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# Mining, farming, and diplomacy. Understanding the human landscape of Bronze Age Sardinia (Italy) through geospatial analysis

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ABSTRACT

Human agency on landscape modification and land use is often seen in terms of socio-economic opportunities vs. natural constraints. In the study of prehistoric cultures this is both a strong source of information about sustenance strategies and community behaviours, and a subject potentially easy to analyse within a limited set of physical and social parameters. The recent advancements in the use of spatial analysis tools in landscape archaeology allow to obtain ever more precise models. However, studies that compare at the same time the geological landscape and social elements are very scarce. We used Point Pattern Analysis and Modelling to investigate megalithic structures (nuraghes) in Bronze Age southwestern Sardinia (Italy) and identify correlations between their spatial patterns and a set of covariates encompassing both environmental (i.e. topography and geological resources) and cultural factors. The models which best represent pattern distribution come from the combination of covariates from both groups.

The models highlight a close distance from known ore deposits and show a clear dependence of Nuragic populations to ore extraction and metallurgy. The availability of fertile soils with moderate permeability and moderately low pH is also significant, as well as a preference to prominent locations with a positive correlation with the Topographic Position Index and the Convexity Index. From a cultural standpoint, we observed a consistent aggregation of simple nuraghes around complex nuraghes at mid-short distances. The occurrence of polycentric patterns can be explained either by the former emerging from the presence of the latter or vice versa, and is typically associated with a loosely stratified social structure devoid of strong hierarchies. These results underscore the efficacy of spatial analysis in disentangling and juxtaposing the physical and social factors influencing the distribution of past culture, and offer new insight on the development of Bronze Age societies in their geographical context.

## 1. Introduction

In the subject of landscape archaeology, disentangling social and physical factors in the land use choices of a community is not an easy task. While the former are dictated by constantly evolving socio-political actions which adapt in time to the internal needs of a population, the latter depend instead on the features and resources of the landscape, often fixed, that communities are able to exploit to their advantage in order to survive and expand. When dealing with pre- and protohistoric cultures, the scarcity of direct information on social norms and land use often only allows speculative interpretations difficult to test in practice. In this case, the use of models derived from spatial analysis tools can provide useful insights to understand the importance of different natural and cultural factors in the distribution of populations.

The relationship of Bronze Age cultures with their territory testifies how the appearance of new complex social forms and structures (Chapman, 2005) corresponded to the widespread adoption of new technologies (Amzallag, 2009; Greenfield, 2010; Sherratt, 1983) and a more efficient exploitation of resources (Barker, 2005; Dolfini, 2020), allowing the expansion of these cultures both in population numbers and land occupation (Broodbank, 2013). Therefore, the analysis of the spatial dimension is fundamental in the investigation of societal

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dynamics. The importance of social space in Bronze Age cultures is well known. Multiple works on settlement patterns and cultural space from the Mediterranean to Eastern Asia (Erb-Satullo et al., 2019; Fisher, 2014; Liu et al., 2019; Savage and Falconer, 2003) highlight the existence of a range of different relationships between settlements and relate them to opposing social structures. On one end of the spectrum lie highly hierarchical arrangements due to the rise to dominance of a restricted number of centres of influence, often associated to complex and rigidly divided societies such as chiefdoms (Liu et al., 2019). On the other end, partitions between different communities are not so clear and the presence of social stratification is less understandable (Johansen et al., 2004).

The distribution of settlements and monuments within the landscape can also heavily rely on the nature and distribution of landforms and of potential resources (Sollars, 2005). The interest for the spatial relationship of Bronze Age communities with their surrounding environment has increased in the last decades, with a shift from the investigation of social space to the physical landscape. Many studies found relationships with geographical partitions (Jaeger, 2016; Liu et al., 2019), topographic variables (Galmés-Alba and Calvo-Trias, 2022; Spencer and Bevan, 2018), climatic parameters (Schirrmacher et al., 2020; Dong et al., 2022), while not as much effort is put on the investigation of the geological landscape and its resources. In the last few years, the advancement of spatial analysis tools in landscape archaeology have provided new models for data interpretation and the ability to compare multiple types of information (Carrero-Pazos et al., 2019; Costanzo et al., 2021; Napoli et al., 2006), giving reliable quantitative information on land use.

One of the most interesting examples from this point of view is certainly the Nuragic culture, established on the island of Sardinia (Italy) between the 18th and 7th centuries BCE (Dyson and Rowland, 2007; Lilliu, 1988; Webster, 1996). Insularity had a great impact on the development of this society: the Nuragic populations had the opportunity to manage a large and diverse territory for centuries in a network of interconnected tribes with little interference from external influence (Lo Schiavo et al., 2009; Minoja et al., 2015; Webster, 2016). As a result, the Nuragic people was able to construct a network of sites of different dimensions and locations (Lilliu, 1988; Moravetti et al., 2017; Namirski, 2020; Usai, 2018) throughout the various landscapes of Sardinia. In such conditions, the settlement choices of the Nuragic culture would supposedly rely on a limited set of factors. Firstly, the characteristics of the topography would determine if a settlement is accessible or can effectively control the surroundings. Secondly, the location and availability of material resources would dictate the survivability of the settlement in terms of access to food and water, or explain its presence by the vicinity of key resources to exploit and distribute among other communities. Lastly, the social and cultural dynamics between the settlements themselves would strongly influence the placement of new settlements based on interconnectivity. This work therefore investigates the relationships of the Nuragic culture with the Sardinian landscape through spatial analysis tools, using the territory of southwestern Sardinia as a case study. The intensity of the Nuragic monuments in the area was previously explored through Kernel Density Estimation (KDE), a nonparametric density-based approach (Mariani et al., 2022). The purpose of the present study is to explore the sites distribution parametrically, in order to find correlations between such spatial patterns and a series of variables related to both environmental (physical landforms and geological resources) and cultural factors. In this way, we aim to provide a comprehensive understanding of land use strategies for the Nuragic civilization, and potentially for other Bronze Age Mediterranean societies.

## 2. Archaeological setting

### 2.1. Nuragic culture

The Nuragic civilization developed in Sardinia between the 18th and the 7th century BCE. As natives of the region, for a thousand years the Nuragic people have been the sole rulers of the land, without relevant interference from outside the island. The decline of Nuragic society starts with the Iron Age and the progressive Punic conquest of Sardinia by the 6th century BCE (Cossu et al., 2018; Dyson and Rowland, 2007; Webster, 1996), which traditionally marks the end of this culture. Archaeological evidence shows a system of tribal control for different portions of the island (Usai, 2018), with separate chiefdoms often allied together (Webster, 1996) or in direct contrast with each other (Lilliu, 1982). Nevertheless, material production and trade and cultural expressions are in general homogeneous (Freund and Tykot, 2011; Webster, 2016), as probably was their social identity (Blake, 1999). In time, tribes progressively became larger and more socially stratified, from small egalitarian communities at the end of the Early Bronze Age (Depalmas, 2005; Lilliu, 1988) to markedly hierarchical networks of settlements in the Recent and Final Bronze Age (Depalmas, 2009a; Moravetti et al., 2017). The Nuragic economy depended mostly on animal husbandry, fishing and agriculture (Depalmas and Melis, 2011; Moravetti et al., 2017), but there is consistent evidence of stronger cultural and commercial bonds between communities within the island and with cultures in the Mediterranean area. Trade was widespread in the eastern and western Mediterranean as well as Northern Europe (Dawson, 2014; Knapp et al., 2022; Ling et al., 2014). Metallurgy also developed greatly during the Bronze Age, with bronze ingots and goods possibly becoming key items for Nuragic trade in the Mediterranean (Amzallag, 2009).

### 2.2. Nuraghes

The Nuragic culture shares its name with the landmark it is most often associated with, that is the nuraghe (Fig. 1). This structure is a round megalithic dry-stone tower essentially conical in shape and several stories tall (Depalmas and Melis, 2011; Dyson and Rowland, 2007; Webster, 2016). Its shape changed over time. The 'corridor' nuraghes, also called proto-nuraghes, built at the beginning of the Middle Bronze Age, were longer with an internal corridor and a shorter height between eight and fifteen meters (Depalmas, 2009b; Depalmas and Melis, 2011). Since the late Middle Bronze Age to the Recent Bronze Age their shape changed into the single towered 'tholos' nuraghe with an open central area and a side stairway leading to the upper floors (Depalmas, 2009a; Webster, 2001). During the Recent Bronze Age appear 'complex' nuraghes made of multiple towers walled and connected by corridor structures, probably through the progressive extension of a former simple nuraghe (Lilliu, 1988). In the same period also appear regular villages made of stone huts around some of the most important nuraghes (Depalmas, 2017, 2009c). By the Final Bronze Age (around 13th to 9th BCE) the construction of nuraghes slowly stopped as increasingly complex villages developed either around previous structures or in unoccupied areas (Boninu et al., 2016; Depalmas, 2017, 2009c; Dyson and Rowland, 2007). The structures were progressively abandoned and often partially dismantled to provide building materials for the expansion of villages (Depalmas, 2009c; Namirski, 2020).

The presence of nuraghes on the territory is very widespread: around more than 7000 structures and remains have been identified and catalogued (Fig. 1a), with some scholars suggesting a potential total number of more than 9000 nuraghes built during the Bronze Age (Contu, 1998; Depalmas, 2018; Dyson and Rowland, 2007). Most of them are identifiable only by their foundations or as ruined stone mounds, as many collapsed or were dismantled by natural and human causes, making the count to a total number controversial. Their distribution is widespread but not random: they are more common on basalt plateaus and in areas

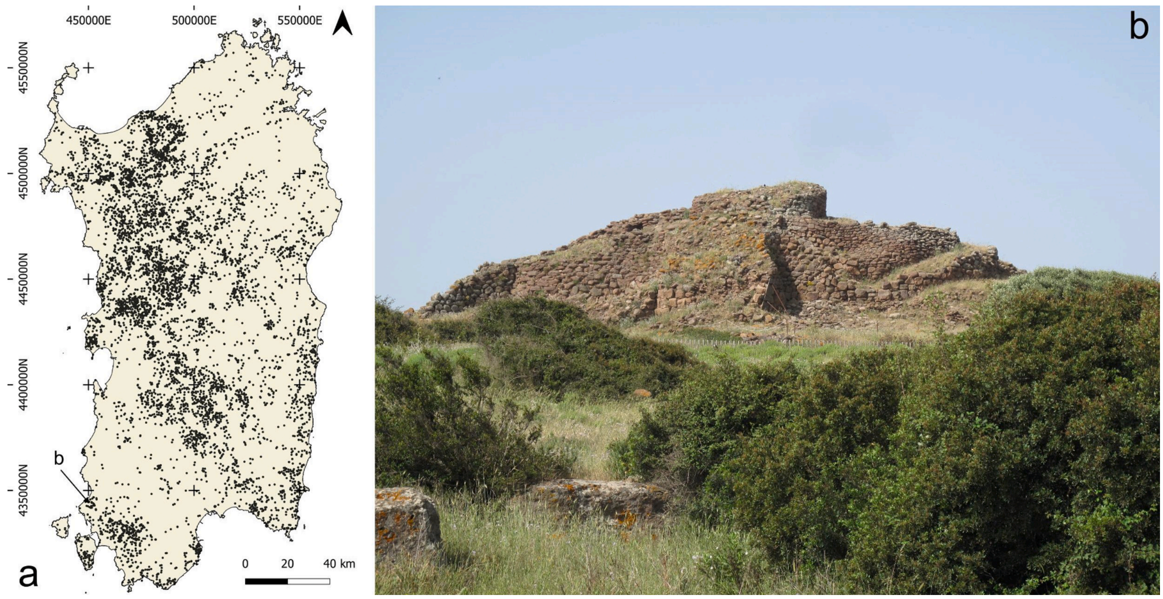


**Fig. 1.** a) Spatial distribution of nuraghes in Sardinia (source: nurnet.net). b) the nuraghe Seruci (Gonnesa, SU) an example of well-preserved complex nuraghe in the study area.
Modified from Mariani et al. (2022).

of volcanic rock (Depalmas and Melis, 2011; Mariani et al., 2022), and stand where possible on solid substrates and elevated positions (Mariani et al., 2022). Their locations are also clearly based on local factors influencing patterns of distributions across the island (Namirski, 2020), and were in some cases replaced by structures of successive cultures (Mariani and Melis, 2022). The function of nuraghes is still debated. The earlier interpretation of the nuraghe as a military structure (strongholds, forts, guard posts, see: Lilliu, 1982) has been challenged in recent years by new theories postulating instead residential, storage, communal, symbolic, or even religious functions (Blake, 2001; Schirru and Vanzetti, 2023; Trump, 1992; Vanzetti et al., 2013). Several studies have tried to employ spatial analysis tools to map and find correlations between different kinds of Nuragic age structures and settlements, either focusing of small groups of structures (Blake, 2001; Cicilloni et al., 2015; Schirru and Vanzetti, 2023; Spanedda et al., 2010) or at larger scales (Cicilloni and Cabras, 2017; Matta, 2020; Namirski, 2020; Stein et al., 2022)

### *2.3. Southwest Sardinia and its geological resources*

Sardinia has a complex landscape in which resources are distributed in a non-homogeneous way, which potentially influences the strategies and lifestyles of human populations. We chose to concentrate our study on the SW portion of Sardinia for several reasons (Fig. 2). First of all, this region is the only one clearly separated from the rest of the island by a visible boundary to its NE, the Campidano graben cutting the island NW to SE. This possibly also represents a population boundary since Nuragic structures can be found on its sides, but very few are located inside of it. This side of the island is especially interesting for its high landscape diversity, which pushed the adaptation to potentially different environments from the coasts to the plains and mountain areas. Inside this area, it is already clear that the distribution of nuraghes follows definite patterns with easily identifiable areas of high concentration and entire portions completely empty (Mariani et al., 2022). SW Sardinia is also one of the largest mining districts in the Mediterranean, rich in metals used in pre- and protohistoric times such as copper, tin, lead, and later iron (Marcello et al., 2008). Multiple easily exploitable open-air mining sites had been likely tapped since the Eneolithic (Freund et al., 2019; Pearce, 2017; Usai, 2005), with many instances of extraction activities during the Nuragic, Punic and Roman periods. Sardinia occupies a key position in the Mediterranean, and was strongly involved in the trade of metals in the Bronze age. The Nuragic contribution to such trade is well attested, though not yet fully known (Kassianidou and Knapp, 2005; Lo Schiavo et al., 2005; Sabatini and Lo Schiavo, 2020). Provenance studies show how copper and tin from outside Sardinia are well represented in the archaeological record, from ingots to manufactured Nuragic objects (Gale, 2006; Lo Schiavo et al., 2005). In fact, Sardinia is rich in findings of oxhide ingots from Cyprus (Kassianidou, 2001; Lo Schiavo, 1988). At the same time, the presence of Sardinian ores in Mediterranean Bronze age findings is less documented: while metal exports from the island are certain, especially towards the Late Bronze Age (Amzallag, 2009; Lo Schiavo et al., 2005), there is uncertainty over the entity of such trade (for an updated review, see: Sabatini and Lo Schiavo, 2020). The role of SW Sardinia in the larger context of Mediterranean metallurgy is not well known.

## 3. Materials and methods

### *3.1. Archaeological and environmental datasets*

The main dataset providing the nature and location of Nuragic structures in the study area comes from the NURNET online database (https://www.nurnet.net/). For the area of study, 551 nuraghe structures were extracted, of which 527 simple nuraghes and 24 complex nuraghes. The dataset provides information only on the nature of the Nuragic structure and its location; no information was provided on the age of the structure (in most cases unknown) or its dimensions. Database accuracy was verified through literature comparisons, satellite observations, and field validation. Discrepancies within a 50 m radius were corrected based on satellite and field validations. The Nuraghe dataset is also necessarily limited by the obliteration of archaeological structures in time. Destruction of sites by slope movements and surface erosion is well known for mountain areas (Mariani et al., 2019) and Mediterranean environments (Ayala, 2012). The recycling of older masonry for the construction of new structures is also documented cause for the loss of prehistoric and protohistoric buildings in the Mediterranean (Ayala, 2012; Leighton, 2005). In Sardinia, however, such dismantling operations were likely restricted to the largest plains due to the limited role of agriculture on land use (Namirski, 2020). This dataset was compared to the environmental variables (spatial covariates) listed below.

Elevation values were acquired from a 10-metre Digital Elevation

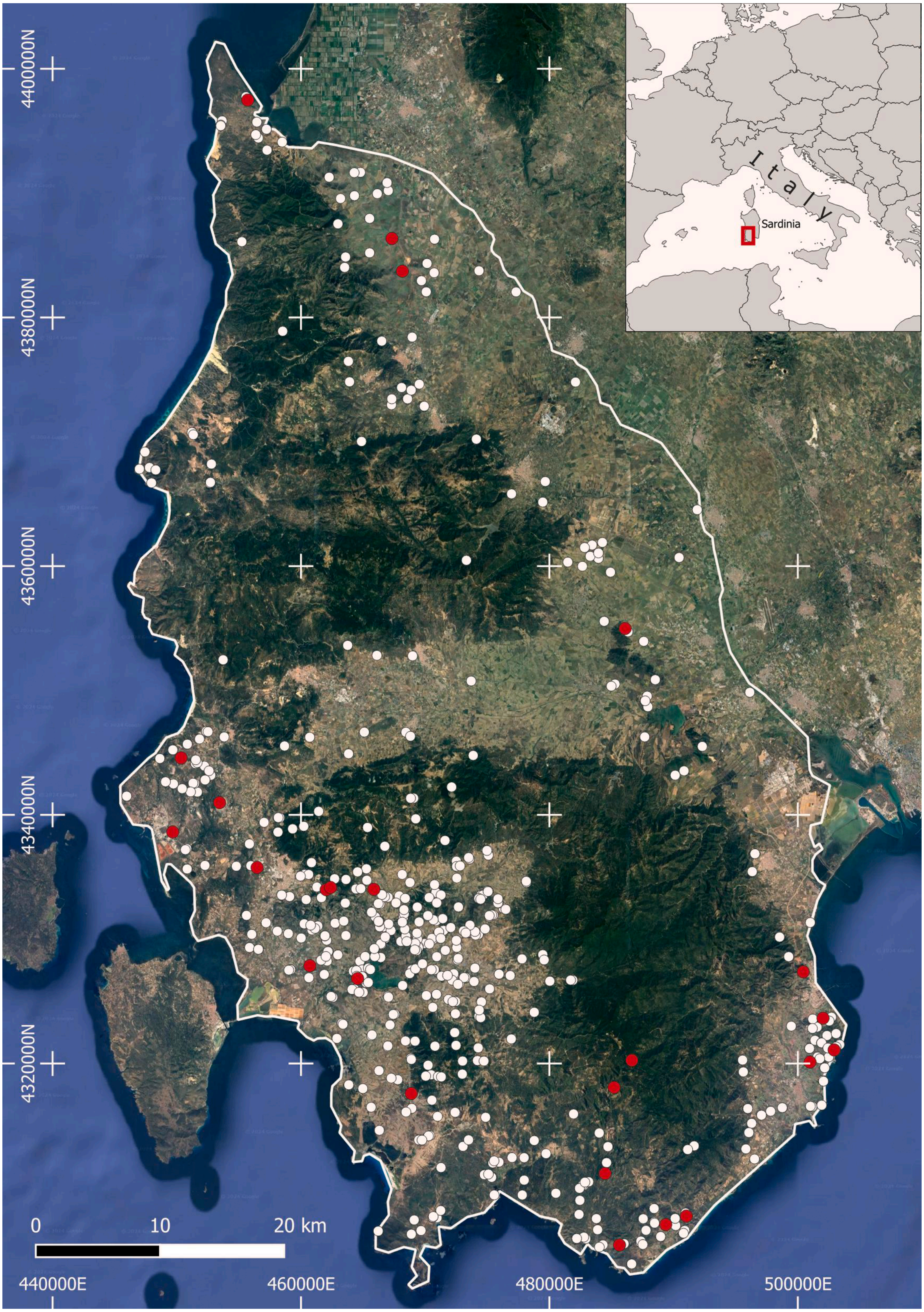


**Fig. 2.** Extension of the study area in SW Sardinia (CRS: WGS84 UTM32N). Satellite images retrieved from GoogleEarth™. The locations of simple nuraghes are represented with white dots, complex nuraghes with red dots.

Model (DEM) of Italy hosted by the TINITALY web repository (Tarquini et al., 2007). The initial DEM resolution was adjusted to 25 m using GRASS GIS (GRASS Development Team, 2023) to expedite computational processes. The Slope and Aspect covariates were computed within R. Aspect values, initially spanning 0° to 359°, were reformulated into two linear variables: Northness and Eastness, which offer enhanced applicability for subsequent analyses. Positive Northness values represent a northward orientation, while negative values signify a southward orientation. Similarly, Eastness delineates an eastward orientation for positive values and a westward orientation for negative values (Costanzo et al., 2021). Furthermore, the Geomorphon covariate characterises fundamental microstructures of the landscape and was derived using the *r.geomorphon* extension within GRASS GIS (Stepinski and Jasiewicz, 2011). Each assigned Geomorphon value (ranging from 1 to 10) denotes a specific landform type: flat area (1), summit (2), ridge (3), shoulder (4), spur (5), slope (6), hollow (7), footslope (8), valley (9), and depression (10) (Jasiewicz and Stepinski, 2013). The Topographic Position Index (TPI) and Convexity Index (CI) were utilised to assess relative topographic features like ridges and depressions. Both methods operate independently of absolute elevation values and effectively emphasise prominent topographic characteristics within an area (Knitter and Nakoinz, 2018). This study calculated TPI using the Topographic Position Index module in SAGA GIS (Conrad et al., 2015) with three different radii: 100 m, 500 m, and 1000 m. Additionally, the CI parameter was derived using the SAGA GIS module Convergence Index.

Vector layers reporting current springs and primary watercourses (not all of them necessarily representing Bronze Age conditions) were obtained from the regional geodatabase (Regione Autonoma della Sardegna, 2023a). Ore locations were referenced from the work of Marcello et al. (2008) and filtered, focusing solely on metals with importance in the metallurgy of Mediterranean Bronze Age, which include Ag, Cu, Pb, Sn, and Au (Giardino, 2005; Serra et al., 2016). Anisotropic cumulative cost from mineral deposits, watercourses, and springs were computed using the GRASS GIS module *r.walk*. To investigate potential influences of soil properties on the spatial distribution of nuraghes, two rasters were developed: one for soil pH and another for soil permeability. The soil permeability raster was generated by rasterizing the substrate permeability vector layer available in the regional database (Regione Autonoma della Sardegna, 2023b). Meanwhile, the soil pH raster grid was derived using a kriging approach in SAGA GIS. 234 sampling points for soil pH retrieved from the regional geodataset (Osservatorio Regionale dei Suoli della Sardegna, 2023) were utilised in combination with slope and the Topographic Wetness Index in a regression kriging process, resulting in a comprehensive estimation of soil pH across the entire study area (Gia Pham et al., 2019).

### 3.2. Spatial analysis tools

Point Pattern Analysis and Modelling (PPA & PPM) delves into the spatial configurations of points within a given space. Its application in landscape archaeology is increasingly popular for investigating both settlement and monument patterns (Basile, 2022; Brandolini and Carrer, 2021; Carrer et al., 2021; Costanzo et al., 2021). A point pattern represents a collection of locations derived from spatial events occurring through a stochastic process within a confined area (Baddeley et al., 2015). The density of such a pattern corresponds directly to the intensity of the underlying process. This intensity can either remain consistent across the region—termed isotropic—or exhibit spatial variability. The former aligns with the Homogeneous Poisson Process (HPP), signifying a stationary and isotropic process. Conversely, a non-uniform event distribution falls under the Inhomogeneous Poisson Process (IPP) (Nakoinz and Knitter, 2016). Within an IPP, exploring whether event intensity correlates with spatial variables (covariates) and quantifying this correlation (First Order Properties) becomes intriguing. Furthermore, during point pattern analysis, it is pertinent to ascertain the independence or potential interpoint dependence among the points (Second Order Properties). Distinguishing between the effects of first and second order properties can pose challenges, as their distinctions are subtle. Spatial interaction often emerges at a smaller scale, while variations at larger scales typically associate with the non-stationary intensity of underlying processes (Carrero-Pazos et al., 2019).

These inherent characteristics were utilised to examine the spatial arrangement of nuraghes within the designated study area. PPA was conducted using the *spatstat* package (Baddeley et al., 2013) within the R software system for statistical computing (R Core Team, 2023). This study aims to evaluate how the environmental characteristics of the region influence the distribution of nuraghes across the landscape and to quantify the clustering of these sites. To address these research inquiries, two complementary null hypotheses were tested using PPA:

- H1: At a landscape scale, nuraghes exhibit uniform density (the point pattern's intensity is both stationary and isotropic). Spatial variables do not impact the spatial distribution of these points.
- H2: At a local scale, nuraghes display complete independence from each other, presenting no spatial correlation

To rigorously examine these hypotheses, we employed nonparametric and parametric tools to analyse the point process intensity. These tools allowed us to assess the influence of three distinct and self-contained environmental factors that potentially govern the distribution of monuments in the landscape: i) The impact of topographic characteristics (elevation, slope, downslope direction), affecting their endurance and visibility from mid/long distances; ii) The implications of water sources and mineral deposits, which might influence transportation costs; iii) The relevance of soil properties pertinent to agricultural activities (such as soil pH and permeability). This preliminary estimation assisted in anticipating potential outcomes of the PPA. Moreover, the analysis delved into exploring the interpoint dependence among sites, aiming to evaluate the potential existence of an intangible societal framework or superstructure. The repository containing the developed code and referred material was published by Brandolini (2024).

### 3.3. Parametric modelling of intensity

In this study, intensity estimation was conducted using parametric methods, where key covariates were aligned with nuraghes point patterns through the application of the PPM function in *spatstat* (Baddeley and Turner, 2005). The PPM framework includes various spatial models that are instrumental in conducting detailed analyses of the interplay between point patterns and spatial covariates. This analysis involved fitting three distinct IPP models, each focusing on different covariates (Table 1): Model 1 concentrated on topographic factors, Model 2 on the ease of access to resources, and Model 3 on soil characteristics. The Pearson correlation test was utilised to assess collinearity among the variables, aiming to prevent overparameterization in the models (VanPool and Leonard, 2011). In this study, we adopted a threshold of $>$ 0.6 to exclude correlated variables.

To evaluate and compare these models, Schwarz's Bayesian Information Criterion (BIC) was utilised (Schwarz, 1978). The BIC calculation is based on the contrast between the model's maximised likelihood and the multiplication of the count of covariates with the number of observations (points). Thus, models with lower BIC values are indicative of superior performance (Neath and Cavanaugh, 2012). Adhering to the principle of parsimony, a stepwise covariate selection method was employed to determine the optimal combination that minimises BIC values, excluding any covariate that lacked significant relevance to the point patterns. Further, a fourth model, termed as the 'hybrid' model (Model 4), was developed, incorporating the most effective covariates from the previous models. The performance of these IPP models was then assessed by comparing them against each other and an alternative

**Table 1**
Result of the BIC stepwise covariates selection and model selection based on BIC weights.

| PPMs | Selected Covariates | Discarded Covariates | BIC | Weights Model 0–1 | Weights Model 0–2 | Weights Model 0–3 | Weights Model 0–4 |
|---|---|---|---|---|---|---|---|
| 0 | - | - | 18204.17 | 0 | 0 | 0 | 0 |
| 1 | Northness, Eastness, TPI100, CI, Geomorphon | Northness, Eastness, Geomorphon | 17682.43 | 1 | 1 | 1 | 0 |
| 2 | distance from ore deposits and streams | distance from streams | 18172.48 | | 0 | 0 | 0 |
| 3 | soil pH, and soil permeability | none | 18073.35 | - | - | 0 | 0 |
| 4 | TPI 100, CI, distance from ore deposits, soil pH, soil permeability | none | 17519.41 | - | - | - | 1 |

baseline model, Model 0. Model 0, a HPP model, was formulated by assigning a uniform value across the point patterns. The hypothesis (H1) posits that if the study sites are evenly distributed across the region and unaffected by spatial variables, Model 0 should demonstrate superior performance compared to the other models. Additionally, BIC weights were used to normalise the performance comparison of all five models, aiding in identifying the model that most accurately represents the spatial distribution of the observed points (Eve and Crema, 2014).

### *3.4. Model fitting and uncovering hidden variables*

To explore potential hidden factors influencing the spatial arrangement of the nuraghes, an evaluation of the interpoint relationship of sites (H2) was conducted using the pair correlation function (pcf) in Model 4. In this analysis, the pcf was computed in *spatstat* using the *'pcfinhom'* function (Baddeley and Turner, 2005), focusing on both the observed site data and 999 Monte-Carlo simulated point patterns. For a comparative visual assessment, the pcf of Model 0 was also calculated to understand the effect of primary properties of the point patterns on their secondary properties.

Upon identifying site clustering in the pcf results, we applied a recognised point interaction model to analyse the observed pattern. In our study, the Widom-Rowlinson penetrable sphere model, also known as the area-interaction process, was found to be more suitable and insightful for interpretation (Baddeley et al., 2015). This model generates patterns of inhibition and clustering based on a buffer zone created around each point in the distribution. This buffer zone can be interpreted as an area of influence for monuments, within which they either draw in or repel other monuments. The area-interaction model was implemented in *spatstat* using the *'AreaInter'* function. In prior archaeological studies (Carrero-Pazos et al., 2019), the selection of the *'AreaInter'* value was assessed based on where observed values indicated strong positive correlation at short distances. In our research, we adopt a novel approach to analytically determine the *'AreaInter'* value in R. The chosen value for *'AreaInter'* in our simulation was ascertained by examining the relationship between two distinct types of Nuragic towers: simple 'tholos' nuraghes and complex nuraghes. To investigate the spatial correlation between these two monument categories, the cross-type nearest-neighbour function Gij(r) was calculated (Baddeley et al., 2015). This estimation of the cross G function involves measuring the distances from each 'simple nuraghes' point (type i) to the nearest 'complex nuraghes' point (type j), and was computed in *spatstat* via the *'Gcross'* function. For refining the selection of *'AreaInter'* value, the list of Gij(r) distances where observed values surpass the confidence envelope (indicative of clustering) was further narrowed down to remove potential outliers. This subset only included values within one standard deviation from the mean of the original data set. This filtering process is a common statistical technique used to focus on values that are close to the average or central tendency of a dataset (Weisberg, 1992).

To assess the Model's goodness-of-fit, the process of calculating residual values was undertaken (Baddeley et al., 2015). Residuals were generated by deducting the fitted intensity function from the observed counts in each segment of the model quadrature. The spatial variability in the model's predictions can be visually examined by plotting a smoothed representation of the residuals across the entire area: instances of positive residuals indicate underestimations of the actual intensity (i.e., site density) by the model, while negative residuals point to overestimations. For Model 5, diagnostic smoothed residual values were computed using the *'residuals.ppm'* function within *spatstat*.

## 4. Results

The results of the Pearson correlation test showed that, among the chosen variables, Elevation, Slope, distance from springs, TPI 500, and TPI 1000 had a correlation too high with other variables (Fig. 3). Based on this, only the topographic and morphometric variables with lower collinearity (Northness, Eastness, TPI100, CI, Geomorphon, distance from ore deposits and streams, soil pH, and soil permeability) were selected for point pattern modelling. Northness, Eastness, TPI100, CI, and Geomorphon were attributed to Model 1, distance from ore deposits and streams to Model 2, and soil pH and permeability to model 3. The efficacy of the selected covariates for the Bayesian Information Criterion (BIC) was confirmed in comparison to the static model (Model 0), utilizing BIC metrics. In this analysis, the point process model (PPM) equipped with topographical factors (Model 1) outperformed not only the static model (Model 0) but also the additional non-static models (Models 2 and 3). Consequently, the findings affirm the non-uniform nature of point process intensity, justifying the rejection of the initial null hypothesis (H1). The rejection of H1 indicates that the spatial arrangement of sites in the study zone is influenced by environmental and landscape factors.

Nonetheless, the iterative covariate selection led to the omission of certain variables in Models 1 (Northness, Eastness, Geomorphon) and 2 (distance from streams), suggesting that not every spatial variable is significantly correlated with the points of interest. Therefore, the composite "hybrid" model (Model 4) was constructed by integrating all variables retained from earlier stages (soil permeability, soil pH, distance from ore deposits, CI, and TPI), achieving the most favourable BIC score (Table 1). Essentially, this composite model (Model 4) more efficiently explicates the IPP's underlying distribution of sites compared to its counterparts (Models 0, 1, 2, 3). The coefficients of Model 4 (Table 2) indicate that nuraghes are more likely to be located in topographically prominent positions within the area, as indicated by a positive correlation with Topographic Position Index (TPI 100) and Convexity Index (CI). With regards to soil parameters, the correlation with permeability is negative, indicating a preference for substrates with mid- to high water-retaining properties, though almost no nuraghes are found in areas with low permeability. Correlation with pH is positive, with the maximum values tending towards pH 7. Finally, coefficients indicate a negative correlation between site locations and distance from ore deposits (the closer the distance, the denser the sites). Looking more closely at the values, nuraghes appear to be located at mid-range distances from mineral sources with peak density at around 300 m (Fig. 4). These observations imply a substantial impact of the chosen environmental variables on the spatial arrangement of these sites.

The application of the pcf function to find potential hidden factors in the spatial arrangement of nuraghes shows that the observed values consistently surpass the 95th percentile of the simulated values (upper

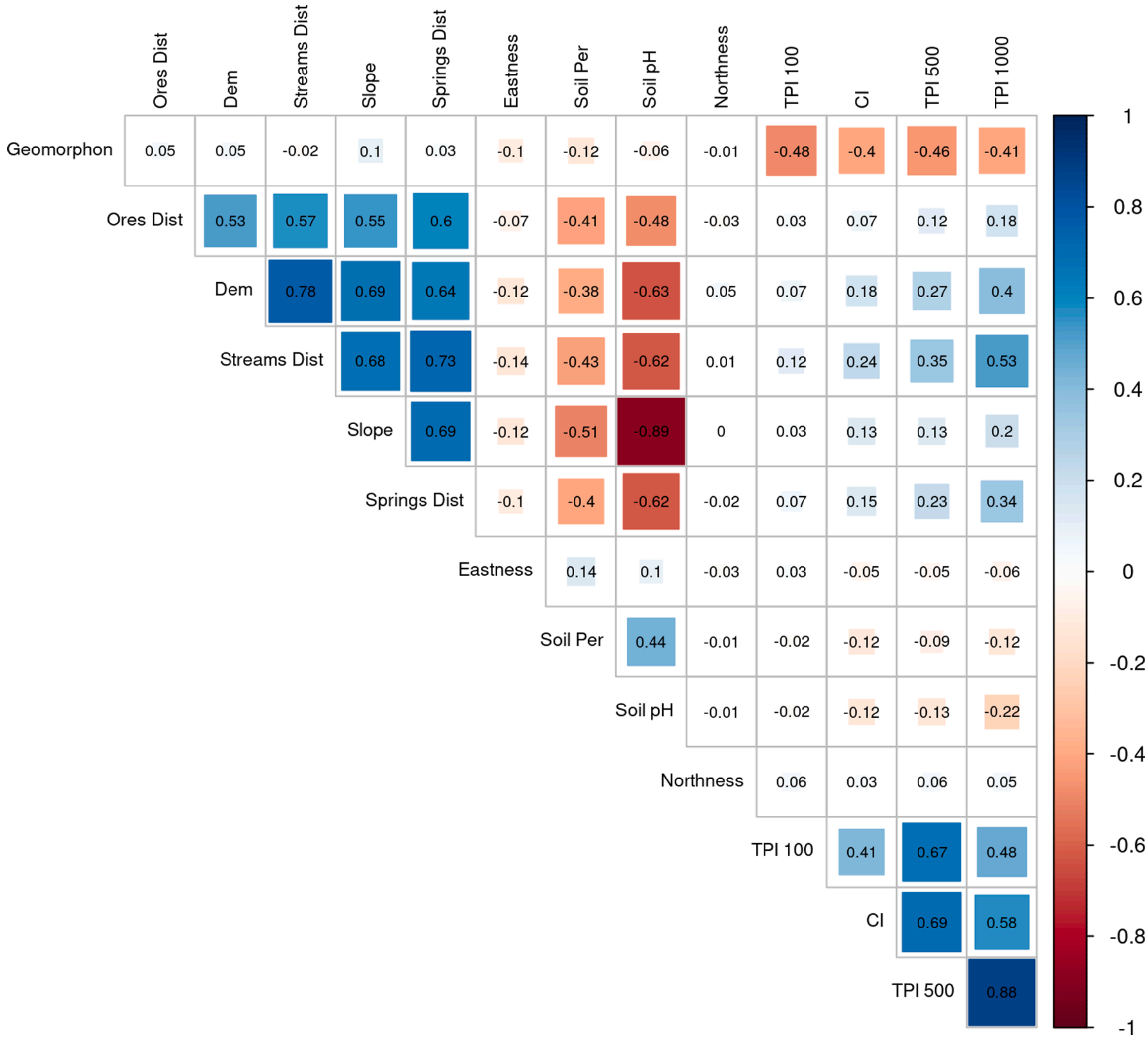


**Fig. 3.** Collinearity signifies a strong linear relationship between multiple predictors. Typically, an absolute correlation coefficient exceeding 0.7 (depicted in dark blue or dark red) between predictors indicates collinearity. For this study, we used a threshold of > 0.6 to eliminate correlated variables.

**Table 2**
Covariates of the BIC-selected Model 4.

| Covariates | Estimate | S.E | CI95.lo | CI95.hi | Z Test | Correlation |
|---|---|---|---|---|---|---|
| (Intercept) | −2.16E+01 | 8.30E−01 | −2.32E+01 | −2.00E+01 | <0.001 | - |
| CI | 1.78E−02 | 1.93E−03 | 1.40E−02 | 2.16E−02 | <0.001 | Positive |
| TPI | 1.05E−01 | 7.84E−03 | 8.97E−02 | 1.20E−01 | <0.001 | Positive |
| Ores | −3.11E−05 | 4.53E−06 | −4.00E−05 | −2.23E−05 | <0.001 | Negative |
| SoilP | −1.44E−01 | 2.85E−02 | −2.00E−01 | −8.85E−02 | <0.001 | Negative |
| SoilPh | 9.47E−01 | 1.19E−01 | 7.13E−01 | 1.18E+00 | <0.001 | Positive |

boundary of the confidence envelope) in both the uniform (Model 0) and non-uniform (Model 4) scenarios. This significantly high positive point correlation clearly extends beyond mere landscape preferences and confirms the existence of further factors influencing nuraghes distribution (Fig. 5). The fundamental pair correlation function validates that the points exhibit spatial clustering within a 2 km radius, evidenced by the black line surpassing the grey envelope. Notably, the black line representing the observed function rises above the Monte Carlo critical envelope at these shorter ranges, only to realign within the anticipated range beyond these distances. An alternate analysis, accounting for the first-order model in the envelope, suggests that despite the relevance of first-order trends, they do not entirely account for the observed clustering, pointing towards a more intrinsic, second-order nature of the clustering inside this 2 km radius.

We chose, in order to explain such clustering, to introduce in our analysis the relationship between simple and complex nuraghes. Since the latter are larger and more spatially dispersed than the former, we hypothesised that the overall spatial pattern of sites in the study area is influenced by a complex social hierarchy between sites of varying sizes. In accordance with this hypothesis, the analysis of clusters through the Widom-Rowlinson penetrable sphere model reveals that at shorter distances (<1800 m) there is a noticeable aggregation of simple nuraghes around complex nuraghes, consistent across the region (Fig. 6). The refining process identifies a maximum radius from the subsetted Gij(r) results of 1350 m, which was chosen as the ‘*AreaInter*’ value for the *’pcfinhom’* function. After integrating this second-order interaction into

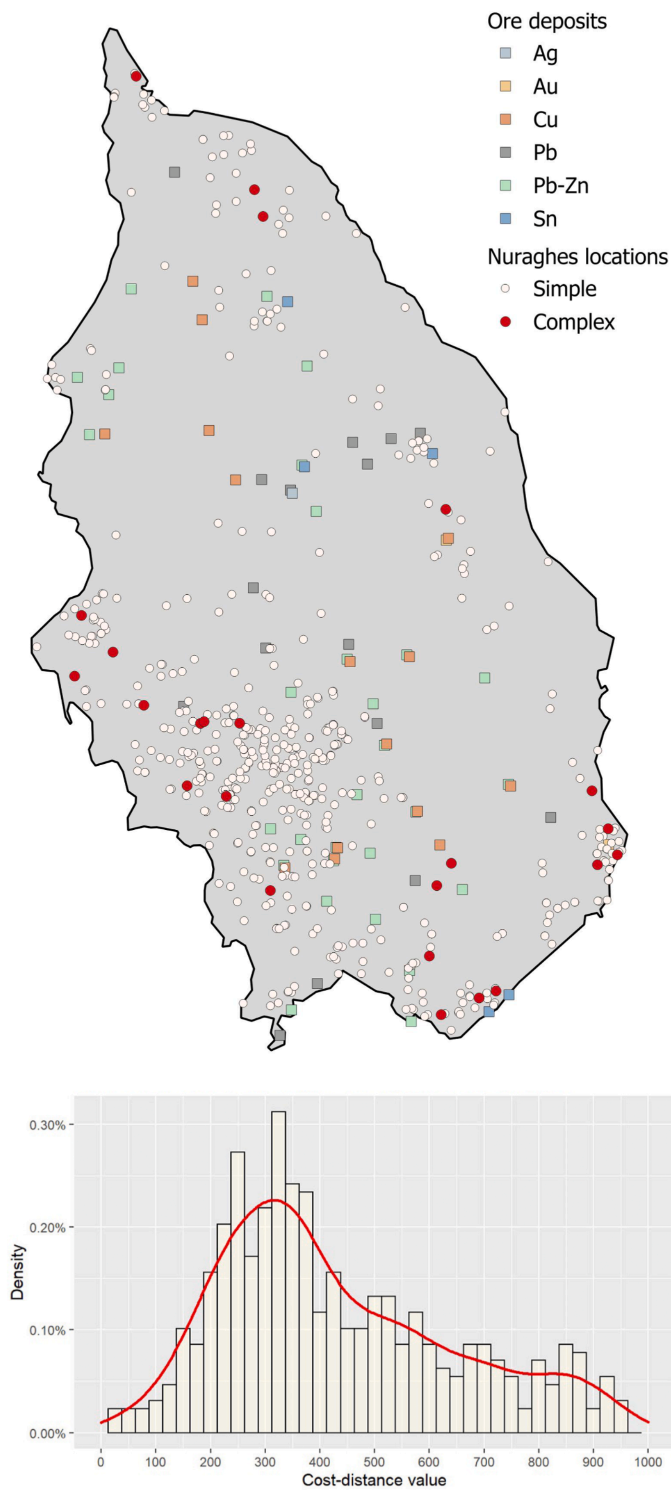


**Fig. 4.** Above: distribution of the known ore deposits considered in this paper (from Marcello et al., 2008) in relation with nuraghe locations. Below: site occurrence according to Cost-distance value from ore deposits.

our first-order model, the observed pair correlation function (illustrated by the black line) now aligns with the critical envelope of the simulation across all interaction distances (Fig. 5). This alignment suggests that the combined first and second-order factors are now capable of explaining the observed point pattern. The smoothed residuals of Model 5 (Fig. 7) generally suggest a consistent prediction level across the area. However, an exception is noted in a central section of the study area, where the model notably underestimates the true site intensity. This specific area, marked by a denser occurrence of nuraghes compared to its vicinity, shows significant positive autocorrelation (indicating that similar values are clustered together) (Cliff and Ord, 1970). This pattern may indicate that this location has emerged as a disproportionately large focal point compared to other areas in the region.

In summary, the distribution of nuraghes sites can be understood through broad environmental locational preferences related to topography, ores and soil parameters, in conjunction with localised site clustering tendencies (Model 5) explained by the interaction between simple and complex nuraghe types.

## 5. Discussion

### *5.1. Farming and mining: the influence of topography, landforms, and geological resources*

The findings from the PPA provide insightful observations regarding both the First and Second Order Properties of the spatial distribution of Nuragic towers in the Sulcis region. As for the former, the results from the models inform not only on a generic relationship with the territory, but more specifically with the distribution of natural resources.

First of all, the vicinity of nuraghes to ore deposits is statistically significant, and tells us about the ability of Nuragic people to tap into local resources. While the area is a well-known mining district where metal artefacts and slag occur inside multiple Nuragic sites (see: Atzeni et al., 2005), a direct correlation with ore sources and Nuragic land use at a wider scale (larger than the single site or group of sites) was never assessed. Available mining sites in the area are numerous and widespread, but often topographically restricted to locations difficult to reach (Marcello et al., 2008; Mariani et al., 2022). It is therefore significant that nuraghes are influenced by such resource. Such significance might mean that most of these deposits were known during Bronze Age and likely exploited in some way. It is of course not plausible that all the considered metals and ores were mined at the same time, since the hypothesized construction and activity of nuraghes spans many centuries. Instead, this correspondence might imply a progressive exploration and potential exploitation of a relevant number of metal sources by Nuragic populations during the course of the Bronze Age. In the context of the larger Mediterranean metal trade context, the relevance of Nuragic metal production remains uncertain with some confirmations. While it is impossible to demonstrate the direct existence of a proper metallurgy district, our findings might still indirectly confirm that the area could have supported widespread mining activities and the exploitation of native ores. Such a network of structures would be in accordance with several sources (Kassianidou, 2001; Sabatini and Lo Schiavo, 2020) which consider the presence of imported ingots as important, but unlikely to explain the whole Nuragic metal industry (Kassianidou, 2001; Lo Schiavo, 1988). In this sense, the construction of nuraghes to mark areas of ore exploitation is likely again related to land and property control, maybe as watchtowers or even as more direct defences.

The constraints related to land use and visibility are also significant. The significance of both water retaining and slightly acidic to neutral soils indicates a specific preference for fertile land in warm to arid environments. Notably, most of the nuraghes in the area stand on soils where pH ranges from 6 to 7, well within the range for most agricultural crops (FAO, 2021). The relationship between Nuragic monuments and areas of high agricultural value is not unexpected (Depalmas and Melis, 2011), but still very relevant in a culture where crop production was indeed a key feature for prosperity. While possible that several topsoil properties shifted in time due to land use changes since the Bronze Age, studies in Sardinia and in the Mediterranean show that pH can be remarkably stable in soil horizons (Evrendilek et al., 2004; Francaviglia et al., 2017; Vacca et al., 2000; Zucca et al., 2010). The correspondence between nuraghes and low soil permeability might also bring the attention to the importance of a stable rock underground for suitable

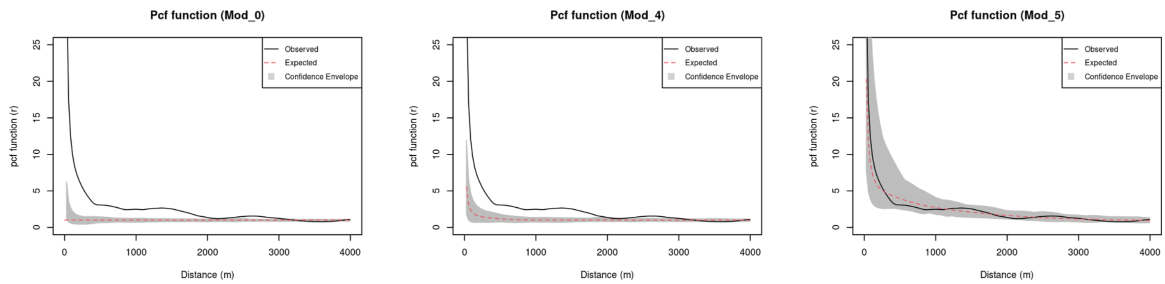


**Fig. 5.** Results of the pair correlations function (pcf) on Models 0, 4 and 5. The observed values consistently surpass the 95th percentile of the simulated values (upper boundary of the confidence envelope) in both Model 0 and Model 4, demonstrating the occurrence of spatial clustering within a 2000 m radius. In Model 5 the observed values fall entirely inside the confidence envelope, indicating that the model explains the observed point pattern.

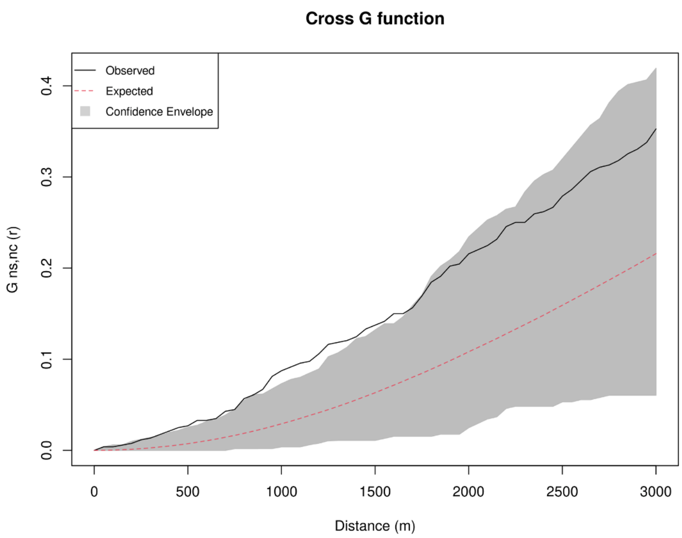


**Fig. 6.** Results of the cross G function. The observed values fall outside the confidence envelope at distances below 1800 m, indicating aggregation of simple nuraghes around complex nuraghes within this range.

foundations. Topographic position is indeed another prominent factor for the distribution of Nuragic towers. The results from CI and TPI basically refer to the search for elevated positions (such as ridges) far higher/farther from depressed areas and channels. The significance of raised platforms might lie on land control over the surrounding pastures and cultivated land guaranteed by the presence of nuraghes (Cicilloni et al., 2015; Depalmas, 2005, 2003), though recent works reassess the relationship between land control and visibility in terms of nuraghes being potentially useful landmarks just as much as mere watchtowers (Schirru and Vanzetti, 2023). Also, a relation with outcrops and ground stability for megalithic structures has also been postulated (Mariani et al., 2022). CI also indirectly points to a distance from the water network possibly to avoid related risks such as flooding. The absence of covariates related to water is quite expected since the location of springs and of some watercourses could have changed in time, especially in plains and flatter areas, but it might also indicate that its availability is apparently not a factor of choice for the building of a nuraghe. This would support the hypothesis of nuraghes as non-residential or service structures (such as castles and temples) sometimes associated to temporary or permanent settlements but with no exclusive connection and that therefore do not need water to function. Conversely, the lack of a relationship with known water sources might still indicate a high dependence on alternative sources of drinkable water, namely the use of wells. Unfortunately these structures are very scarce in literature and referred to villages instead of Nuragic towers (Depalmas et al., 2021; Usai et al., 2012), so there is scant support for this hypothesis.

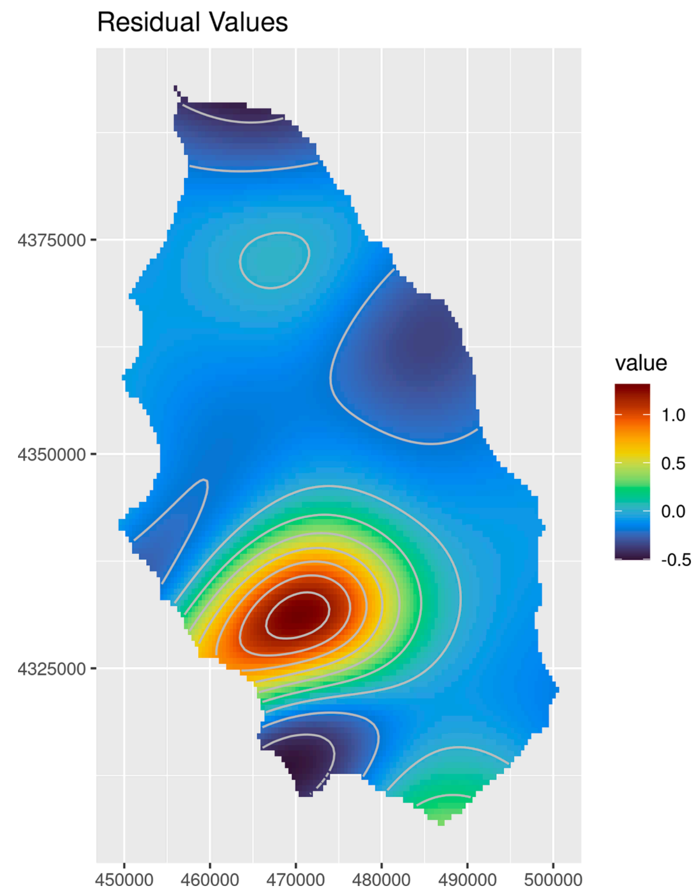


**Fig. 7.** Residual values of model 5. Instances of positive residuals, characterised by a red hue, arise in scenarios where the model's predictions fall short of the actual intensity, typically indicative of site density. Conversely, negative residuals, denoted by a blue hue, manifest in situations where the model's estimations exceed the true intensity.

### *5.2. Diplomacy or community? Simple-complex nuraghes relationship and cultural significance*

The literature on the social structure of Nuragic communities has seen a major shift in the last few decades. Traditionally the Nuragic society was described as a rigidly hierarchical system of many small chiefdoms controlled by a warrior elite (Lilliu, 1988; Webster, 1996) and constantly at war with neighbouring tribes. The appearance of complex nuraghes was seen as the rise of power centres with a ruling aristocracy who controlled larger territories but never completed the passage to a single unified kingdom (Blake, 2015). Nevertheless, the establishment of such ruling caste is still not clearly supported by the expanding archaeological evidence (Perra, 2020; Tronchetti, 2012; Usai, 2006). Many authors have started to discard a strict chiefdom model in favour of less centralised and more egalitarian social structures (Broodbank, 2013; Perra, 2009), with some even postulating a system of anarchic leadership, devoid of hierarchy and elite roles (Araque González, 2019, 2014).

Indeed, our results of the second order properties suggest the existence of a spatial structure within the nuraghe culture. The consistent aggregation of simple nuraghes around complex nuraghes throughout the region at mid-short distances (< 1800 m) suggests the existence of a polycentric pattern usually related to a loosely stratified social structure with no strong hierarchies (Tronchetti, 2012; Usai, 2006). Other than that, it is difficult to understand if the emergence of complex nuraghes derived from concentrations of simple structures or vice versa, since most surveyed Nuragic towers and settlements are not dated; also, other parts of the island might show instead different patterns. Nevertheless, the archaeological narrative clearly defines the appearance of the complex nuraghe as a later event (Depalmas, 2009b, 2009a; Usai, 2018), so the formation of polycentric clusters is likely the result of the progressive cohesion of people around local centres where finally a complex nuraghe was established. On the other hand, it is also plausible to assume that these patterns were reinforced in time by the addition of other satellite simple nuraghes inside the area of influence.

We can look at the social importance of complex nuraghes in opposite ways. On one hand, the rise of "power centres" can represent a symbol of the cooperation of the community around a single nucleus without the need to implicate a ruling caste or social stratification (Usai, 2018). The joint effort involved in the erection of large megalithic structures such as complex nuraghes showed the strength of the new community and at the same time created symbolic places of interaction that would permanently connect all the participating parties (Araque González, 2014). On the other hand, it can also represent the range of influence of the central community over the surrounding territory in terms of "capital privilege". In fact, the observed patterns do not exclude the development of local elites, either as a leading cause for the construction of complex nuraghes or as the consequence of the resulting hegemony of such places over larger areas. Nevertheless, attention must be made when extrapolating, especially since settlement nucleation probably served different purposes according to location, as it was for other parts of Sardinia (Namirski, 2020). On this matter, the still debated function of nuraghes remains difficult to address, though all the elements seem to point to a certain versatility of these structures depending on their location. For certain, their symbolic value for the Nuragic populations, as it is for Sardinian people today, cannot be overstated.

## 6. Conclusions

The use of spatial analysis tools on regional scale monument datasets allowed us to get a detailed model on the main interactions between the distribution of Bronze Age monuments and both the main components of the physical landscape and the social relevance of those sites. The employment of a "nature vs culture" set of variables highlights the complexity of the choices involved in the spatial distribution of people in the Bronze Age. Separating amongst such distinct sets of factors can be simplistic and is necessarily incomplete. Nevertheless, our findings highlight the correspondence between the distribution of nuraghes and topographic position (TPI and CI), soil fertility (permeability and pH), and especially ore exploitation for metalworking. These strong links with the landscape and its geological resources emphasize the Sardinian case as an example of the adaptation of Bronze Age cultures to the territory, and are key to inform about the development of metallurgy, and strategies of land use and land control. At the same time, we found the occurrence of a polycentric pattern that can only be explained in terms of social landscape, by giving the complex nuraghes a hegemonic role in Nuragic society. This helps in confirming the existence of a hierarchy within the structure of the community, be it either symbolic or more linked to social organization, something that has been postulated in literature but never parametrically observed.

These results clearly indicate how it is possible to effectively deploy spatial analysis to detach and compare the physical and social factors acting on the distribution of past cultures, to understand their role on land occupation practices, and to draw models of their separate influence in the behaviour of past communities. Furthermore, since the use of PPA and PPM does not discriminate by the nature of the covariates employed and is independent from time and location, this double approach can be easily applied to the reconstruction of land use preferences of past cultures regardless of period and location in the world.

## CRediT authorship contribution statement

**Guido Stefano Mariani:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Filippo Brandolini:** Writing – original draft, Validation, Software, Methodology, Investigation. **Rita T. Melis:** Writing – review & editing, Supervision, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Data and code availability

Zenodo repository (developed code, datasets): https://doi.org/10.5281/zenodo.8042979

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