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ORIGINAL ARTICLE

Studies on archaeological olive fruitstones from the Archaic and Punic periods (7th–3rd century BC) of Sardinia, Italy

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Abstract

Recent archaeological investigations in the lagunas di Santa Giusta and Mistras, waterlogged sites in central-west Sardinia, Italy, have enabled the recovery of archaeobotanical remains, exceptional in terms of quantity and preservation, dated to the Archaic and Punic periods in the 7th–3rd century BC. Among the finds was a significant amount of *Olea europaea* fruitstones (endocarps), which are discussed here. The morphometric features of these fruitstones, extrapolated by image analysis, were analysed statistically and compared to modern wild olive populations and cultivars. Thanks to the image analysis, it was possible to recognize the presence of *O. europaea* var. *sylvestris* (wild olive) and *O. europaea* var. *europaea* (cultivated olive) from the Archaic and Punic periods and to make suggestions about their use. Moreover, most of the cultivated type fruitstones identified by the statistical analysis can be attributed to a group of modern Sardinian cultivars, providing new data on the origin of cultivation and use of olives in Sardinia.

Keywords Archaic and Punic periods · Morphometry · Olive domestication · Waterlogged sites

Introduction

The genus *Olea* L. (olive) includes several species distributed over tropical and southern Africa, southern Asia and China, as well as Australia, New Caledonia and New Zealand (Mabberley 2017). Only *Olea europaea* L. ssp. *europaea* occurs in the Mediterranean region, in various wild (var. *sylvestris*), domesticated (var. *europaea*) and feral forms (Mulas 2013). As shown by various studies, oleaster, the wild form, is the only ancestor of the domesticated olive (Angiolillo et al. 1999; Lumaret et al. 2004; Breton et al. 2006, 2009; Zohary et al. 2012; Besnard et al. 2016, 2018). It grows naturally in a great part of the Mediterranean area, with a distribution range coinciding with the area with a typical Mediterranean climate, where it dominates the scrub (Bacchetta et al. 2003; Carrión et al. 2010). The domesticated olive covers a wider area, extending also to the northern regions of the Mediterranean (Carrión et al. 2010; Zohary et al. 2012), as well as other parts of the world with a suitable climate.

As shown from archaeological data both from the eastern and the western Mediterranean, wild olive before its domestication was used for its fruits and as a source of wood already during the Palaeolithic and Neolithic

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(Kislev et al. 1992; Buxó i Capdevila 1997; Terral 2000; Rodríguez-Ariza and Montes Moya 2005; Weiss 2009; Kaniewski et al. 2012; Besnard et al. 2018).

The first signs of olive domestication have been found at various Chalcolithic sites in the eastern Mediterranean; this makes the olive one of the first fruit trees to be domesticated in this region (Zohary et al. 2012). The most ancient find is from Tuleilat Ghassul, in Jordan north of the Dead Sea. A considerable number of olive stones were found there and have been attributed to the domesticated variety, and dated to 6,800–5,800 BP (Zohary and Spiegel-Roy 1975; Lovell et al. 2010; Zohary et al. 2012; Weiss 2015). Nevertheless, the origin of its domestication is still under debate (Besnard et al. 2018). Some studies hypothesise that during the Bronze Age, or even earlier, the domestication process fully developed in the southeast Mediterranean and Aegean regions and then gradually spread to the western Mediterranean (Terral et al. 2009; Zohary et al. 2012; Newton et al. 2014; Pérez-Jordà et al. 2017; Valamoti et al. 2018; Langgut et al. 2019; Livarda et al. 2021). For the northwestern part of the Mediterranean, the possibility of early independent episodes of domestication has also been suggested (Terral et al. 2004; Besnard et al. 2018).

Regarding the spread of *Olea* cultivation to the western Mediterranean, it is certain that Phoenicians and Greeks played an important role, taking domesticated olives from the eastern Mediterranean together with cultivation techniques to the west (Zohary et al. 2012). Nevertheless, it seems that the domestication process in this area was more complex, and it is not yet completely understood. Genetic and morphometric analyses have been used to study the complex processes that led to the different olive varieties and cultivars and to describe them (Baldoni et al. 2006; Breton et al. 2006, 2009; Belaj et al. 2011; Muzzalupo et al. 2014; Besnard et al. 2016). These studies suggest that the cultivated olive was introduced to the western Mediterranean from the east (Besnard et al. 2018). However, secondary domestication events may also have taken place, in which local wild varieties could have been domesticated at various times and in different places from those where olives were first domesticated (Hancock 2012). There are hints for early domestication on the Iberian Peninsula since the Bronze Age (Terral et al. 2009) as well as on the Italian Peninsula (D'Auria et al. 2017). Numerous hybridisations between introduced varieties or cultivars and local oleasters might then have followed in different regions throughout the millennia (Breton et al. 2009; Newton et al. 2014; Besnard et al. 2018). During the 1st millennium BC, domesticated olives would have spread to almost all parts of the Mediterranean basin (Zohary et al. 2012). Later, during the Roman Empire, the cultivation of olives and trade in olive products gradually increased; at its peak, the production of olive oil in the Roman world could have reached up to a billion litres per year (van der Veen 2018).

Olives are stone fruits composed of several different layers: the outer and middle ones are the epicarp and mesocarp, and the inner layer is the endocarp or fruitstone, which encloses the seed (Cappers and Bekker 2013). The endocarp represents almost the only type of olive macrofossil remains other than charcoal found in archaeological excavations.

Olive growing is nowadays one of the most important features of Italian agriculture, and also one of the most ancient ones (Caracuta 2020). In Sardinia, oleaster is found in the natural vegetation (Bacchetta et al. 2003) and domesticated olives are widely cultivated (Bandino and Sedda 2013; Piras and Lovicu 2013; Chessa 2013). Various episodes of the introduction of domesticated plants to Sardinia from different parts of the Mediterranean could have occurred throughout history because of its central position, which could have facilitated contacts with different areas, and due to the many colonisation and conquest events there (Erre et al. 2010; Cossu 2013; De Santis 2013; Ferrante 2013).

Currently, according to the FAO Olive Germplasm Plant Production and Protection Division, the world olive germplasm contains some 2,600 cultivars, many of which require better identification and characterisation (FAO 2010). The presence of homonyms and synonyms, as well as the different states of research in different regions, can generate misunderstanding in their classification, although genetic analysis is a reliable tool to correct misclassifications (Ganino et al. 2006; Díez et al. 2012; Muzzalupo et al. 2014; Belaj et al. 2016; El Bakkali et al. 2019; Khadari et al. 2019). A continuous improvement of the classifications is necessary for better use, selection and propagation choices.

Morphometric features involving the different characteristics of the fruitstones are currently used to define the cultivars (Ganino et al. 2006). Computerised image analysis of olive fruitstones is particularly suitable, as these do not seem to undergo significant variations from different environmental conditions and cultivation techniques, reducing the number of factors that could influence the measurements (Terral et al. 2004; Belaj et al. 2016). Therefore, morphometric analysis can be used to compare the shapes and dimensions of archaeobotanical remains with modern specimens, with the great advantage of using a low cost and non-destructive method (Newton et al. 2006, 2014; Terral et al. 2009; Bourgeon et al. 2018).

Various approaches have already been used in studies of the olive germplasm (Bronzini de Caraffa et al. 2002; Baldoni et al. 2006; Erre et al. 2010; Muzzalupo et al. 2014). For example, in a recent study on Sardinian olives, Piras et al. (2016) successfully applied morpho-colorimetric techniques, which have also proved useful for other plant species, such as *Vitis vinifera* L. (Orrù et al. 2013; Ucchesu et al. 2015), *Prunus domestica* L. (Sarigu et al. 2017; Frigau et al. 2020) and *Malus domestica* Borkh. (Sau et al. 2018, 2019).

The present study investigated archaeological olive fruitstones found in the archaeological contexts of the lagunas di Santa Giusta and Mistras in Sardinia, dated to the Archaic and Punic periods, covering a time span from the 7th to the 3rd century BC. The morphometric characteristics of the archaeological olive fruitstones were measured by digital image analysis, and their characteristics were compared to those of stones from modern wild and cultivated olives by linear discriminant analysis (LDA). The aims were to obtain information about the presence of cultivated olives during the Archaic and Punic periods in Sardinia and to discover the similarities between the archaeological remains and modern cultivars to obtain hints about their origins.

Materials and methods

Archaeological contexts

The lagunas di Santa Giusta and Mistras are located in the central and the northern part of the Gulf of Oristano (Fig. 1).

The laguna di Santa Giusta is situated next to the ancient city of Othoca, one of the most important settlements during the Archaic and Punic period in Sardinia (Del Vais 2010). The lagoon, with depths from 40 to 150 cm, has an approximately circular shape and an area that in winter reaches 900 ha. The Soprintendenza Archeologica per le Province di Cagliari e Oristano and the University of Cagliari investigated the site since 2005 through underwater surveys, coring of the sediments and stratigraphic excavations that have enabled a good reconstruction of the deposition sequences (Del Vais and Sanna 2009, 2012). The investigations showed the presence of a large area of dispersed archaeological material, mainly transport amphorae and worked wood at least in part from a ship, lying in the middle of the lagoon under a thick layer of mud. Two main phases of site formation have been detected up to now, with deposits dating to the 6th–5th and the third-second centuries cal BC (Del Vais and Sanna 2009, 2012; Del Vais 2018). The interpretation of the site is still debatable; the deposit may have been formed by natural events such as flood episodes that caused the loss and deposition of materials from a harbour (Del Vais and Sanna 2009, 2012, 2019). The pieces of wood, which provided radiocarbon dates, were all very well preserved. Therefore the excavators suggested that only a little time could have passed between the formation of the sites and the deposition of the covering sediment that provided the anaerobic conditions necessary for the preservation of the organic material (Del Vais and Sanna 2012). Geomorphological studies are being done to understand the ancient shape and development of the lagoon and coastline; they will also help in reconstructing and interpreting the formation of the archaeological site. Several transport amphorae, most of them unbroken, were recovered during the excavations and the sediment inside them was sieved to recover remains of their contents (Sabato et al. 2019).

Fig. 1 Locations of the excavation areas in the lagunas di Santa Giusta and Mistras, central-western Sardinia

Laguna di Mistras has been identified as the harbour of the city of Tharros from the 7th until the 3rd century BC (Pascucci et al. 2018; Del Vais et al. 2020). The lagoon, elongated in shape and parallel to the shore was partially closed by a coastal barrier. In 2009, the Soprintendenza Archeologica and the University of Cagliari made a survey inside the lagoon to investigate a submerged structure, identified as an artificial barrier dating to the Punic period. The various materials found in the area and their contexts cover a broad time span reaching from the late Punic period to the first centuries of the Roman era (Pascucci et al. 2018). However, the macrofossil remains considered here were found in association with materials dating to the 3rd–2nd century BC (Del Vais et al. 2020), which seems their most probable age, in good correlation with the radiocarbon dates from other organic material found in the area (Pascucci et al. 2018). During 2014 and 2015, the University of Cagliari excavated in two different parts of the sandy barrier located inside the lagoon, a former beach. According to the preliminary results, the stratigraphic units from which the materials for the present study were sampled date from the 7th to the 4th century BC (Pascucci et al. 2018). However, as many of the finds from the excavation campaigns are still under study, the dating of the different layers of the sites is not yet certain. In any case, the archaeological and geomorphological investigations suggest that the area was in use since the 7th century cal BC. The artificial barrier investigated in 2009 was built as early as the 4th century cal BC to create a protected area for the boats. Its construction contributed to

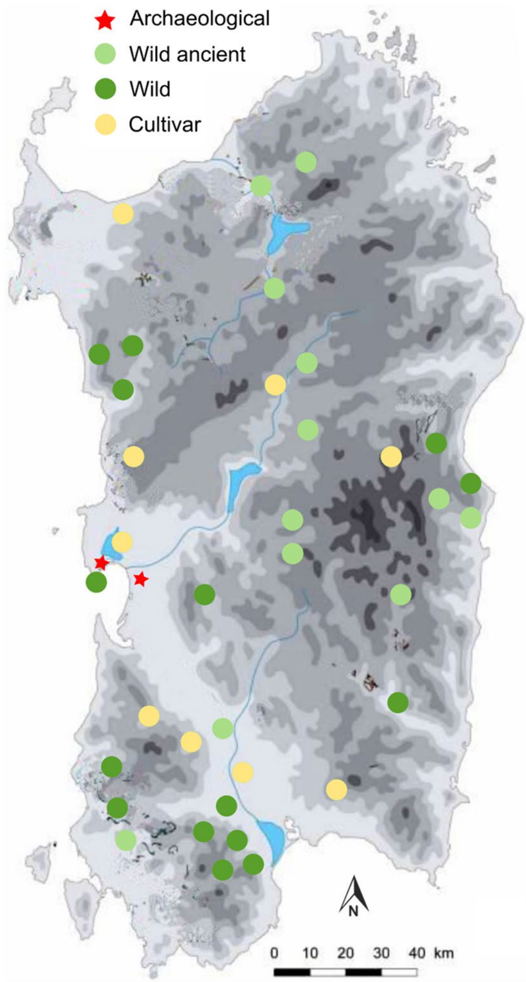

Fig. 2 Sampling locations of archaeological remains, ancient wild, younger wild and cultivated olives

the accumulation of the sediments in the area and the development of a palaeobeach. The lagoon finally silted up and was already abandoned during the Roman Imperial period (Pascucci et al. 2018). The archaeological material found on the three sites investigated in Mistras is represented by potsherds, especially of transport amphorae, and by animal bones, wood and plant macroremains.

Modern reference samples

The modern olive fruitstones used in this study as reference samples were collected from wild ancient trees, wild populations and from cultivars (Fig. 2, ESM Table 1). The samples collected from these ancient trees come from 15 different locations, where the trees for the collection were chosen, taking into consideration their monumental dimensions, from 3 to 12.6 m in circumference measured at 1.3 m from the ground (Fig. 2, ESM Table 1). According to their location and size, they can be considered as very old wild olives, and not feral forms (Piras et al. 2016).

Fruits of *O. europaea* var. *sylvestris* (oleaster) were collected from 18 wild young populations selected for their maximum distance and isolation from cultivated areas, to try and avoid possible hybrids, at least as much as possible (Fig. 2; Piras et al. 2016). Furthermore, olives from 62 cultivars were sampled in several different years from the field collections of Agris Sardegna (the agricultural research agency of Sardinia) and in olive groves in the main growing areas. The cultivars sampled as comparative material are representative of the olive diversity of the entire Mediterranean basin, as the main cultivars from Spain, France, Italy, Tunisia, Greece and Turkey were analysed (ESM Table 1). Sardinian germplasm in particular is represented by 23 cultivars, enabling a more detailed analysis. The cultivars were grouped according to their similarity to the groups of varieties and certified by their genetic affinities (Erre et al. 2010; Bandino and Sedda 2013; Chessa 2013; Olea databases 2021 (ESM Table 2).

Fruits were collected from different trees within the same population of the wild olives, and of the same variety of the cultivars, to ensure the greatest morphological variability within each; they were sampled in autumn when the olives were fully ripe, to ensure the complete morphological development of the fruitstones. Then the fruit flesh (exocarp and mesocarp) was removed and the fruitstones thoroughly cleaned. In total 10,919 modern olive stones were included in the analysis.

Archaeological samples

Olive fruitstones, well preserved thanks to the waterlogged and anaerobic conditions at the sites, were recovered both from the lagunas di Santa Giusta and Mistras (Fig. 3). The material from Santa Giusta came from four transport amphorae, typical of the Sardinian Phoenician and Punic traditions (Ramon Torres 1995). The most ancient ones are finds A158 and A97 and their study enabled A158 to be identified as type Ramon T-1.2.1.2. (Del Vais and Sanna 2012), dated to the first two thirds of the 6th century BC (Ramon Torres 1995), while A97 was identified as type T-1.4.4.1. (Del Vais and Sanna 2012), dated to the 5th century BC (Ramon Torres 1995). The other two amphorae, A153 and A230, are the elongated type T-5.2.1.3, dated to the 3rd–2nd century BC (Ramon Torres 1995; Del Vais and Sanna 2012). The dating is also confirmed by the stratigraphy of the context (Del Vais and Sanna 2009, 2012). A total of 14 olive fruitstones were found inside the amphorae from Santa Giusta.

In the Mistras material, 44 and 53 fruitstones respectively from the 2014 and 2015 excavation campaigns were found from the sampling and sieving of the sediment. The finds came from different layers (SU 26, 31, 32, 34 and 35 of the

Fig. 3 The archaeological fruitstones analysed. **a**, Mistras 2009; **b**, Mstras 2014; **c**, Mistras 2015; **d**, Santa Giusta; scale bar = 1 cm; photos by Ignazio Sanna

Table 1 Sites, samples and fruitstones from the lagunas de Santa Giusta and Mistras

Site	Amphora/stratigraphic unit	Group code	Date c. BC	Nr. fruitstones
Santa Giusta	SGT-ST ANF 158	SGT-ST A	6th–5th	3
	SGT-ST ANF 97			3
	SGT-ST ANF 230	SGT-ST B	3rd–2nd	4
	SGT-ST ANF 153			4
Mistras 2014	MIS14 Section	MIS14	7th–5th	4
	MIS14 US26			3
	MIS14 US31			11
	MIS14 US32			9
	MIS14 US34			7
	MIS14 US35			6
Mistras 2015	MIS15 US24	MIS15	6th–4th	8
	MIS15 US25			23
	MIS15 US26			22
Mistras 2009	MIS09	MIS09	3rd–2nd	29

The broad date range is given according to the preliminary results, as the site data are still being studied

2014 excavation and SU 24, 25 and 26 of the 2015 excavation). Another 29 olive fruitstones were recovered from the 2009 Mistras underwater excavation.

In order to maintain the good preservation of the fruitstones, after their recovery they were stored in de-ionized water at 5 °C in the Sardinian Germplasm Bank (BG-SAR) (Porceddu et al. 2017). A total of 139 archaeological olive stones were analysed (Table 1).

Image analysis

Digital images of all the archaeological and modern fruitstones were acquired using an Epson Perfection V550 flatbed scanner with a resolution of 400 dpi, on a scanning area not exceeding 1,024×1,024 pixels. Each accession was scanned twice, first with a white and then a black background (Bacchetta et al. 2008).

The images were then processed and the morphometric parameters of each fruitstone were measured with the ImageJ v. 1.52 open-source software (http://rsb.info.nih.gov/ij).

The plugin Particles8 (http://www.mecourse.com/landinig/software/software.html) was used to measure 26 morphometric variables on each fruitstone (Table 2, Fig. 4).

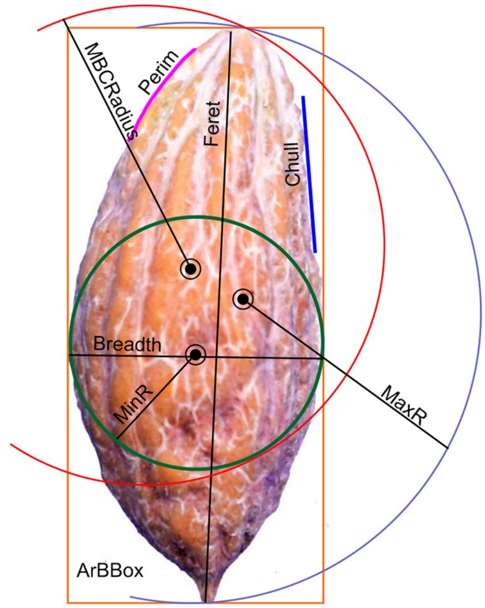

Fig. 4 The principal morphometric features measured on each fruitstone; the terms are described in Table 2

Table 2 List of morphometric dimensions measured on each olive fruitstone

Parameter	Description
Perim	Perimeter, calculated from the centres of the boundary pixels
Area	Area inside the polygon defined by the perimeter
Pixels	Number of pixels forming the endocarp image
MinR	Minimum radius of a circle centred on the middle of the fruitstone
MaxR	Maximum radius of a circle centred on the middle of the fruitstone
Feret	Greatest axis length
Breadth	Greatest axis breadth
CHull	Convex hull or convex polygon calculated from pixel centres
CArea	Area of the convex hull polygon
MBCRadius	Radius of the minimal bounding circle
AspRatio	Aspect ratio, = length/breadth
Circ	Circularity = 4·π·area/perimeter^2
Roundness	Roundness = 4·area/(π·length^2)
ArEquivD	Area equivalent diameter = $\sqrt{}$((4/π)·area)
PerEquivD	Perimeter equivalent diameter = area/π
EquivEllAr	Equivalent ellipse area = (π·length·breadth)/4
Compactness	Compactness = $\sqrt{}$((4/π)·area)/length)
Solidity	Solidity = area/convex_area
Concavity	Concavity = convex_area-area
Convexity	Convexity = convex_hull/perimeter
Shape	Shape = perimeter^2/area
RFactor	RFactor = convex_hull/(length·π)
ModRatio	Modification ratio = (2·MinR)/length
Sphericity	Sphericity = MinR/MaxR
ArBBox	Area of the boundary box around the diameter = length·breadth
Rectang	Rectangularity = Area/ArBBox

Statistical analysis

All the morphometric variables were used to build a database of the descriptive features of the fruitstones. Linear discriminant analysis (LDA) was then used to compare the archaeological examples, considered as unknown cases, to the modern ones. LDA was done with SPSS v. 27.0.1.0 statistical software. LDA is generally used to identify or classify unknown groups characterised by quantitative and qualitative parameters (Fisher 1936, 1940; Sugiyama 2007); it allows minimising the between-class distance and maximising the within-class distance, achieving maximum class discrimination (Hastie et al. 2001; Holden et al. 2011; Rencher and Christensen 2012; Kuhn and Johnson 2013).

For the LDA, Wilk's Lambda method was used with the following default values: for the variable entering the model, $F \geq 3.84$ was set, and for the variable removed from the model, it was $F \leq 2.71$ (Venora et al. 2009). Cross-validation was also used, to verify the performance of the validation system. Before applying the linear discriminant analysis, all data were standardised. In addition, a Box M test was done to evaluate the homogeneity of the covariance matrices of the variables used for the LDA. For the verification of the homoscedasticity (equality) of the variance of the dependent variables, the standardised residual was estimated (Haberman 1973; Morrison 2004). To compare the empirical distribution of discriminant functions and their cumulative distribution, the Kolmogorov–Smirnov test was used. Finally, Levene's test was done to evaluate the equality of the discriminating functions (Levene 1960).

Results

Discrimination between wild and cultivated olive in the modern reference material

Figure 3b–d show the frequency and dispersion of the standardised residuals, as well as the normal probability plot (PP) between the cumulative probability expected and observed, according to the statistical tests mentioned above. The Kolmogorov–Smirnov test showed a significance value lower than 0.05. Before comparing archaeological remains with modern reference material, discrimination analysis of *Olea europaea* ssp. *europaea* var. *europaea* (cultivated olive) and *Olea europaea* ssp. *europaea* var. *sylvestris* (oleaster) was done, and an overall 95.6% correct identifications was found (Table 3, Fig. 5).

Figure 3a shows the LDA results from the modern reference material of the two subspecies of *O. europaea,* olive and oleaster. The two discriminant functions achieved by the stepwise process only included 11 of the 26 measured morphometric features. The first five discriminant features are shown in ESM Table 3, with the respective values of F-to-remove, Wilks' test and Lambda, which can be used to compute the canonical variable score of the two discriminant functions.

Discrimination of archaeological remains

To determine the differences and similarities among the remains found in the various amphorae from Santa Giusta and the two different archaeological areas at Mistras, discriminant analysis was applied. The analysis of the measurement data from the fruitstones found in the amphorae, grouped according to their provenance and chronology (SGT-ST A, SGT-ST B) showing a good discrimination of the samples and 85.7% of the stones could be identified correctly, 66.7% of the SGT-ST A remains and 100% of SGT-ST B ones (Table 4).

A second comparison was made between the fruitstones found in the two different areas of Mistras. The discriminant analysis correctly identified 70.5% of the remains from Mistras 2014 and 73.6% from Mistras 2015 (Table 5).

Comparison of archaeological remains with modern reference material: cultivars and wild groups

Next, the five groups of archaeological remains (Mistras 2009, 2014, 2015, Santa Giusta SGT-ST A and SGT-ST B) were inserted into the model as unknown groups and

Table 3 Percentages of correct identifications of modern *Olea europaea* ssp. *europaea* var. *europaea* and *Olea europaea* ssp. *europaea* var. *sylvestris* fruitstones as well as of the archaeological remains from Mistras 2009, Mistras 2014, Mistras 2015 and Santa Giusta; in brackets, the numbers of items analysed, in bold, the highest values of correct identification

	O. europ. ssp. *europ.* var. *europaea*	*O. europ.* ssp. *europ.* var. *sylvestris*	Total
O. europ. ssp. *europ.* var. *europaea*	**95.9** (7,523)	4.1 (325)	100 (7,848)
O. europ. ssp. *europ.* var. *sylvestris*	5.3 (143)	**94.7** (2,435)	100 (2,678)
Cross-validated			95.6% (10,526)
Mistras 2009	**69.0 (20)**	31.0 (9)	100 (29)
Mistras 2014	31.8 (14)	**68.2 (30)**	100 (44)
Mistras 2015	**54.7 (29)**	45.3 (24)	100 (53)
Santa Giusta (SGT- ST A)	16.7 (1)	**83.3 (5)**	100 (6)
Santa Giusta (SGT- ST B)	–	**100.0 (8)**	100 (8)
Cross-validated			95.6% (10,666)

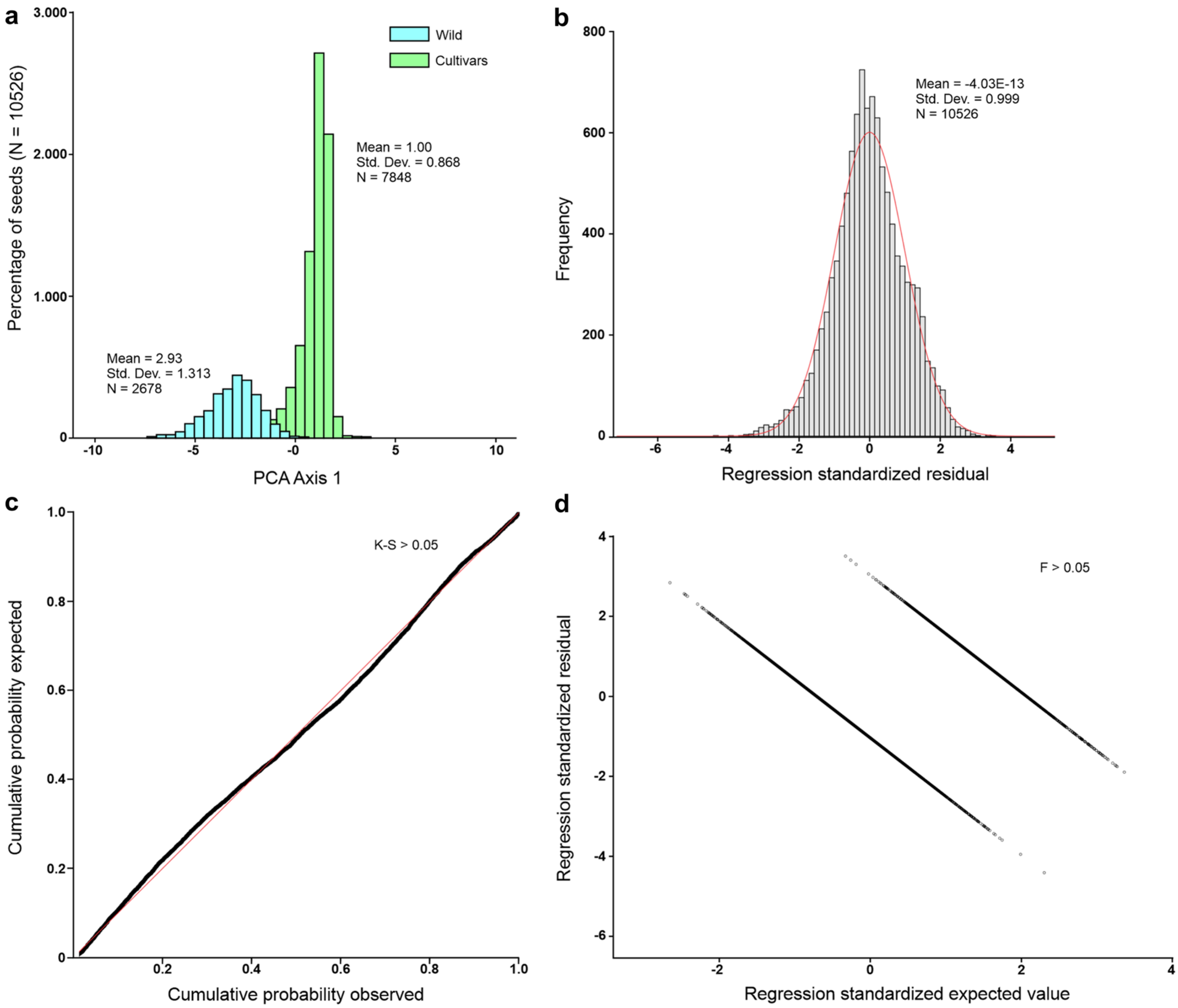

Fig. 5 **a** Graphs showing the discriminating function scores for *Olea europaea* ssp. *europaea* var. *europaea* and *Olea europaea* ssp. *europaea* var. *sylvestris*; **b**, histogram of the standardized residuals; **c**, dispersion plot of the standardized residuals, from Levene's test (F); **d,** normal probability plot (P–P) from Kolmogorov–Smirnov's test (K–S)

compared with the modern reference samples of cultivated and wild olives (Table 3).

The SGT-ST A remains were identified by LDA as 16.7% cultivated and 83.3% wild (Table 5, Figs. 4 and 5), but those from SGT-ST B were 100% in the wild group (Table 3, Figs. 4 and 5). For the Mistras 2009 remains, 69% were identified as cultivated olives and 31% as wild type (Table 5, Fig. 4). Cultivated olives were 31.8% and wild type 68.2% of the material from Mistras 2014 and 54.7% and 45.3% from Mistras 2015 (Table 3, Figs. 6 and 7).

Table 4 Percentages of correctly identified archaeological olive stones from Santa Giusta; for further explanations see caption of Table 3

	SGT-ST A	SGT-ST B	Total
SGT-ST A	**66.7 (4)**	33.3 (2)	100.0 (6)
SGT-ST B	–	**100.0 (8)**	100.0 (8)
Cross validated			85.7% (14)

Table 5 Percentages of correctly identified archaeological olive fruitstones from Mistras 2014 and Mistras 2015; for further explanations see caption of Table 3

	Mistras 2014	Mistras 2015	Total
Mistras 2014	**70.5** (31)	29.5 (13)	100 (44)
Mistras 2015	26.4 (14)	**73.6** (39)	100 (53)
Cross validated			72.2% (97)

Comparison of archaeological fruitstones assigned by LDA to wild and cultivar groups with each single accession of modern reference material

The archaeological fruitstones identified as wild type were compared to individual modern wild populations in Sardinia (Table 6).

The remains from the SGT-ST A, SGT-ST B and Mistras 2009 material contained the most wild type fruitstones. Those from SGT-ST A matched the populations of wild ancient olive trees CU_M, LA_M and OZ_M and the modern wild population CL (Table 6). The fruitstones from SGT-ST B matched the populations of wild ancient olive trees LA_M, OZ_M and VI_M (Table 6). Those from Mistras 2014 and 2015 both mostly matched OZ_M. Some other Mistras 2014 stones matched AR and CD, but others from Mistras 2015 showed the highest resemblance to CU_M (Table 6). The nine fruitstones from Mistras 2009 matched those from wild ancient olive trees, but not clearly any one population (Table 6).

Finally, the archaeological remains of cultivated olives were compared to the individual modern cultivar accessions (Table 7).

We attributed varying percentages of the archaeological fruitstones to several modern accessions. Except in the case of Santa Giusta, from where only one fruitstone was classified as cultivated type, the other remains had a general similarity to a large number of modern cultivars, but not any particular one (Table 7). Thus, the majority of the cultivated type fruitstones from Mistras 2009, 2014 and 2015 seem to show morphometric similarities to the modern varieties LE, MAN, MO, SG4, CAS, KON, COR, CU and MAI (ESM Table 2), but some from Mistras 2009 and 2015 matched NU (Table 7).

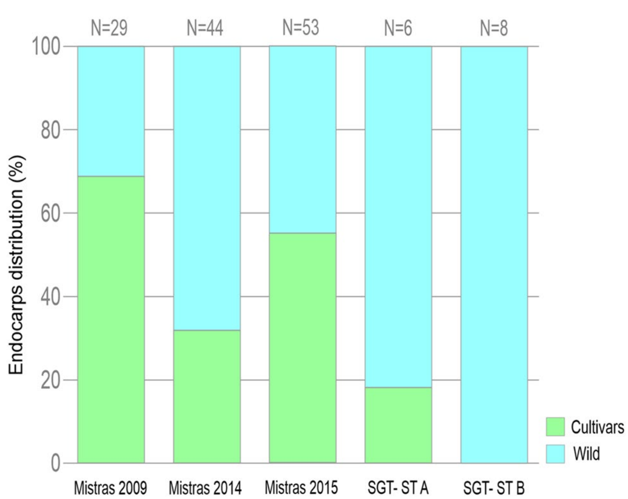

Fig. 6 Bar charts showing the percentages wild type and cultivated type fruitstones identified by LDA from the sites

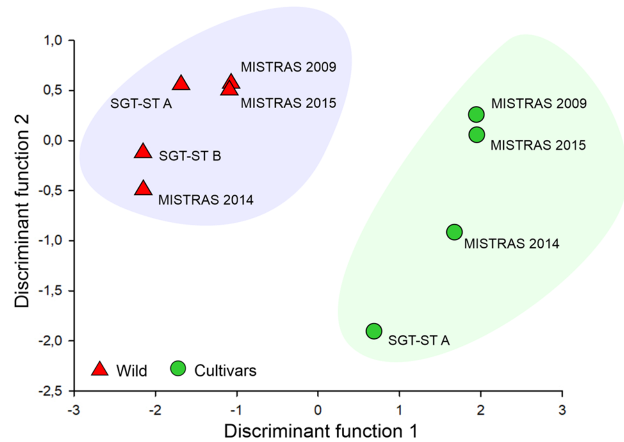

Fig. 7 Scatter diagram showing the discriminating function scores of the wild and cultivated type fruitstones, represented by the average of their coordinates (centroid)

Discussion

The comparison between the archaeological olive remains from Santa Giusta and Mistras and modern material from ancient wild trees, wild olives and modern cultivars shows various aspects of the olives in the Archaic and Punic periods in Sardinia. In the case of the Santa Giusta material, statistical analysis has revealed how the remains from SGT-ST A (6th–5th c. BC) and SGT-ST B, (3rd–2nd c. BC) can be separated into two groups according to their chronology, with little misidentification. Both groups were recognised as wild olives, except one stone from SGT-ST A, which was classified as cultivated and similar to the cultivar PE. The wild type fruitstones had most similarity to the modern wild olive types from ancient trees, OZ_M in the case of SGT A and VI_M for SGT B. However, significant similarities were also found with other accessions, from both ancient and younger wild trees, and therefore a precise match cannot be reported.

The remains from the various excavations in laguna di Mistras provided rather different results. Comparison between the remains from similar contexts in Mistras 2014 and 2015, dating to the Archaic and Punic periods (7th–4th c. BC) showed a certain amount of similarity between the samples.

The majority of the remains from Mistras 2014 were identified as wild type; those from Mistras 2015 were half

Table 6 Percentages of correctly identified archaeological olive fruitstones from Santa Giusta, Mistras 2014 and 2015 compared to the modern wild populations in Sardinia; for further explanations see caption of Table 3

Code	Correct classification of modern wild	Archaeological endocarps allocation				
		SGT-ST A (5)	SGT_ST B (8)	MISTRAS 2014	MISTRAS 2015	MIS09 (9)
AT_M (48)	2.1 (1)	–	–	3.6 (1)	–	11.1 (1)
BA_M (12)	83.3 (10)	–	–	–	–	–
GP_M (36)	19.4 (7)	–	–	–	–	–
BO_M	25.0 (3)	–	–	3.6 (1)	–	–
CU_M (12)	66.7 (8)	20.0 (1)	–	–	15.4 (4)	11.1 (1)
LA_M	41.7 (5)	20.0 (1)	12.5 (1)	7.1 (2)		11.1 (1)
OZ_M (11)	63.6 (7)	40.0 (2)	12.5 (1)	**21.4 (6)**	**19.2 (5)**	–
PA_M (12)	50.0 (6)	–	–	–	–	–
US_M (12)	63.6 (7)	–	–	3.6 (1)	–	–
LU_M (12)	8.3 (1)	–	–	3.6 (1)	–	–
SS_M (228)	24.2 (55)	–	–	3.6 (1)	7.7 (2)	11.1 (1)
SA_M (36)	13.9 (5)	–	–	–	3.5 (1)	–
SE_M (36)	25.0 (9)	–	–	–		–
VI_M (23)	47.8 (11)	–	25.2 (2)	7.1 (2)	7.7 (2)	11.1 (1)
MN_M (60)	35.0 (21)	–	–	–	–	11.1 (1)
AR (120)	30.8 (37)	–	–	10.7 (3)	3.8 (1)	–
BO	4.2 (5)	–	–		–	–
CD (144)	22.0 (29)	–	–	10.7 (3)	–	–
CL (126)	3.2 (4)	20.0 (1)	–	3.6 (1)	–	–
GP (120)	2.5 (3)	–	–	–	–	–
SP (108)	14.8 (16)	–	–	–	3.8 (1)	–
IC (117)	20.5 (24)	–	–	–	–	–
MA (119)	9.3 (11)	–	–	–	–	–
MF (120)	1.7 (2)	–	–	–	–	–
PS (119)	26.9 (29)	–	–	–	–	–
SM (120)	84.3 (97)	–	–	3.6 (1)	–	–
SN (120)	3.4 (4)	–	12.5 (1)	–	3.8 (1)	–
SE	0.0 (0)	–		–	–	–
CS (119)	15.0 (15)	–	12.5 (1)	7.1 (2)	–	–
TE (83)	6.0 (5)	–	–	3.6 (1)	–	–
TR (131)	12.7 (14)	–	–	–	7.7 (2)	–
PAW (195)	19.5 (38)	–	12.5 (1)	–	7.7 (2)	–
VI (92)	50.0 (46)	–	12.5 (1)	7.1 (2)	**19.2 (5)**	–
Overall 20% (2,678)						

wild type and half domesticated type, whereas those from Mistras 2009 were mostly cultivated morphotypes. In a more detailed comparison, the archaeological remains with wild features resembled a wide range of modern wild accessions, while the remains of cultivated olives likewise resembled various modern cultivars.

From the archaeological point of view, it should be kept in mind that both sites were to some degree related to the transport of goods and, in the case of Mistras, recognised as a possible harbour. Therefore, the presence of imported material is possible, although the association of the olive remains with other archaeological finds that are mostly recognisable as local products suggests that the olives were also local, or at least regional, either wild or cultivated. In any case, some of the remains were clearly of cultivated olives. As stated by Sabato et al. (2019), the association of olive stones with transport amphorae could be an indication of their transport as fruits or their use as ingredients of prepared food products. On the other hand, as the contexts were clearly not production sites, it is not possible to comment on extraction of oil.

It should be noted that in the case of the transport amphora A97 from Santa Giusta, other remains as well as the olive stones were found. It contained one *Prunus domestica* (plum) fruitstone, *Pinus pinea* (stone pine) and *Corylus*

Table 7 Percentages of correctly identified archaeological olive fruitstones from Santa Giusta, Mistras 2014 and 2015 compared to the modern cultivars in Sardinia; for further explanations see caption of Table 3

Code	Correct classification of modern cultivars	Archaeological endocarps allocation			
		SGT_ST A (1)	MIS09 (22)	MIS 2014 (14)	MIS 2015 (29)
SG1	18.1 (74)	–	–	–	3.4 (1)
CA	13.8 (30)	–	–	7.1 (1)	–
SG2	15.7 (54)	–	–	–	–
G1	25.7 (55)	–	–	–	–
SG3	5.1 (11)	–	–	–	–
HB	56.9 (120)	–	–	–	–
KA	41.7 (90)	–	–	–	–
KO	52.3 (114)	–	–	–	–
LE	10.1 (22)	–	10.0 (2)	7.1 (1)	6.9 (2)
MAN	43.4 (92)	–		7.1 (1)	6.9 (2)
MO	36.4 (78)	–	5.0 (1)	–	3.4 (1)
SG4	21.5 (162)	–	–	7.1 (1)	3.4 (1)
NB	56.9 (123)	–	–	–	–
SG5	13.7 (123)	–	–	–	–
NE	45.2 (98)	–	–	–	–
PE	60.9 (70)	100 (1)	–	14.3 (2)	–
PI	49.3 (107)	–	–	–	–
SG6	39.6 (90)	–	–	–	–
SEM	39.4 (85)	–	–	–	–
SV	19.0 (40)	–	–	–	–
AS	15.3 (15)	–	–	–	–
BC	60.7 (51)	–	–	–	–
BS	29.0 (29)	–	–	–	–
CAR	74.7 (71)	–	–	–	–
CAS	68.4 (67)	–	15.0 (3)	–	3.4 (1)
KON	29.6 (29)	–	–	7.1 (1)	6.9 (2)
COR	40.0 (38)	–	–		10.3 (3)
CU	24.5 (24)	–	5.0 (1)	7.1 (1)	6.9 (2)
ER	17.0 (17)	–	5.0 (1)		
LEU	46.0 (46)	–	–	7.1 (1)	6.9 (2)
LU	23.2 (23)	–	–		3.4 (1)
MAI	35.4 (35)	–	20.0 (4)	21.4 (3)	10.3 (3)
MAU	25.0 (26)	–	–	7.1 (1)	–
MEM	54.2 (52)	–	–	–	–
NM	24.2 (22)	–	5.0 (1)	–	–
NO	52.3 (46)	–		–	–
NU	40.6 (39)	–	35.0 (7)	–	17.2 (5)
OL	42.9 (9)	–	–	–	–
PAS	22.7 (10)	–	–	–	–
PIC	24.0 (23)	–	–	–	6.9 (2)
SF	57.6 (57)	–	–	7.1 (1)	
TI	30.0 (30)	–	–	–	3.4 (1)
UP	59.6 (56)	–	–	–	–
Overall 31.3% (7,968)					

avellana (hazel nut) remains, as well as zooarchaeological remains (Ucchesu et al. 2017). This kind of mixture of plant and animal products has also been found in other contexts from Santa Giusta and other Archaic and Punic contexts in Sardinia (Vivanet 1892, 1893; Pallarès 1986; Moscati 1991; Poplin 2014; Ucchesu et al. 2017; Del Vais and Sanna 2009, 2012, 2019; Sabato et al. 2019; Sanna 2019).

Our knowledge of the state of agriculture and the use of plants in the ancient world has grown considerably from archaeobotany in the last few decades. In the case of Sardinia, several studies have already shown the importance of fruit growing in the local agriculture, including *Vitis vinifera* (grapevine) since the Bronze Age (Ucchesu et al. 2015), *Prunus domestica* from the Phoenician and Punic periods (Ucchesu et al. 2017) and a variety of other fruits, among which *O. europaea* has already been mentioned (Del Vais and Sanna 2009, 2012; van Dommelen et al. 2018; Sabato et al. 2019). Moreover, the past presence of *O. europaea* in the area of Tharros and Mistras is already known thanks to results from studies of pollen, charcoal and wood remains, even if these techniques cannot separate wild and domesticated olives (Nisbet 1980; Lentini 1997; Acquaro et al. 2001; Di Rita and Melis 2013; Mureddu et al. 2020). Our results also agree with those from other parts of the western Mediterranean, which have shown the important roles of the eastern and western Phoenicians (Punic people) and the Greeks; this is particularly true for the development of gardening and the importance of fruit growing (Pérez-Jordà et al. 2017, 2021). This study adds some significant information about the olive, which has great agricultural and economic value at the global scale.

Conclusions

The morphometric analysis of the olive fruitstones from the lagunas di Santa Giusta and Mistras has provided data that are useful for clarifying the state of olive domestication in Sardinia during the Archaic and Punic periods. The use or at least the presence of wild olives was detected from the two contexts, and a high percentage of domesticated olives was found from the Mistras contexts. The results show the presence of domesticated olives in Sardinia at least since the Archaic and Punic periods. Further analysis and improvements to the database of archaeological and modern olive fruit-stone dimensions will be useful in future investigations for a better reconstruction of the history of olive domestication and for understanding the origins of the modern cultivars.

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