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Received: 12 September 2022 | Accepted: 6 February 2023

DOI: 10.1002/pan3.10461

PEOPLE AND NATURE | BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

Ecology meets archaeology: Past, present and future vegetation-derived ecosystems services from the Nuragic Sardinia (1700–580 BCE)

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Handling Editor: Charles Watkins

Abstract

1. Incorporating archaeology within the ecosystem services (ES) framework can offer decision-makers lessons from the past and a broader sustainability perspective. Given the claimed archaeology-ES link, the island of Sardinia (Italy) offers an unparalleled opportunity where a unique archaeological heritage occurs in an area of high biodiversity value. More than 5000 nuraghi, megalithic edifices distinctive of the Nuragic civilization (1700–580 BCE), are still present on the island.
2. By crossing the map of Vegetation Series (VS) with nuraghi occurrences, we aimed at acquiring a long-term perspective on the interactions between Nuragic people and the vegetation as ES provider, so as to enrich our understanding of the past and the present, and potentially inform future practice for the region of Sardinia. A VS is here intended as a hypothesis of a succession of plant communities that can potentially succeed each other over time in a particular land unit.
3. The vegetation-derived ES represented a driving force in the land occupation strategies of the Nuragic people, who preferred, for their settlements, the mesophiluos cork oak VS and secondary the deciduous broad-leaved ones, which, with fresh climatic conditions on fertile substrates and gentle slopes on effusive magmatic rocks, can provide land for grazing and agriculture. Conversely, the Nuragic land occupation strategies shaped the VS, transforming the landscape into agro-silvo-pastoral systems. Our results suggest that the origin of the present agro-silvo-pastoral landscapes (i.e. *Pascolo arborato/Dehesa*) in Sardinia could be traced back to the Nuragic civilization.

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4. The interaction between humans and vegetation in Sardinia is ancient, reciprocal and dynamic. This interaction is crucial for the survival of the present agro-silvo-pastoral landscapes that represent important suppliers of provisioning, regulating and cultural ES. Among others, these landscapes are a good example of intimate and sustainable relationships between people and nature and provide a marked sense of place and identity for Sardinia inhabitants.
5. This transdisciplinary approach linking plant ecology with archaeology offered archaeology a better understanding of the environmental settings and subsistence of the Nuragic civilization and provided plant ecology with a long-term perspective on human-vegetation interactions.

KEYWORDS
archaeology, ecosystem services, Nuragic age, transdisciplinary approach, vegetation and people, vegetation maps

1 | INTRODUCTION

Although the ecosystem service (ES) framing has been criticized for managing nature to maximize the overall value of the human condition ('nature for people')—as opposed to a more nuanced one that recognizes the two-way, dynamic relationships between 'people and nature' (Mace, 2014)—it still represents a crucial quantitative tool for decision-making and for meeting the challenges of the 21st century to secure the life-support systems underpinning current and future human well-being (Guerry et al., 2015).

Recently, Katz (2022) claimed that incorporating archaeological knowledge in ES (and vice versa) would set better theoretical and knowledge-based frameworks for understanding human resource management and utilization, human impact on the environment and sustainable natural resource management. Within the context of long-term socio-ecological dynamics, an ES-archaeology nexus could offer decision-makers lessons from the past and a broader perspective of sustainability (Guerry et al., 2015; López de la Lama et al., 2021). Finally, this approach would open new avenues for ecology, economy and archaeology, offering archaeology a better understanding of the environmental settings and subsistence of past human societies and providing ecology and economy with a long-term perspective on human-environment interactions (Katz, 2022).

In view of the claimed archaeology-ES link, the island of Sardinia (Italy) offers an unparalleled opportunity where a unique archaeological heritage occurs in an area of high biodiversity value. Indeed, Sardinia is included among the top 30% areas of 'science-policy biodiversity consensus regions', defined as regions of high biodiversity importance and institutional recognition worldwide (Cimatti et al., 2021). Additionally, the Nuragic civilization, settled in Sardinia during the Bronze and Early Iron Ages (1700–580 BCE, Nuragic Age) (Depalmas & Melis, 2010; Perra & Usai, 2018), left an impressive number of archaeological sites, spread all over the island. The most striking elements of the Nuragic culture are conical, several-storied, dry-stone towers known as nuraghi, with more than 5000 units currently mapped and identified.

However, since no written records of the Nuragic civilization have been discovered (Melis, 2003), not much is known about the land occupation strategies of the Nuragic people, and how they interacted with their environment (Depalmas, 2018; Vanzetti et al., 2013). Most of the existing knowledge addresses the physical landscape of Nuragic people (i.e. geologic and geomorphologic conditions for nuraghi settlements) (Depalmas & Melis, 2010), while little is known about their relationship with the biotic domain (i.e. vegetation and the related ES), generally constrained to rough descriptions of their preferred habitats (e.g. pastures, highlands, lowlands) performed either locally or over a limited subset of nuraghi (Ialongo, 2018; Mariani et al., 2022).

This gap is also related to the lack of past vegetation data over large areas. Indeed, in Sardinia, sedimentary deposits suitable for paleobotanical analyses are scarce and mostly located in coastal areas (Beffa et al., 2016; di Rita & Melis, 2013; Pedrotta et al., 2021), hindering the required degree of accuracy and confidence in terms of space and time.

With due caution, biodiversity maps, often confined to conservation or management applications (Malavasi, 2020), can be used to partially overcome such a lack. Specifically, the map of Vegetation Series (VS) of Sardinia can provide a summarized knowledge about vegetation dynamics (Loidi & Fernández-González, 2012) to be potentially combined with historical data to derive valuable information about people-vegetation interactions and coevolution (Bazan et al., 2019, 2020). The map of VS identifies homogenous environmental units in their bioclimatic and lithomorphological characteristics (Blasi et al., 2004) which share the same potential natural vegetation (PNV)—usually a specific type of forest—defined as the vegetation that would become established under the present climatic and edaphic conditions if the human influence was removed (Farris et al., 2010; Mueller-Dombois & Ellenberg, 1974). It should be noted that a VS, rather than predicting specific past pre-anthropic vegetation, suggests a succession of plant communities that can potentially succeed each other over time in a particular land unit

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(Loidi et al., 2010). Within each VS, dynamically connected successional stages differing from PNV (e.g. coppice, shrubland, grassland or grazing land, cropland) are related to the intensity of disturbance driven by human impact (Bazan et al., 2020; Loidi et al., 2010). Such impact is particularly relevant in the Mediterranean Basin, which has been almost entirely manipulated or 'redesigned' by man over the last 10,000 years (Blondel, 2006).

In light of this, we here build on two assumptions: (a) in Sardinia, the actual layout of VS is inexorably intertwined with the interaction of present and past human societies, and (b) the distribution of VS is, with due caution, comparable to those of the last 4000 years. The available palaeoecological research supports this latter assumption, confirming that, during the Bronze and Early Iron Ages, Sardinia was mainly covered with evergreen broadleaved forests similar to those presently occurring, and no consistent changes in the floristic composition occurred (Beffa et al., 2016; Buosi et al., 2015; di Rita & Melis, 2013; Pedrotta et al., 2021; Pittau et al., 2018). Indeed, besides the widespread climate fluctuations characterizing all circum-Mediterranean regions (though not well documented for Sardinia) during the Holocene (<10,000 BCE), the most important (and long-lasting) impact on the environment came from human activities (Lai, 2018; Thompson, 2005).

That being said, within an archaeology-ES framework that crosses the map of VS with nuraghi occurrences in Sardinia, we aimed at acquiring a long-term perspective on the interactions between Nuragic people and the vegetation as ES provider, so as to enrich our understanding of the past and the present, and potentially inform future practice for the region of Sardinia. To this end, we first assessed whether the occurrence of nuraghi was clustered or uniformly distributed across Sardinia. Then, we tested whether the observed spatial pattern of nuraghi was significantly associated with any of the VS. Together with the geomorphological and past bioclimatic (1200 BCE) profiles of nuraghi sites, our analysis allowed us to identify those VS that were more populated, exploited or managed in terms of ES by Nuragic people while suggesting where their 'footprint' on the actual Sardinian landscape is more likely to have occurred. ES are here identified with three main ES categories (la Notte et al., 2017): provisioning services (directly provided physical goods), cultural services (non-material benefits), and regulating/supporting services (benefits from mediation or moderation of natural phenomena or conditions).

2 | MATERIALS AND METHODS

2.1 | Archaeological background and data

The Nuragic civilization settled in Sardinia during the Bronze and Early Iron Ages (1700–580 BCE, Nuragic Age). No written records have been discovered with references to the Nuragic people mostly coming from classical Roman literature and from much later times, being less informative and reliable (Melis, 2003). However, archaeological evidence suggests that the Nuragic societies were, especially at the beginning, of a tribal type, that is compact, with minimal rank differences and weak functional specialization (Perra, 2009). Nuragic people used to erect round stone towers called nuraghi, many of which are still standing. Nuraghi probably carried out all the material and symbolic functions which were necessary to the Nuragic communities' life, within a mostly agricultural economic system and a social structure which was beginning to differentiate (Usai, 2021). Two main types of nuraghi appeared in time (1700–1200 BCE): the early 'corridor' nuraghe or proto-nuraghe and the later 'tholos' nuraghe, the latter built as a single tower or as the complex union of multiple towers (Cappai & Pulina, 2017; Lilliu, 1988). Later (1200–580 BCE), the use of nuraghi diminished as increasingly complex villages developed, either around older nuraghi structures or in new areas (Depalmas & Melis, 2010). Therefore, nuraghi (and nuraghi villages) use may have varied, but overall, they were mostly multifunctional dwelling places; they were also used for land control, resource management, and to demonstrate the power and wealth of the communities that owned them (Depalmas, 2018). The construction of nuraghi villages ended with the Carthaginian conquest of the island of Sardinia in 510 BCE, which also marks the end of the Nuragic age (Depalmas & Melis, 2010).

The occurrence of nuraghi and their remains in Sardinia was accurately mapped through a citizen science project coordinated by the Nurnet Foundation. The resulting map is freely available from an online archaeological database (source: https://www.nurnet.net/). For this study only data about nuraghi and nuraghi villages occurrences were downloaded, excluding other structures available in the database (i.e. sacred wells, giants' tombs), which could have different uses and meanings from those of dwelling places and the related household activities. A total of 5453 nuraghi and nuraghi villages (5162 nuraghi and 291 villages) have been recorded across the Sardinia region in the Nurnet database, although archaeologists traditionally estimated the original number as ranging between 7000 and 9000 units (Contu, 1997; Depalmas, 2018; Lilliu, 1988).

For simplicity, and due to nuraghi being the predominant structure in our data, we here collectively refer to nuraghi and nuraghi villages as nuraghi. Differences among types of nuraghi and villages were not considered for the analysis.

2.2 | The map of the vegetation series of Sardinia

The map of VS of Sardinia (Bacchetta et al., 2009) was produced as a part of the larger map of VS of Italy (1:350,000) (Blasi et al., 2004). Specifically, the map is the result of the integration of two processes: (1) the definition of environmental units through a hierarchical land classification; (2) the definition of the VS pertaining to each environmental unit through phytosociological field data and the expert knowledge of the relationships between present vegetation communities, environmental factors and vegetation dynamics (Blasi et al., 2004).

The hierarchical land classification depicts the landscape at progressively finer spatial (and temporal) scales in relation to four

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different factors: (1) land regions, based on macroclimate; (2) land systems, based on lithology; (3) land facets, defined on a geomorphological basis; (4) environmental units, based on the bioclimate at a finer spatial scale. In this context, the environmental unit's map helps to define the spatial distribution of PNV, which is usually a specific forest type. Other vegetation types occurring within the environmental unit and dynamically related to this forest type are named 'replacement communities'.

With respect to the map of VS of Sardinia, 23 main VS were identified (see Supplementary Material 1), 21 of them being exclusive of the Sardinian biogeographic sub-province and 2 of the Corsican-Sardinian province (Bacchetta et al., 2009).

2.3 | Testing the association between nuraghi and VS

2.3.1 | Test of clustering of nuraghi

We tested whether nuraghi occurred more clustered in space than expected under a 'Complete Spatial Randomness' scenario (hereafter CSR), which would correspond to the structures being independently and uniformly distributed across Sardinia. To this aim, we computed the pair correlation function for nuraghi using the *pcf.ppp* R function (SPATSTAT package; Baddeley et al., 2015). In short, the pair correlation function measures the dependence between points in a spatial point pattern. Positive values of the function indicate clustering of the points, whereas negative values indicate inhibition (the function is equal to 1 under stationarity CSR). For a formal test, we compared the observed pair correlation function to a simulated 95% global envelope of the function computed under CSR (*envelope* R function, SPATSTAT package; Baddeley et al., 2015).

2.3.2 | Torus translation test

To test whether the distribution of nuraghi was associated with specific VS, we performed the torus translation test (Wiegand & Moloney, 2014). This test assesses the association between a clustered point pattern (i.e. the nuraghi) and categorical environmental layers (i.e. the map of VS). To perform the test, we:

1. counted the observed number of nuraghi falling within each VS (O_i);
2. simulated *n* 'null model' point patterns by randomly displacing nuraghi across Sardinia while keeping their relative positions fixed (*rshift.ppp* R function with 'torus' edge correction, SPATSTAT.RANDOM package; Baddeley et al., 2015); this way, any possible relationship between nuraghi and the VS patches was broken while the inherent clustering of nuraghi remained unchanged;
3. computed the average number of nuraghi falling within each VS across all simulations (Ei);
4. compared O_i against E_i using the X^2 statistic. The null hypothesis was that the location of nuraghi was independent of the spatial configuration of the VS. Under the null, the X^2 statistic is chi-squared distributed with degrees of freedom equal to the number of VS minus 1 (i.e. 29). We set the type I error (i.e. α) to 0.05.

When shifting the nuraghi points randomly to produce simulated 'null model' point patterns (step 2), some points fell outside the Sardinia boundary and had to be excluded. To reduce the effect of the smaller number of points in the simulated vs observed patterns, we only included those simulated patterns consisting of at least 70% (i.e. 3817) of the original points. From the 5000 simulations we ran, 2057 patterns met these criteria and were therefore used. For the same reason, a weighted average had to be used in step 3, with weights corresponding to the actual sample size of each simulated pattern.

Finally, we visually compared O_i and E_i to assess whether some specific VS category was more (or less) populated, exploited or managed in terms of ES by Nuragic people than expected under the null hypothesis of independence between nuraghi occurrence and VS spatial pattern.

The R code for reproducing the spatial analysis can be found at: https://github.com/ManueleBazzichetto/Sardinia.

2.4 | Geomorphological and climatic profile of nuraghi

Although information about some geomorphological and climatic conditions can be empirically derived from the VS typology, we enriched and improved the description of the environmental conditions characterizing Nuragic sites by relying on specific environmental layers: historical bioclimatic data (from 1300 to 1201 BCE) about mean annual air temperature (Bio01—C°) and annual precipitation (Bio12—kg m^{-2}); altitude (DEM—m) and slope (degrees). We retrieved historical climatic data from the CHELSA database (Karger et al., 2023). Altitude and slope were derived from European Digital Elevation Model (EU-DEM), version 1.1 (https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1). Our selection of the time interval is related to the beginning of the Final Bronze Age (1200–1000 BCE) when nuraghi were not built anymore and the building of villages had started (Dyson & Rowland Jr., 2007). Therefore, we assume that all the analysed nuraghi had already been built during the selected period.

Additionally, distance from rivers and lithology were also considered (both available from http://www.sardegnageoportale.it/). Lithological classes are here described with the first level of details, and are a total of 8 classes (see Supplementary Material 2).

3 | RESULTS

3.1 | Nuraghi and VS

Although nuraghi were found across almost all the VS, for simplicity, the results here refer to the five VS most populated by nuraghi (SA13, SA19, SA20, SA21, SA22; see Figures 1 and 2; Table 1). These

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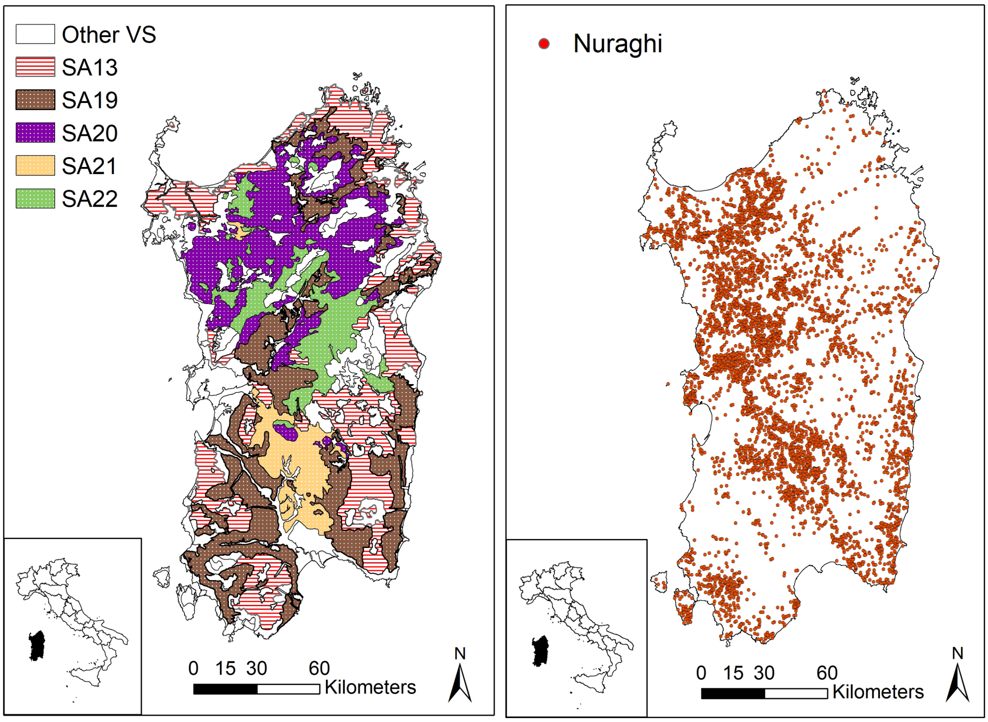

FIGURE 1 On the left side the map of the five VS of Sardinia most populated by nuraghi: SA13—Sardinian, thermo-meso-Mediterranean holm oak series (*Prasio majoris-Querco ilicis* Σ *quercetosum ilicis* and *phillyretosum angustifoliae*); SA19—Sardinian calcifuge, thermo-meso-Mediterranean cork oak series (*Galio scabri-Querco suberis* Σ); SA20—Sardinian, central western Mediterranean, calcifuge, meso-Mediterranean cork oak series (*Violo dehnhardtii-Querco suberis* Σ); SA21—Sardinian, basiphilous, thermo-meso-Mediterranean Virgilio oak series (*Lonicero implexae-Querco virgiliane* Σ); SA22—Sardinian, calcifuge, meso-supra temperate Sardinian oak series (*Loncomelo pyrenaici-Querco ichnusae* Σ). On the right side the map of the distribution of nuraghi across Sardinia.

five VS account for 69% of the total area of the Sardinia region and host 75% of the total number of nuraghi (Figure 1).

The pair correlation function evidenced that nuraghi were significantly clustered within approximately 1 km (see Supplementary material 3).

The torus translation test indicated that the distribution of nuraghi was significantly associated with the VS map (X^2 = 1814.297, degrees of freedom = 29, $p<0.05$). For the five selected VS, the comparison between the observed and expected number of nuraghi under CRS within each VS category is displayed in Figure 2 (for the entire set of VS, see Supplementary material 4).

Four VS, two belonging to the mesophilous cork oak forests (SA19—*Galio scabri-Querco suberis* Σ and SA20—*Violo dehnhardtii-Querco suberis* Σ) and two different types of deciduous broad-leaved oak forests (SA21—*Lonicero implexae-Querco virgiliane* Σ and SA22—*Loncomelo pyrenaici-Querco ichnusae* Σ) were more populated by nuraghi than expected.

The mesophilous cork oak forests VS (SA19 and SA20) hosted the first and second highest number of nuraghi respectively, followed by the deciduous broad-leaved oak forests VS (SA21 and SA22).

One VS, belonging to the deciduous broad-leaved oak forests (SA13—*Prasio majoris-Querco ilicis* Σ *quercetosum ilicis* and *phillyretosum angustifoliae*) was less populated by nuraghi than expected under CSR. SA13 is the second most widespread series in the region, yet only the fifth in terms of observed nuraghi.

Importantly, almost half of nuraghi (2.352 nuraghi out of 5.453) were found in the two VS belonging to the cork oak VS: *Galio scabri-Querco suberis* Σ and *Violo dehnhardtii-Querco suberis* Σ (SA19 and SA20).

3.2 | Geomorphological and climatic profile of nuraghi

At the regional scale, the bioclimatic profile of nuraghi was characterized by warm mean annual air temperature (median temperature = 15.6°C) and moderate annual precipitation amount (median precipitation = 753 mm) (Table 2; Figure 3). The geomorphological profile was characterized by low-medium altitude (median altitude = 396 m a.s.l.) and flat areas (median slope = 2.3°; Table 2; Figure 3). Besides, nuraghi were always extremely close to rivers (median distance from rivers = 424.1 m) and mainly occurred on A2 substrates (effusive magmatic rocks) (Figure 3).

4 | DISCUSSION

Within an archaeology-ES framework that crosses the map of VS with nuraghi occurrences in Sardinia, we acquired a long-term explorative perspective on the interactions between Nuragic people

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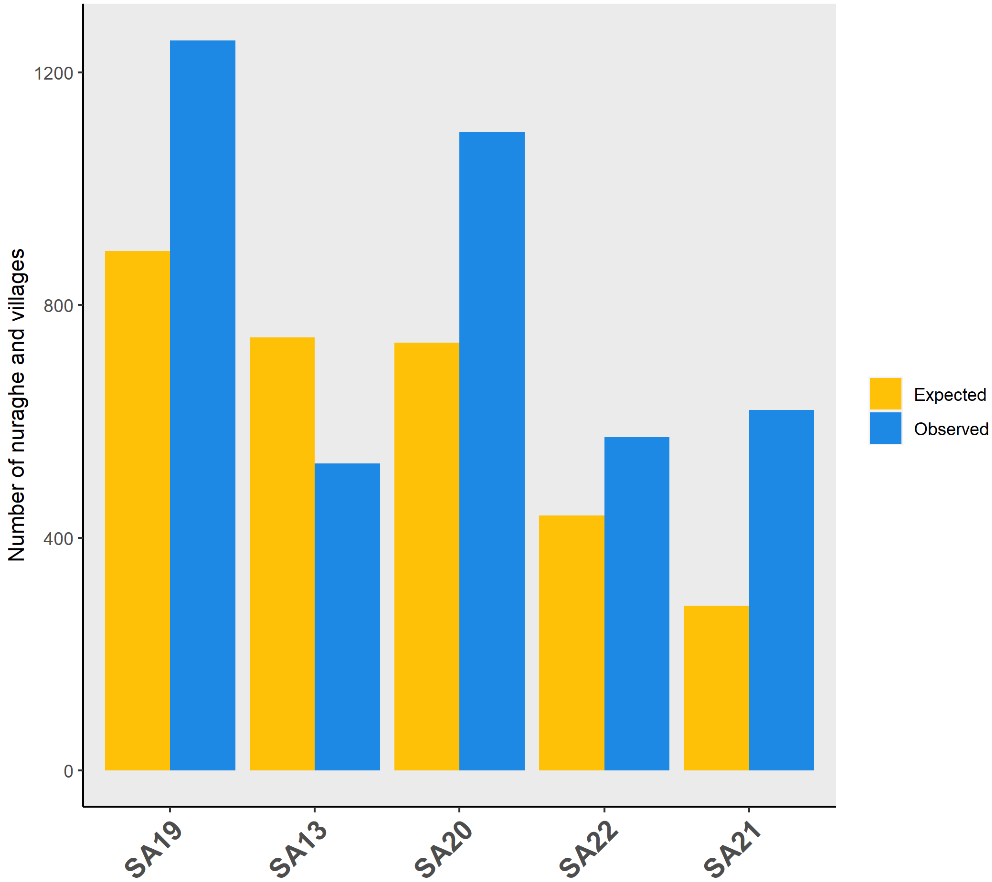

FIGURE 2 Comparison between observed (blue bars) and expected (orange bars) under complete spatial randomness number of nuraghi for the five most populated VS.

and vegetation. Overall, the occurrence of nuraghi was significantly associated with the spatial configuration of VS, pointing to the importance of the vegetation (bound to specific environmental conditions) and the related ES as driving forces for the Nuragic land occupation strategies.

Specifically, the distribution of nuraghi, which appeared significantly occurred in small clusters of approximately 1 km, was associated with specific VS, suggesting that some VS were more convenient than others in terms of ES. Among the five most common VS of Sardinia, Nuragic people were heavily dependent on the ES provided by two mesophiluos cork oak forests VS (SA19—*Galio scabri-Querco suberis* Σ and SA20—*Violo dehnhardtii-Querco suberis* Σ) and two deciduous broad-leaved oak forests VS (SA21- *Lonicero implexae-Querco virgiliane* Σ and SA22—*Loncomelo pyrenaici-Querco ichnusae* Σ). These four VS all featured fresh climatic conditions and were characterized by fertile substrates and gentle slopes on effusive magmatic rocks, ideal for agricultural and grazing practices. Indeed, archaeological evidence suggests that Nuragic people relied substantially on the exploitation of forests, cutting down and burning trees to gain land for agriculture and grazing (Depalmas & Melis, 2010). Concerning agriculture, archaeobotanical studies identified *Hordeum vulgare*, *Triticum aestivum/durum*, *Triticum dicoccum* and *Vicia faba* as the most cultivated crops (Bakels, 2002) As to grazing, animal husbandry was practised by Nuragic people with a prevalence of sheep, goats and cattle, although also wild fauna (e.g. deer and swine) is found (Depalmas & Melis, 2010).

The cork oak VS (SA19 and SA20) seem to play an essential role in the land occupation strategies of the Nuragic people, probably because of the several provisioning ES they could provide (Bagella et al., 2020) and its low mortality by the fire with above-ground sprouting (Carrión et al., 2000). These series are historically managed for pasture and browse for livestock, cereal cropping, firewood, charcoal, fruits, oils, berries, mushrooms, wild animals and, especially recently, for cork (Torres, 2010). There is also some archaeological evidence of Nuragic people using cork for insulating nuraghi walls (Melis, 2003) and other possible uses (e.g. storing food) (Depalmas & Vidili, 2011). In these cork oak VS, grasslands rich in edible legumes, ascribed to the Poetea bulbosae class, can also grow (Seddaiu et al., 2018). Besides, these VS lie on hydromorphic soils where water naturally stagnates for long periods giving rise to the typical 'paulis', used in the Sardinian language to name Mediterranean temporary ponds (Bagella et al., 2016). In Sardinia, 'paulis' are traditionally used for various purposes, including watering animals, which reasonably allows us to assume similar possible uses during the Nuragic Age.

Besides, the dense shrubby layer of the cork-oak series (SA19 and SA20) is characterized by *Pyrus spinosa*, *Crataegus monogyna*, *Arbutus unedo* and *Erica arborea*, while in its termophilous aspects

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TABLE 1 Description of the five VS most populated by nuraghi. Observed and expected (under CSR) number of nuraghi are also reported.

Code of VS	Name of VS	Observed number of nuraghi	Expected number of nuraghi	Comparison
SA13	Sardinian, thermo-meso-Mediterranean holm oak series (*Prasio majoris-Querco ilicis Σ quercetosum ilicis* and *phillyretosum angustifoliae*)	528	744	−
SA19	Sardinian calcifuge, thermo-meso-Mediterranean cork oak series (*Galio scabri-Querco suberis Σ*)	1255	893	+
SA20	Sardinian, central western Mediterranean, calcifuge, meso-Mediterranean cork oak series (*Violo dehnhardtii-Querco suberis Σ*)	1097	735	+
SA21	Sardinian, basiphilous, thermo-meso-Mediterranean Virgilio oak series (*Lonicero implexae-Querco virgiliane Σ*)	620	283	+
SA22	Sardinian, calcifuge, meso-supra temperate Sardinian oak series (*Loncomelo pyrenaici-Querco ichnusae Σ*)	573	438	+

TABLE 2 Values of the geomorphological and climatic profiles of nuraghi.

	Median	1st quartile	3rd quartile
Temperature (°C)	15.6	14.7	16.5
Precipitation (mm)	753	679	834
Altitude (m a.s.l.)	396	244	548
Slope (degrees)	2.3	1.3	4.1
Distance from rivers (m)	424.1	199.9	727.8

(subassociation *myrtetosum communis*) is characterized by *Pistacia lentiscus* and *Myrtus communis* (Bacchetta et al., 2009). These plants were important ES providers for Nuragic people and still are in nowadays Sardinian rural society. For instance, *Arbutus unedo* has several therapeutic properties (e.g. astringent, diuretic, sedative or antibiotic), its wood is ideal for making tools, and it is also an excellent fuel (Atzei et al., 1991, 2004). Similarly, the coal derived from *Erica arborea* can generate a great deal of heat, which is necessary for metalworkers, and its wood is durable and extremely resistant, being a perfect construction material. Moreover, excellent honey can be produced by flowers of *E. arborea*. *Pistacia lentiscus* oil was part of the diet of the Nuragic people and was also used for lighting (Atzei et al., 2004). Fruits of *Pistacia* and *Myrtus* were traditionally used for dyes.

In Sardinia, cork oak VS, and to a lesser extent deciduous broad-leaved oak forests VS, are nowadays represented by open woodlands structurally similar to savannas, which are known as *Pascoli arborati* or wood grasslands (Bagella et al., 2020). These can also be found in Spain (*dehesa*), in Portugal (*montado*) and other Mediterranean areas. Three main rural activities are simultaneously practised in a single space: forest product harvesting, livestock husbandry and agriculture (Blondel, 2006; Joffre et al., 1999). They are considered remnants of the old agro-silvo-pastoral landscape management system (Capelo et al., 2012), whose formation resulted from human-mediated disturbances, including forest clearance by fire and exploitation. These agro-silvo-pastoral landscape may have been present in prehistory, partly promoted by the use of fire by early humans, as often happened in other savannas associated with early human occupations (Bugalho et al., 2011).

In this context, the archaeology-ES link can help understand the origin of the actual Sardinian landscape, suggesting that Nuragic people likely promoted the formation of these savannas-like formations. Palynological investigations regarding the Bronze Age support this hypothesis, documenting consistent deforestation in Sardinia, with a change from densely forested landscapes

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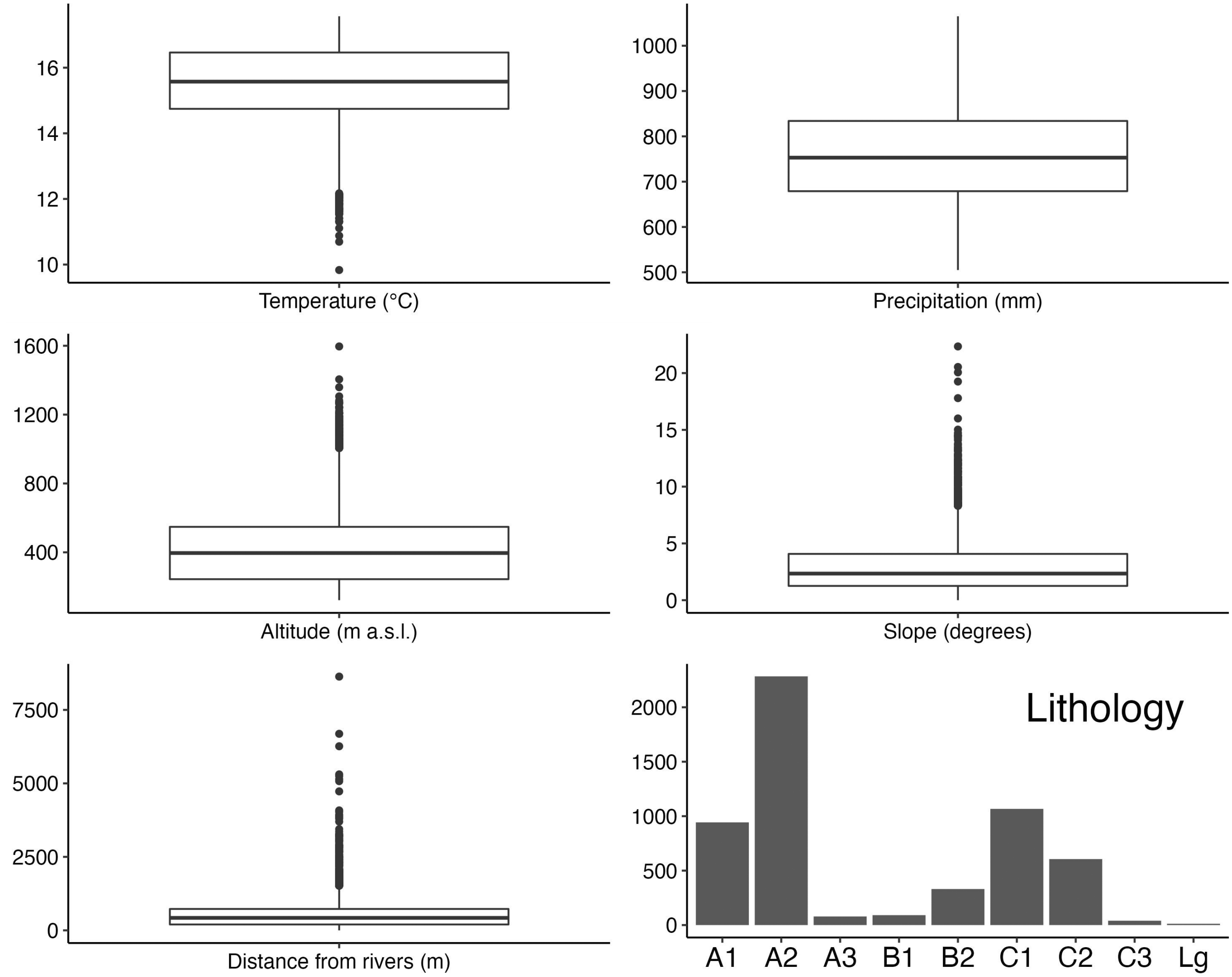

FIGURE 3 Boxplots of the geomorphological and climatic profile of nuraghi. See Supplementary Materials 2 for lithological classes.

to more degraded forests (Bakels, 2002; Beffa et al., 2016; Buosi et al., 2015; di Rita & Melis, 2013; López et al., 2005; Pedrotta et al., 2021). Additionally, this is in line with Grove & Rackham's theory (Grove & Rackham, 2001), stating that the present character of the Mediterranean landscape was likely achieved prior to many written records through a combination of increasing aridity and Bronze Age clearances between 3000–1000 BCE. In light of the sustainable and long-term management that can possibly be traced back to the Nuragic civilization, these agro-silvo-pastoral landscapes also represent cultural ES suppliers of important spiritual and cultural values (Katz, 2022). Crowded with nuraghi, they provide a marked sense of place and identity for Sardinia inhabitants, which consider the Nuragic civilization, together with their heritage, as the foundation of the Sardinian feeling of historical and cultural identity (Frongia, 2012). The word *nuraghe* itself—*nurac* in the Roman inscription carved on the lintel of Nuraghe Aidu Entos at Bortigali (Gasperini, 1992)—is a living piece of memory, a venerable linguistic residue of the Bronze Age, still surviving after many changes of language in Sardinia. Similarly, these landscapes provide a good example of intimate and sustainable relationships between people and nature. We know that sustainability may be achieved with traditional management techniques, which, mimicking that of tropical savannas, do not result in dramatic changes in certain major functions of the ecosystems while promoting biodiversity (Blondel, 2006; Joffre et al., 1999). In ecological terms, this management type provides an optimal, functional equilibrium between water demand and supply that does not push beyond the thresholds of resistance and resilience that characterize Mediterranean ecosystems (as opposed to modern agriculture) (Blondel, 2006).

Nonetheless, it has been estimated that, although included in the Habitat Directive (Annex I 6310 'Dehesas' with evergreen *Quercus* spp) (Ramírez-Hernández et al., 2014; Rivieccio et al., 2020), these habitats could disappear in 100–125 years (Rossetti & Bagella, 2014), pointing to the need to preserve such habitats together with the related traditional management and ES.

As for the less populated VS, in the widely distributed SA13 (*Prasio majoris-Querco ilicis* Σ *quercetosum ilicis* and *phillyretosum*

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angustifoliae), we observed a much lower number of nuraghi than expected. Nuragic people probably avoided settling on this VS, as it consists of arid environments, often occurring on rocky and steep areas, which hamper agricultural and grazing practices.

Overall, our findings are in accordance with previous archaeological inquiries, mostly conducted at the local scale and selected archaeological sites (Depalmas, 2008; Depalmas & Melis, 2010; Mariani et al., 2022; Vanzetti et al., 2013). At the wider scale of the whole Sardinian region, we can confirm the importance of water availability and geomorphology. Climatic conditions also appeared as a driver of land occupancy. The role of water is unsurprisingly crucial, since, in the Mediterranean area, water is central to the concerns of its peoples, and nuraghi were always found in proximity to river networks or ponds (Mariani et al., 2022). Geomorphology also plays a major role: nuraghi occur in almost all the lithological classes but mostly on magmatic (basalt plateaus or volcanic rocks) and sedimentary rocks (Depalmas & Melis, 2010). On the contrary, alluvial and coastal deposits were avoided. This is probably related to building techniques: being heavy megalithic structures, nuraghi need a substrate strong and stable enough to bear their weight (Cappai & Pulina, 2017; Mariani et al., 2022). Additionally, they were mostly made from local stone blocks and could be transported over very short distances.

It should be noted that, although this research highlighted a significative association between nuraghi and VS distribution, it represents a first explorative perspective about vegetation-derived ES supply and demand/utilization of Nuragic people in Sardinia. Indeed, given the wide spatial and temporal scale of the analyses and the lack of important information (e.g. extensive paleobotanical data and written records from the Nuragic civilization), the risk is of drawing too general and deterministic conclusions about the human-nature relationship and eco-evolution of the Sardinian landscape that could be disproportionately used in informing policy. On the contrary, a local, topographical site scale analysis, where a historical explanation of 'placed environmental knowledge' is performed, is still of paramount importance in disentangling the complexity of the historical dynamics that have affected current ecosystems and their biodiversity, and from there inform conservation and ES policies (Cevasco, 2007; Cevasco et al., 2015; Grove & Rackham, 2001). Similarly, it is important to remind that this study does not aim at describing all the variables driving the distribution of nuraghi. Indeed, the spatial organization of a population is not only a function of environmental causes (e.g. VS), but also of socio-economic factors (French, 2010). Further analyses should be performed at the local scale and commenting on all the VS while accounting for socio-economic factors to disentangle the complexity that shaped the distribution of nuraghi across Sardinia.

5 | CONCLUSIONS

This paper suggests that the interaction between humans and vegetation in Sardinia is ancient, reciprocal and dynamic. Vegetation, together with the related environmental conditions, represented a driving force in the land occupation strategies of the Nuragic people, who preferred for their settlements, the mesophiluos cork oak VS and secondary the deciduous broad-leaved ones, which, with fresh climatic conditions on fertile substrates and gentle slopes on effusive magmatic rocks, can provide land for grazing and agriculture and several related ES. Conversely, the Nuragic land occupation likely shaped the vegetation and transformed the landscape into agro-silvo-pastoral systems.

FIGURE 4 A Nuraghe within the typical agro-silvo-pastoral landscape of Sardinia (Photo by Giuseppe Mozzo). [Corrections added on 17 March 2023, after first online publication: The figure 4 caption has been updated.]

Remarkably, our findings suggest that the origin of the current agro-silvo-pastoral landscapes (i.e. *Pascolo arborato*) in Sardinia can be traced back to the Nuragic civilization. These present landscapes, crowded with nuraghi (Figure 4), represent important suppliers of provisioning, regulating and cultural ES. Among others, they are a good example of intimate and sustainable relationships between people and nature and provide a marked sense of place for Sardinia inhabitants, which consider the Nuragic civilization, together with their heritage, as the foundation of the Sardinian feeling of historical and cultural identity.

Finally, this paper confirms the utility of incorporating archaeological knowledge in ES (and vice versa), which can enrich our understanding of the past and the present and potentially inform future practice for the region of Sardinia. Such a transdisciplinary approach linking plant ecology with archaeology, although challenged by the different and often contrasting languages and methodologies, offered archaeology a better understanding of the environmental settings and subsistence of the Nuragic civilization and provided plant ecology with a long-term perspective on human-vegetation interactions. Last but not least, this approach also pointed to alternative ways of using biodiversity maps, often confined to conservation or management applications.

AUTHOR CONTRIBUTIONS

Marco Malavasi, Simonetta Bagella and Manuele Bazzichetto conceived the ideas and designed the methodology; Manuele Bazzichetto, Marco Malavasi and Vojtěch Barták analysed the data; Marco Malavasi and Simonetta Bagella discussed the results

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in view of the vegetation domain and led the writing of the manuscript. Stefania Bagella, Anna Depalmas and Antonello Gregorini supervised the archaeological approach. Marta Gaia Sperandii and Alicia Acosta contributed to the writing, review and editing. All authors contributed critically to the drafts and gave final approval for publication.

ACKNOWLEDGEMENTS

The authors thank Clara Farina and Diego Corraine for the abstract translation in Sardinian language (Sa limba sarda comuna).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All the data and the R code for reproducing the spatial analysis can be found at: https://github.com/ManueleBazzichetto/Sardinia.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Supplementary Material 1: List of the land units identified in the map of VS of Sardinia (1:350,000) (Bacchetta et al., 2009).

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Supplementary Material 2: Lithological classes of Sardinia described with the first level of details.
Supplementary Material 3: Pair correlation function measuring the dependence between points (nuraghi) in a spatial point pattern.
Supplementary Material 4: Comparison between observed (blue bars) and expected (orange bars) under complete spatial randomness number of nuraghi for all the VS.

How to cite this article: Malavasi, M., Bazzichetto, M., Bagella, S., Barták, V., Depalmas, A., Gregorini, A., Sperandii, M. G., Acosta, A. T. R., & Bagella, S. (2023). Ecology meets archaeology: Past, present and future vegetation-derived ecosystems services from the Nuragic Sardinia (1700–580 BCE). *People and Nature*, *5*, 938–949. https://doi.org/10.1002/pan3.10461

25758314, 2023, 3, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.10461 by Csic Organización Central Om (Oficialia Mayor) (Urici), Wiley Online Library on [24/11/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License