rise of Nuragic sanctuaries is a response to a profound societal and economic crisis that characterized the Nuragic civilization around 1200 BC. Despite being generally associated with the cult of water, the rise of these new types of settlements also corresponds to a period of increased metal production as well as internal and external metal trade. Metal-workshops and other economic activities are well-known in these sites, however, without identifying which role the sanctuaries had in the metal-production and distribution system. In this paper, I argue that the rise of the sanctuaries acted as symbolic, territorial and economic nodes within and between Nuragic settlements and natural resources. The study takes advantage of spatial analysis applied with two different methods: spatial analyses through Network Analysis and GIS (Least Cost Path) to investigate networks and mobility patterns between sanctuaries, settlements and mineral resources. The results will be used to understand the role of sanctuaries in the Nuragic landscape in connection to the mineral resources and settlements.
Keywords: Nuragic sanctuary, metal resources, mobility networks, GIS Analysis; Network Analysis.

Riassunto: Lo scopo del presente studio è quello di investigare il ruolo dei santuari nuragici in relazione ai sistemi insediativi, al controllo delle risorse minerarie ed alla circolazione dei metalli tra il Bronzo Finale (1200-900 a.C.) e la prima Età del Ferro (900-700 a.C.) in Sardegna. Lo sviluppo dei santuari nuragici nasce come risposta ad una profonda crisi economica e sociale che investe la società nuragica intorno al 1200 a.C. Spesso definiti come 'compound' territoriali con lo scopo di unire a mantere gli equilibri tra più insediamenti, vengono generalmente associati al culto delle acque o interpretati come centri di produzione e redistribuzione di risorse. Il loro sviluppo corrisponde anche ad un periodo di intensa produzione metallurgica e di commercio di prodotti in metallo sia interno che esterno all'isola. Nonostante ciò, un modello che concettualizzi il ruolo dei santuari nel controllo delle risorse metallifere e nello scambio di prodotti in metallo, non ha ancora trovato spazio nella letteratura scientifica. Nel presente articolo il santuario viene presentato come un'entità simbolica, territoriale ed economica, utilizzato come nodo nella connessione tra insediamenti nuragici e risorse

naturali. Lo studio si avvale di analisi spaziali tramite GIS e Network Analisi: Analisi dei Costi Percorrenza (Least Cost Path) sono state utilizzate per indagare eventuali trend nella mobilità di individui tra santuari, insediamenti e risorse metallifere. La Network Analysis per comprendere se la posizione dei santuari abbia avuto un ruolo centrale nella gestione delle risorse naturali e nello scambio di metalli o altri prodotti di pregio tra le comunità nuragiche.
Parole chiave: Santuario nuragico, risorse metallifere, mobilità, analisi GIS, analisi Network.

INTRODUCTION

In the evolution of the Nuragic landscape (1700-700 BC), Sardinian archaeological research has employed several types of spatial and networks analyses in an effort to comprehend the social and economic use of the Nuragic cultural landscape, however with much emphasis on the Bronze Age stone-built towers, named '*nuraghi*' (USAI 2003, 2009; DEPALMAS 1998, 2003; CICILLONI *et alii* 2014). Synchronic and diachronic variations on mobility and networks have been addressed mostly through Visibility and Cost Surface Analysis (e.g. DE MONTIS, CASCHILI 2012; SANNA 2014; SCHIRRU 2017; CABRAS 2018). These two types of spatial analyses are tightly connected and therefore useful as they can reveal aspects of the social organization of space in a particular area or region (i.e. VAN LEUSEN 1998; WHEATLEY, GILLINGS 2002; MEHRER, WESCOTT 2006; PECERE 2006; DAVID, THOMAS 2008; EARLE 2016). However, spatial analysis has very rarely included the broader range of Nuragic monuments, especially those related to the "sacred landscape" (e.g. BLAKE 2001, 2008; IALONGO 2011, 2017; CICILLONI *et alii* 2019, 2020).

At the beginning of the Final Bronze Age (1200 BC), the rise of Nuragic sanctuaries has been interpreted as a response to a profound societal and economic crisis that invests the Nuragic civilization around 1200 BC (i.e. PERRA 2009; LO SCHIAVO *et alii* 2009; CÁMARA SERRANO, SPANEDDA 2014). Frequently associated with the cult of water, the control, production, and redistribution of metal items, the rise of these new types of settlements corresponds to a period of increasing metal production, internal and external metal-trade (CAMPUS *et alii* 2010; BERNARDINI 2017). The Nuragic sanctuaries are acknowledged to be part of this commodity chain in the landscape, however, without identifying at which level (i.e. FADDA 2014; BERNARDINI 2017).

Theorized as 'territorial compound' (i.e. LILLIU 1982, 1988; LO SCHIAVO *et alii* 2009, DEPALMAS 2014a; USAI 2015) and recently as 'polifunctional' places (BERNARDINI 2017), their role in a model that investigates the control of metal resources and the internal mobility of raw materials has never been conceptualized or tested. The present article seeks to remedy this omission and add to our knowledge about the long-term development of the human-made landscape of the Nuragic Bronze Age and Early Iron Age.

This paper aims to investigate the role of the sanctuaries in a broader landscape perspective in regards to their connection with the surrounding settlements and metalliferous resources and the mobility of raw-material during the Final Bronze Age (1200-900 BC) and Early Iron Age (900-700 BC) in Nuragic Sardinia.

Firstly, an overview of the available archaeological data and state of the art on the interpretation of the Nuragic sanctuaries is presented. Secondly, the study applies two methods (Network Analysis and Least Cost Path) to understand the possible role of the Nuragic sanctuaries in the control of important mineral resources, such as copper and lead-silver, and highlight the positions of the sanctuaries within the internal market-place and their relationships with other types of settlements. Thirdly, in the results and conclusion sections, a description of the possible role of the Nuragic sanctuaries based on accessibility to metal resources and degree of networking with the contemporary Nuragic settlements is proposed.

STATE OF THE ART

The sanctuary as a religious and political reference

The study of Sardinia's sacred landscape in the Bronze and Iron Age has consistently attributed significance to the sanctuaries in Nuragic society as well as in the way this society developed. Following the generally accepted Nuragic chronology, the sanctuaries developed during the Final Bronze Age (1200-950 BC), albeit possibly with maximum expansion in the Early Iron Age (950-720 BC). However, earlier settlement phases are evident at most of the sites (e.g. FADDA 2000; DEPALMAS 2009; SALIS 2010, 2017; CAMPUS 2015), hence allowing for an earlier beginning of the Bronze Age proper. The sanctuaries are typically understood as sites of unifying reference for the people and organizations of a larger area, 'confederate compounds' in Lilliu's wording (1982, 1988). This means that Nuragic sanctuaries could have served as centres for religious and political aggregation of dispersed communities. Following this interpretation, the societal transformation begun by the abandonment of the Nuragic towers and the collapse of the traditional political economy at the beginning of the Final Bronze Age (1200-950 BC) may have paved the road for the rise of a new social class. This possible aristocracy boasted political authority and high-ranking identity while being ideologically entrenched in both military and religious practices (CÁMARA SERRANO, SPANEDDA 2014: 153).

In the Nuragic sanctuaries, 'aristocratic' men and women would have been in charge of cults while simultaneously exercising their social power by controlling nearby metal resources and by flaunting their superior rank through certain prescribed ritual practices (IALONGO 2013).

A coexistence between cult and metallurgy is substantiated by the significant process of the metal hoarding and the massive production of metal artefacts, in particular the so-called '*bronzetti*'. The phenomenon of the ritualistic display of votive offerings (IALONGO 2013) have been coupled into a model of wealth redistribution by Webster (2015): the elite groups can decide, by using the mechanism of hoarding, the number of prestige goods circulating within the community under their control (IALONGO 2011, 2017; CAMPUS *et alii* 2010). Thus, the sanctuaries appear as multi-functional places where the religious spaces and the cult of water were used to tie the upper class to a divine domain while at the same time building either political or ideological consensus (BERNARDINI 2017).

The sanctuary in the Nuragic landscape

Rather than forming very dense settlement patterns like in the Middle and Late Bronze Age (i.e. ANGIUS *et alii* 2012; VANZETTI *et alii* 2013), in the Final Bronze Age and Early Iron Age the Nuragic sanctuaries gather different communities and created a new and different type of network (USAI 2015). The main information about their geographical location within the Sardinian landscape relies on observational data: the Nuragic sanctuaries with their annexed clusters of round buildings are usually situated across mountain passages and high-lying plateaus or in certain areas otherwise with an abundant availability of water (FADDA 2017: 231, SALIS 2017: 253). Certainly, the need for water resources during the Late and Final Bronze Age seems to be one of the main attributes connected to the development of the wells, and it was perhaps attributed sacredness only in a second phase (DEPALMAS 2014a: 484; PAGLIETTI 2015; SALIS 2017).

According to Depalmas (2014a), each site adapts to the morphological features of the landscape. In some cases, the Nuragic sanctuary developed as different groups of buildings distributed in an extended area, other sanctuaries are located in more defined natural settings, like a plateau or a hill, where it is easier to quantify the extension of the site (DEPALMAS 2014a: 487). Furthermore, an attempt to clarify the site selection of the sanctuaries has been presented by several authors who, in general, univocally interpret the position of the Nuragic sanctuaries as strategic, i.e. at the centre of 'political units' (i.e. LILLIU 1988; SPANEDDA 2002, 2007, 2010; IALONGO 2011, 2017; CICILLONI *et alii* 2019, 2020) Nevertheless, Ialongo (2017) argues that Nuragic sanctuaries "*are built in scarcely populated, unproductive territories, probably inside those buffer zones or 'no man's land*'" (IALONGO 2017: 13, Figure 8:13).

On the other hand, other scholars discuss the importance of the location of the sanctuaries at the limit of ecological boundaries, overlooking fertile agricultural plains and maintaining visual control over major-contemporary Nuragic settlements located in territories devoted to agriculture and husbandry (DEPALMAS 2005; SPANEDDA 2007, 2010; CICILLONI *et alii* 2019, 2020).

In sum, the position of the Nuragic sanctuaries within the landscape seems related to several variables without a unique interpretation at the moment. These factors include the morphology of the landscape, availability of resources, ideological and stragic control over territories, and as the role of the sanctuaries as nexuses for the Nuragic communities.

Sanctuaries, metal production and mineral resources: a review of the archaeological evidence

Nuragic sanctuaries are mostly characterized by their relationship with water and metal. The large accumulation of metal scraps and the deposition of hoards containing fragmented pieces of metal objects illustrates the significant connection between the ritual place and metallurgy (Fig. 1). Mostly related to the cult of water, the Nuragic sanctuaries usually are characterized by their 'polifunctionality' (BERNARDINI 2017: 213). Within an extended area, the ritual and the profane activities (especially metallurgy) are connected but organized in separated spaces, such as spaces for ceremonial and ritual performances as well as areas for the accumulation and production of metalwork or other goods (BERNARDINI 2017).

The sanctuary is also described as a centre for the redistribution and control of economic resources, especially metal ores and metal production (e.g. BERNARDINI 2017; FADDA 2017). It became the institutionalized site for the management and distribution of prestige goods and it was likely the institutional market for metal trade and the sharing of new ideas and knowledge (i.e. LO SCHIAVO *et alii* 2009; WEBSTER 2015).

The connection between metal production, trade, and divine protection during the Final Bronze Age and the Early Iron Age should be discussed. The organization of copper and bronze production in Nuragic Sardinia is a subject about which very little is known except at a technological level (e.g. LO SCHIAVO *et alii* 2005; LO SCHIAVO 2018). Studies regarding, for example, metalworks such as the Nuragic bun ingots revealed a heterogeneous distribution of the production spread across Sardinia (e.g. LO SCHIAVO 2018), but were unable to shed light on the distribution process itself.

Although at the moment, there is no significant trace of mining activities neither of "primary" casting workshops in Bronze Age and Early Iron Age Sardinia (i.e. LO SCHIAVO *et alii* 2005: 292, LO SCHIAVO 2014), during recent fieldwork at the Nuragic sanctuary of *Matzanni*-Vallermosa (South-West Sardinia) remains of crushing tools, such as *'teste di mazza'*, were discovered. The tools are usually associated with mining activities or the crushing of metalliferous ores (MARTELLOTTA *et alii* 2020; MATTA *et alii* 2020), and are therefore a possible clue about the mineral extraction and primary casting that took place at the sanctuary.

A different discussion concerns the "metal-working (or secondary) workshops" (for the definition see LO SCHIAVO *et alii* 2005: 292) where the bronzes were produced, repaired, and finished. In this case, numerous examples of possible foundries, dated to the Final Bronze Age and Early Iron Age, are detected in the Nuragic sanctuaries: Hut 4 in the village of *Sant'Anastasia- Sardara*, the foundry in the Nuragic sanctuary of *S'Arcu is Forros*-Villagrande Strisaili, the foundry in the village of *Sa Sedda 'e Sos Carros*- Oliena, and perhaps in the sites of *Abini*-Teti; *Monte Sant'Antonio*-Siligo; *Serra Niedda*-Sorso where crucible fragments have been uncovered (IALONGO 2011) and *Funtana Coberta*- Ballao (MANUNZA 2008). It is possible that the metal would come to the Nuragic sanctuary in the form of pre-refined raw material and transformed *in situ*.

When considering the exploitation of mineral resources, Fig. 2 shows the location of the Sardinian mineral resources (lead, copper, and tin) that were possibly exploited during the Bronze and Iron Age (PINARELLI 2004; VALERA *et alii* 2005).

The highest concentration of copper and lead-silver deposits lie in the so-called *Iglesiente* in the southwest, and the *Sarrabus* in thesoutheast; however, significant deposits were also located in the northwest (*Calabona* and *Argentiera*), as well as *Funtana Raminosa* in the central region of Sardinia.

Sardinia has a few cassiterite mineral outcrops at *Perdu Cara* and *Canale Serci* in the area of Vallermosa-Fluminimaggiore (southwest Sardinia, VALERA *et alii* 2005: 95), but due to the scarcity of near-surface tin minerals, Sardinian archaeologists has deemed it unlikely that Nuragians used Sardinian tin (VALERA *et alii* 2005). On Sardinia, tin ingots were located in the Nuragic sanctuary of Abini-Teti, in the hoard of Forraxi Nioi-Nuragus and in the 'foundry' of La Maddalena-Silanus/Lei. A few years ago, more tin ingots were discovered in the Nuragic sanctuary of S'Arcu is Forros-Villagrande Strisaili (LO SCHIAVO 2003; FADDA 2003). In all these contexts, tin ingots were found in association with copper, lead and iron bars, leading Lo Schiavo (2003) to the interpretation that melting and alloying operations could have taken place at these sites, although no trace of furnaces has been discovered so far (LO SCHIAVO 2003). Lead Isotope Analysis (LIA) demonstrated mostly the use of local mineral resources in Nuragic metal production and, still now several data support the hypotheses of extraction from superficial deposits (Fig. 2) (LUGLIÉ, LO SCHIAVO 2009).

Lo Schiavo *et alii* (2005) published several LIAs on metalworks from Nuragic sanctuaries such as *Sedda 'e sos Carros*, *Santa Vittoria*, *Abini*, *Gremanu*, *Sant'Anastasia* and *S'Arcu is Forros*, revealing that the provenance of the lead was mostly from the Iglesiente's area (Fig. 2). However, copper from the ore of *Funtana Raminosa* and the area of Calabona (Alghero) has been detected as well (LO SCHIAVO *et alii* 2005; MONTERO RUIZ 2017). In two cases, in the sanctuaries *S'Arcu is Forros- Villagrande Strisaili* and *Abini- Teti*, some of the artefacts matched with some deposits on the northeast area of Sardinia (cfr. *Correboi*, see VALERA *et alii* 2005: 75; BEGEMANN *et alii* 2001; CINCOTTI *et alii* 2003; LO SCHIAVO *et alii* 2005). Therefore, LIA demonstrated both the use of immediate local resources together with metals circulating across Sardinia.

THEORETICAL FRAMEWORK AND RESEARCH QUESTIONS

Nowadays the concept of Nuragic sanctuary has become very broad, comprising every kind of structure or building in which traces of religious activities are found (DEPALMAS 2005, 2014a; IALONGO 2011). This may well have the implication that so-called sanctuaries do not have the same significance and function, and some are clearly directly attached to local settlements whilst others are larger with specific positions in the landscape and hence with possible central or unifying functions in a larger geographical area. The variability and the number and types of buildings on the sites must then be taken into account and the same goes for geographical position. Sanctuaries are often investigated for their architectural features (e.g. LILLIU 1988; FADDA 2000, 2014; MANUNZA 2008; SALIS 2017), but they also have a physical dimension in the landscape which is the expression of their social, cultural, economic and geographic context. The environmental and geographical conditions of cult sites, such as visibility or networking, have been created by the repetition of human activities and beliefs, therefore its physical dimension is strictly embedded in the social-economic structure of a community and ecological space (KNAPP 1999; WHEATLEY, GILLINGS 2002; PAPANTONIOU, VIONIS 2017). Prior studies have noted the importance of considering the sacred landscape as a way to establish social identity, power and to reinforce economic or religious institutions (PAPANTONIOU, BOUROGIANNIS 2018). Scholars stress the importance of investigating it not only as a ritual or symbolic place, but as part of the strategic organization of human activities in the past (ALCOCK 1993; KNAPP 1999).

One approach to conceptualize the Nuragic sacred landscapes is to analyse their networks in the geographical space through the study of movement as support in understanding the social behaviour of a community (LLOBERA 2000: 66; MLEKUZ 2014; CABRAS 2018). The movement through space provides information on the perception of the space, territorial boundaries, relationships and power (PAPANTONIOU, VIONIS 2017; PAPANTONIOU, BOUROGIANNIS 2018). The movement could be also related to the creation of economic systems or sacred areas (e.g. BELL, LOCK 2000; HOWEY 2007). Furthermore, the understanding of movement within a landscape is strictly connected to what is achievable or not in terms of resources, strategic control and other factors, or what is defined as the "*affordance*" of a certain resource or territory (GIBSON 1979; INGOLD 2000; VEHAGEN *et alii* 2014, 2019). However, the control of resources and the mobility of raw materials was restricted by many other factors, such as transportation capacity, trade routes, technology, and selection of the imported and exported products, political and cultural borders (e.g. 'modes of production': EARLE *et alii* 2015; EARLE, SPRIGGS 2015).

On the other hand, from a network analysis perspective, movement is a form of social and spatial arrangement consisting of connected entities or elements (KNAPPETT 2013; RADIL, WALTHER 2018) Networks are also concerned with individuals within the networks or how an actor is connected to the rest of the network and what strategies they develop to exercise their agency (RADIL, WALTHER 2018). Thus, when network are applied in the geographical space, places are seen as a series of "unique localized settings" linked to other places and also as possible conduits for the flow of resources, as well as ties for communities and social homogeneity (RADIL, WALTHER 2018).

This study examines the topographical setting of the Nuragic sanctuaries in a broader landscape perspective considering its relation with the nearest settlements and the natural resources (metalliferous resources). The aim is to address the following research questions: 1*) Does the role of Nuragic sanctuaries relate to any specific geographical position in the landscape in this networked-system?* 2) *How did the control of mineral resources and the transport of raw materials work internally in Nuragic Sardinia during the FBA and the EIA?*

So far, we have seen that not all the Nuragic sanctuaries had the same importance or function, and even among those listed by Ialongo (2011) and Depalmas (2014a), it would be possible to make a differentiation among those in which a 'production centre' could be traced and those where the ritual component is the most prevailing.

If sanctuaries establish direct control over mineral resources and are considered primary production centres, the Nuragic communities would locate them as close as possible to that resource, in order to minimize transportation costs. On the contrary, if the settlement is the primary production centre and the sanctuary is mostly related to the distribution process, then the sanctuary itself would be located in a strategic position with possibly a high degree of networking with other settlements. A stronger network component would explain perhaps the way far distant raw materials would travel from one side to the other across Sardinia.

DATA AND METHODOLOGICAL APPROACHES

In order to address to the hypotheses, 16 Nuragic sanctuaries have been selected, together with the list of mineral resources previously mentioned (Fig. 3; Table 1). The selection of the sanctuaries is based on the work of Depalmas (2014a) and Ialongo (2011; 2017), where the Nuragic sanctuaries were identified based on specific topographical and archaeological features (i.e. presence/ absence of open-air structures for hosting visitors, presence/absence of meeting huts, such as *Capanna delle Riunioni* etc.) (Table 1).

The analysis will not be restricted to the sanctuary itself but will extend to the surrounding area and include other elements of the landscape such as settlements (Fig. 3). The Sardinian Bronze Age landscape supported a significant number of settlements. Scholars have listed 8000 nuraghi classified based on the number of towers (*nuraghe monotorre*, *nuraghi complesso*). However, these type of analyses assume that only contemporary sites are included. This is a big ask of many archaeological sites, as even those dated in the same period may not be occupied at the same time and many of them are plagued by chronological uncertainty.

A list of 245 Nuragic settlements[1] , has been selected for this study. Twenty-eight of those settlements are likely still inhabited during the Final Bronze Age and Early Iron Age, and were classified in this study as 'major settlements'. The remaining samples are listed based on their general classification which, according to literature and excavation reports, were still in use during the Final Bronze Age-Early Iron Age (LILLIU 1988; DEPALMAS 2009; MELIS 2017). Although the list of settlements is likely incomplete, especially in those areas where extensive survey reports are lacking, the dataset is still extensive enough to draw meaningful conclusions.

The methodology includes Network Analysis (NA), and a type of spatial analysis known as Least Cost Path Analysis (LCP). Both the methods will be explained in detail in the respective sections.

While the NA allows to reconstruct a network in the landscape through the simultaneous connection of multiple nodes and allows to understand the importance of a particular node

[1] Many of these settlements comprise extended villages nearby the nuraghe.

in the network based on its number of links, the LCP allows to visualize a specific set of routes in the landscape which may have been strategic to reach natural resources or places. In this sense the combination of the two methods becomes complementary in the understanding of the development of a particular set of routes or connections between the sanctuaries and different landscape features (VERHAGEN *et alii* 2019: 233; FULMINANTE *et alii* 2016; DA VELA 2019).

First analysis: Network Analysis

In the first part, the application of the NA is used to understand the degree of centrality of Nuragic sanctuaries in their relation with the settlements/ resources. Generally, the use of Network Analysis (NA) in archaeology provided a useful tool to explore possible network-patterns among archaeological data (i.e. RIVERS *et alii* 2013; ÖSTBORN, GERDING 2014; FULMINANTE 2016).

The method takes advantage of the "graph-theory," a field of mathematics which allows users to represent large datasets through different types of graphs (i.e. BRUGHMANS 2010; KNAPPETT 2013). A network is made of two components: a list of the *nodes* composing the network, and a list of *edges*, or ties (the interactions between nodes). Graphs generally express the amount and intensity of certain connections between nodes based on the number and frequency of their links, which are expressed by centrality indices of the nodes: *Indegree centrality* (its number of connections); *Betweenness centrality* (number of times a node acts as a bridge amid two other nodes.); *Closeness centrality* (the closeness of a node to the entire network). The Centrality Index indicates the extent to which a node is connected to all the other nodes in the network, i.e. the number of links established.

The NA visualizes the data as a graph that links two or more nodes (in our case, sanctuaries, settlements and mineral resources) via edges which, in the geographical space, have an irregular spatial extent (VERHAGEN *et alii* 2019). In simple words, the larger the number of sites surrounding the sanctuary, the larger I assume the degree of networking that a sanctuary had. The networks produced in this study used the open-source software *Gephi 0.9.2* (https://gephi.org/). The algorithm used to the graph representation was *GeoLayout* (GRANJEAN 2015).

The network connections were established and weighted based on three buffer zones which were used to calculate the number of settlements within 5 km, 10 km, and 30 km from the sanctuaries considering more frequent contacts between nodes on the basis of their geographic proximity (Fig. 4). From 0-5 km the nodes would be given a weight-value of '5'; from 5-10 km the nodes would be given a weight-value of '2'; from 10-30km the nodes would be given a weight-value of '1'. Depending on the degree of centrality of each site, the nodes will appear in the graph larger or smaller. The same method has been used for the mineral deposits.

Network Analysis Results

The results of the Network Analysis shown in Figure 5 and Table 2 reveal promising information regarding the possible role of the Nuragic sanctuaries in relation to the Nuragic settlements and the mineral deposits. Table 2 shows the different Degree Centrality values and therefore different levels of connections and interaction between the nodes.

The sanctuaries with the highest values are those that establish the largest number of links with settlements. Santa Vittoria and Santa Cristina are those with the most valuable connections in terms of geographical proximity to the sanctuary, in this case meaning that many sites were very close to the sanctuary, therefore creating a stronger network (Fig. 5). Although the sanctuaries of Funtana Coberta, Abini and Jann'e Pruna show the lowest Indegree and Betweenness centrality values, they still present quite high values in Closeness centrality, meaning that despite their few connections with the Nuragic settlements, those sanctuaries had the shortest distance to the surrounding settlements and therefore the ability to spread information faster through the network. (Fig. 5, Table 2).

Three larger nodes, Santa Vittoria, Santa Cristina and Monte Nuxi, seem to define the limits of specific geographical areas in the Sardinian landscape as I am going to explain in the Discussion paragraph. Interestingly, some of the settlements are linked to more than one sanctuary, as shown in the NA graph. Thus, the ability to access sanctuaries within 5-10 or 30 km may have created a hierarchy among the settlements and therefore a stronger or weaker relationship with the sanctuary or the resources.

Finally, considering the number of connections with the ore deposits, the centrality values are generally similar among all the sanctuaries with the two exceptions of Matzanni and Funtana Coberta (Table 2). The data suggests that the geographical proximity to a mine district had a secondary role but that there is not enough data at the moment to support the idea of a direct control on extraction processes or the use of the sanctuaries as 'primary workshops', as we are going to show also in the LCP analysis.

Spatial analysis: Least Cost Path

In order to support the results from the Network Analysis, especially those regarding the control of mineral deposits, I analysed the data by applying a second method: the Least Cost Path (LCP).

The LCP analysis is a distance analysis tool within GIS[2] that uses the path between two locations that costs the least to determine the most cost-effective route between a source and destination. When using LCP analysis in GIS, the neighbours of a raster cell are evaluated and the generated path moves to the cells with the smallest accumulated or cost value. The completed path is the smallest sum of raster cell values between the two points and it has the lowest cost (CHAPMAN 2006). The spatial analysis considers the distance to the

[2] Software QGIS 3.4.

closest sites from its source, by considering all the possible geographical restriction (for instance, rivers, mountains, slopes) which cannot be detected with the linear-Euclidean distance.

The second method (LCP) uses 'energy-cost' algorithms and implies that an individual would be able to walk 5 km on a flat surface in 1 hour (i.e. HIGGS, VITA FINZI 1972; MINETTI *et alii* 2002), with a maximum of 10 km per day and, 30 km in non-frequent journeys (for example for the procurement of mineral resources, cfr. HOLT 2015). The spatial analysis is used to understand the control of mineral resources and considers the geographic distance from the source (sanctuary and settlements) to the closest sites within a maximum of 30 km. The cost is expressed with the variables of walking-time and distance.

Due to the chronological uncertainty of the majority of the settlements, in this analysis, the LCP has been generated between the following vectors:

1) 28 'major' settlements towards ore deposits.
2) Sanctuary towards ore deposits.

The results will highlight which site (sanctuary or settlement) had likely the main control of the surrounding mineral resources based on routes and walking- time distance.

The construction of the terrain model is based on a DTM which gives diverse information regarding the morphology of the terrain surface although it considers only the geodetic surface, excluding the 'obstacles' located on it (vegetation, buildings, etc.) (CABRAS 2018; CHAPMAN 2006: 81).

This research employed a DTM, downloaded from the "*Carta Tecnica Regionale della Regione Sardegna* (1:10.000)". The construction of the DTM model has been implemented with the addition of several sources of geographical information, both in raster and vector formats like Hydrography, and Sources[3]. The DTM has been the basis for the Cost Surface Analysis (CSA) modelling.

The CSA, or cost grid, is a raster grid, in which each cell of the grid has been assigned a 'cost' value. The cost value could be represented by different features within the landscape (topographic or feature costs) that create obstacles or reduce the speed of movement (i.e. VAN LEUSEN 1998; HARRIS 2000; CHAPMAN 2006). In this paper, the construction of the cost grid employed three main criteria: slope, height (altitude) and hydrography. Each grid was reclassified (tool *r. reclass*) and summed by map algebra (*raster calculator*) (Figure 6).

The Cost Distance model was created from previous CSA, by using the function *r.walk* (AITKEN 1977; LANGMUIR 1984). In general, the Cost Distance model' calculates the minimum cumulative travel cost within an anisotropic surface from a source (e.g. the Nuragic sanctuaries) to each location on a raster surface (e.g. STANCIC *et alii* 1995; HARE 2004; GIETL *et alii* 2007). In the raster file, each cell represents a cost of movement. The function *r.walk*

[3] The vectors and raster files can be easily downloaded from the webpage www.sardegnageoportale.it (Sardegna Mappe).

sums the cumulative travel-time cost due to a different walking speed associated with downhill and uphill movements (https://grass.osgeo.org/grass64/manuals/r.walk.html). In this case, the walking speed takes into account the formula elaborated by Aitken (1977) and Langmuir (1984) which calculates the time (seconds) to cover 1 meter. The Cost Surface and the Cost Distance models have been the bases for the Least Cost Path Analysis.

Least Cost Path Results

The data, shown in Table 3, demonstrate a primary control of the Nuragic settlements over the mineral resources rather than the sanctuaries. Table 3 and 4 illustrates the comparison of the average time-distance between sanctuaries and settlements towards important copper and lead-silver deposits. Although the plot (Table 3-4) illustrates a similar travel-distance of the sanctuaries and settlements to the deposits, a closer look at the routes generated by the LCP revealed a primary access to the ores from the Nuragic settlements rather than from the sanctuaries (Fig. 7-8). Furthermore, the results highlight that the location of those settlements nearby a specific deposit is often in between the ore and the sanctuary (Fig. 7-8 as an example), which seems to be at the centre of this local system.

Generally, the distance between the sanctuary and the mineral deposit is never below 10 km, therefore too distant for a direct control on the extraction processes. The only exceptions are the two cases of *Gremanu-* Correboi (copper deposit) and *Matzanni-* Canale Serci (tin deposit), where the distance is below or within 5 km (Table 4). Four sanctuaries are very far away from mineral resources. The copper deposit of *Calabona* (Alghero) is further than 30 km from both the Nuragic sanctuaries of *Monte Sant'Antonio-* Siligo and *Serra Niedda-* Sorso. The same situation applies to the sanctuaries *Su Monte-*Sorradile; *Santa Cristina-*Paulilatino.

Finally, the results of the LCP substantially confirm the centrality values obtained by the NA. The results demonstrated also that not all the sanctuaries are placed close to mineral deposits, yet their position may be associated perhaps with the control of other types of natural resources. However, even those sanctuaries near to ore deposits did not have direct access to deposits due to geographical constraints (i.e. landscape morphology) and architectural constraints, such as the presence of a large Nuragic settlements in front of the deposit.

Discussion

The approach applied in this study potentially permits both a vertical analysis (from local to island-wide scale) of the interconnections between the nodes, as well as a horizontal analysis (sanctuaries, settlements, resources). The study suggests some general observations that are presented below.

Considering the data from the Network Analysis, similar centrality values may be the reflection of alike types of interaction between the sanctuary and its surrounding settlements within a local scale, meaning that for most of the sanctuaries, a strategic position 'in between' settlements played an important role for communication and favoured the flow of copper, information, and goods among the Nuragic communities (Betweeness and Closeness centrality). Here, the NA results build on existing archaeological evidence of the use of the Nuragic sanctuaries as collecting points and centres for redistribution of raw material (copper, lead, amber) and goods (e.g. IALONGO 2013; BELLINTANI 2016; BERNARDINI 2017).

The position of the Nuragic settlements seems to define their 'units' around one sanctuary. The closer a settlement is to a sanctuary, the higher the probability that the community would have belonged to that sanctuary. This element is supported also by recent studies on territorial control of the Nuragic sanctuaries based on visibility (CICILLONI *et alii* 2020).

The results also stress a correlation between the sites with the highest centrality values and those sites' topographical complexity. For instance, *Santa Vittoria* and *Santa Cristina* as well as *Monte S. Antonio,* present high centrality values and have structures to host pilgrims or potential trading-activities. This latter consideration needs further attention. Many scholars agree on the 'federal' function of extended sanctuaries such as Santa Vittoria (LILLIU 1988; CICILLONI *et alii* 2019, 2020), built to host not only local communities, but also visitors from all across the island, perhaps for specific occasions. Therefore, the position of these type of sanctuaries could be related to areas with a higher density of Nuragic settlements, therefore displaying a stronger settlement-network in the NA graph.

The use of the sanctuaries as federal compounds can also be related to the network edges, showing that from a settlement an individual could sometimes reach a second sanctuary within a buffer of 30km. If we assume a good level of interaction between the Nuragic communities, the possibility to access to another sanctuary's territory may support the idea of the use of some of the sanctuaries as markers of territorial borders, federal compounds, meeting points, or markets. Three larger nodes (Santa Vittoria, Monte Nuxi and Santa Cristina) are also located at the limit of specific territorial geographical borders in Sardinia: the Campidano plain, the area of Gennargentu and the Abbasanta plain which leads toward the Nurra fertile plain. At the moment however, there are not enough data regarding the site of Monte Nuxi to consider it a federal sanctuary. The presence of sanctuaries at the limit of territories is more in line with the interpretation of Nuragic sanctuaries suggested by Depalmas (2005, 2014a).

In the second analysis, the results from the LCP generally support the data of the NA.

The data show that different sanctuaries are a similar distance from the same copper or lead-silver deposit, which is expressed in the NA by similar low values on Betwenness and Closeness centrality (Table 2).

When the access to important copper ores applies to the Nuragic settlements, a stronger or weaker control of the ore deposits is reflected by the ease of access between the settlements and deposits. The spatial analysis highlighted that often more than one settlement could access to the same ore deposit. The data could be interpreted in terms of the strategic position of the settlements, perhaps belonging to the same 'territorial unit'. Nevertheless, if we assume that those settlements do not belong to the same territorial unit, perhaps the sanctuary locations may be interpreted as territorial claims or restricted borders on important economic resources. Conversely, if we assume a high level of interaction, then perhaps the sanctuary may have found a role as mediator in the access to territories and resources among the different communities.

During the FBA-EIA in Sardinia, no dominant mining centre existed or has been discovered, so the metal production did not result in a local advantage of one group over others (i.e. LO SCHIAVO 2003; LO SCHIAVO *et alii* 2005). However, we could consider that, with the extension of the long-distance metal trade and the enlargement of networks at the beginning of the Final Bronze Age (ca. 1200 BC), the production and the control of mines and products were taken under control of more powerful communities, under the administration of the Nuragic sanctuaries.

The analysis demonstrated that most of the sanctuaries were close to many of these settlements nearby the mineral deposits. Although direct control over the extraction process is not possible to prove at this stage, amongst other functions, the sanctuaries may have served to secure territorial claims and ideologically protect the access to copper-bearing for several Nuragic communities.

Thus, the ability to access multiple mineral deposits applies both to several sanctuaries and settlements, even though it is probable that the settlements had the direct management over the ore as primary production centre (or primary workshop, LO SCHIAVO 2014). This data supports the hypothesis already established by Lo Schiavo (2014) that the sanctuaries were used as "secondary workshop" for the production of metal in the late phase of the Nuragic civilization. The short distance between settlements and sanctuary likely lowered the cost-energy demand, to move semi-refined copper products from the mining centres to the sanctuaries that was later transformed, collected or redistributed via the sanctuary thanks to its larger and strong network.

In sum, the use of LCP and the Network Analysis opens the possibility to a non-exclusive relationship with the mineral resources, supporting the idea of the sanctuaries in between ecological boundaries of Sardinia. On the other hand, I do not exclude the possibility that the sanctuaries far from any ore deposits acquired the metal from distant areas through several mechanisms of exchange by providing other types of valuable goods.

Finally, when considering the role of the Nuragic sanctuaries in a historical perspective, the socio-economic crisis that enveloped the Nuragic civilization around 1200 BC is usually associated with a reassessment of the settlement pattern, with the abandonment of many of the *nuraghi* and the concentration of the population on major centres, as well as an increase of some specialized activities, such as the metal-production (DEPALMAS, MELIS 2010; LO SCHIAVO *et alii* 2009). These new arrangements of the Nuragic society may be considered one of the factors that encouraged the development of the Nuragic sanctuaries with a significant role as territorial nodes from the Final Bronze Age throughout the Early Iron Age.

While coastal and agrarian settlements gain economic power, most of the internal Nuragic settlements saw a decline at the beginning of the Final Bronze Age (ca. 1200 BC). With the constriction of the *nuraghi*, the Nuragic sanctuaries arose, changing the economic model. From 1100-900 BC, the metal trade is extremely intensified with more partners and may have changed the commodity chain system. The strategic position of the settlements was the first step for the collection of the raw materials towards internal regions.

Located across important riverine or mountain routes, the sanctuaries assume the role of accumulation, control and redistribution of metal and other goods among internal Nuragic communities (DEPALMAS 2005; BERNARDINI 2017; IALONGO 2017). The sanctuaries with their position in between settlements embody several tasks (all related and caused by the enlargement of the trade network) such as collecting points of goods, nodes for redistribution of imports, and they perform functions as social, ritual and administrative centres. Furthermore, they seems to occur in-between contact zones between tribes and, perhaps, ecological zones.

With regional products available at the market places, local chiefs could control contacts with external traders or local agents with the settlements along the coasts and the sanctuaries acting as a transit zone for both domestic and foreign metal. As service centres, the Nuragic sanctuaries likely functioned in hierarchical networks as demonstrated by the NA, with high-order markets carrying more specific goods. Depending on their rank, these central markets acted as foci of services for a surrounding community or at an island-wide level.

The methods proposed in this paper demonstrated some limitations, as well as the potential of it in the study of the Nuragic landscape. Some of the limitations are implied in the nature of the dataset, the lack of extensive surveys and reports and general knowledge regarding the Nuragic past landscape as already mentioned. However, the combination of the two methods demonstrated also its great potential for the analysis of the sacred landscape in Bronze and Iron Age Sardinia and the relationship with the Nuragic settlements and the natural resources.

CONCLUSIONS AND FUTURE WORK

In conclusion, the model proposed in this paper attempts to explain the complex and intricate system of networks and interactions between the Nuragic sanctuaries, settlements and resources.

Although it is risky to apply deterministic values to the location of the sanctuaries, the available evidence may suggest that the sanctuaries acted as a nodal point of a network of sites that were associated with the control of several aspects of the Nuragic economy. Their role as mediator, collector and provider for the circulation of metal goods was certainly one of these aspects. This study revealed that their location had different profiles of centrality, interactions and networks for certain periods of the time. On the other hand, the model proposed also demonstrated some limitations, due mostly to the need of more complete and exhaustive datasets of Nuragic settlements together with a better chronological structure in order to identify contemporary buildings and their functions. This study does not aim to definitively resolve this problem, but rather present a methodological approach that could be used in the study of the Nuragic Landscape.

These data must be interpreted with caution because they may be affected by gaps in the research and missing sites in the list of recorded Nuragic settlements. The study of the sacred landscape and the use of Nuragic sanctuaries is still an ongoing debate, and is often avoided due to scarcity of data. The selection of sanctuaries presented in this paper is the one currently accepted by the most of the scholars; however, further works or excavations may enlarge this list.

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Site	City	Extension (hectares)	Ritual architecture	Settlement	Classification (Ialongo 2011)	Traces of metallurgical activity	Hoards/ Storage	Meeting'-structures (i.e. Recinto delle Feste)	Site's chronology	Sanctuary's chronology	References
Sant'Anastasia	Sardara	Unknown	Sacred well	Village	Proper sanctuary	x	x	x	EIA	EIA	Taramelli 1918; Ugas, Usai 1987; Ialongo 2011
Santa Vittoria	Serri	22	Sacred well	Village	Proper sanctuary	? (Foundry?)		x	MBA-EIA	FBA-EIA	Taramelli 1909; 1914; Lilliu 1988; Zucca 1988; Ialongo 2011; Porcedda 2019
Abini	Teti		Recinto; Sacred source	Village	Probable sanctuary	x	x	x	RBA-EIA	FBA-EIA	Puddu 2013; Depalmas 2014b; Tatti 2015; Salis 2015
Serra Niedda	Sorso	Unknown	Sacred well	Village?	Proper sanctuary	? (crucible fr.)			RBA-EIA	RBA-EIA	Ialongo 2011
Monte S. Antonio	Siligo	2	Sacred well	Village?	Proper sanctuary	? (crucible fr.)	x	x	MBA-EIA	EIA	Ialongo 2011
S'Arcu e is Forros	Villagrande Strisa	Unknown	Megara	Village?	Proper sanctuary	x	x		MBA-EIA	FBA-EIA	Fadda 1991; 2014; 2017
Romanzesu	Bitti	7	Sacred source; Megara	Village	Proper sanctuary		x (amber)	x	MBA-EIA	RBA-EIA	Fadda 2002; Ialongo 2011; Moravetti *et alii* 2017
Gremanu	Fonni	7	Sacred well; Megaron	Village	Proper sanctuary	x		x	MBA-EIA	FBA-EIA	Fadda 1997; Ialongo 2011; Moravetti *et alii* 2017
S. Cristina	Paulilatino	2	Sacred well	Village	Proper sanctuary			x	MBA?-EIA	FBA-EIA	Lilliu 1988; Moravetti 2003
Sa Sedda'e sos carros	Oliena	4	Sacred source	Village	Proper sanctuary	x	x	x	RBA-EIA	FBA-EIA	Fadda 2005; Ialongo 2011
Su Monte	Sorradile	Unknown	Sacred source	Village?	Proper sanctuary			x	RBA-EIA	RBA-EIA	Santoni, Bacco 2003; Santoni 2015; Moravetti *et alii* 2017
Matzanni	Vallermosa	8	Sacred wells	Village	Probable sanctuary	? (testa di mazza)		?	RBA-EIA	RBA-EIA	Nieddu 2007; Matta *et alii* 2020
Funtana Coberta	Ballao	Unknown	Sacred well	Village	Probable sanctuary	x	x		RBA-FBA	RBA-FBA	Taramelli 1919; Manunza 2008
Jann'e Pruna	Irgoli	Unknown	Recinto; Sacred source	Village?	Probable sanctuary				RBA-EIA	FBA-EIA	Fadda 2002; Depalmas 2014
Monte Nuxi	Esterzili	Unknown	Sacred sources	Village	Probable sanctuary			?	RBA-FBA	RBA-FBA	Salis 2010
Sa Carcaredda	Villagrande Strisaili	Unknown	Megaron	Village	Probable sanctuary		x		MBA-EIA	FBA-EIA	Fadda 1992, 2017; Moravetti *et alii* 2017

Table 1: List of the Nuragic sanctuaries selected for this study. The table summarizes the main topographical features of each sanctuary and whether traces of metallurgical activities or metal storages have been discovered. Another element considered is the presence of particular 'open-air' structures, such as '*Recinto delle Feste*' in Santa Vittoria di Serri, usually interpreted as areas for hosting pilgrims and trading activities.

Centrality Index	Type of Network	Matzanni	Sant'Anastasia	Santa Vittoria	Funtana Coberta	Abini	Serra Niedda	Monte S. Antonio	Monte Nuxi	Sa Carcaredda	S'Arcu e is Forros	Su Romanzesu	Gremanu	S. Cristina	Sa Sedda'e sos carros	Su Monte	Jann'e Pruna
	Sanctuary-Settlements	21	21	43	2	1	11	25	45	19	19	8	6	61	4	27	2
Degree Centrality																	
	Sanctuary-Mine deposit	9	4	4	6	3	0	0	5	4	4	2	4	0	4	0	3
Betweenness Centrality	Sanctuary-Settlements	1556,5	3313,5	4470,75	5,01724	0	55	300	4468,23	1176,17	1176,17	45,5	9,33333	2173,5	124,333	626,5	19,5
	Sanctuary-Mine deposit	3,44	1,64	0,25	3,44	0,25	0	0	0,25	0,25	0,25	0	0,25	0	0,25	0	0,25
Closeness centrality	Sanctuary-Settlements	0,1739	0,2263	0,2797	0,2168	0,3397	1	1	0,2787	0,2185	0,2185	0,1285	0,1556	0,7977	0,1632	0,4522	0,1035
	Sanctuary-Mine deposit	0,55	0,51	0,51	0,55	0,51	0	0	0,51	0,51	0,51	0,48	0,51	0	0,51	0	0,51

Table 2: Degree centrality values of the Nuragic sanctuaries in their connection with settlements and mineral deposits. The Centrality Index indicates the extent to which a node is connected to all the other nodes: Indegree centrality (number of connections); Betweenness centrality (number of times a node acts as a bridge between two other nodes.); Closeness centrality (the closeness of a node to the entire network).

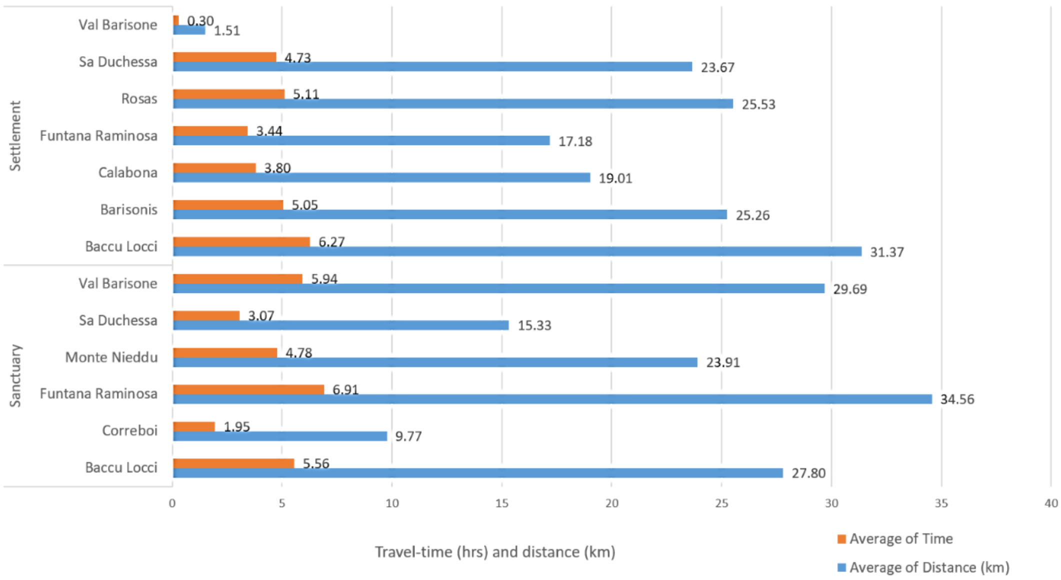

Table 3: Average walking time-distance of the Nuragic sanctuaries and settlements towards the principal ore deposits also detected by the Lead Isotope Analysis. The plot shows that on average there was not a significant difference between sanctuaries and settlements in terms of time-distance, and the advantage was due to the strategical position of the settlements and, probably, the control of the routes towards the copper/ lead-silver deposits.

Name ID	Type	Copper deposit	Time (Hrs)	LCP-Distance (km)
Gremanu	Sanctuary	Correboi	1,02	5,10
S'Arcu e is Forros	Sanctuary	Correboi	2,05	10,25
Sa Carcaredda	Sanctuary	Correboi	2,79	13,97
Matzanni	Sanctuary	Sa Duchessa	3,07	15,33
Santa Vittoria	Sanctuary	Baccu Talentinu/Bau	4,66	23,30
Santa Vittoria	Sanctuary	Monte Nieddu	4,66	23,30
Funtana Coberta	Sanctuary	Baccu Talentinu/Bau	4,90	24,52
Funtana Coberta	Sanctuary	Monte Nieddu	4,90	24,52
Funtana Coberta	Sanctuary	Baccu Locci	5,56	27,80
Jann'e Pruna	Sanctuary	Val Barisone	5,94	29,69
Santa Vittoria	Sanctuary	Funtana Raminosa	6,91	34,56
San Pietro	Settlement	Val Barisone	0,30	1,51
Sa Domu 'e S'Orcu	Settlement	Sa Duchessa	1,73	8,67
Nolza	Settlement	Funtana Raminosa	3,09	15,43
Palmavera	Settlement	Calabona	3,18	15,92
Adoni	Settlement	Funtana Raminosa	3,79	18,94
Appiu	Settlement	Calabona	3,81	19,04
S. Imbenia	Settlement	Calabona	4,42	22,09
Sa Domu 'e S'Orcu	Settlement	Barisonis	4,54	22,68
Sa Domu 'e S'Orcu	Settlement	Rosas	4,66	23,31
Sirai	Settlement	Rosas	5,55	27,76
Sirai	Settlement	Barisonis	5,57	27,83
Casteddu de Fanaris	Settlement	Sa Duchessa	5,97	29,83
s'Ulimu	Settlement	Baccu Locci	6,27	31,37
Seruci	Settlement	Sa Duchessa	6,50	32,50

Name ID	Type	Lead-silver deposit	Time (Hrs)	LCP-Distance (km)
Gremanu	Sanctuary	Correboi	1,02	5,10
S'Arcu e is Forros	Sanctuary	Correboi	2,05	10,26
Sa Carcaredda	Sanctuary	Correboi	2,79	13,97
Matzanni	Sanctuary	Monte Zippiri	3,24	16,20
S'Arcu e is Forros	Sanctuary	Gennargentu	4,11	20,53
Funtana Coberta	Sanctuary	Genna Tres Montis	4,21	21,05
Su Romanzesu	Sanctuary	Sos Enattos	4,46	22,29
Gremanu	Sanctuary	Gennargentu	4,73	23,67
Sa Carcaredda	Sanctuary	Gennargentu	4,81	24,04
Sant'Anastasia	Sanctuary	Montevecchio	5,46	27,31
Su Romanzesu	Sanctuary	Guzzurra	5,64	28,21
Jann'e Pruna	Sanctuary	Guzzurra	5,79	28,93
Matzanni	Sanctuary	Monteponi	6,16	30,79
Matzanni	Sanctuary	S'Oreri/Santa Lucia	6,27	31,37
Jann'e Pruna	Sanctuary	Sos Enattos	6,39	31,95
Santa Vittoria	Sanctuary	Genna Tres Montis	6,60	32,98
Sant'Anastasia	Sanctuary	Monte Zippiri	6,67	33,35
Sa Sedda'e sos carros	Sanctuary	Sos Enattos	6,75	33,73
Casteddu de Fanaris	Settlement	Monte Zippiri	1,85	9,27
Seruci	Settlement	Monteponi	2,90	14,50
Sa Domu 'e S'Orcu	Settlement	Monteponi	3,18	15,88
S. Imbenia	Settlement	Argentiera	4,91	24,54
Sirai	Settlement	Monteponi	5,08	25,41
Domu Beccia	Settlement	Montevecchio	5,11	25,54
Cuccurada	Settlement	Montevecchio	5,24	26,21
Noddule	Settlement	Sos Enattos	5,63	28,19
Sa Domu 'e S'Orcu	Settlement	S'Oreri/Santa Lucia	5,95	29,75
Palmavera	Settlement	Argentiera	6,04	30,18
Sa Domu 'e S'Orcu	Settlement	Monte Zippiri	6,06	30,30
Arrubiu	Settlement	Genna Tres Montis	6,16	30,81
Genna Maria	Settlement	Montevecchio	6,33	31,66
Su Mulinu	Settlement	S'Ortu Becciu	6,86	34,28

Name ID	Type	Tin deposit	Time (Hrs)	LCP-Distance (km)
Casteddu de Fanaris	Settlement	Canale Serci	3,84	19,18
Appiu	Settlement	Sa Bumbarda	3,81	19,04
Arrubiu	Settlement	Su Suergiu	6,90	34,50
Palmavera	Settlement	Sa Bumbarda	3,18	15,92
Sa Domu 'e S'Orcu	Settlement	Perdu Cara	5,97	29,87
Sa Domu 'e S'Orcu	Settlement	Canale Serci	2,95	14,73
S. Imbenia	Settlement	Sa Bumbarda	4,42	22,09
Matzanni	Sanctuary	Canale Serci	0,89	4,44
Funtana Coberta	Sanctuary	Su Suergiu	3,58	17,88
Matzanni	Sanctuary	Perdu Cara	5,07	25,36

Table 4: Example of walking time-distance from each site (sanctuary/ settlement) towards copper deposits. The table shows the specific time an individual needed to perform in order to reach the copper ore within a maximum distance of 30 km.

ID	LABEL	CITY	TYPE	GEOGR. COORD. N	GEOGR. COORD. E
1	Casteddu de Fanaris	Vallermosa	MAJOR SETTLEMENT	39,3423	8,8389
2	Noddule	Nuoro	MAJOR SETTLEMENT	40,387778	9,284444
3	Adoni	Villanovatulo	MAJOR SETTLEMENT	39,7858333	9,1730556
4	Genna Maria	Villanovaforru	MAJOR SETTLEMENT	39,6345962	8,8543592
5	Appiu	Villanova Monteleone	MAJOR SETTLEMENT	40,4455556	8,4197222
6	Arrubiu	Orroli	MAJOR SETTLEMENT	39,661944	9,2975
7	Burghidu	Ozieri	MAJOR SETTLEMENT	40,6834694	8,9642322
8	Su Mulinu	Villanovafranca	MAJOR SETTLEMENT	39,634167	8,993889
9	Losa	Abbasanta	MAJOR SETTLEMENT	40,116667	8,790278
10	Lugherras	Paulilatino	MAJOR SETTLEMENT	40,097778	8,713889
11	Nolza	Meana Sardo	MAJOR SETTLEMENT	39,9171438	9,0731275
12	Oes	Giave	MAJOR SETTLEMENT	40,479722	8,774444
13	Orolio	Silanus	MAJOR SETTLEMENT	40,2921726	8,9020804
14	Orolo	Bortigali	MAJOR SETTLEMENT	40,2877143	8,8133553
15	Palmavera	Alghero	MAJOR SETTLEMENT	40,5952616	8,2427465
16	Santa Barbara	Bauladu	MAJOR SETTLEMENT	40,0077841	8,6758548
17	Santu Antine	Torralba	MAJOR SETTLEMENT	40,4865684	8,7697182
18	Serbissi	Osini	MAJOR SETTLEMENT	39,845278	9,461111
19	Seruci	Gonnesa	MAJOR SETTLEMENT	39,248889	8,424444
20	Sirai	Carbonia	MAJOR SETTLEMENT	39,169722	8,495833
21	s'Ulimu	Ulassai	MAJOR SETTLEMENT	39,73	9,426389
22	Su Nuraxi	Barumini	MAJOR SETTLEMENT	39,7058333	8,9905556
23	Cuccurada	Mogoro	MAJOR SETTLEMENT	39,664444	8,747778
24	Sa Domu 'e S'Orcu	Domusnovas	MAJOR SETTLEMENT	39,323611	8,64
25	S. Imbenia	Alghero	MAJOR SETTLEMENT	40,622778	8,196389
26	S'Uraki	San Vero Milis	MAJOR SETTLEMENT	40,015278	8,582222
27	Domu Beccia	Uras	MAJOR SETTLEMENT	39,6897522	8,7102056
28	San Pietro	Torpe	MAJOR SETTLEMENT	40,6378573	9,6681719

Table 5: Nuragic settlements mentioned in the text.

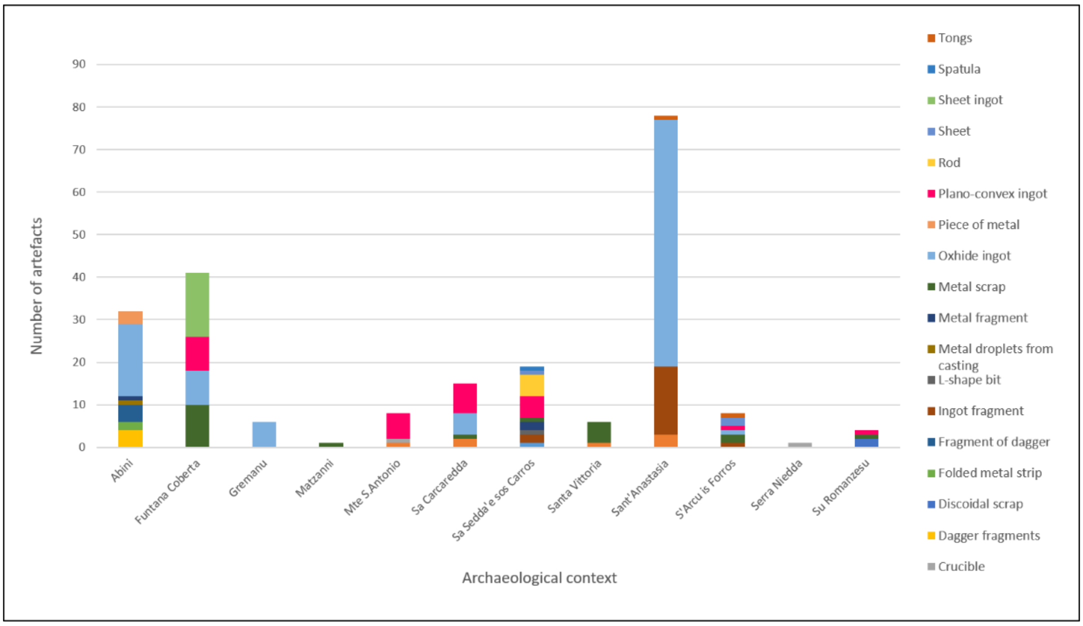

Fig. 1: Nuragic sanctuary and metallurgical activities. The plot shows the number of metallurgical remains (ingots and metal scraps), and tools (tongs, chisels, crucibles) found in different Nuragic sanctuaries. Data source: various authors (plot: V. Matta).

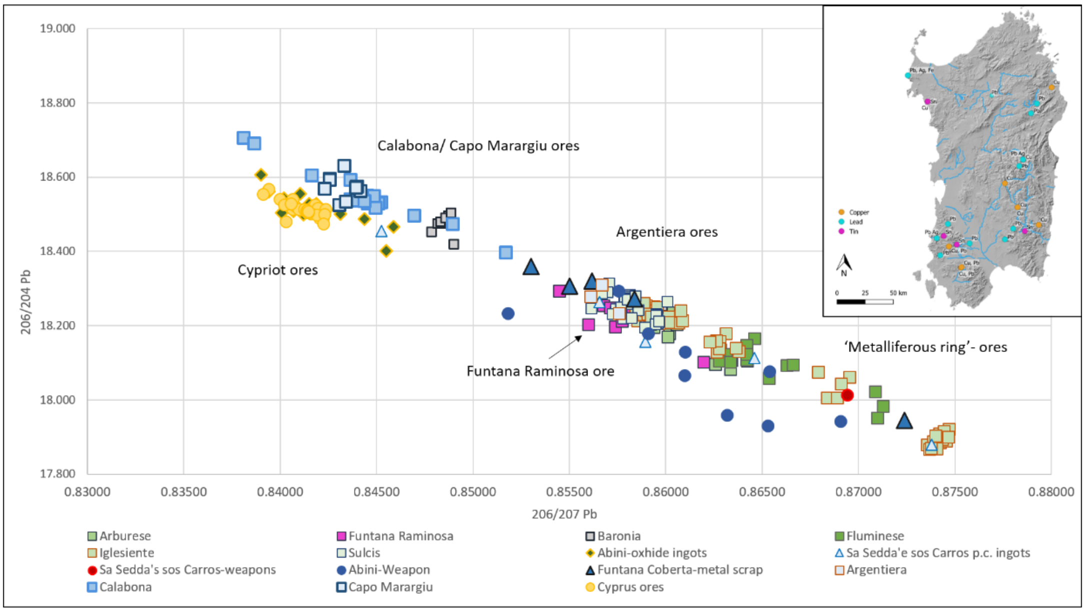

Fig. 2: The provenance of metalliferous ores in artefacts discovered at the Nuragic sanctuaries. The plot demonstrates that artefacts from different Nuragic sanctuaries have different lead isotope ratios confirming the exploitation of varied mineral ores in Sardinia from different regions. On the top right of the graph, the map shows the position of the most important mineral deposits in the Bronze Age Sardinia (VALERA *et alii* 2005). Data source: OXALID and various authors (Plot and map: V. Matta).

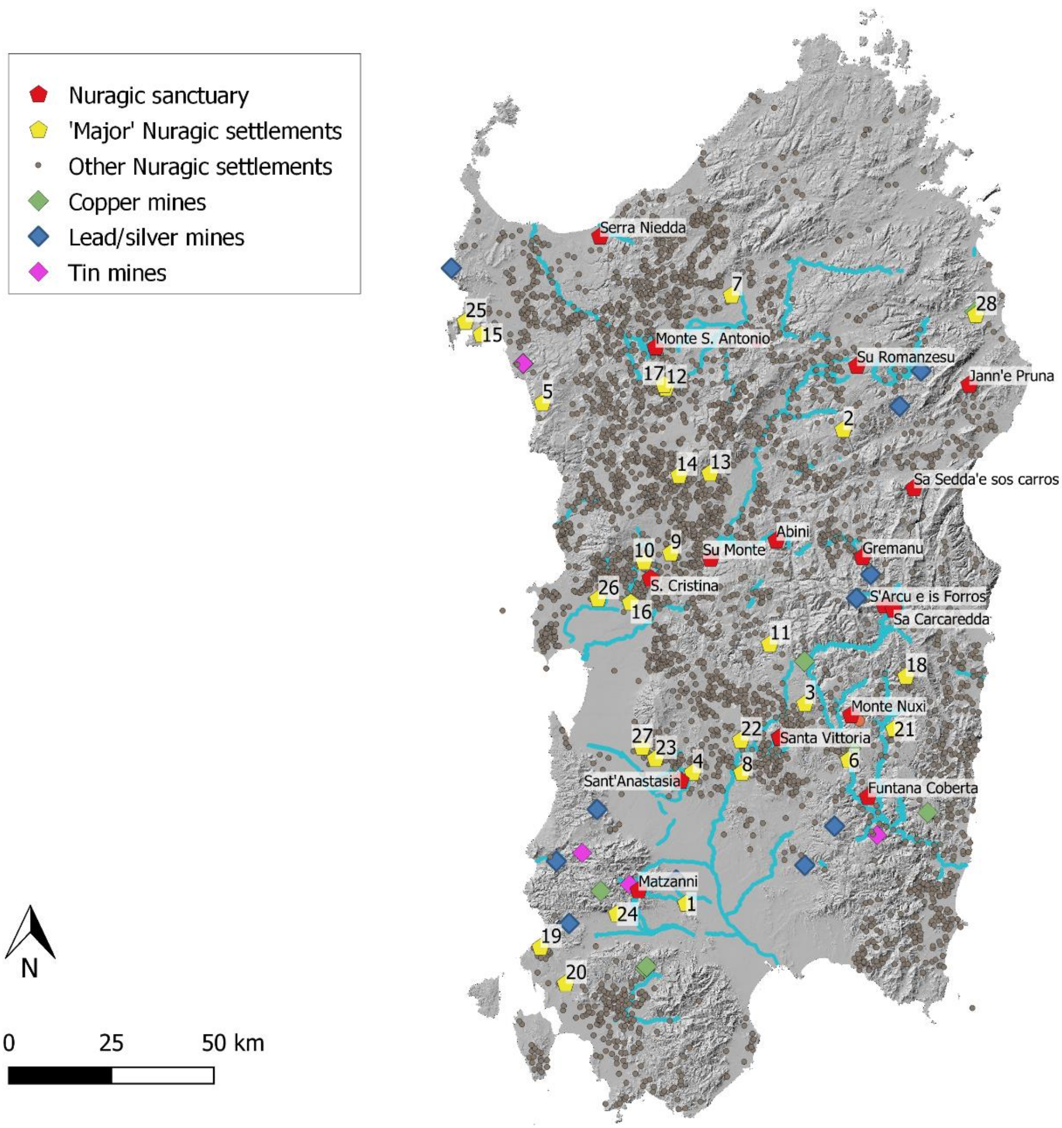

Fig. 3: The map shows the location of sites selected for the spatial analysis. In red the 16 sanctuaries, in yellow the 28 major Nuragic settlements, in green the copper sources, blue the lead/ silver sources and pink the tin sources. An additional selection comprises 217 Nuragic settlements (*nuraghi complessi* and villages, brown dots) which are classified only based on topographical features and plagued by chronological uncertainty. Data source: various authors, 'Map of Nuraghi' (tharros.info) (map elab. V. Matta).

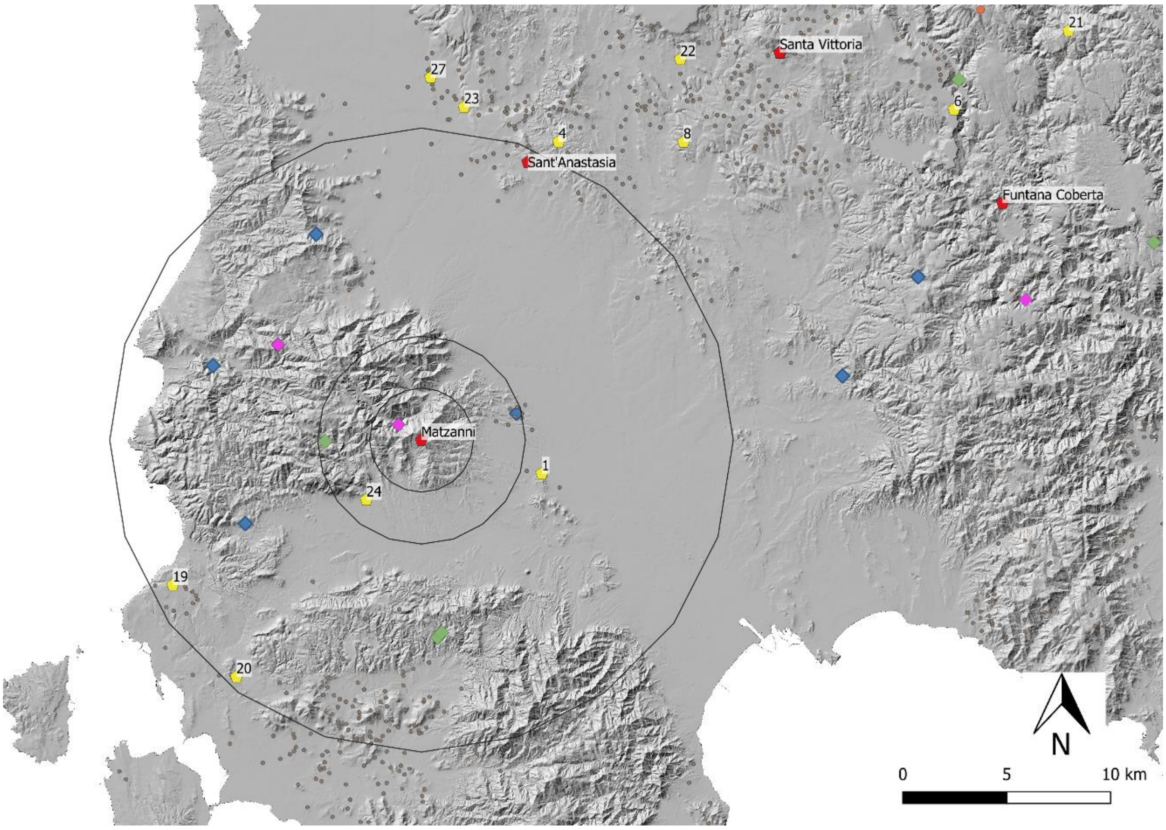

Fig. 4: Example of the buffer zones which were used to calculate the number of settlements within 5 km, 10 km, and 30 km from the Nuragic sanctuaries. The analysis considers geographical proximity to settlements/ resources as a significant factor for the establishment of stronger or weaker networks in the landscape.

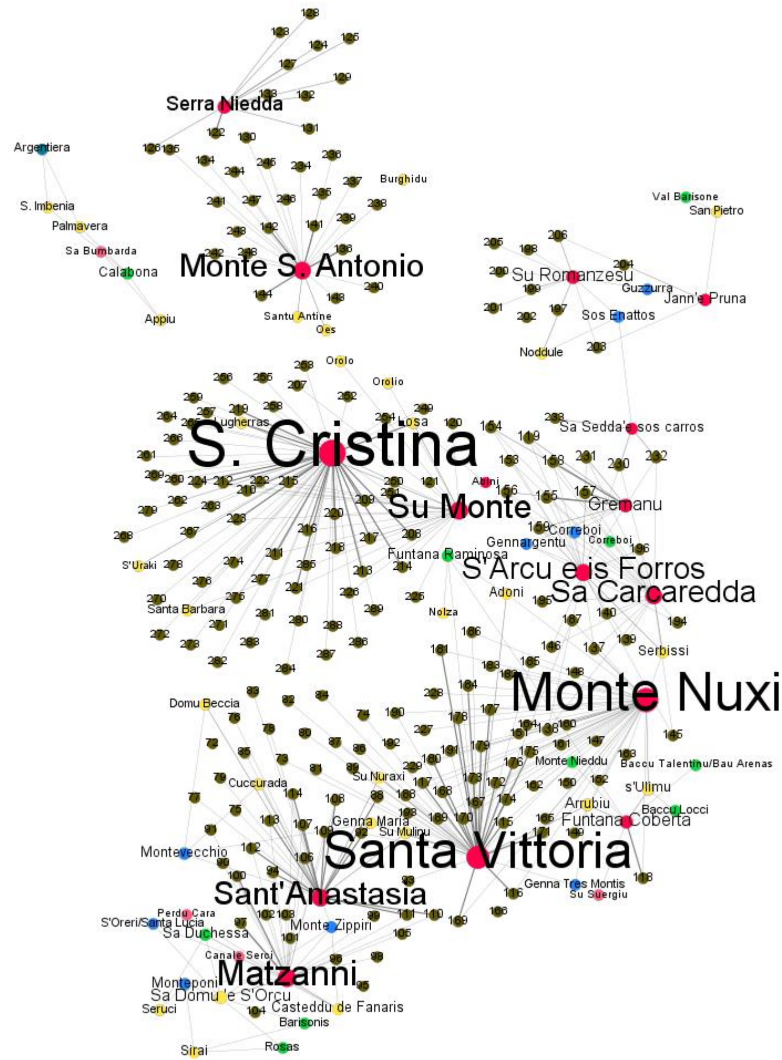

Fig. 5: Network graph showing the connections between sanctuaries (in red), major settlements (yellow), other Nuragic settlements (brown), and ores (green, blue, pink). The links are based on geographical proximity, the larger is the node the larger the number of connections. The thicker is the edge the closer are the nodes between them.

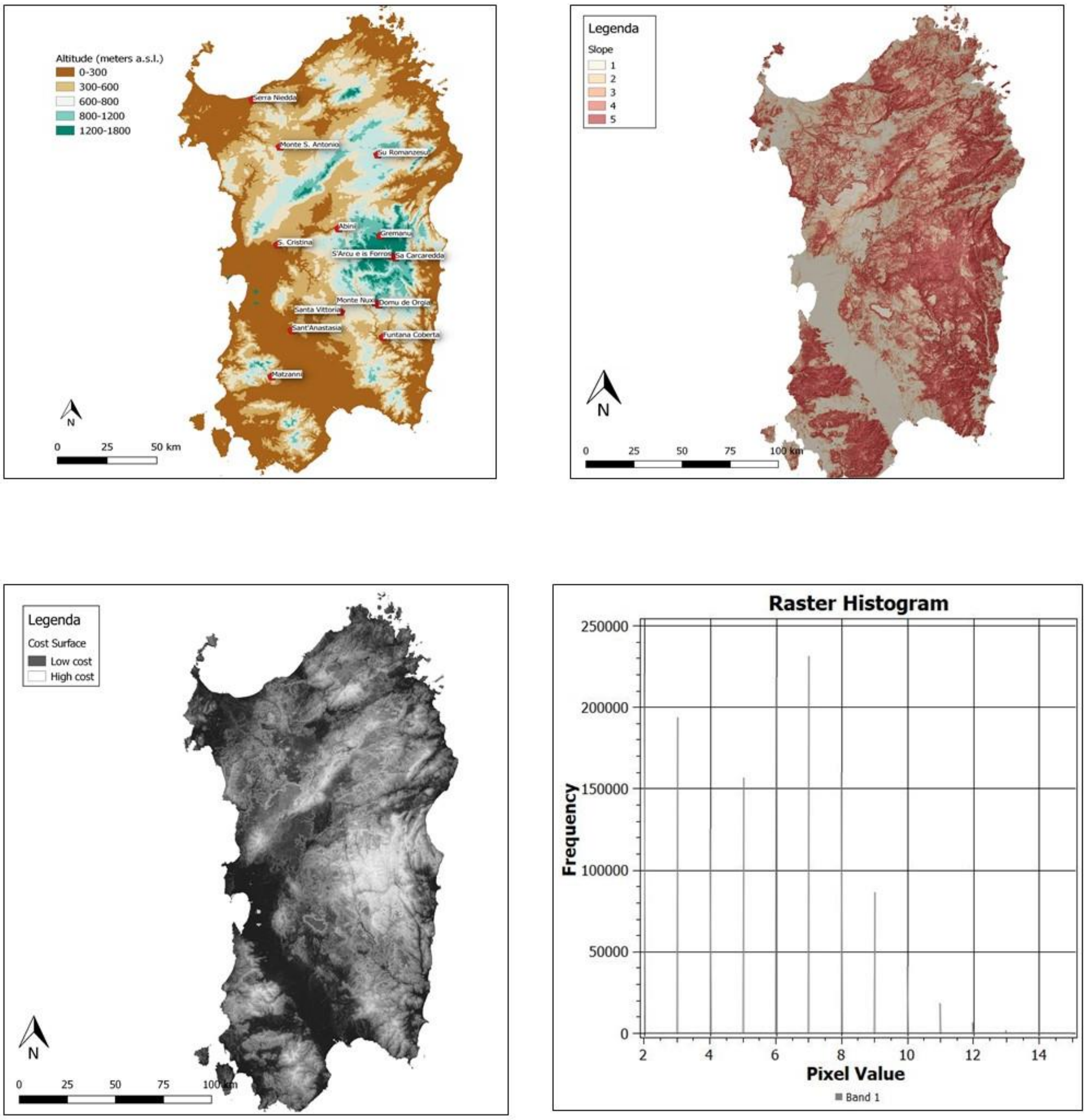

Fig. 6: Cost Surface Analysis of Sardinia DTM (Digital Terrain Model). The construction of the cost grid employed three main criteria: altitude (top left), slope (top right) and hydrography (not visible in the raster file). On the bottom left, the Cost Surface used to create the Cost Distance/ Least Cost Path models from the Nuragic sanctuaries/ settlements, whereas on the bottom right the histogram shows the CSA values after the reclassification of the raster-criteria.

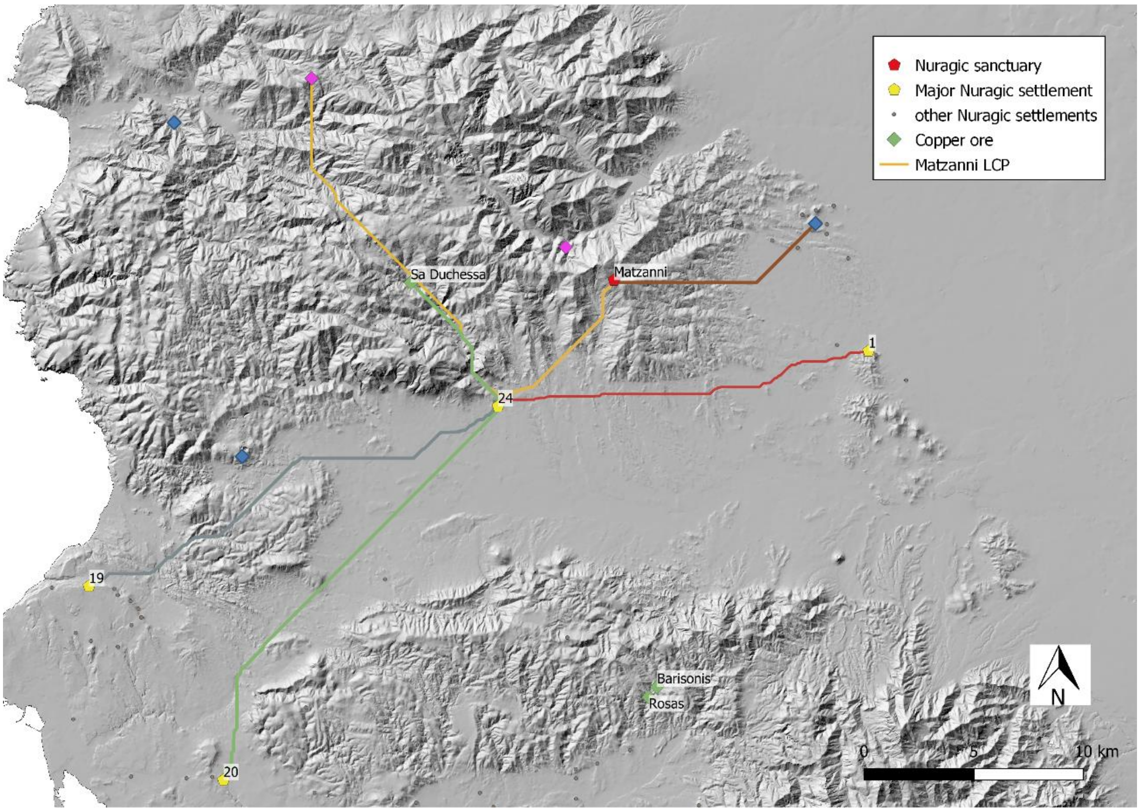

Fig. 7: LCP from the Nuragic sanctuary of Matzanni (in red) and its surrounding settlements (yellow) towards the copper deposit of Sa Duchessa (green) and the tin deposit of Perdu Cara (pink). The LCP clearly shows the control of the Nuragic settlement of Sa Domu'e S'Orcu (n. 24) over the copper ore. Despite the geographical proximity of the sanctuary to the ores, the optimal route proposed by the model had to pass necessarily across the settlement's territory. The same result appears also when applied to the other settlements in that area.

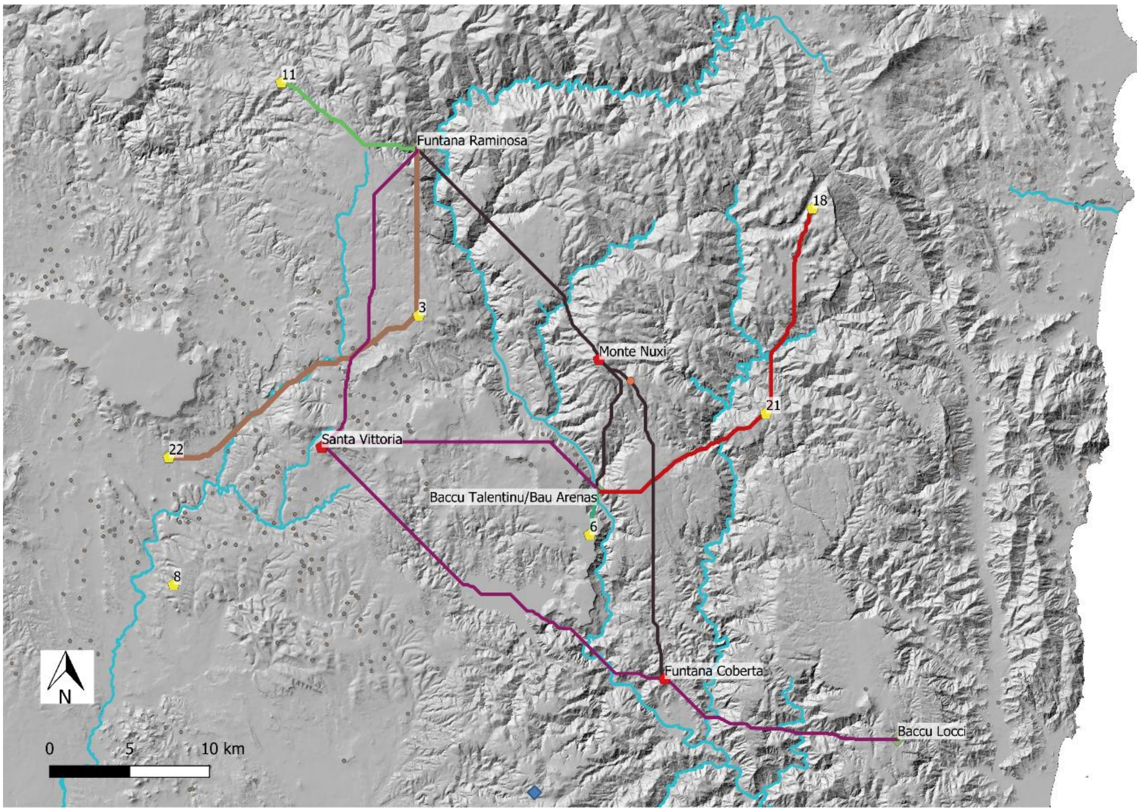

Fig. 8: Another similar example of LCP from several Nuragic sanctuaries (Santa Vittoria, Monte Nuxi, Funtana Coberta) towards the near copper ores of Funtana Raminosa and Baccu Talentinu. In this case, the Nuragic settlements of Adoni (n. 3) together with nuraghe Nolza (n. 11) had a primary (shared?) control over the copper ore of Funtana Raminosa. A similar result was obtained when the LCP has been run toward Baccu Talentinu, near the monumental complex of Arrubiu (n. 6). Perhaps the position of the sanctuaries acted as a territorial mediator in the access to natural resources.