



# A spatial statistical study of the distribution of Sardinian nuraghes

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## ABSTRACT

The spatial distribution of nuraghes throughout the Island of Sardinia still raises many questions. In this paper, we apply spatial statistical methods to investigate their relations with topographical features and with related objects nearby. We use the non-stationary G- and J-functions. To model interactions with topographic variables we use the non-stationary Poisson model. We find that the elevation of the nuraghes show a uniform distribution between 0 and 400 m, and with a peak in distances to *holy wells* of approximately 5 km. As expected, we found a clustered pattern, with clustering occurring in the mid-west, the centre and the south west of the Island. We further observed a very strong interaction with *domus de janas*, and a strong spatial interaction for distances in the range between 0 and 1000 m with the pre-Nuragic *dolmens* and *menhirs*, and the collective funerary structures, the so-called Nuragic *giants' tombs*. We conclude that the study is useful to quantify spatial patterns of pre-historic sites, in particular if these occur in a great abundance and provides new insight into the spatial relations of the different pre-historic objects and buildings.

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Nuraghe; spatial statistics; prehistoric objects; spatial distribution; spatial interaction



## 1. Introduction

Nuraghes are the most representative and characteristic prehistoric monuments in Sardinia (Italy), the second-largest Island in the Mediterranean Sea (Blake 2010). Dated back to the Bronze Age, these conical stone towers are generally built in basalt or granite and they are largely distributed across the Island. Their large number (>7,000) and size (generally between 10 and 20 m in height) make these monuments a focus of archaeological investigation for many scholars worldwide. However, although several hypotheses have been proposed so far, like military strongholds, meeting halls, religious temples or ordinary dwellings, there still is no consensus on the origin and function of the nuraghes (Benati 2009; Di Rita and Melis 2013; Freund 2014; Pecci et al. 2020).

Methodological research for archaeological research included spatial statistical methods (Hodder and Orton 1976; Carr 1991), network analysis (Peeples 2019) extensive use of statistical methods (see, for instance, Buck, Cavanagh, and Litton 1997; Robertson 1999; Buck 1999) and use of Geographical Information Systems (GIS) and remote sensing images (Hritz 2014). At the scale of the Island of Sardinia, nuraghes, despite their sometimes impressive size and shape, can be considered as point objects (Bailey and Gatrell 1995). These points may show

a pattern that can be informative about the spatial distribution of factors that are of influence on their position and spread and their relations with other, similar objects like *menhirs* and *dolmens*. In that sense, such an analysis, which is very well able to analyse the large number of nuraghes, can be very insightful. Similar analyses in the past addressed site phosphate data (Buck, Cavanagh, and Litton 1988), where research was done on deviations from randomness in the patterns (Wilson, S.M., Melnick, D.J. 1990), whereas predictive modelling was carried out by Finke, Meylemans, and Van de Wauw (2008) and Verhagen and Whitley (2012). Recent research further emphasizes the importance of GIS (Verhagen 2018). Quantitative analysis on nuraghes is relatively limited, with De Montis and Caschili (2012) as an important exception, making the relation with landscape planning.

The analysis of recurring features among the population of nuraghes has been the interest of scholars. It is only recently that the research community has focused on the exploration and understanding of their spatial occurrence. The non-random patterns of nuraghes have been questioned by many researchers but the current literature is largely qualitative, whereas several indications for continuing with a quantitative analysis are already given.

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Our aim is to address an issue left open in an important contribution by Gary S. Webster (2015) that provides a comprehensive synthesis of evidence bearing on current understandings of Sardinian prehistory. The author observes that ‘it is long been recognized that MBA (Middle Bronze Age, AS) settlements, in particular the nuraghes, tend to occur within larger clusters or aggregates’ (p. 62). In other words, a spatial structure seems to emerge from the data. Furthermore, the author reports an important and curious relationship between altitude and nuraghes presence: ‘in both the highland regions above approximately 500 m and the lowlands below 200 m, nuraghes are less common’ (p. 47).

These simple stylized facts encouraged and motivated us to explore the spatial distribution of nuraghes by employing a spatial statistical analysis, since any quantification of Webster’s observation are lacking so far.

The objective of the study is to make a quantitative analysis of clustering of nuraghes in Sardinia as well as in two smaller Islands off the coast. Relations with other types of prehistoric buildings and settlements and with environmental variables are to be explored. This will lead to a better, quantitative understanding the pattern of nuraghes over the Island. The data that we will use are publicly available data (Melis 2005).

The next section provides an overview of nuraghes development. Then, in the following two sections, we describe the data as well as our methodology. Finally, in the last two sections, we present the empirical results and draw the conclusions.

## 2. Background

Sardinia was inhabited since the Upper Palaeolithic period, dated to around 25,000 years ago (Contu 1998). The oldest complete human skeleton (nicknamed ‘Amsicora’) was found in 2011 in the territory of Arbus, located in the southwest coast of the Island. It dates back to about 9,000 years ago, the period of transition between the Mesolithic and the Neolithic. During the latter and the Chalcolithic age, i.e. between the 6th millennium and 1800 BC, a number of cultures flourished in the Island. Their existence is documented by the discovery of many settlements in which archaeologists found refined potteries, ancient meals, grave goods and votive figurines (Contu 1998). This period marks the debut of the megalithism in Sardinia with the erection of many statues like *menhirs* and *dolmens*. This phase is also characterized by the construction of the *domus de janas*, i.e. ‘House of the Fairies’ or ‘House of the Witches’, being a type of hypogean tomb well distributed throughout the Island, with the exception of Gallura, a sub-region in North-Eastern

Sardinia (Ugas 2005). They consist of several chambers resembling houses in their layout, not rarely decorated with reliefs or etchings of magical and religious symbols (Lilliu 1967). The evolution of these cultures, probably with the influence of other population originated in Central Europe (Lilliu 2004), led to the emergence of a new culture, the so-called Nuragic civilization. For this reason, scholars generally refer to the above-mentioned cultures as the pre-Nuragic period of Sardinia.

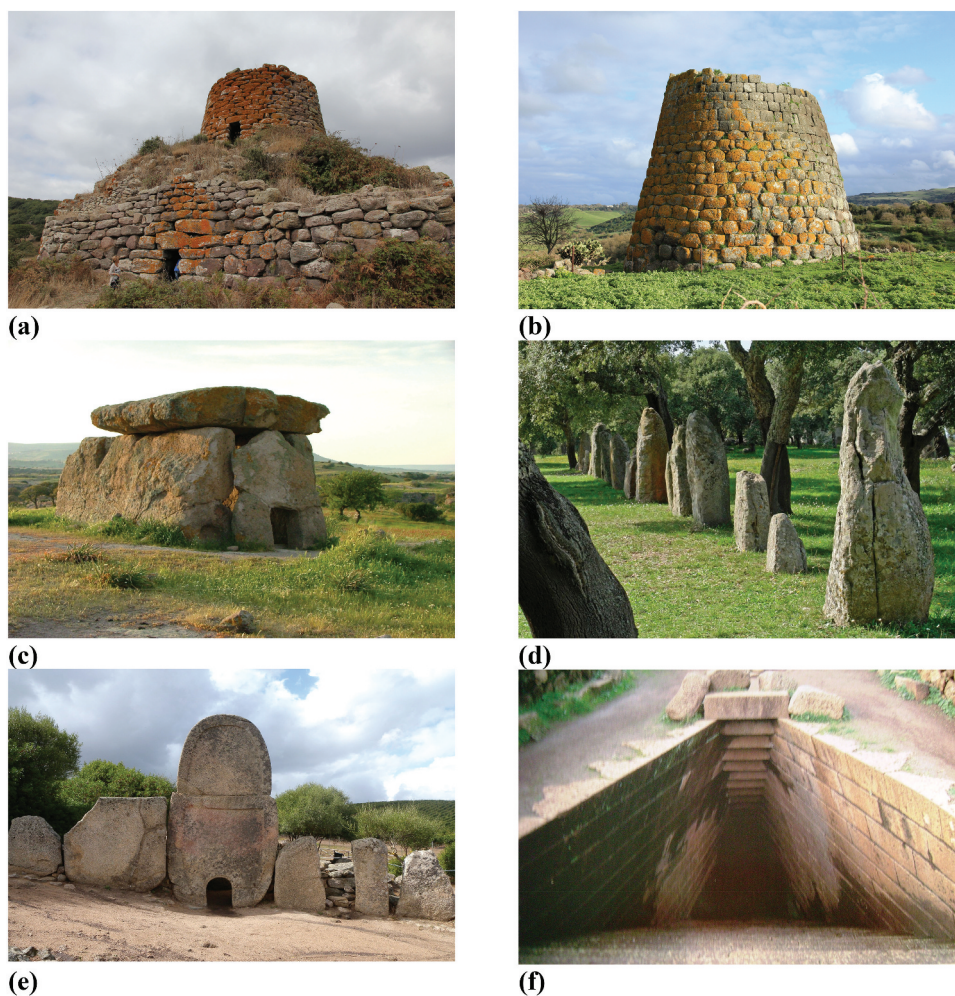
The nuraghes are the most characteristic product of this civilization, born in the early Bronze Age, around the 18<sup>th</sup> century BC. It is a new style of megalithic architecture unique to Sardinia, the so-called nuraghe style, that gives the name to this culture. On the origin of Nuragic civilization, scholars still do not converge to a unique conclusion (Moravetti et al. 2017). Probably, as in other populations in Western and Mediterranean Europe during the Chalcolithic, people needed to protect their villages especially in the north of the Island that is more exposed to invasions. They place the villages on steep hills and to be able to defend the most exposed sides by large megalithic walls (Melis 2007). Sometimes, small, semi-circular enclosures as in Monte Baranta (Olmedo) or quadrangular enclosures as in Fraigata (Bortigiadas) were built in addition to the large walls, with entrances containing small spaces on the edge of the plateau: almost a sort of ancient bastion of defence (Moravetti 2002). Probably this type of primordial buildings gives the concept of the nuraghes that has been developed and refined then in the following centuries (Melis 2007). In fact, the concept of the nuraghes evolved over time, and we can distinguish several, age related, constructions.

Between the end of the Ancient Bronze Age and the beginnings of the Middle Bronze Age (XVIII-XV century BC) the first proto-nuraghes were built, also known as corridor nuraghes (Lilliu 2005). The proto-nuraghes have a squat appearance and generally irregular base with one or more corridors and some rare covered cells. These constructions are characterized by massive walls, limitedly exploited with few narrow spaces, in which the most functional part had to be the platform of the upper terrace (Melis 2007). An evolution of the latter proto-nuraghes, XV-XIV century BC, consists of a type of building with one or more rooms also on the ground floor. This is the prelude to the construction of the tholos-covered room, which will characterize the standard nuraghe. Standard nuraghes consist of fortified buildings with high towers. A common distinction is into the simple nuraghe with a single tower and a complex nuraghe formed by a bastion equipped with a variable number of towers added to a main tower, like a sort of keep, connected by massive curvilinear or sinuous walls

(Moravetti et al. 2017). The ancient proto-nuraghe, probably, will continue to be used even when the most advanced architecture of the standard nuraghe has already spread, perhaps fulfilling particular tasks.

The Nuragic civilization spread all over the Island, encompassing also all the smaller Islands off the coast and even the South of Corsica. Their use is debated and may have been used for different purposes, like social, military, religious or astronomical roles, or as tombs (Lilliu, 2006). However, the nuraghes are not the only testimony of this culture. Archaeologists were able to track also other forms of settlements or buildings: Nuragic *holy wells*, i.e. structures dedicated to the cult of waters, the so-called *giants' tombs*, i.e. collective funerary structures, and Nuragic villages, i.e. small

urban settlements with structures devoted to specific functions and served by infrastructures (Figure 1). Many studies document the existence of intense trade relationships between Nuragic people and other population of the Mediterranean Sea. Around 900 BC, however, the Nuragic civilization wanes. Nuraghes are no longer built and indeed, are systematically disassembled and devastated. The arrival of the Phoenicians first and the Romans later determined the end and the slow disappearance of this civilization. Today, however, it is still possible to document an extraordinary number of nuraghes all across the Island which serve as a testimony of the magnificent past of the Nuragic civilization. Unfortunately, there are no written testimonies of that period, whereas testimonies of other peoples are all



**Figure 1.** Some of the prehistorical constructions in Sardinia: (a) nuraghe orolo; (b) nuraghe nieddu; (c) dolmen mores; (d) menhir pranu muteddu; (e), giants tomb coddu vecchio; (f) and holy well pozzo sacro santa cristina. sources: (a): [https://commons.wikimedia.org/wiki/File:Bortigali\\_-\\_Nuraghe\\_Orolo\\_\(10\).JPG](https://commons.wikimedia.org/wiki/File:Bortigali_-_Nuraghe_Orolo_(10).JPG), Author: Gianni Careddu; (b) [https://upload.wikimedia.org/wikipedia/commons/8/80/Codrongianos\\_-\\_Nuraghe\\_Nieddu\\_%2806%29.JPG](https://upload.wikimedia.org/wikipedia/commons/8/80/Codrongianos_-_Nuraghe_Nieddu_%2806%29.JPG); Author: Gianni Careddu; (c) [https://upload.wikimedia.org/wikipedia/commons/5/52/DOLMEN\\_DI\\_MORES.JPG](https://upload.wikimedia.org/wikipedia/commons/5/52/DOLMEN_DI_MORES.JPG), Author: Giovanni Seu; [https://upload.wikimedia.org/wikipedia/commons/a/a4/Sardinien\\_Goni\\_Pranu\\_Muteddu\\_menhir-reihe.jpg](https://upload.wikimedia.org/wikipedia/commons/a/a4/Sardinien_Goni_Pranu_Muteddu_menhir-reihe.jpg); author: hans peter schaefer; source giant's tombs: [https://upload.wikimedia.org/wikipedia/commons/7/78/Coddu\\_Vecchio\\_10.JPG](https://upload.wikimedia.org/wikipedia/commons/7/78/Coddu_Vecchio_10.JPG), Author: Royonx; [https://upload.wikimedia.org/wikipedia/commons/8/85/Pozzo\\_Sacro\\_Santa\\_Cristina.JPG](https://upload.wikimedia.org/wikipedia/commons/8/85/Pozzo_Sacro_Santa_Cristina.JPG); Author: Shardan.

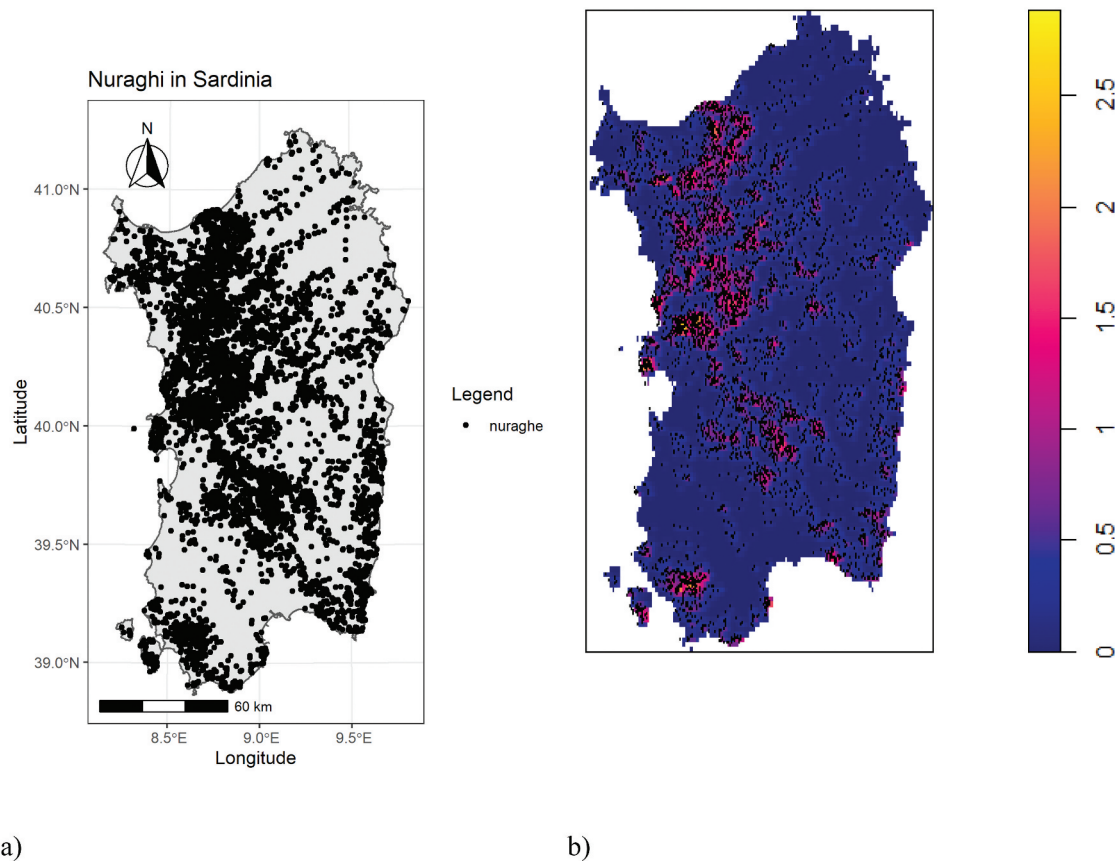


from a very late period. These are not of great use since they provide very little information, perhaps based upon distant legends handed down for generations, when the Nuragic Civilization no longer existed (Lilliu 2005; Melis 2007).

### 3. The nuraghes and other megalithic structures in Sardinia

The Island of Sardinia covers approximately 24,000 km<sup>2</sup>, and is located in the middle of the West Mediterranean Sea with a population density of 69 km<sup>-2</sup>. It is surrounded by a number of small Islands, like the Island of Sant'Antioco (109 km<sup>2</sup>), Asinara (52 km<sup>2</sup>), San Pietro Island (50 km<sup>2</sup>), Island of La Maddalena (20 km<sup>2</sup>) and Caprera (16 km<sup>2</sup>). At present, there are some 7,000 nuraghes in Sardinia, of a large variety of sizes, shapes and ancestry, dating back from the period of the early bronze age towards the iron age, which corresponds to the period between the 18<sup>th</sup> and the 8<sup>th</sup> century BC. A database containing all relevant information is shared by the official site of the Autonomous Region of Sardinia ([http://](http://webgis.regione.sardegna.it/)

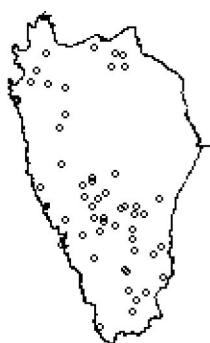
[webgis.regione.sardegna.it/](http://webgis.regione.sardegna.it/)). The spatial distribution of the nuraghes is shown in Figure 2. They mainly occur on the mainland of Sardinia, but also on three smaller Islands, off the coast (Figure 3). On mainland Sardinia there are 6,000 nuraghes registered and present in our database. The Island of Sant'Antioco (South-West of Sardinia) has 66 nuraghes, the San Pietro Island (South-West of Sardinia) accounts for 6 nuraghes, whereas the Island of Malu 'Entu (0.8 km<sup>2</sup>, central-west Sardinia) has a single nuraghe. On mainland Sardinia, a high concentration occurs in the middle west of the Island, whereas on the south-west corner and also on the eastern coast there are high concentrations of nuraghes. The absence of nuraghes along the line separating the south-west high concentration area and the central and central west high concentrations could be due to the intensive use of the land by farmers and other settlers, who may have used the collected stones for other purposes (Melis 2003). Based upon this distinction, we split the data below into six sub-regions (East Coast, Mid North, the Middle, the South West, the West and the Rest of Sardinia) in order to have more location-



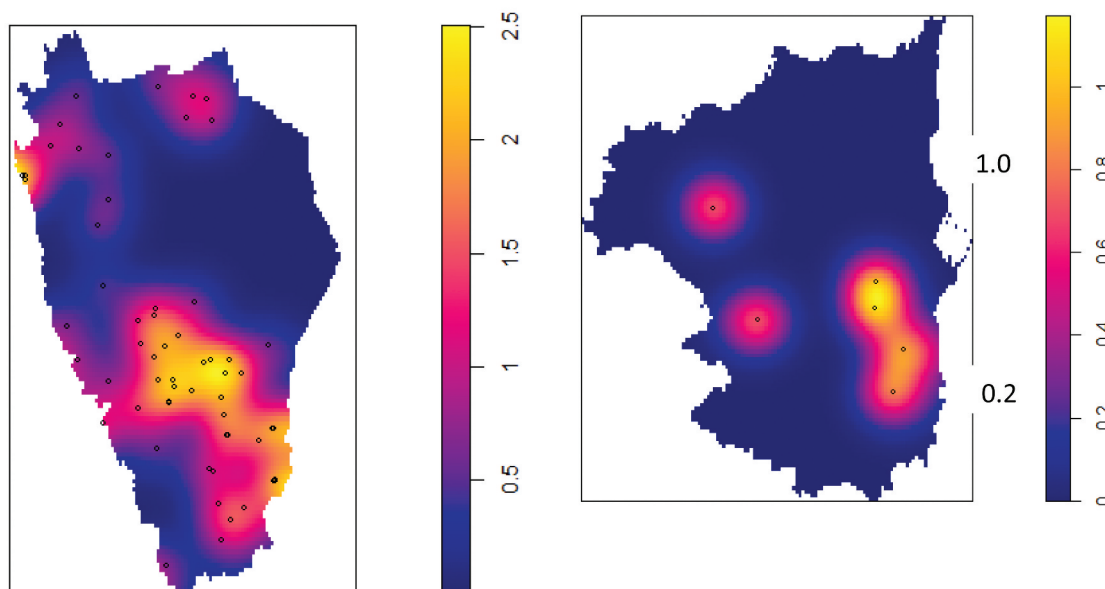
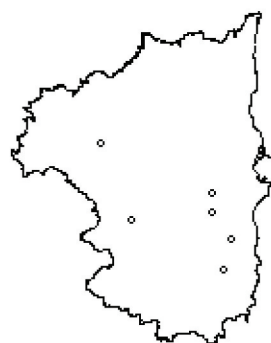
**Figure 2.** Spread of the nuraghes in Sardinia (a), each point represents a single nuraghe; and density of the nuraghes (b), expressed in the number of nuraghes per km<sup>2</sup>. The density is obtained as a kernel function, with range parameter  $\delta = 1153$  m.



## Isola di Sant'Antioco



## Isola di San Pietro



**Figure 3.** The distribution and density of nuraghes on the two Islands Island of Sant'antioco (left) and Island of San Pietro (right).

specific information. Nuraghes also occur in the nearby Island of Corsica (the so-called *Torrean civilization*, Ugas, 2005; Costa 2004), but they are not included in this study.

## 4. Methodology

### 4.1 Descriptive statistics

To estimate the spatial density, we have used the kernel density estimation. We determined the Diggle-Berman estimator to find the optimal band width (Berman and Diggle 1989). In order to explore the relation with the explanatory variables (elevation, slope and distance to the sea), we compiled frequency plots.

### 4.2 Spatial clustering

To address the issue of the non-random distribution of the nuraghes, we turn to spatial statistical methods (Baddeley, Rubak, and Turner 2016). At the scale of the Island of Sardinia, the collection of nuraghes can be seen as the realization of a point process, presenting objects that possibly show a distinctive pattern, i.e. densities that vary because of topographic features. Because of their large number, such an analysis is indispensable and can be insightful to quantify relationships with topographic factors. During the past decades, spatial point pattern analysis has developed as a methodology to identify and quantify relationships between observed point data and their determining variables. For spatial

clustering, we explored different methods, but concentrate in this paper on the inhomogeneous  $G$ - and  $J$ -functions.

At the scale of Sardinia ( $S$ ), the nuraghes exhibit a collection of points irregularly located within a bounded region of space. The density of the processes is denoted by  $\lambda_S$ , which is equal to the number of nuraghe per  $\text{km}^2$ . Initially, we will assume that the number of points in  $S$  with area  $|S|$  follows a homogeneous Poisson distribution with mean  $\lambda_S|S|$ . This assumption will be relaxed later. Also, there are no interactions among the points; points neither inhibit nor encourage each other. The observed pattern is assumed to be generated by external, explanatory variables. Although this may not be fully true for nuraghes, as conditions to create a single nuraghe may favour the construction of another nuraghe nearby. Such an explanatory analysis, however, may be insightful.

Formally, given  $n$  nuraghes with locations denoted by the vectors  $x$  in  $S$ , the  $x$  are considered an independent random sample from the uniform distribution on  $S$ . For each  $s \in S$ , let  $d(s, N)$  be the distance from  $s$  to the nearest nuraghe. Then the empty space function of  $N$  for  $r \geq 0$  equals

$$F(r) = \Pr(d(s, N) \leq r) \quad (1)$$

i.e. the probability of observing at least one nuraghe closer than  $r$  to the arbitrary point  $s$  (Diggle, 1983). Under stationarity,  $F(r)$  does not depend upon  $s$ . A completely spatially random (CSR) pattern of nuraghe will show an  $F$ -function equal to

$$F(r) = 1 - \exp(-\pi\lambda_S r^2) \quad (2)$$

(Diggle, 1983). An aggregated distribution has an  $F$ -function below this function, as on short distances less points are encountered on average than for a random pattern, whereas a regular pattern has an  $F$ -function above it. Related to the  $F$ -function is the nearest neighbour distance function  $G(r)$ , being the distribution function of the distance from a nuraghe with location vector  $x$  to its nearest neighbour with location vector  $y$ ,

$$G(r) = \Pr(d(x, y) \leq r) \text{ for } r \geq 0 \quad (3)$$

(Diggle, 1983). The function  $G(r)$  can be interpreted as the conditional distribution of the remainder of  $N$  given a nuraghe at location  $x$ . A heuristic description of  $1-G(r)$  is the probability that a disk with radius  $r$  centred at a randomly selected nuraghe does not contain another nuraghe. Again,  $G(r)$  does not depend upon  $r$  because of stationarity. A completely spatially random (CSR) pattern of points with density  $\lambda_S$  shows a  $G$ -function equal to

$$G(r) = 1 - \exp(-\pi\lambda_S r^2) \quad (4)$$

(Diggle, 1983). An aggregated distribution has a  $G$ -function higher than this function, as on short distances more nuraghes are encountered than for a random pattern, whereas a regular pattern has a  $G$ -function below it. To estimate  $G(r)$ , we consider the distances  $r_i$  for the  $i$ -th pair of points. Then the empirical distribution function (EDF) for the  $G$ -function equals

$$G^*(r) = \frac{2}{n(n-1)} \sum_i r_i \leq r \quad (5)$$

Comparison of inter-point distances to distances with respect to a reference point, say  $s = 0$ , yields the  $J(r)$ -function, defined as

$$J(r) = (1 - G(r))/(1 - F(r)) \quad (6)$$

(Van Lieshout and Baddeley 1996). For completely spatially random processes,  $J(r) = 1$  as numerator and denominator are both equal to  $\exp(-\pi\lambda_S r^2)$ , whereas for clustered nuraghes,  $J(r) < 1$  and for regular patterns  $J(r) > 1$ .

To describe the multivariate spatial point pattern generated by the distribution of the nuraghes with related prehistoric objects, we follow Cox and Lewis (1972). Let  $X = (X_1, X_2)$  be a  $bi$ -variate point process in  $S$  with jointly stationary components. Specifically,  $X_1$  are the nuraghes, whereas  $X_2$  are for instance the *dolmens*, *domus de janas*, *holy wells* or any other related possibly related prehistoric object. As for the univariate analysis, spatial statistical inference for  $X$  is based upon distances, either between a fixed reference point  $s \in S$  and the points of  $X$ , or between the points of  $X$  themselves. Thus, for each  $s \in S$ , let  $d(s, X)$  be the distance from  $s$  to the nearest object of any of the components of  $X$ . Then the empty space function of  $X$  for  $r \geq 0$  equals

$$F(r) = \Pr(d(s, X) \leq r) \quad (7)$$

i.e. the probability of observing at least one object closer than  $r$  to the arbitrary point  $s$ . Similar interpretations for stationarity apply to the bivariate analysis as for the univariate analysis. The empty space function of  $X_i$ ,  $i \in \{1, 2\}$  is denoted by  $F_i(r)$ . The nearest neighbour distance function  $G_i(r)$ , i.e. the distribution function of the distances from an object to its nearest object,

$$G_i(r) = \Pr(d(s, X_i) \leq r) \text{ for } r \geq 0 \quad (8)$$

The function  $G_i(r)$  can be interpreted as the conditional distribution of the remainder of  $X$  given an object at location  $s$ . Its components are denoted by  $G_{11}(r)$ ,  $G_{12}(r)$ ,  $G_{21}(r)$  and  $G_{22}(r)$ , respectively, where we note that  $G_{12}(r)$  need not be equal to  $G_{21}(r)$ . As for the univariate analysis, the function  $J(r)$  is defined as

$$J(r) = (1 - F(r))/(1 - G(r))$$

Nonstationary extensions of the functions defined above also termed the inhomogeneous  $G$ - and  $J$ -functions (Van Lieshout 2010). They are based on the assumption that the underlying point pattern is non-stationary. Inhomogeneous nuraghes patterns may occur if some parts of an area show a different density of nuraghes than other parts of an area. Nuraghes, for instance, could be clustered around water bodies, they could show higher densities close to the sea, or at a specific elevation. Inhomogeneity is characterized by the density  $\lambda_S(x)$  that depends upon the location vector  $x$ . For instance, the point pattern could be modelled as generated by a heterogeneous Poisson point process.

### 4.3 Explanatory variables used for spatial modelling

Several hypotheses are relevant for explaining and better understanding the distribution of the nuraghes. For instance, it is well known that elevation plays a role as documented by (Cicilloni, Mossa, and Cabras (2015), (2016)) for the case of Mogoro area (Sardinia) and by Tedeschi and Scanu (2017) in North-Western Sardinia, but the exact quantification for the whole Island has been missing so far. There could be relation to slope of the terrain as it is unlikely that nuraghe were on steep slopes (Cicilloni and Cabras 2014; Spanedda, Cámara Serrano, and Salas Herrera 2010), because if presumed agricultural or religious use, well as with the distance to the Mediterranean coastline as one may assume that coastal control was an important activity (Spanedda, Cámara, and Puertas 2007). In order to test these hypotheses, the following explanatory variables were used in our research:

- The elevation variable was derived from the NASA Shuttle Radar Topography Mission (SRTM) data available at 30 m resolution. This mission has gathered topographic data, i.e. Digital Elevation Model (DEM), at 90 and 30 m resolution for 80% of the Earth's land surface. To remove the possible errors present in the SRTM data (Farr et al. 2007) such as the sinks or local pits, we applied the 'Fill sinks' algorithm implemented in the ILWIS software (<https://www.itc.nl/ilwis/>).
- The slope terrain characteristic was derived from the SRTM data using the *terrain* package implemented in the R open-source software. The slope variable was calculated in degrees.
- The distance to the Mediterranean coastline was calculated using the *sf* package implemented in the R software. The coastline data were downloaded from the ArcGIS Online cloud-computing

platform. Although elevation and slope may have changed somewhat over a period 4300 years (the oldest recorded date in Webster (2015)), they are most likely still approximately the same. The position of the coastline may also have changed, and hence this variable that should explain sea influences of their position, is approximate only.

### 4.4 Spatial modelling

Spatial modelling was carried out at several levels. At the first instance for Sardinia as a whole, where we took the patterns as being generated by a heterogeneous Poisson process. As the second step, we considered the six sub-regions. As the third step, we carried out individual analyses for each of the subareas defined as the East Coast, Mid North, the Middle, the South West, the West and the Rest of Sardinia. This distinction and their delineations was done on the basis of *in situ* knowledge.

## 5. Results

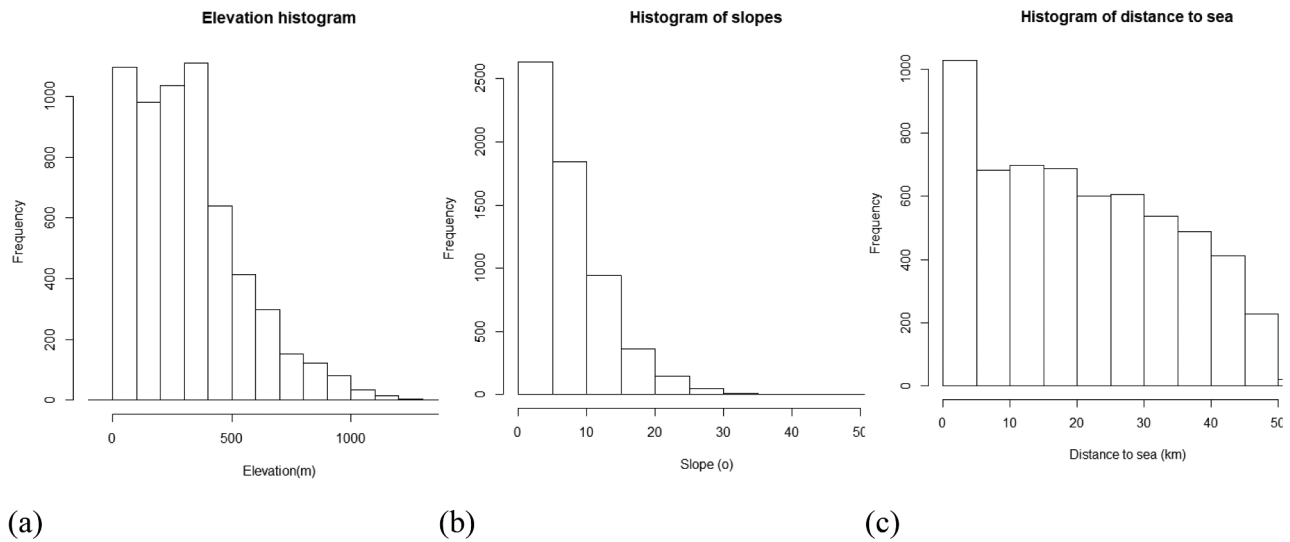
### 5.1 Descriptive analysis

Figure 4a shows that nuraghes are seemingly uniformly distributed over the elevations between 0 and 400 m, whereas their numbers rapidly decline with increasing elevation. They are still present though also at the higher elevations (>1,400 m). This tells us that their use is manifold, however largely determined by human activities and settlements that mainly occurred at lower elevations. The relation with slopes in Figure 4b is as expected, as nuraghes are mainly built on relatively flat slopes, where again we notice a single nuraghe at a relatively steep slope. From Figure 4c we notice that a large percentage of the nuraghes is relatively close to the sea (<5 km away), whereas their frequency remains close to uniform with an increasing distance up to, say, 30 km. Hence, there is little evidence that the position of nuraghes on the Island is related to distance to the sea. Here, we have to realize that we analysed the distance to the present coast line, while the sea level was nearly 2 m lower in Sardinia about 2400 years ago (Antonioli et al. 2007) and may have affected the position of the shore line to an unknown degree.

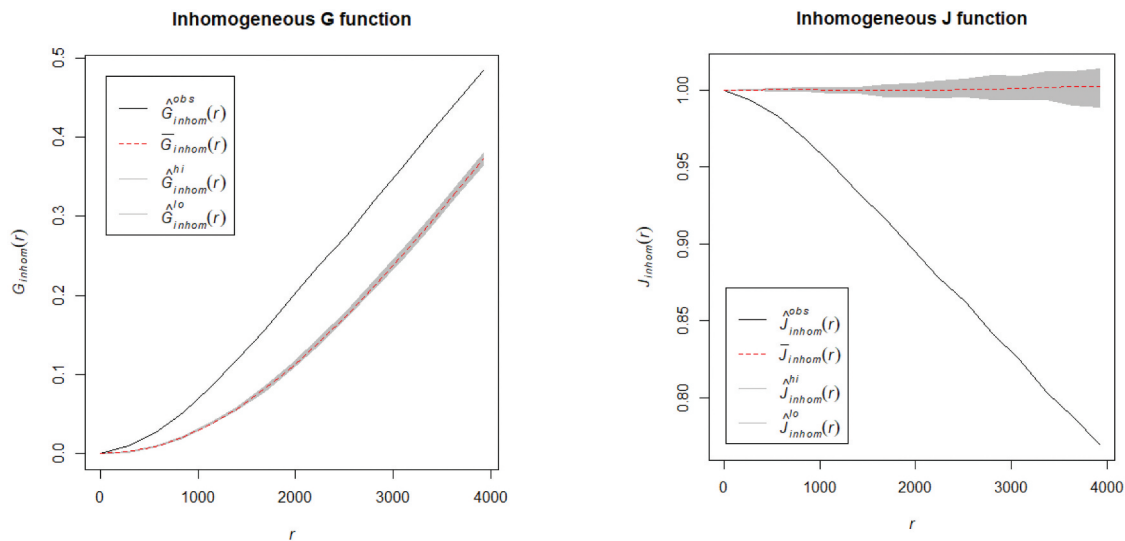
### 5.2 Spatial clustering: the main Island Sardinia

The (inhomogeneous)  $G$ -function provides a very strong evidence of clustering as it is far outside the confidence interval for randomness (Figure 5). fig the





**Figure 4.** The relation of nuraghes with three topographic variables: (a) elevation, (b) slope and (c) distance to the sea.



**Figure 5.** The (inhomogeneous) G- (left) and J-function (right) with 95% confidence bounds in grey. The hypothesis of randomness will not be rejected if an observed G- or J-function occurs within the confidence area. Both functions express a clear indication of clustering, even occurring at small distances. Note that because of the large number of data, the confidence bounds are narrow.

(inhomogeneous)  $J$ -function, also showing strong evidence of clustering, as the observed  $J$ -function departs from the confidence interval for small distances.

### 5.3 Spatial modelling

We next distinguish between the six sub-regions, and focus on elevation, which we considered as the most intriguing explanatory variable. We carried out an Analysis of Variance of the elevations in the six regions as identified earlier (Table 1) where we took the East Coast region as the reference. This choice is arbitrary and does not affect the significance. The results showed

highly significant effects (Residual standard error = 204.5 with 5,979 df), although the  $R^2$  value is low (0.1873). Elevations in the Rest of Sardinia sub-region are significantly different from the elevation in the East Coast region at the 0.05 level only. A boxplot confirms the large and significant differences. Elevations of the nuraghe locations in the Mid Coast, the Middle and in the Rest of Sardinia sub-regions are significantly higher than that in the East Coast sub-region, while those in the West and the South West sub-regions are significantly lower. This is also shown in the boxplots of Figure 6, where East coast and Rest show similarity in elevation, while differing from the other sub-regions.

**Table 1.** Analysis of variance outcomes for the average elevation in the six sub-regions. The std. error indicates the spread around the estimated means and the t-value and  $\Pr(>|t|)$  shows the significance that the east coast mean elevation is different from 0 (first line) and that the elevations in the other sub-regions are significantly different from that in the east coast sub-region (lines 2–6).

Coefficient	Estimate	Std. Error	t value	$\Pr(> t )$
East Coast	291.927	7.298	40.000	<2e-16 ***
Mid North	382.288	9.270	9.748	<2e-16 ***
Middle	416.632	8.789	14.189	<2e-16 ***
South West	134.413	11.083	-14.212	<2e-16 ***
West	195.747	9.806	-9.809	<2e-16 ***
Rest	315.476	11.088	2.124	0.0337 *

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1.

**Table 1.** Analysis of Variance outcomes for the average elevation in the five sub-regions. The Estimate for Intercept is the estimate for the East Coast region, whereas the other estimates are the differences with that value.

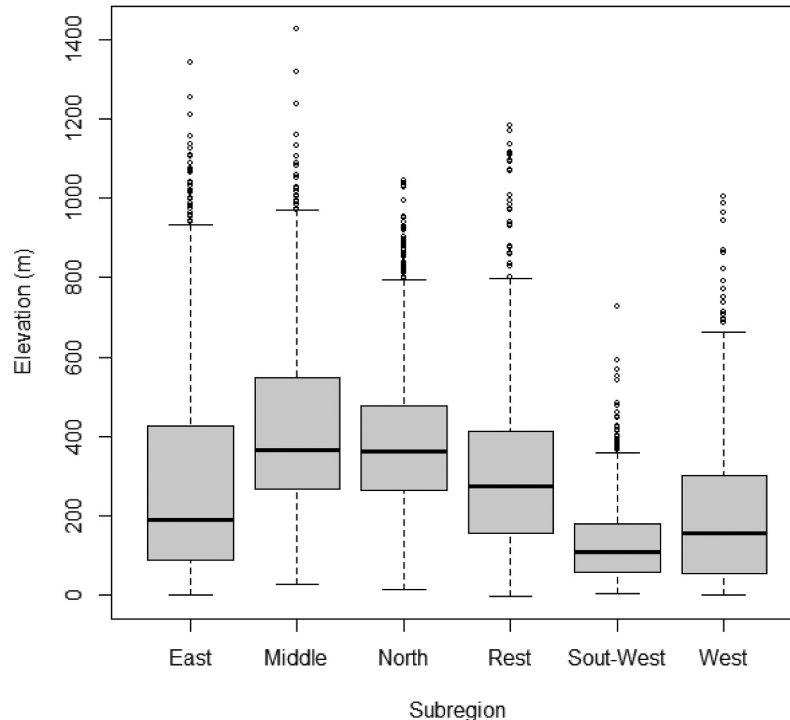
We next fitted a stationary Poisson model to relate topographic variables with explanatory topographic variables. The model showed an intensity  $\lambda_s$  value equal to 0.2496 nuraghes per  $\text{km}^2$ , with a standard error equal to 0.0129. It is not surprising that the main density significantly differs from 0.

**Table 2.** Diggle-Berman estimates for Sardinia and the three Islands.

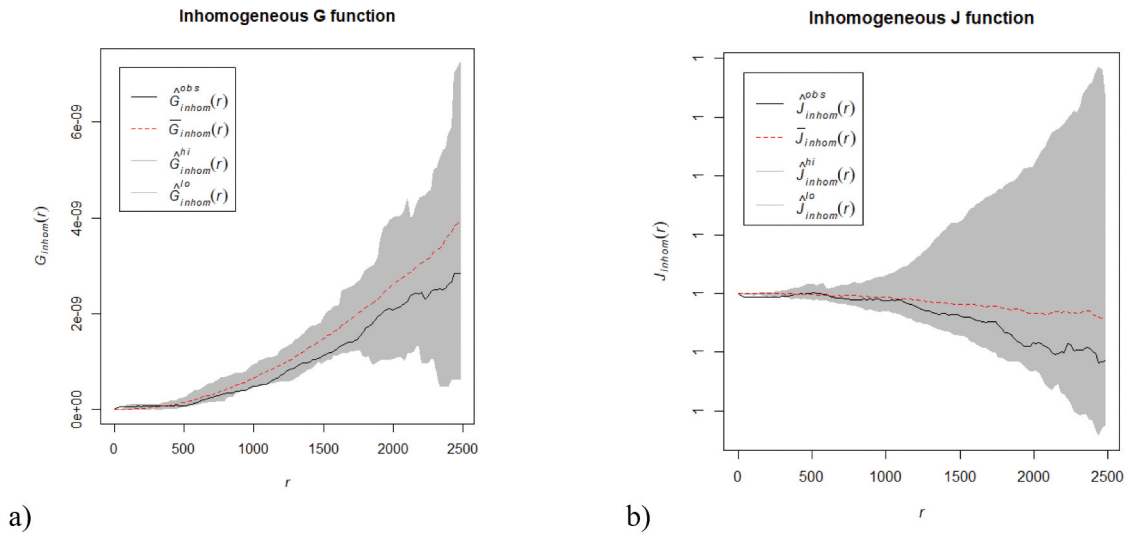
Island	$\sigma$ (m)
Sardinia	1153
Island of Sant'Antioco	675
Island of San Pietro	481
Island of Malu'Entu	NA

#### 5.4 The three Islands

Identifying the optimal bandwidth, we used Diggle and Berman's mean square error cross-validation method. For the whole of Sardinia, this value was 1153 m, while for the two Islands these values were equal to 675 and 481 m. No Diggle-Berman estimate for optimal bandwidth as the Island of Malu'Entu could be obtained, as this Island contains only a single nuraghe. Such smaller values can either point to the physical conditions, or to the social conditions. A lower bandwidth may indicate that the process behind constructing nuraghes was less clustered, and hence more incidental on the smaller Islands. The physical explanation would then be that Sardinia has larger suited areas for constructing nuraghes than the two smaller Islands. The social explanation would be that on Sardinia there is a stronger centre from which the nuraghes were established. [Table 2](#)



**Figure 6.** Box plot of the elevations in the six sub-areas. The bold lines show the median, the boxes the interquartile range and the whiskers are up to 1.5 times the interquartile ranges. Values outside the whiskers are identified as outliers.



**Figure 7.** The inhomogeneous G-function (a) and the inhomogeneous J-function (b) for the isle of Sant'Antioco, with grey areas showing the 95% confidence intervals. Curves estimated with different methods are indicated, while the dotted red curve indicates spatial randomness. As this falls well into both confidence intervals, there is no significant deviation from randomness.

No Diggle-Berman estimate for the Island of Malu'Entu could be obtained, as this Island contains only a single nuraghe. The other two values are slightly different, but have the same order of magnitude. As both Islands are close to the Sardinian coast, it indicates that the process behind building nuraghes at different sites was similar. That is also evidenced by the inhomogeneous  $G$ - and  $J$ - functions show that the observed pattern does not significantly differ from a random pattern (Figure 7).

## 6. Interaction with other pre-nuragic and Nuragic settlements

In this section, we present the analysis of the interaction between the spatial occurrences of nuraghes and other pre-Nuragic, namely *dolmens*, *menhirs* and *domus de janas*, and Nuragic settlements, namely *giants' tombs*, *holy wells* and villages. Densities of nuraghes as well as those of the other pre-historic features are displayed in Figure 8.

The values of the densities are different, as is indicated by the scale bars, but the patterns are interesting to compare. For instance, the density of the nuraghes shows at a first glimpse a relation with that of the *giants' tombs*, but for instance much less with the villages and the *holy wells* – these are concentrated in the southern and south-western parts of Sardinia, whereas the nuraghes are much more concentrated in the north. We will now explore the relations in more detail.

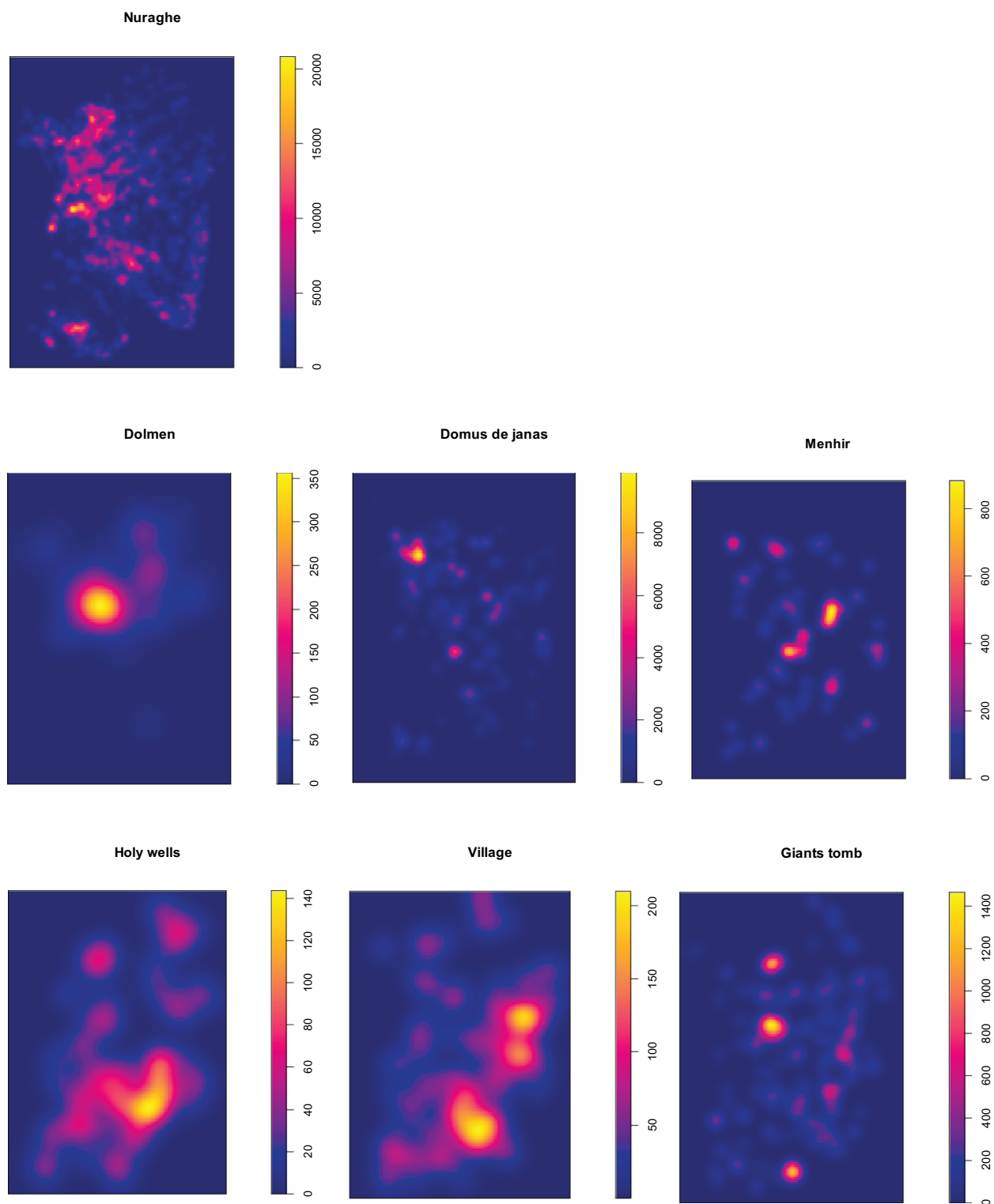
### 6.1 Interaction with dolmens

Figure 9a shows the positions of the *dolmens* in Sardinia, and Figure 9b the  $G_{12}(r)$  function between *dolmens* and nuraghes. There is a clear clustering up to distances of  $\sim 900$  m, indicating that up to that distance *dolmens* and nuraghes have a higher density than one would expect under randomness. Hence, this distance is an indication of a relation between *dolmens* and nuraghes. Since *dolmens* refer to the pre-Nuragic period (before 6000 BC), it could be the case that nuraghes were built within  $\sim 900$  m from existing structures which could be interpreted as indicator of a certain persistence in location choice even over long time periods.

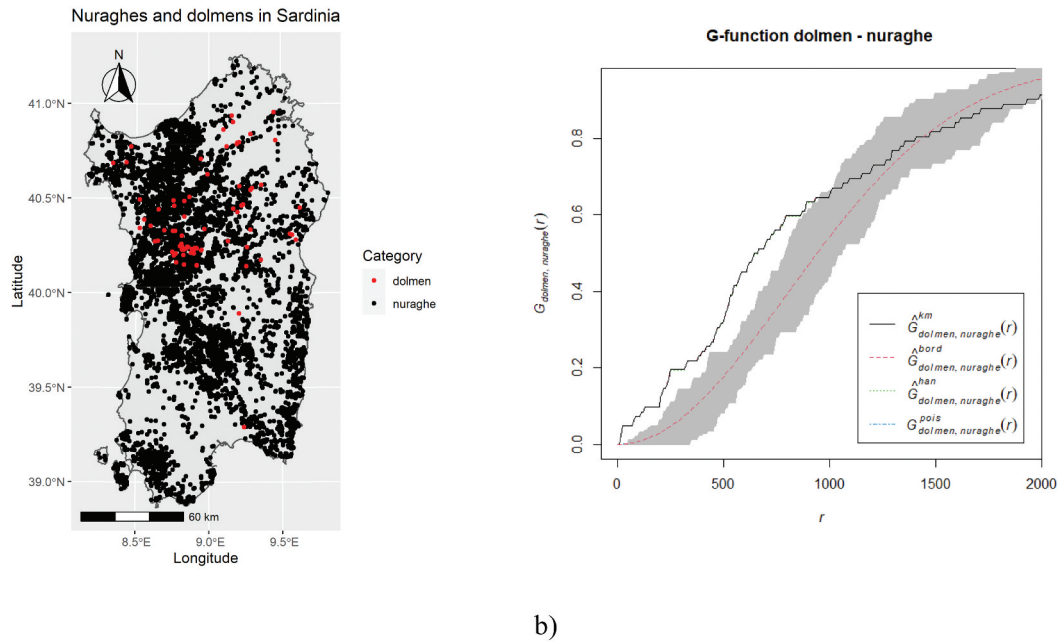
### 6.2 Interaction with menhirs

Figure 10 shows the relation between nuraghes and *menhirs*. There is a less strong relation than for the *dolmens*, although some clustering is still visible up to distances of  $\sim 600$  m. According to our data, there are 113 *menhirs* in Sardinia. As for the case of *menhirs*, these date from the early bronze age, and hence correspond with the pre-Nuragic period. The G-cross function between nuraghes and *menhirs* shows again a clustering, to distances slightly lower than that for of *dolmens*, but the interaction is essentially similar. Note, in addition, that for distances beyond 2 km, the interaction becomes regular. Still, as before, this spatial relationship seems to confirm the existence of a sort of persistent places across the two ages.





**Figure 8.** Densities for the different prehistorical objects on Sardinia: *a) nuraghes, b) dolmens, c) domus de janas, d) menhirs, e) holy wells, f) villages, g) giants'tombs.*

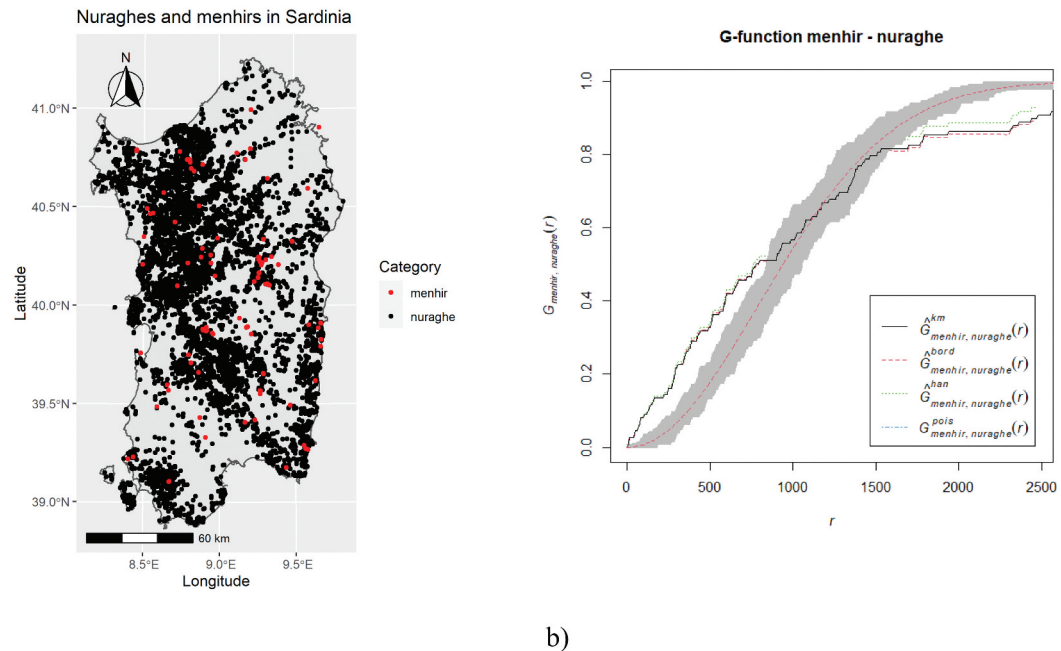


**Figure 9.** The positions of nuraghes (black) and dolmens (red) on Sardinia (a) and the cross density curve (b).

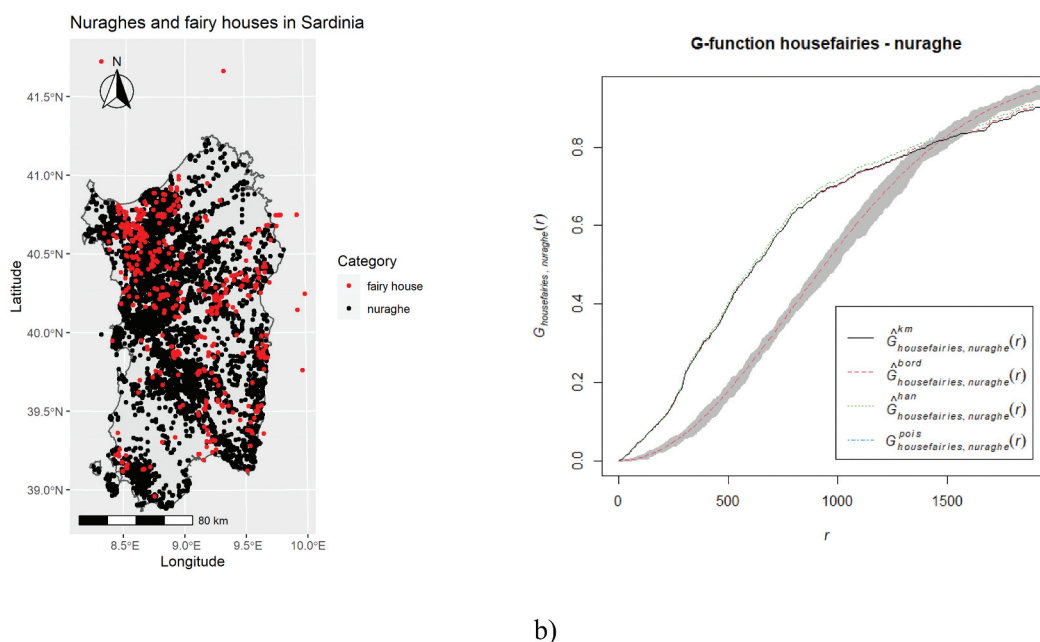
### 6.3 Interaction with domus de janas

Also, the presence of the *domus de janas* could be related to that of nuraghes. In Sardinia, there are 911 sites identified as such, even located on small Islands outside mainland Sardinia. There is a clustering visible (see Figure 11a) that seems to coincide with that of the nuraghe. To explore the spatial relation we used as before the G-cross function and constructed the 95% confidence bounds around it.

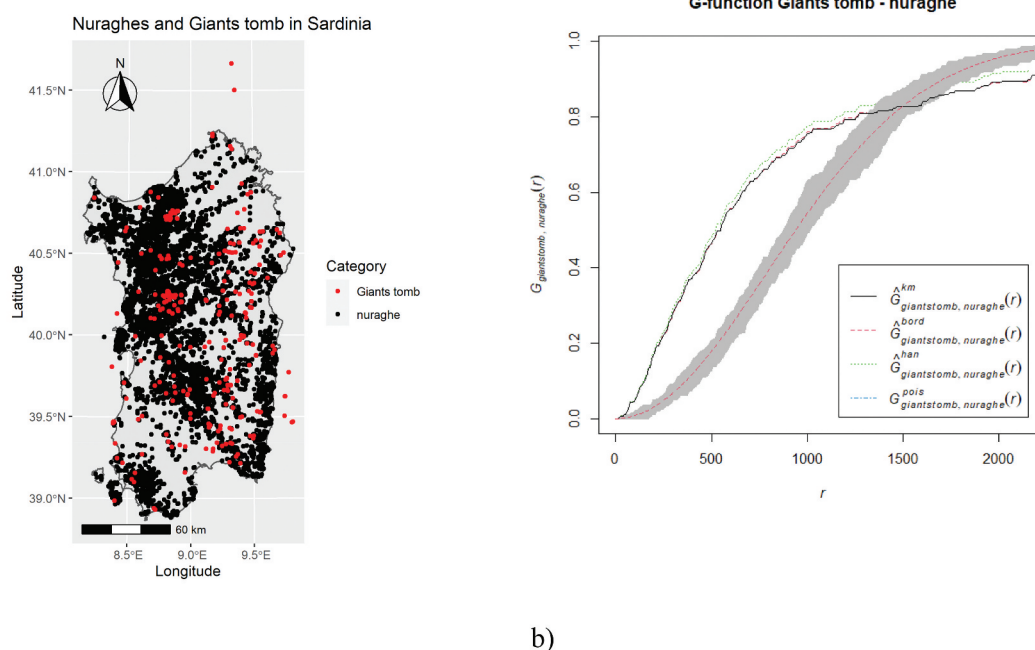
We see a strong and highly significant clustering between the house fairies and the nuraghes. This clustering extends sharply to distances up to 1200 m (Figure 11b), and then it disappears. This points to a very close relation between the two types of pre-historic constructions. For instance, at a distance of 500 m from a house fairy one would expect to have a probability equal to 0.15 to come across a nuraghe when there was no



**Figure 10.** The positions of nuraghes (black) and menhirs (red) on Sardinia (a) and the cross density curve (b).



**Figure 11.** The positions of nuraghes (black) and house fairies (red) on Sardinia (a) and the cross density curve (b).



**Figure 12.** The positions of nuraghes (black) and giants' tombs (red) on Sardinia (a) and the cross density curve (b).

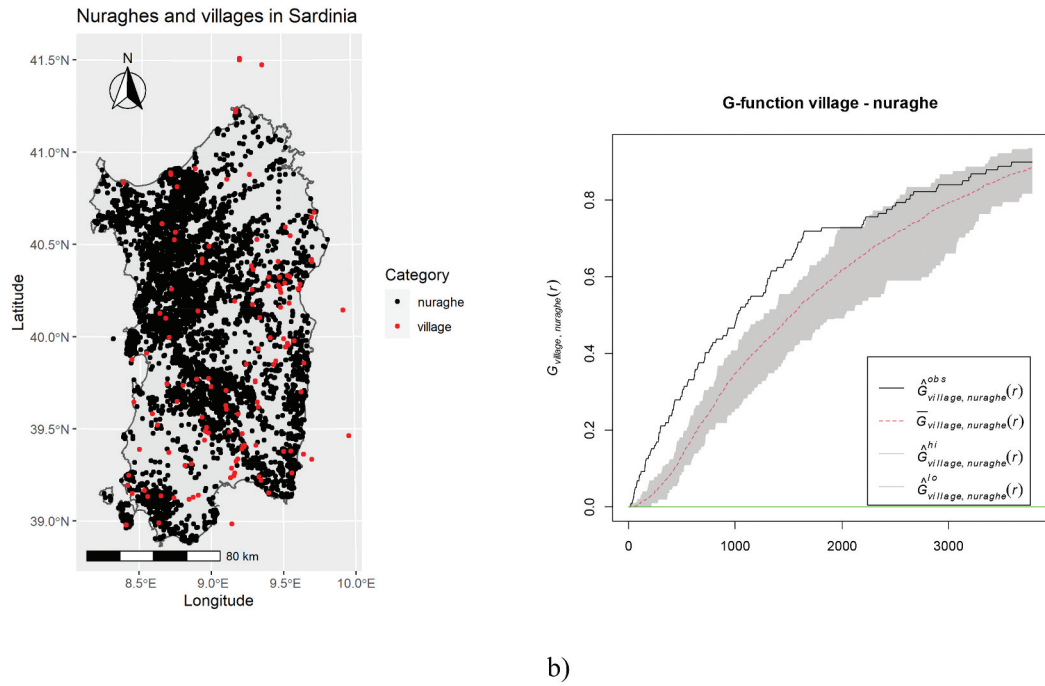
relation – see the dotted red line in Figure 11b. However, evidence shows that that probability equals 0.4 and is significantly higher than 0.15.

#### 6.4 Interaction with giants' tombs

In Sardinia, there are also 293 *giants' tombs*, referred to the Nuragic period. Exploring the relation between *giants' tombs* and nuraghes reveals an even stronger

clustering than with *dolmens* and *menhirs* (Figure 12). The clustering as such is much stronger, whereas it also extends over a longer distance of more than 1200 m. This is a clear empirical evidence that the *giants' tombs* and the nuraghes have a similar – so far unknown – relationship. It seems to be reasonable since the two structures come from the same age. However, this strong spatial relationship could shed a new light on the understanding of nuraghes' functions.

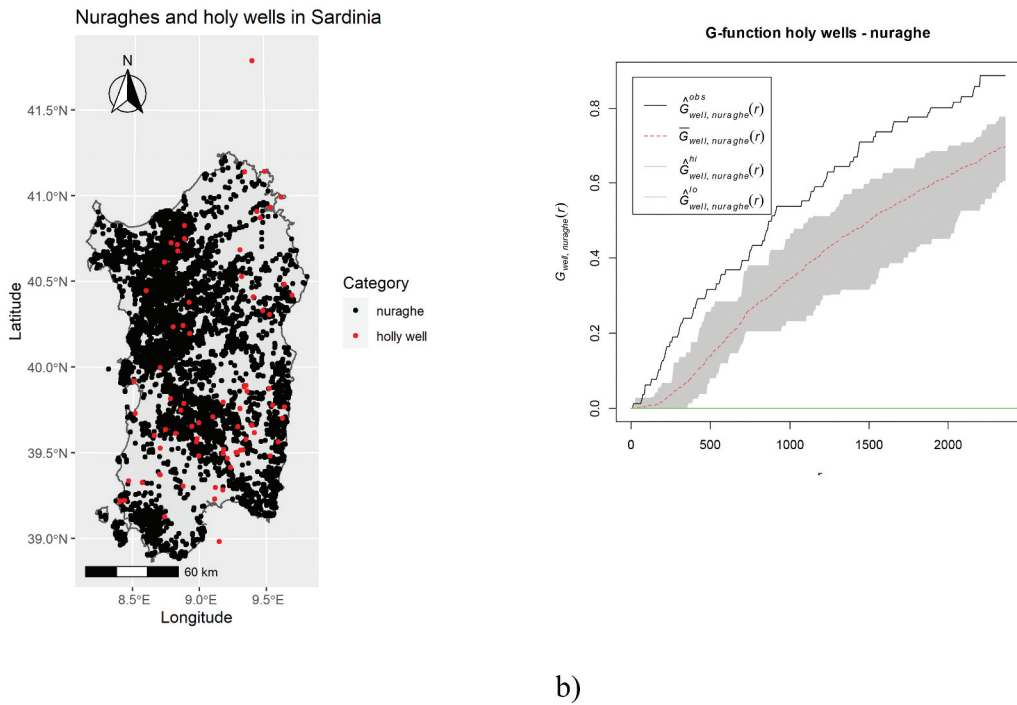




**Figure 13.** The positions of nuraghes (black) and villages (red) on Sardinia (a) and the cross density curve (b).

a)

b)



**Figure 14.** The positions of nuraghes (red) and holy wells (blue) on Sardinia (a) and the cross density curve (b).

a)

b)

### 6.5 Interaction with nuragic villages

The position of the Nuragic villages is relatively well known, and they could be related to nuraghes. It is reported, for instance (Webster 2015) that the use of a nuraghe can be varying, ranging from religious purposes to a ritual use. Hence, the distance relation with the documented villages is important to explore.

Figure 13, however, does not show much evidence of a relation between Nuragic villages and nuraghes. There could be various explanations: the first explanation is that a nuraghe served as a village in itself. Otherwise, the nuraghe had a totally different purpose, complementary to that of a village. Second, the concept of a village could come from a different time period, when the idea of where to establish a village was different from that of constructing a nuraghe. A third explanation could be that due to the construction materials used at that time, Nuragic villages mainly formed by simple stone roundhouses with straw roofs. So, the overtime destruction, abandoning or reuse of these structures could have caused the loss of many villages and their memory. Furthermore, the Nuragic villages located in strategic positions, for instance in order to have direct control of the waterway or the sea, could have been replaced by modern urban areas due to the importance of the location. The weak interaction between villages and nuraghes may also support the idea of pilgrimage, which by definition involves a journey.

### 6.6 Interaction with holy wells

For Nuragic *holy wells*, there is a significant and very pertinent clustering visible for all explored distances (Figure 14). They provide the evidence of the deep religiosity of the Nuragic people. These temples were a place of pilgrimage and ceremonies. Therefore, it is reasonable to document a statistically significant relationship between nuraghes and Nuragic *holy wells*. These findings need to be further analysed in future studies since they can provide new insights about nuraghes' purpose and uses.

## 7 Discussion

In this study, we have applied a spatial statistical analysis in a GIS of the spread of nuraghes in the Island of Sardinia. Spatial statistics clearly shows the opportunity to deal with the large amount of nuraghes that occur, while the GIS environment is essential to integrate the data and visually display the patterns and findings. We investigated clustering of nuraghes and related it with the proximity of topographical variables as well as other types of objects. In particular, the relationship with the

pre-Nuragic *dolmens* and *menhirs* and the *giants' tombs* was very illustrative, showing a clustering up to distances of 1000 m, which indicates a 15 minute walk between the two. If the spatial cooccurrence between nuraghes and *giants' tombs* or *holy wells* is in some sense predictable since both come from the same culture, the significant statistical association between pre-Nuragic and Nuragic settlements is an important result that is worth to be further explored and studied. This analysis sheds a new light on the importance of location for the Nuragic culture and how it was strongly related to the ones of previous ages, namely Neolithic, Chalcolithic and early Bronze Age. Through a deep analysis of this location persistence across ages and cultures, insights into purposes and functions of nuraghes may appear, which are still unclear. Furthermore, the understanding of spatial associations among Nuragic and/or pre-Nuragic sites could help in discovering new ones, in identifying hot-spot areas in terms of a particular culture. In this sense, spatial statistical methods can support further archaeological questions, for instance by establishing and testing the significance of coined hypotheses.

There is a limit for this type of analysis, in particular in terms of the quality of the data. We were not able to analyse the data from one of the smaller Islands, because of lack of nuraghes. Also, inclusion of nuraghes on the nearby Island of Corsica was outside the scope. Such an analysis would be very illuminating, though, as it may show similarities and dissimilarities which could further enhance the scientific understanding.

This research could further be extended towards other and similar archaeological objects that could be observed at a restricted scale. One could think of pre-historic chimneys in Ireland, Viking settlements around the North Sea area, and other well-recognizable objects. Although the specific questions may be different, the type of analysis (clustering, spatial modelling, analysing relations with topographic variables, observing relations with other objects) remains similar. Note that in this paper we have assumed a contemporaneous cultural significance for Sardinian edifices, even though the features were built at different times. This is reasonable since the features are all monuments which, by definition, endure.

An interesting study on nuraghes concerned the visibility and network analysis of De Montis and Caschil (2012). Like our study, they showed the importance of landscape archaeology in the spatial distribution of nuraghes. Our paper indicates that there are multiple landscape components such as dolmens and menhirs that are important to the geography of nuraghes. De Montis and Caschil showed that a hierarchical organization and not a random structure is prominent in an inter-visibility

network, thus identifying consistent rules influencing the construction of Nuragic settlements. Their conclusion that inter-visibility cannot be considered the sole factor that influenced the placement of Nuragic towers is confirmed in our paper: inter-visibility among nuraghes is most likely connected with the presence of other human and natural resources dating from the same period of time, or before.

For the nuraghes, a complicating aspect would be to include the temporal component in the analysis. Webster (2015) identifies different age classes: the early bronze age, middle bronze age, late bronze age and the iron age. Such information is at present not stored in the databases, but it would be a fantastic opportunity to better understand the process of how and why nuraghes were established at the very locations where they have been found. We explored the data as represented on the maps in Webster (2016), but then we would have too much locational uncertainty, in particular given the relatively low numbers shown.

## 8 Conclusions

From the spatial statistical analysis on the occurrence of nuraghe in Sardinia, we derive the following main conclusions.

- (1) There is a clear and significant relation between the position of nuraghes and both elevation and slope on the Island of Sardinia. Nuraghes in particular follow a uniform distribution over elevations between 0 and 300 m, while with increasing elevation their number rapidly decreases. They commonly occur on relatively flat areas, but incidentally they also occur at steeper slopes.
- (2) There is a very strong clustering relation between nuraghes and prehistoric edifices. A strong correlation was found in particular with *domus de janas* and *giants' tombs* for distances upto 1200 m. Clustering occurs as well with other prehistoric remnants, such as *menhirs* and *dolmens* upto 900 m. A much weaker correlation, however, occurred with prehistoric villages, possibly due to behaviour of individuals in nuraghic times.

Further research should aim to find historical and geomorphological explanations for the observed patterns.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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