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Down with the roots. Phytoliths as biocultural traces in historical olive agroecosystems of Sicily

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Within the multidisciplinary framework of historical ecology, in this study plant morphology, oral history, and soil analyses are combined with phytoliths to reconstruct shifts in management and environment of historical and living olive agroecosystems on the island of Sicily (Italy). The use of phytoliths in the study of historical agroecosystems is still a developing field. We present the collaborative work done on three historical olive agroecosystems (Bosco Pisano, a wild olive wood; Cozzo del Lampo, a Mediterranean olive orchard; Malìa, remnant of past agroforestry), where we have collected and analyzed phytolith assemblages to trace correlations between environmental dynamics and (agri)culture, as unfolding over the latest six millennia. We demonstrate that the cumulative ecological legacies in historical agroecosystems are traceable through phytolith analyses. Bosco Pisano allows for a calibration of the tree cover density, based on phytolith evidence. Meanwhile, Cozzo del Lampo and Malìa have evolved from a shrubland-type of environment to fruit gardens and open grasslands, with establishment of olive trees in between as key vegetation elements. Both these examples show the longevity of combined land uses, especially the grazing adapted olive cultivation in Malìa. In gaining clues on clear variations in land use, as abandonment and intensification, our results demonstrate that phytoliths can shed light also in local past intercultural exchange of knowledge. The integrated methodology presented here allows to appreciate how the biological and cultural diversity in historical agroecosystems has shaped their current state and inspires present-future management.

KEYWORDS

plant morphology, *Olea*, past analogues, biocultural heritage, soil analysis, historical ecology, land use change

1 Introduction

Studies on historical agroecosystems are important for their management in face of current environmental issues (e.g., climate change, loss of biodiversity, soil impoverishment). Their cumulative ecological legacies also contain clues to the range of practices possible in the past and present. Currently, we still lack a deep understanding of how and to what extent the present biological and cultural diversity in historical agroecosystems has been shaped by land use processes over time (Cevasco et al., 2015; Agnoletti and Emanueli, 2016). Perspectives examining the correlations between the long-term presence of historical agroecosystems and the current states of certain rural landscapes are still missing. Similarly, there is a void of research on multiple baselines and drivers at different scales (Pauly, 1995; Ligtermoet et al., 2023). Historical agroecosystems tend to be studied by different disciplines separately, while they would be better understood through integrated and transdisciplinary approaches, which can appreciate their wider array of spatial and temporal processes. Studies have shown the potential in combining diverse methods and sources (oral history, paleoecology, spatial analysis), as epistemic perspectives, for the exploration of historical agroecosystems (Crumley, 2012; Barthel et al., 2013a, 2013b) and their key role for the maintenance of local biocultural diversity (Baiamonte et al., 2015; Cohen et al., 2023; Gkisakis et al., 2018; Ferrara, 2024).

Phytoliths have strong potential for the reconstruction and assessment of past and present agroecosystems (e.g., Pokrovsky et al., 2024; Witteveen et al., 2023), especially when combined with other sources (traditional ecological knowledge, geospatial data, historical maps, just to name a few). Research on the application of phytolith analysis for the investigation of agricultural practices, species domestication, food production, and their environmental impacts through the Holocene is not new (e.g., Kealhofer, 2003; Iriarte et al., 2010; Pearsall and Hastorf, 2011 for a general introduction on the method; Dickau et al., 2016; Hill et al., 2023). While this strand of research deals with the investigation of human-nature ecological interactions at certain points in the past, the use of phytoliths in the study of living historical agroecosystems is still a developing field. In such respect, our work - for the first time - applies phytolith research in the investigation of agroecosystems that have maintained certain vegetation elements (i.e., century-old olive trees) over millennia, which thus characterize these agroecosystems as historical elements in an always-changing landscape. The scope of our work is to trace the historical ecology of these agroecosystems by catching, through phytolith analysis, variation patterns (as new and abrupt shifts or gradual changes, both in land use and broader environmental dynamics) within long-term stability trends represented by the very persistence of these historical agroecosystems until today. From this derived knowledge, we could gain insights on how these agroecosystems have evolved and interacted with anthropogenic disturbances (land use) and environmental (microclimate, vegetation cover, local biodiversity) elements over time, while maintaining essential features of stability over centuries, if not millennia.

In our work, we combine plant morphology, oral history, and soil analyses with phytoliths (Ferrara et al., 2025). This paper in particular focuses on phytolith assemblage analysis in historical olive (*Olea europaea* L.) agroecosystems still present on the island of Sicily (Italy). These remnants of very old agroecosystems in today's landscape allow studying land use dynamics and broader environmental changes over centennial and even millennial time scales. A single gram of olive leaf can produce around 40,000 phytoliths, and they have been extracted from leaves, bark, wood and fruits of *Olea europaea* L (Tsartsidou et al., 2007), as well as from olive oil sediments (Loeta Tyree, 1994). Nonetheless, no taxonomic demarcation by phytolith signature has been published so far to understand which phytolith morphotypes could be diagnostic of Olea. The main obstacle to research development on Olea taxonomic demarcation via phytolith signature is the difficulty of discriminating taxonomically phytoliths from woody dicotyledons (Bremond et al., 2005a; Testé et al., 2020), and only a few studies are available on the topic (An, 2016; Lisztes-Szabó et al., 2019; Liu et al., 2021; An and Xie, 2022; Boyd et al., 2024). Due to such limitations, in this paper we conceptualize plant microfossil biogenic silica (phytoliths) stored in the soil of historical olive agroecosystems as biocultural traces of past and present human-nature interactions and environmental dynamics. Phytolith assemblages are here considered as indicators of entangled cultural land use practices and ecological dynamics over the long term, in environmental contexts where other proxies (e.g., pollen, macrofossils, charcoal) are not available.

Furthermore, as will be argued, as biocultural traces of past local vegetation and land uses, phytoliths can inform about how the historical olive agroecosystems under investigation have responded to analogous shifts we face today or in the future. As such, they can provide relevant evidence we may want to consider in our management, when it comes to handle current and prospected climatic variations and other forms of stress.

Section 2 in the paper describes the three areas on the island of Sicily selected as case studies. These are remnants of historical olive agroecosystems, each of them is unique in the local history of land use and management of the olive tree. Section 3 is dedicated to our methodological approach, based on the assumption that phytolith assemblages stored in soil layers of historical olive agroecosystems are biocultural records from previous local vegetation dynamics and (agri)cultural practices. In Section 3, the local phytoliths ecology is introduced as well, together with details on the sampling method and analytical approaches adopted to investigate the extracted assemblages.

The potential of phytolith analysis to estimate the openness of historical olive agroecosystems, to understand how land uses in different historical periods have contributed to shape the current structure of ancient olive groves, and how biological diversity can be correlated to human presence on a site are presented in Section 4. These results are further interpreted in Section 5, within a perspective that considers soil-extracted phytolith assemblages as biocultural traces that can allow gaining new knowledge on historical and intertwined ecological-cultural phenomena happening on a site. The importance of past analogues to inform agroecosystems management and conservation policies is emphasized. The paper concludes by proposing further research

on phytolith assemblages as biocultural proxies in agricultural soils with a deep history.

2 Study areas

In this paper, we propose phytoliths as biocultural traces in three historical olive agroecosystems on the island of Sicily chosen as study areas: Bosco Pisano, represented by a wild olive patch included in a mosaic forested area (in the municipality of Buccheri, Siracusa Province), Cozzo del Lampo, a hill covered by century-old olive trees in the municipality of Villarosa, Enna province, and Contrada Malìa, within a rural district in the municipality of San Mauro, Palermo province (Figure 1).

The case study areas are remnants of three specifically different olive agroecosystems. Each represents individual spatial and temporal tree arrangements, resulting from distinct local historical land uses and intentionalities. Thus, each case study area per se exemplifies a unique case of management and maintenance history. Below, the morphological characteristics of these historical olive agroecosystems and their ecology are briefly introduced, based on surveys conducted in 2022, 2023 and 2024, in combination with collected oral history and traditional ecological knowledge.

2.1 Bosco Pisano

Bosco Pisano is a patch of woodland located on the slopes of the Iblei Mountains, nowadays a Nature 2000 site (ZSC ITA090022 – Bosco Pisano). The landscape unit is a mosaic where open woodlands and pasturelands alternate. The vegetation is dominated by the presence of *Olea europaea* var. *sylvestris*-dominated formations (EUNIS habitat type G2.41), *Quercus suber* (EU Habitat Directive 9330) and *Quercus pubescens* (EUNIS G1.732) woods, pseudo-steppe with grasses and annuals of the *Thero-Brachypodietea* (EU Habitat Directive 6220), *Sarcopoterium* sp*inosum* phryganas (EU Habitat Directive 5420), and Western Mediterranean and thermophilus scree (EU Habitat Directive 8130). Bosco Pisano lies on volcanic rock outcrops (Carbone et al., 1986) with prevailing very shallow andic brown soils and lithosols, where rock outcrop is abundant (Fierotti et al., 1988). The area chosen as case study, 780 m^2 large (Figure 2), includes an unusual almost monospecific wild olive cluster (Figure 3). It is a unique example of wild olive woodlands that might have been much more widespread in the past and currently represented by few fragmented patches occurring occasionally in the entire region.

As part of the study, an assessment was made of the tree morphology and grafting events since the olive trees in Bosco Pisano, even though wild olive, have the typical multistemmed

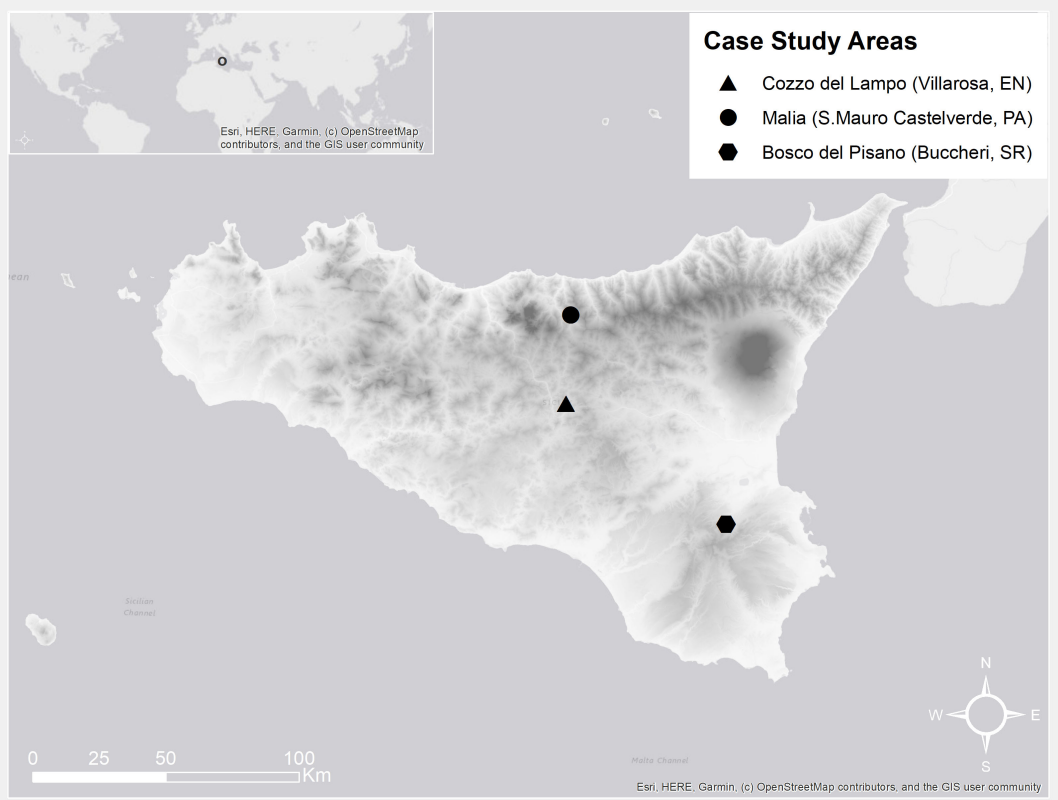

FIGURE 1
Location of the three study areas on the island of Sicily: Bosco Pisano, Cozzo del Lampo, Malìa (Image source: Ferrara, 2024).

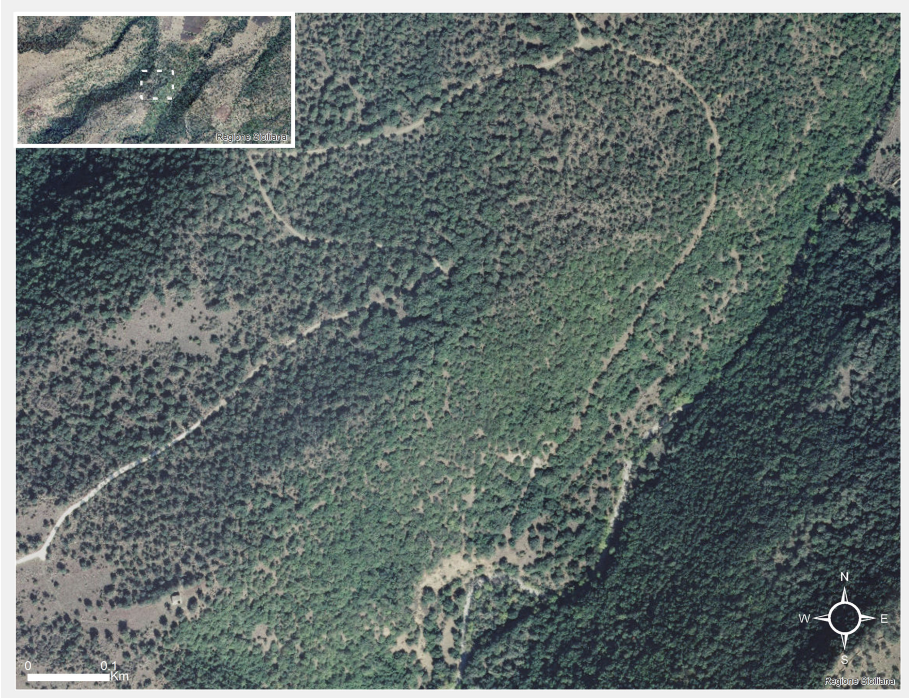

FIGURE 2
Bosco Pisano case study location and its broader area (Image source: Ferrara, 2024).

shape of coppiced cultivated individuals (as for instance in Cozzo del Lampo, cf. 2.2). The olive wood was likely used for fuelwood, fodder-branches, and timber. Coppicing practices (the cut of tree branches and trunks at or near the ground level) are already mentioned in written sources from the 17th century and there may also be charcoal kilns in the vicinity (Garfì and Di Pasquale, 1988). Historical reconstructions of the local land use (cf. Di Pasquale et al., 2004) dates from the 17th century onwards. Until the last century, the local landscape spatial patterns probably resembled present-day grazing areas, such as the *Dehesas* or *Montados* (in Spain and Portugal respectively). During the 1940s and 1950s, this territory became virtually abandoned, except for cork harvesting and grazing. The area is today used for overwintering of animals, as part of a transhumance practice (cf. Garfì and Di Pasquale, 1988).

Di Pasquale et al. (2004) suggest that the wild olive dominated stands are probably the most ancient and stable units, when compared to other more recent forest communities, as the *macchia* formations (estimated as c. 60-year-old), resulting from the decline of coppicing, and the cork oak stands, most likely

FIGURE 3
(a) Bosco Pisano, with its cluster of wild olive trees, **(b)** Peculiar shapes of the olive trees branches in Bosco Pisano, due to the reiterated cuttings done in the past to provide *in situ* fodder for grazing cattle.

originated in its current settings at the end of the 19th century, now largely senescent and unable to rejuvenate due to the lack of natural regeneration owed to overgrazing.

Garfì and Di Pasquale (1988) further suggest that this woodland is a relict of wider oak forests, existing until the classic age in Sicily (i.e., Diodorus Siculus, Bibliotheca, 4–84). This wood made of wild olive trees represents a now forgotten form of past land use of the olive, and for this reason is an important case study.

2.2 Cozzo del Lampo

Cozzo del Lampo is a hill of approximately 1.28 km^2, located in a rural area of inner Sicily, and characterized by the abundance of large size (c. 12–15 m in circumference) domesticated century-old olive trees (Figure 4). These agroecosystems are Mediterranean formations of *Olea europaea* var. *europaea* (EUNIS G2.91), with presence of Mediterranean subnitrophilous grass communities (graminoid formations that may cover post-cultural or pasture lands, EUNIS E1.61), sub-Mediterranean deciduous thickets (EUNIS F3.2) and diss formations (EUNIS E1.433). Along the slopes of the hill, these agroecosystems are intermixed with Mediterranean tall-grasses (EUNIS E1.4), evergreen sclerophyllous scrubs (EUNIS E1.2A) and riparian thickets close to the water streams (EU Habitats Directive 92D0). The hill, as a mosaic of *Olea europaea* var. *europaea* groves in terms of land use, is then surrounded by cereal and fallow fields. Since the 1950s post-war land reorganization in Sicily, these olive groves have been managed as small family holdings maintained for self-consumption and/or recreation.

Cozzo del Lampo is an elevated area with slopes and/or protruding rocks of the *Terravecchia Formation* (i.e., interbedded quartzite pebbles, sandstone and shale sequences, cf. Grasso and Pedley, 1988). The size and configuration of the olive trees suggest that they are century-old, though no exact dating is available. The olive trees are found in places where it was extremely hard or impossible to plough the land manually.

Field surveys were carried out in collaboration with farmers and pruners (cf. Ferrara and Ingemark, 2023; Ferrara et al., 2024b). Trunk and spout morphology was assessed, together with crown shape and size, past grafting and pruning events if visible on the tree. Some trees have likely been grafted from the roots of previous wild olive individuals (*sensu* La Mantia, 2005), since no signs of grafting is evident on the trunks. Several consecutive coppicing (tree cuts at or near the ground level) and pollarding (tree cuts higher at the trunk level) events are visible, resulting in the current multi-stemmed and multi-branches habit of these century-old olives. Both coppicing and pollarding as pruning techniques have the aim to foster self-renewal in the tree (Rackham, 2018). According to the size and shape criteria specified by Schicchi and Raimondo (2011), the olive trees in Cozzo del Lampo could potentially be as old as 800 or 1,000 years (Figure 5). Finally, their spatial arrangement is distinctive compared to more recent olive orchards, resembling a mosaic of diverse configurations unique to this area (Ferrara et al., 2024a).

The Morello valley, where the hill is located, has been inhabited since prehistory (Giannitrapani et al., 2014). Archaeological surveys in one olive orchard were carried out by Tegerdal Hune (2022), resulting in the location of an undated site. Giannitrapani et al. (2014) suggest an abandonment phase in the entire valley from

FIGURE 4
Cozzo del Lampo hill with its mosaic of different olive spatial arrangements (Image source: Ferrara, 2024).

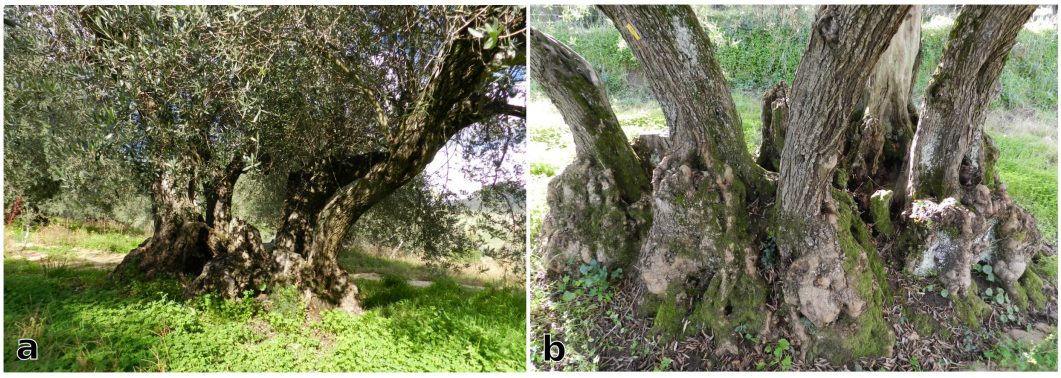

FIGURE 5
A century-old olive tree **(a)** with its multiple stems **(b)** surrounding the main decaying stump (Image source: Ferrara, 2024).

late Antiquity to the 14th century. This was followed by slow repopulation and, from the 18th century, the consolidation of an extensive feudal estate, characterized by intensive cereal cultivation (Verga, 1993; Carocci, 2010). A redistribution of land to peasants took place after the end of World War II. Based on recent collection of oral histories and geonarratives (cf. Ferrara et al., 2024b), until c. 1950 fruit trees (such as *Pyrus pyraster* L. (Burgsd.), *Punica granatum* L., *Prunus spinosa* L. subsp. *spinosa*, to name a few) were cultivated in between these olive trees, resembling the intercropping system of the "Mediterranean garden". Outmigration from the area remains a problem today (Fondazione Migrantes, 2022), though small-scale farming activities persist, mainly involving cereal and livestock production (Ferrara and Lindberg, 2023).

2.3 Malìa

The third study area presented in this paper is located in a rural district called Malìa, in the Madonie Mountains, known as a biodiversity hotspot due to remnants of semi-natural vegetation (Baiamonte et al., 2015). The *Olea europaea* var. *europaea* formations (EUNIS habitat type G2.91) in the Malìa study area are found in permanent mesotrophic pastures and aftermath-grazed meadows (EUNIS E2.1) dominated by Mediterranean subnitrophilous grass communities (EUNIS E1.61), *Calicotome infesta* (EUNIS F5.515), *Ampelodesmos mauritanica* dominant formations (EUNIS F5.53), Medio-European rich-soil thickets (EUNIS F3.11) and *Spartium junceum* scrubs (EUNIS S53). The study area surveyed has an extension of approximately 550 m^2 (Figure 6), and it is embedded in a tangled web of *Quercus pubescens* (EUNIS G1.732) *Quercus suber* (EU Habitat Directive 9330) woods and Italic poplar galleries (EUNIS G1.314). Here too, during fieldwork, we assessed the morphology and grafting events visible on the century-old olive trees. Evidence of past grafting, done on semi-mature wild and feral trunks at more than 1.5 meters from the ground (Figure 7), suggests an adaptation of protect cultivated olives to grazing animals. Based on their trunk size and overall physiognomy, these olive trees are estimated to be century-old.

Numidian Flysch, a rare Oligocene to mid-Miocene deep-marine sandstone and mudstone formation (Hubert Thomas, 2011; Pinter et al., 2016), emerges until the surface in certain places, making the topography very steep and soil layers shallow. In this agroecosystems, the spatial distribution of century-old olive trees appears random, growing directly from and among the bedrock, even in the steepest parts of the hill slope. In addition, numerous olive trees are located in the most remote and inaccessible places (Figure 8).

Local reconstructions of Holocene vegetation and fire dynamics show the expansion of open grasslands from the 5th millennium BCE onwards, on top of previously closed woodlands (Tinner et al., 2016). This grassland expansion, alongside other evidence, has been linked with human activities (Belvedere and Forgia, 2010; Forgia et al., 2013, 2021). Unfortunately, documentation for the more recent period remains scarce.

From interviews with local residents, the area had a similar socio-economic history as Cozzo del Lampo. It was part of a large estate, which after the end of World War II was parceled into small plots, bought by the farmers already working the land. Malìa represents a past multifunctional space, for cultivation and grazing, while also providing fuelwood and timber (cf. Ferrara et al., 2023), which suggests this case study to be representative of an old agroforestry model (similar to those in Antiquity), characterized by the high presence of grazing activity and sparsely planted olive trees.

3 Material and methods

A few scholars have tested the potential of multiproxy vegetation reconstructions in millennial old olive agroecosystems. Cohen et al. (2023) analyzed land use factors (spatial context, management type and intensity) and environmental conditions. Jouffroy-Bapicot et al. (2021) traced the transition from Mediterranean woodlands to olive agroecosystems. Meanwhile, Moriondo et al. (2013) used historical ranges of olive cultivation as a paleoclimate proxy to model future environmental and agricultural scenarios. These pioneering studies demonstrate how multiproxy methods and interdisciplinary approaches are crucial to

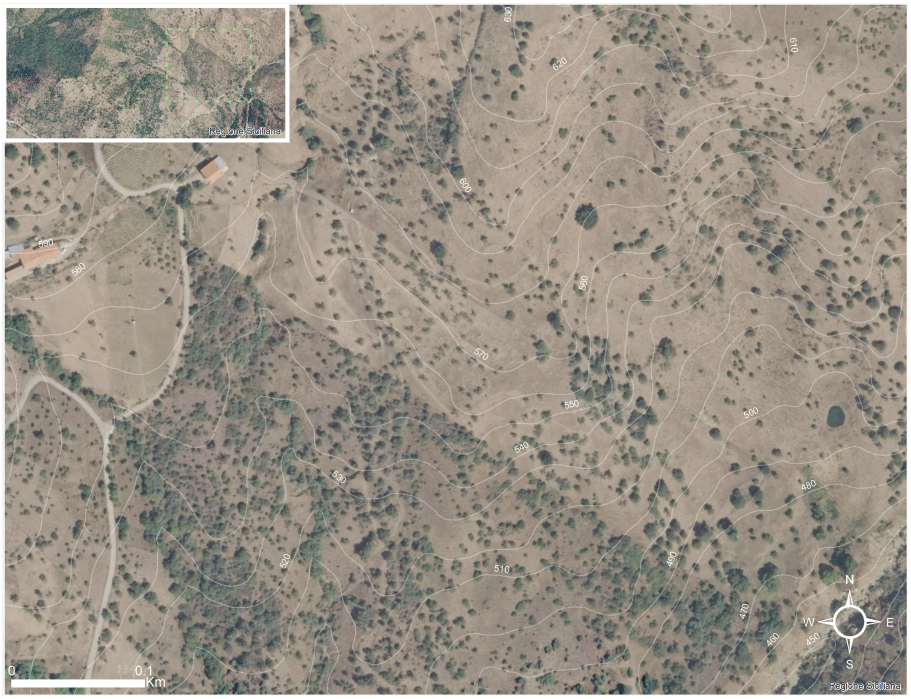

FIGURE 6
Location of the study area and its surrounding landscape in contrada Malìa (Image source: Ferrara, 2024).

reconstruct the historical ecology not just of olive agroecosystems, but of other types of agroecosystems with a deep history as well. As reviewed above, the case studies presented here have been investigated spatially (Ferrara and Wästfelt, 2021; Ferrara et al., 2024a; Ferrara and Wästfelt, 2025) and through oral narratives, local ecological knowledge and written sources (Ferrara and Ingemark, 2023; Ferrara and Lindberg, 2023; Ferrara et al., 2023; Ferrara et al., 2024b). In this paper, for the first time phytolith assemblage analysis is integrated into a historical ecology study of ancient olive agroecosystems still present in today's landscape.

3.1 Phytoliths as biocultural traces

Phytoliths are used in this paper to reconstruct past vegetation, land use and broader environmental dynamics (Pearsall and Trimble, 1984; Strömberg et al., 2007; Aleman et al., 2014; Feng et al., 2017). Phytoliths have also been used to study erosion patterns and paleoclimate (see review in Qader et al., 2023). In old soils, phytoliths are preserved due to silica resistance to decay (Pearsall, 2015). Although phytoliths have an enormous potential in studying and assessing agricultural soils, such field of research is underdeveloped

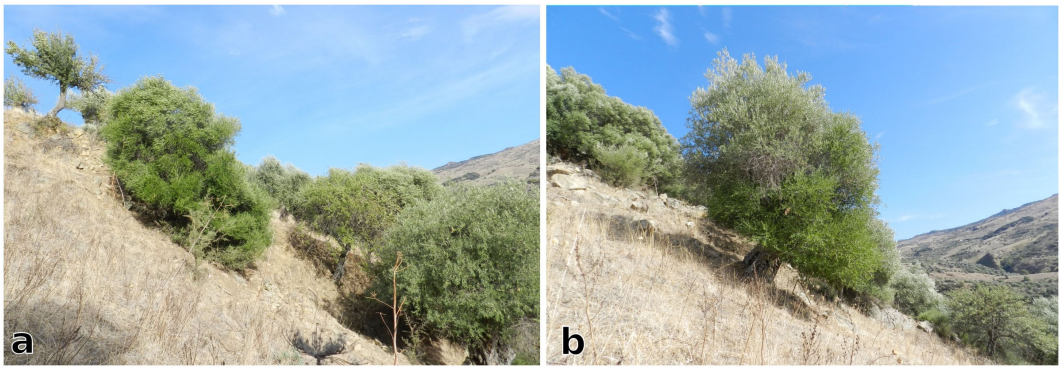

FIGURE 7
The difference between wild and domesticated olive trees can be appreciated from the different shades of green of the trees´ crown. Darker green (as in **(a)**) indicates wild and/or feral olive. Lighter green are leaves from domesticated olives. The olive tree in **(b)** shows the coexistence of both, wild and domesticated; it is also a good example of a grafting event happened on a semi-mature trunk at more than 1.5 meter of height. Note the slope (Image source: Ferrara, 2024).

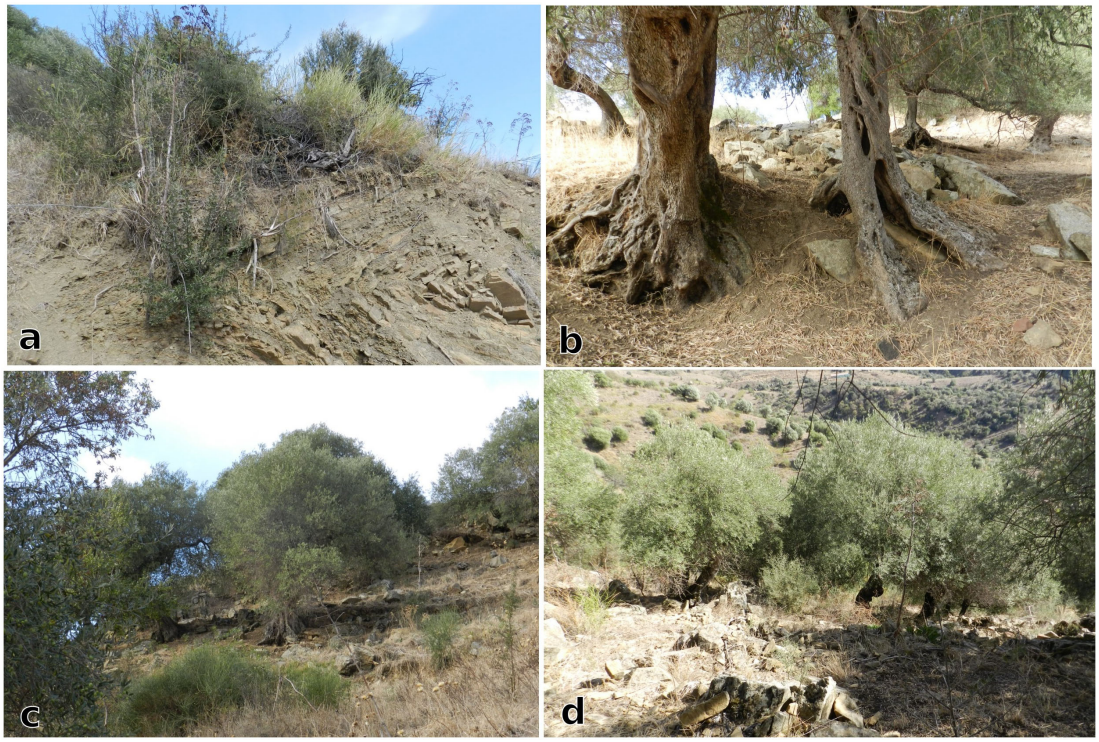

FIGURE 8
(a) Local vegetation, including wild olive, growing on Numidian Flysch bedrock; **(b–d)** Domesticated olive trees growing among the bedrock. Note the slope and the natural bedrock terraces in Figures 7c and d (Image source: Ferrara, 2024).

(though see Meunier et al., 1999; Fernández Honaine et al., 2006; Liang et al., 2015; Hussain et al., 2023; Pokrovsky et al., 2024; Benvenuto et al., 2025 for positive examples). Plants and soils act as a Si 'filter' (cf. Vandevenne et al., 2012, 243), transforming the dissolved silica (DSi) originated from mineral weathering into biogenic silica (BSi). Such biogenic silica is then returned to the soil when plants decay. Along this cycle, vegetation and soils changes caused by specific land use activities, such as the removal of biomass during harvest, affect the Si quantity and distribution (Barão et al., 2020). Through phytoliths analysis, we can thus trace how vegetation composition and assemblages have been shaped by land use practices. By approaching the historical olive agroecosystems present in the study areas as containing legacies of their past-present agricultural and silvicultural use, we developed a methodological approach that would allow investigating this biocultural heritage. By ideally following the roots of century-old olive trees underground, we explored the memory of the soil through the analysis of phytolith assemblages (Piperno, 2006). By comparing the relative frequencies through time of all diagnostic phytoliths (Strömberg, 2004), first of all we intended to observe if distinctive assemblages along the stratigraphic profiles could lead to distinguish patterns of change in vegetation and habitats structure (Strömberg et al., 2013). Secondly, we considered if the correlation between different vegetation communities represented by these assemblages could offer new interpretative perspectives about past land use practices (included successional trajectories along gradients of human disturbance, cf. Witteveen et al., 2023), climatic and broader environmental trends over the long term in these agroecosystems.

Therefore, testpits were opened in each of the case study areas, for the extraction of phytoliths from soil layers following a protocol developed by Mazuy et al. (2024) specifically for these types of agro-ecological contexts, as detailed in Section 3.2. Where available, ^{14}C dates were modeled to provide a relative age-depth.

The identification of phytolith morphotypes (Figure 9 for examples) to categorize into assemblages has followed local phytoliths ecology (Section 3.3) and phytolith assemblages ratios have been interpreted according to four different indices (Section 3.4), in order to provide indication of specific plant communities structures, composition and variation patterns along each profile and when comparing the three different sites.

3.2 Sampling and laboratory procedure

Soil sampling for phytoliths extraction and analysis was adapted to the specific geological features in each study area and the spatial composition of their century-old olive trees.

In Bosco Pisano, two profiles of 20 cm depth were opened (Figure 10a, Table 1), resulting in two samples. Sampling here aimed to estimate tree cover density through phytoliths signature in *Olea* wood formations (cf. 2.1 for habitats characterization), so to employ it as a local tree cover threshold when interpreting the results from the other two case studies.

In the two study areas Cozzo del Lampo and Malìa, five testpits 1.5 m deep were opened in each area, and soil sampled every 10 cm,

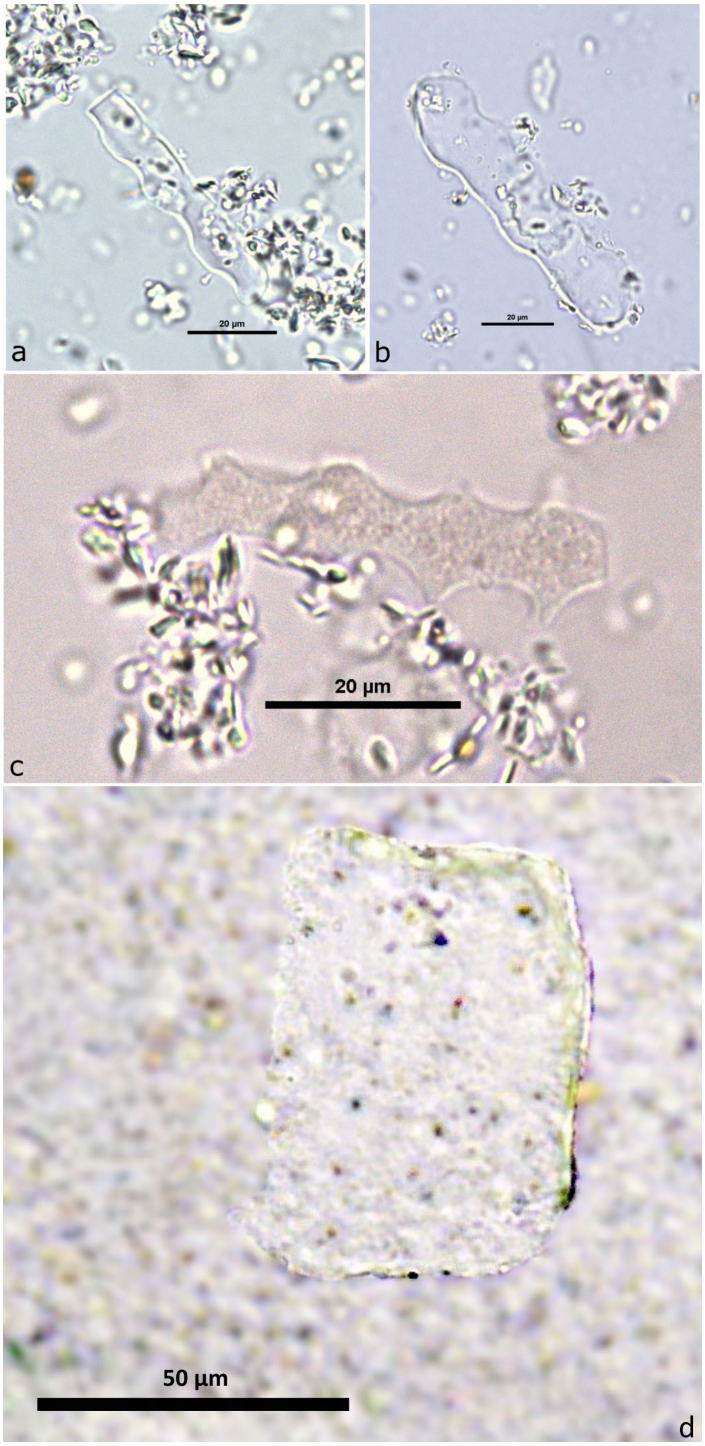

FIGURE 9
Examples of phytoliths morphotypes extracted from the case study areas: elongate sinuate **(a)**, crenate **(b)**, and dendritic **(c)** from Malìa (Image source: Ferrara, 2024); blocky **(d)** from Bosco Pisano (Image source: Ferrara et al., 2025).

resulting in a total of 75 samples per study area (Table 1). In Cozzo del Lampo, the testpits followed the slope transect with an interval of 40 meters (Figure 10b). In Malìa, a transect was not possible due to the shallow soil depth in recurrent places. The testpits were placed near olive trees in an area with relative soil thickness and were local residents said there had been cereal and/or legumes cultivation and pasture (Figure 10c, Table 1).

Stratigraphic analyses were carried out for the profiles excavated in Cozzo del Lampo and Malìa (Supplementary Material S1). Three charcoal samples from Cozzo del Lampo and two samples from Malìa

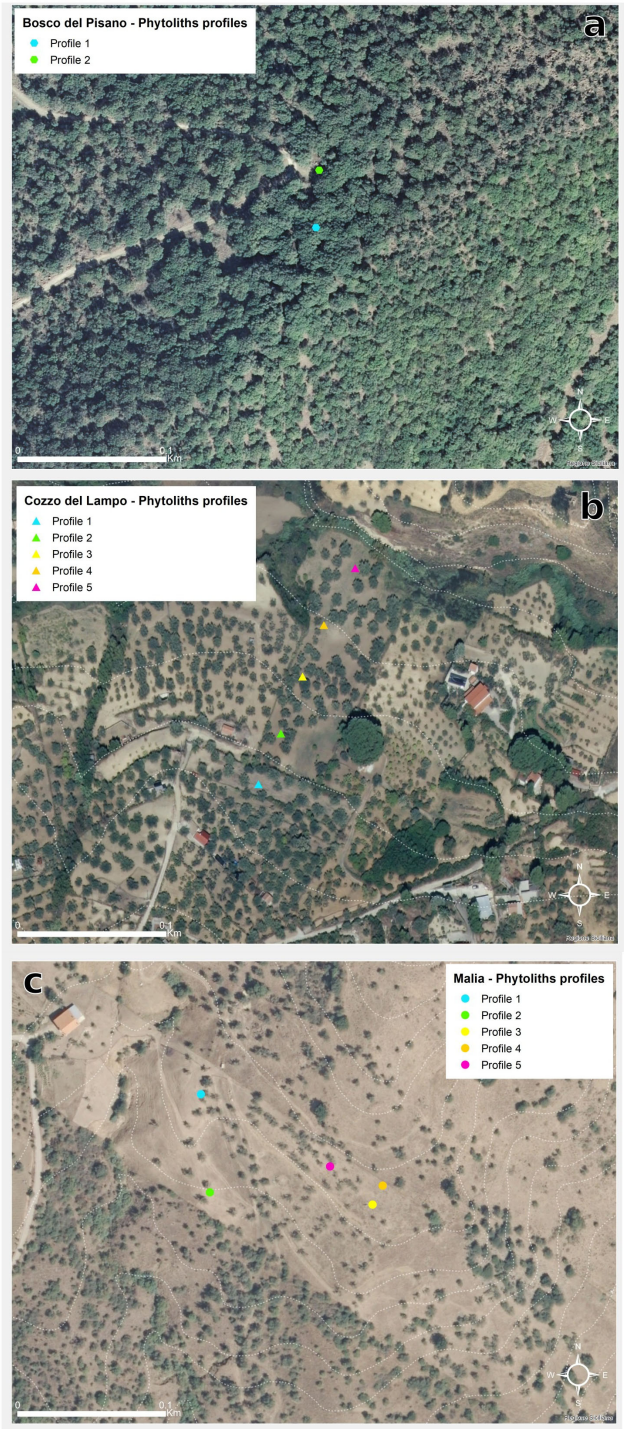

FIGURE 10
Location of the soil profiles excavated in each study area for sampling. **(a)** Bosco Pisano; **(b)** Cozzo del Lampo; **(c)** Malia (Image source: Ferrara, 2024).

were submitted for radiocarbon dating at the Ångström Laboratory, Uppsala University. Dates were calibrated by the laboratory using IOSACal v0.4.1 and the IntCal20 calibration curve (Reimer et al., 2020). A Bayesian age-depth model was produced in R (R Core Team, 2021) using the package Bacon (Blaauw et al., 2022) and the uncalibrated dates for Cozzo del Lampo samples are published already in Ferrara and Wästfelt (2025).

Phytolith extraction was done at the Paleobiology Laboratory (Department of Earth Sciences, Uppsala University), following the protocol developed in Mazuy et al. (2024). This protocol allows extracting quantities of biogenic silica suitable for phytolith morphotypes analysis, from soils and contexts with low phytoliths concentrations. The samples have been first deflocculated through magnetic stirring. Thereafter, the fine fraction (200 µm) is treated

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TABLE 1 Coordinates, elevation and slope values of soil profiles in each of the three study areas (Bosco Pisano, Cozzo del Lampo, Malìa) (Ferrara, 2024).

Bosco Pisano			
Profile	Coordinates	Elevation (m.a.s.l.)	Slope (%)
1	37° 10' 57.88" N 14° 52' 31.04" E	468.8	9.9
2	37° 10' 59.13" N 14° 52' 31.12"	453.4	7.2
Cozzo del Lampo			
Profile	Coordinates	Elevation (m.a.s.l.)	Slope (%)
1	37° 35' 12.43" N 14° 11' 34.14" E	474.4	8.3
2	37° 35' 13.54" N 14° 11' 34.74" E	467.2	11.4
3	37° 35' 14.79" N 14° 11' 35.32" E	458.7	9.6
4	37° 35' 15.92" N 14° 11' 35.90" E	453.5	15.2
5	37° 35' 17.17" N 14° 11' 36.74" E	444.4	18.8
Malìa			
Profile	Coordinates	Elevation (m.a.s.l.)	Slope (%)
1	37° 53' 18.73" N 14° 12' 33.99" E	622.5	9.4
2	37° 53' 16.59" N 14° 12' 34.27" E	607.4	8
3	37° 53' 16.35" N 14° 12' 38.76" E	616.6	9.4
4	37° 53' 16.77" N 14° 12' 39.04" E	620.5	9.6
5	37° 53' 17.18" N 14° 12' 37.58" E	618.9	18.5

with hydrochloric acid 33% (to remove carbonates) and then boiled in a hot bath (80°C) with potassium hydroxide 10% for 15 minutes (to remove organic matter). Phytoliths are then extracted by heavy liquid flotation (using sodium polytungstate, SPT at 2.35 density) and in a hot bath (80°C) with hydrogen peroxide 30% for 1 hour to remove further organic matter.

Being collected on the island of Sicily, where the volcano Etna has been active for thousands of years, our soil samples contain a high amount of cryptotephra, which is silica glass (GSi). The density of cryptotephra is similar to that of phytoliths and biogenic silica more in general (BSi) (≤ 2.3 g cm-3), consequently silica glass is also separated together with phytoliths during the heavy liquid extraction process. In our specific case, the final BSi residue represents thus the sum of phytoliths and cryptotephra. Consequently, whatever quantitative assessment of the silica fraction extracted from our samples would be misleading in terms of specifying the exact amount of phytoliths content. A further separation between tephra particles and phytoliths would have been necessary to obtain such specific measures, which however could have caused partial loss of the already phytolith-low content of the studied samples (cf. Mazuy et al., 2024). Since cryptotephra is clearly distinguishable from phytoliths under microscope and being mainly interested in analyzing relative abundance of phytolith morphotypes and their assemblages variability to gain qualitative information about changes in vegetation composition, land use and plant behavior, the quantitative determination of the biogenic silica content in our samples was out of the scope of the work presented in this paper.

3.3 Local phytoliths ecology

Though different parts of a plant produce diverse phytolith morphotypes, several phytoliths can be commonly identified to subfamily level (Table 2). Phytoliths attributed to dicotyledonous (plants having two embryonic leaves in their seeds, such as trees and

TABLE 2 Attribution of phytolith morphotypes to plant taxa and plant parts (Ferrara, 2024).

Morphotypes	Source plant taxa	Plant organs or parts
Bulliform	Poaceae	Leaf/Culm
Elongate entire	Monocotyledon	Leaf
Elongate sinuate	Poaceae	Leaf/Culm
Elongate dendritic	Poaceae	Inflorescence
Trapeziform	Poaceae (Panicoideae/Pooideae C3 subfamily)	Leaf
Rondel	Poaceae (Pooideae C3 subfamily)	Leaf, straw
Crenate	Poaceae (Pooideae C3 sub-family)	Leaf
Saddle	Poaceae (Chloridoideae C4 subfamily)	Leaf
Bilobate	Poaceae (Panicoideae/ Pooideae) C4	Leaf, stem
Polylobate	Poaceae (Panicoideae/ Pooideae) C4	Leaf, stem
Cross	Poaceae (Panicoideae/ Pooideae) C4	Leaf, stem
Spheroid psilate	Dicotyledons	Wood/bark
Spheroid ornate	Dicotyledons	Wood/bark
Tracheary	Dicotyledons	Leaf
Blocky	Dicotyledons	Wood/bark
Jigsaw	Dicotyledons	Leaf
Acute bulbosus	Monocotyledon and Dicotyledons	Hair and/or epidermal cells

shrubs) from temperate areas, as our case studies, are globular (or spheroid) (Bozarth, 1992; Alexandre et al., 1997; Albert et al., 1999; Runge, 1999; Delhon et al., 2003) and tracheary (Bozarth, 1992; Alexandre et al., 1997; Madella et al., 1998; Albert et al., 1999; Runge, 1999; Delhon et al., 2003; Jarl and Bruch, 2023). They can also be jigsaw (Carnelli et al., 2004; Kawano et al., 2006; Gu et al., 2008; An and Lu, 2015; Potì et al., 2019; Hayashi et al., 2021) and blocky (Tsartsidou et al., 2015; An, 2016; Boixadera et al., 2016; Ntinou and Tsartsidou, 2017; Burguet-Coca et al., 2020; Kraushaar et al., 2021; Tencariu et al., 2022). Even relatively modest percentages of these morphotypes can be interpreted as substantial, as dicots have a low phytolith production (Carnelli et al., 2004; Tsartsidou et al., 2007).

Grasses (monocotyledon plants, i.e. having only one embryonic leaf in the seeds) of the Poaceae family produce elongate, papillate, acute bulbosus and bulliform flabellate forms (Twiss et al., 1969; Fredlund and Tieszen, 1994; Piperno, 1988; Ball et al., 2001; Neumann et al., 2019). Elongate phytoliths present morphological variations in vegetative parts (the elongate sinuate type is formed in leaves, and simple elongate in stems). Elongate dendritic and papillate forms are produced by the flowering parts of Poaceae (glumes, lemma and palea, also named inflorescence). Dendritic long cells are commonly associated with the chaff of domesticated Pooideae, such as wheat, barley and oat (Rosen, 1992; Ball et al., 1999; Portillo et al., 2006; Albert et al., 2008). However, dendritic forms are also found in wild grasses (Novello and Barboni, 2015), thus their attribution must be carefully assessed.

Acute bulbosus is a morphotype produced in the interior part of the hair cells, above all in grasses (Alexandre et al., 1997; Barboni et al., 2007). Being produced in sedges and dicots as well, this morphotype is not considered here diagnostic. Nonetheless, it has been included in the counted morphotypes due to the limited amount of phytoliths in certain layers correlated with the stratigraphy (cf. Supplementary Material S1).

Bulliform flabellate and blocky morphotypes are produced in the bulliform cells of leaves (Mader et al., 2020), which usually silicify in a later stage of plant life (Moulia, 1994). Bulliform flabellate phytoliths allow leaves to bend to avoid excessive water loss, and their formation is directly influenced by environmental conditions such as high evapotranspiration (Bremond et al., 2005b; Novello et al., 2012).

Specific grass silica short cell phytoliths (hereafter GSSCPs, Neumann et al., 2019) can be diagnostic of the following Poaceae subfamilies (Table 2). C3 grasses in cool moist/temperate climate (Pooideae) are associated with **rondels** (Twiss et al., 1969; Fredlund and Tieszen, 1994; Piperno and Pearsall, 1998; Barboni and Bremond, 2009). Rondels are produced also in the Arundinoideae (cf. Tencariu et al., 2022). The **trapezoid** (Barboni and Bremond, 2009) and **Crenate** morphotypes (Twiss et al., 1969; Fredlund and Tieszen, 1994; Barboni et al., 2007) are mainly produced in Festucoid grasses (Tsartsidou et al., 2007).

Chloridoideae are C4 grasses found in dry and hot environments. These are dominated by **saddle** forms (Piperno, 2006; Madella et al., 2016) and **rondels** found together with saddles (cf. Bamford et al., 2006; Barboni and Bremond, 2009). Warm and wet environments tend to support C4 Panicoideae where species have many morphotypes as **bilobate** (Twiss et al., 1969; Fredlund and Tieszen, 1994; Barboni and Bremond, 2009), **polylobate** (Twiss et al., 1969; Fredlund and Tieszen, 1994; Neumann et al., 2019) and **cross** morphotypes. Bilobate phytoliths can also occur in a few Festucoid grasses and some Chloridoid grasses (as pointed out by Metcalfe, 1960; Danu et al., 2020).

3.4 Phytolith assemblage analysis

Phytoliths were identified and counted using light microscopy at ×400 magnification. Their morphotypes were categorized into plant taxonomic groups according to the International Code for Phytolith Nomenclature (ICPN) (Neumann et al., 2019) and the PhytCore online database (Albert et al., 2016). In addition, the UMR 7264 CEPAM CNRS-Université Côte d'Azur (Nice, France) was consulted for identifications. Only those recognized morphotypes listed in the International Code for Phytolith Nomenclature (ICPN) (Neumann et al., 2019) were counted, with a minimum of 200 phytoliths per sample. Such an amount is attested to give statistically interpretable assemblages (cf. Strömberg, 2009; Zurro Hernández, 2018), above all in soil samples coming from specific contexts (e.g., farming systems, arboriculture) where the concentration of phytoliths can be lower if compared with their higher concentration in soils of very specific environments, such as grasslands and archaeological sites (Cabanes et al., 2011).

The relative abundance of each phytolith morphotypes per soil layer was calculated based on the total sum. Along each excavated profile, phytolith assemblages were analyzed using four indices, to assess if the diachronic variability in their ratios could be informative of changes in vegetation structure and compositions, as well as land use practices and plant behavior to climatic disturbances.

The *long/short cell index* measures the ratio of long cells vs short cells. Short cells phytoliths are impregnated with silica as soon as they form (Sangster, 1970), while silicification of long cells become more intense with age (Rencheng et al., 2017). Thus, the ratio of long cells to short cells in a phytolith assemblage may provide information about the composition of grasses in terms of mature versus young grasses (Delhon et al., 2024). The formula used to calculate the long/short cell index here is *Long/short cell index = long cells (elongate entire + sinuate + dentate + dendritic)/short cells (GSSCPs).*

The *Fs-index* (Bremond et al., 2005b, 2008) can provide information on local microhabitats and/or climatic conditions, since an abundance of bulliform flabellate phytoliths is correlated with an increase in evapotranspiration and/or prolonged water stress (cf. Bremond et al., 2005b; Mader et al., 2020).

The formula used to calculate the Fs-index here is *Fs-index = bulliform/GSSCPs* (Bremond et al., 2005b, 2008).

The Dicot/Poaceae index (*D/P index*) measures the ratio of dicotyledons morphotypes (D) versus Poaceae morphotypes (P). This index allows to estimate the tree cover density (Alexandre

et al., 1997), since based on the assumption that open habitats have a higher proportion of grass phytoliths (Strömberg et al., 2018). The lower the D/P value, the more open the habitat. In Mediterranean environments, 0.1 is the lower limit in the D/P index to distinguish between dicotyledon- and grass-dominated assemblages (Delhon et al., 2003).

Even though the D/P index has a standard formula (D/P) (cf. Alexandre et al., 1997), the variables indicating Poaceae and Dicots have been interpreted by scholars in slightly different ways (for a detailed review cf. Ferrara, 2024). Building on the standard D/P index (called here D_a/P *index*, considering as diagnostic of dicots only spheroid and tracheary morphotypes), Ferrara (2024) has developed also a local D/P index (D_b/P *index*), which includes also the blocky (blocky polyhedral and cubic) and jigsaw morphotypes as diagnostic of dicots from local samples.

The formulas used to calculate the *D/P index* are the following:

$$D_a/P \text{ index (cf. Bremond et al., 2005a; 2008)} = Spheroid + Tracheary/GSSCPs$$

$$D_b/P \text{ index} = Spheroid + Tracheary + Jigsaw + Blocky/GSSCPs$$

The *inflorescence/culm-leaves index* measures the ratio of Elongate dendritic phytoliths (from inflorescence bracts) versus Elongate entire and Elongate sinuate (from culms and leaves) (Piperno, 1988; Tsartsidou et al., 2007; Delhon et al., 2020). The ratio of the index varies according to the presence of the whole plant or residues from straws and spikelets, and this information can be indicative of local agricultural practices (e.g., harvest) and/or cereal processing (Delhon et al., 2020).

The formula used is *Inflorescence/culm-leaves index = elongate dendritic + dentate/elongate entire + sinuate.*

Results are presented in diagrams drawn using the software TILIA 3.03 (Grimm, 1993) (Section 4).

4 Results

Dating semi-natural soil profiles in open agricultural environments is difficult due to frequent and constant anthropogenic land use. Consequently, our age-depth model must be considered as tentative. The age depth model resulting from the radiocarbon dates suggests that the historical period under investigation through phytolith assemblage analysis may cover however several millennia.

4.1 Woodland (Bosco Pisano)

Two testpits (20 cm deep) were opened in two locations with a different density of tree cover (Figure 10a): Profile 1 is characterized by a dense tree cover; Profile 2 is located in a more open space but still inside the olive wood. Phytoliths are abundant in both the samples from Bosco Pisano, which is somewhat surprising considering its vegetation (woodland), but less surprising if we take into consideration the low historical anthropogenic impact on the soil of this area.

Pooideae morphotypes dominated with the high percentage of short cells phytoliths (on average 34% vs long cells 46%). The most common morphotype are rondel and trapezoid. These phytoliths were formed mainly in the leaves and the stems of grasses. Phytoliths from grass inflorescence (dendritic) are not present in the phytolith records. Phytoliths from woody and herbaceous dicotyledons are present in the two samples representing, on average, 9% (including also the blocky morphotype, cf. Section 3.3 for D_b/P *index* specifications), nonetheless, phytoliths from grasses are still dominant. Morphotypes related to other monocotyledons are low, with C4 grass phytoliths at only 1.25%.

An analysis of phytolith morphotypes assemblages was done using the D_a/P and D_b/P *indices* and the results are indicative. Overall, both indices result above the standard threshold of 0.1 for woodland estimation, except for D_a/P of Profile 2 (less dense tree cover), which is 0.08. Furthermore, Profile 1 (with dense tree cover) has higher values of both indices than Profile 2 ($D_a/P = 0.13$ vs 0.08; $D_b/P = 0.34$ vs 0.17). Results from Bosco Pisano, despite lack of soil depth, allowed for a calibration of the D/P index in relation to the other case study areas.

4.2 Shrubland to olive orchard (Cozzo del Lampo)

Phytolith morphotypes are abundant in most of the samples throughout the five profiles from Cozzo del Lampo. The only layers where it was not possible to extract phytoliths were samples taken in eroded bedrock (Profile 2, 56–150 cm; Profile 4; Profile 5, 92–150 cm) (cf. Strömberg et al., 2018). We begin here giving an overview of the results from all profiles analyzed and then focus on specific profiles.

4.2.1 General results

The phytolith morphotypes of Cozzo del Lampo are predominantly from the Pooideae subfamily (C3), with a high percentage of short cells phytoliths (in average 32.55% vs long cells 35.56%), above all rondel and trapezoid, formed mainly in the leaves and stems of these plants. Phytoliths from grass inflorescence (the dendritic morphotype, cf. Figure 9c) are present in very low percentages (0.6%). In the literature, dendritics are usually indicators of domestic crops and high water availability (Rosen and Weiner, 1994; Ball et al., 1999; Albert et al., 2008; Jenkins et al., 2011a, b). Their limited presence here may suggest that only wild grasses were predominant in the site.

Morphotypes related to other monocotyledons, such as C4 grasses phytoliths, are scarce (0.42%) or absent.

Meanwhile, phytoliths from woody and herbaceous dicotyledons are also present in all the samples, although in small amounts (7.15%). This value is, however, significant since dicotyledonous plants are minor phytolith producers (Albert and Weiner, 2001; Carnelli et al., 2001; Tsartsidou et al., 2007). Within this group,

phytoliths from the wood and bark (spheroids) are more abundant (6.76%) than those from leaves (tracheary and jigsaw, 0.38%), quite probably due to preservation issues that dicots phytoliths have (Albert and Weiner, 2001; Tsartsidou et al., 2007).

4.2.2 Profile 1

Only Profile 1 had identifiable charcoal sufficient for dating. This profile was dated at 13 cm, 110 cm and 142 cm below the ground surface. Since the dates obtained at 110 cm (6475 ± 41 BP) and 142 cm (5619 ± 35 BP) show a reverse chronology, not unusual for these heavily impacted soils, an age-depth model was generated based on the younger date (Ferrara and Wästfelt, 2025). Based on the age-depth model the oldest age is c. 6700 years ago, with an average sediment accumulation rate (i.e., sedimentation time) of ca. 35 years/cm.

From the phytolith diagram of Profile 1, we can distinguish at least five different temporal phases (Figure 11). The oldest phase, Phase 1 (150–130 cm), is characterized by a slight increase of the three indices *long/short cell index*, *Fs-index* and *D/P index*. This tells that a higher presence of mature grasses and dicots (observed in the long/short cell index and D/P index curves) is accompanied by an increase in their evapotranspiration rates (suggested by the Fs-index curve). Such an increase in the curve of the Fs-index may attest the beginning of a substantial variation in local climatic conditions towards more warm and dry conditions. According to the age-depth model, this phase could have covered the period 4849–3854 BCE. What shown by the phytoliths evidence in this phase is coherent with published palynology and paleoclimate reconstructions, which have attested in the region droughts at around ca. 5550–4550 BCE (Zanchetta et al., 2007; Carroll et al., 2012; Peyron et al., 2013).

Phase 2 (130–110 cm, 3854 BCE – 2871 BCE, end of Neolithic - beginning of Bronze Age) is characterized by a marked correlation between land cover and climate, as we see peaks in both the D/P indices and the Fs-index. These peaks may signify the natural expansion of xerophilous taxa (e.g., *Olea*, *Pistacia*), attested by palynological and paleoclimatic reconstructions as well telling that, around ca. 4050 BCE, there were reduced rainfall, progressive increasing dryness and aridification (Zanchetta et al., 2007; Sadori et al., 2008; Carroll et al., 2012; Peyron et al., 2013).

In Phase 3 (110–90 cm, 2871–1882 BCE, Bronze Age), the presence of trees is slightly reduced, while there is an increase in both mature grasses (but no evidence of flowering) and grasses cut in their young stage. The water stress signal of plants remains however strong. Paleoclimatic records (Sadori et al., 2015) attest these dry conditions, predominant until a cooler phase starting approximately at 2600 BCE.

Phase 4 (90–40 cm) corresponds to a period between 1882 BCE to CE 576, covering a wide temporal range of Sicilian history (from Early Bronze Age to late Antiquity). This phase is characterised by the substantial reduction of trees (cf. D_b/P index) and an increase in grasses reaching their maturing stage, but flowering evidence is absent (cf. long cell/short cell index). There is a notable increase in grasses cut instead in their young phase (indicated above all by the high presence of the rondel morphotype).

The last temporal phase (Phase 5, 40–0 cm) may cover the period from CE 576, thus from Late Antiquity, until today, according to the age-depth model. In this phase, we see a further reduction of dicot plants (attested by the reduction of blocky morphotypes) from the previous phase. There is, moreover, a reduction of grasses kept mature accompanied by an increase in the presence of young grasses.

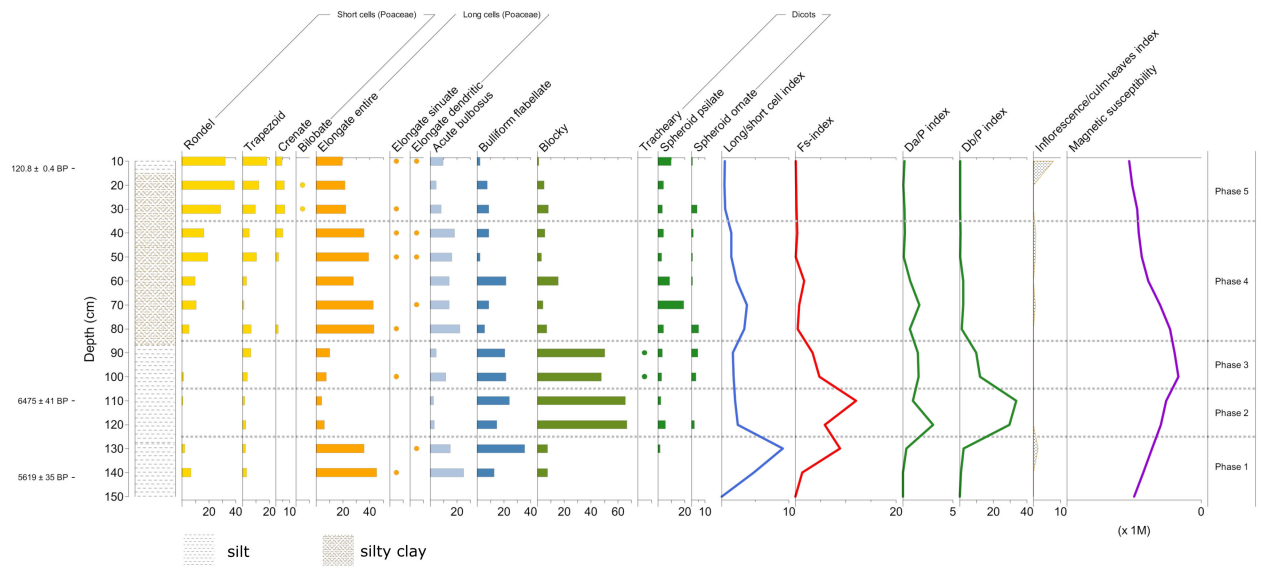

FIGURE 11
Phytolith diagram showing percentages of morphotypes from Cozzo del Lampo, Profile 1. Yellow and orange bars: grass phytoliths; green bars: dicots phytoliths. Dots indicate morphotypes < 1%. Inflorescence/culm-leaves index shown with exaggeration factor (60x). Note the difference in scale between the indices (Image source Ferrara and Wästfelt, 2025).

In Profile 1 of Cozzo del Lampo, the stratigraphic layers from Phase 1 to Phase 4 are dominated by grass phytoliths produced in the stems and leaves of these grasses, while the representation of grass inflorescences is very low (only present on the most recent layer, 10–0 cm). This is not surprising in natural grassland contexts, where the proportion of elongate dendritic phytoliths (indicators of grass spikelets) usually remains low (Novello and Barboni, 2015). In Cozzo del Lampo, the very low input of grass inflorescences, either domesticated or wild, might suggest on one side the harvesting of grasses before the complete formation and silicification of the inflorescence bracts. On the other side, such a low amount of inflorescence bract phytoliths could also be evidence of intense grazing before grasses reach their mature inflorescence (Delhon et al., 2020). Furthermore, the long/short cell index confirms a higher percentage of mature grasses in the older phases of the profile, and their progressive reduction over time. This might be due to preservation issues of short cell phytoliths along the profile or be related to historical changes in land use towards practices that have favored a more increased presence of young grasses (this could have been the case of heavy tilling practices). However, even though elongate entire phytoliths are very common in grass leaves, especially stem and culm epidermis, they are also formed in non-grass vegetation (Neumann et al., 2019, 9). Unfortunately, this is an understudied issue, thus our interpretation of the results from the long/short cell index must be considered with caution.

Along the profile, the Fs-index curve indicate periods of water stress experienced by local vegetation, which may be linked with warmer and drier climatic conditions, particularly in Phase 2. In coincidence with this period of water stress, both the D/P indices peak and this may indicate the natural expansion of xerophilous taxa in the area. Furthermore, even though phytolith production is far more important in grass than in dicots (Delhon, 2010), the presence of high percentages of dicot phytoliths in Phase 2 and 3 can suggest the presence of a semi-open habitat resembling a shrubland-type of environment. As both the D/P indices curves significantly decrease with time from 90 cm (beginning of Phase 4) until today, we can then infer the disappearance of certain species of arboreal vegetation (shrubs)? and the further opening of this landscape. Similar patterns were observed by Blinnikov (2005) in the historical boundaries between open grasslands and conifer forests in USA, as well as by Silantyeva et al. (2018) and Solomonova et al. (2019) who, relying on the floristic composition of forest vs. meadow vs. steppe in the Russian Altay, demonstrated the utility of using rondels as indicators of open habitats.

4.2.3 Profile 3

Profile 3 (Figure 12) show the historical transition from agroforestry model of land use into the present olive orchard. This is attested by the prevalent presence of grasses, accompanied with a constant low presence of dicots phytoliths along the entire profile, if not in the uppermost layer.

At the bottom of the profile (from 150 to 111 cm), we see simultaneous peaks of all four indices, telling that in this phase land cover may have been characterized by the presence of both mature grasses (attested by the peak in the inflorescence/culm-leaves and long/short cells index) and arboreal vegetation (peak in the D/P indices), within an overall increase in dryness conditions (cf. peak of

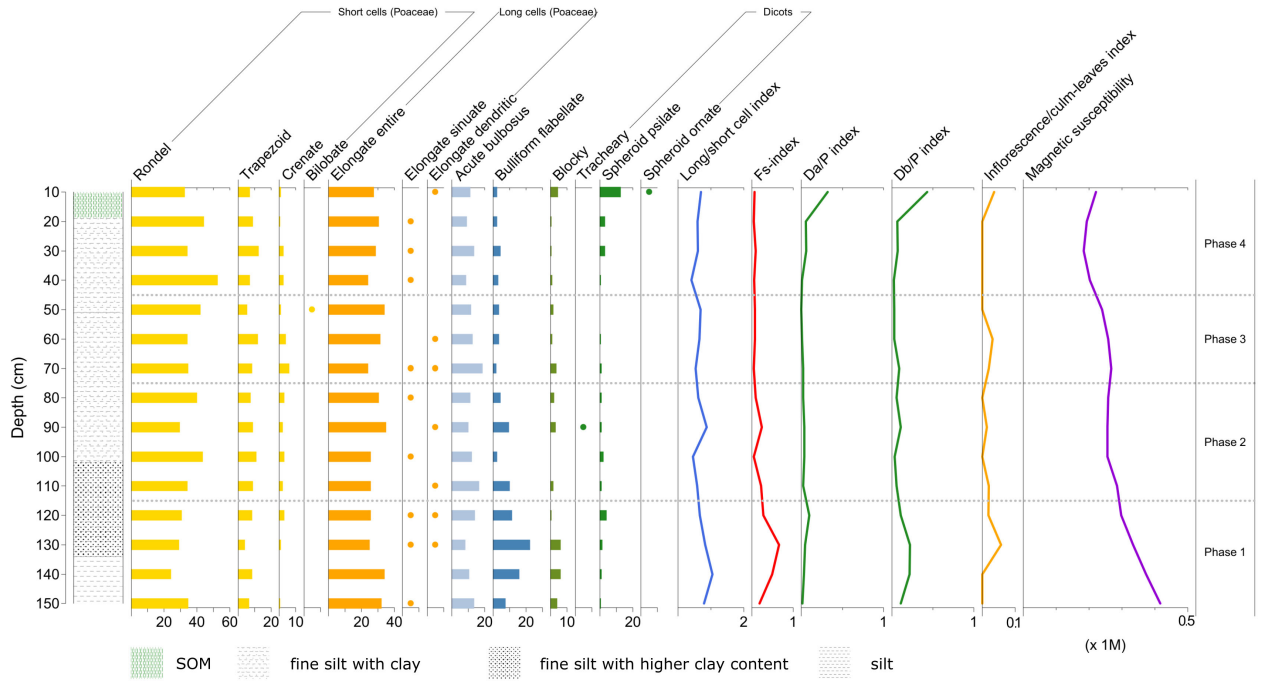

FIGURE 12
Phytolith diagram showing percentages of morphotypes from Cozzo del Lampo – Profile 3. See diagram legend in Figure 11 caption (Image source: Ferrara and Wästfelt, 2025).

the Fs-index). At 90 cm (Phase 2), there are slight peaks in both the Fs-index and the D_a/P index (above 0.1), again associated with a peak of the inflorescence/culm-leaves index and the long/short cell index. The potential land use pattern could resemble an agroforestry model, with intercropping practices.

Another interesting phase along the profile could be at 75–45 cm (Phase 3), characterized by a higher peak of the inflorescence/culm-leaves index, but now associated with a slight decrease of dicots and long cells grasses, transitioning into a further slight decrease of dicots (< 1%). This trend may suggest the progressive opening of the local environment, now featured by the presence of less trees. The soil in between 70 and 60 cm is also characterized by the inclusion of highly fragmented and minute pottery shards, which suggests anthropogenic presence at the site at those levels.

The topsoil layer in Profile 3 (Phase 4) is characterized by a higher presence of dicots phytoliths, which may attest the presence of fruit trees in the area until recently (Ferrara et al., 2024b; Ferrara and Wästfelt, 2025).

4.3 Agroforestry (Malìa)

In Malìa, the only ^{14}C age obtained from collected charcoal is very recent, consequently it was not possible to date any of the profiles. Even with the absence of a tentative chronology, the phytolith record in Malìa still provides diachronic information.

Phytoliths are abundant in most samples, apart from those layers with eroded bedrock (Profile 1, 60–150 cm; Profile 2; Profile 3, 80 cm and 100–150 cm; Profile 4, 50 cm and 80–150 cm; Profile 5, 150 cm). Detailed stratigraphic descriptions of each single profile are provided in Supplementary Material S1.

Similar to Cozzo del Lampo, all the phytolith records in Malìa are characterized by a morphological predominance of grasses from the Pooideae subfamily (C3), given by the high percentage of short cells phytoliths (31.4%) vs long cells (46.76%). The most common morphotypes recognized are rondel and trapezoid, formed mainly in the leaves and the stems. Phytoliths from grass inflorescence (dendritic) are present in low percentages, values which are however higher than in Cozzo del Lampo (3% vs 0.6%). Morphotypes related to other monocotyledons are scarce (0.45%). Phytoliths from woody and herbaceous dicotyledons are omnipresent in small amounts (5.83%). Wood and bark types (spheroids) are more abundant (5.71%) than from leaves (tracheary, 0.11%).

The assemblage analysis of the phytolith record from Malìa indicates specific environmental and land use history dynamics, which can be correlated with alternate periods of land abandonment. Profiles 4 and 5, described in details below, represent the most indicative cases of these dynamics.

4.3.1 Profile 5

As in Cozzo del Lampo, in the lowest and earliest layers, the profiles in Malìa show simultaneous peaks in the three indices long/short cells, Fs-index and D/P index, which may indicate a phase of shrubland growth due to warmer and drier conditions (Figure 13). At that time, vegetation composition was dominated by trees/shrubs and mature grasses.

Phases 2 and 4 are both characterized by a reduction of the two indices featuring overgrowing of tall grasses, shrubs and trees (long/

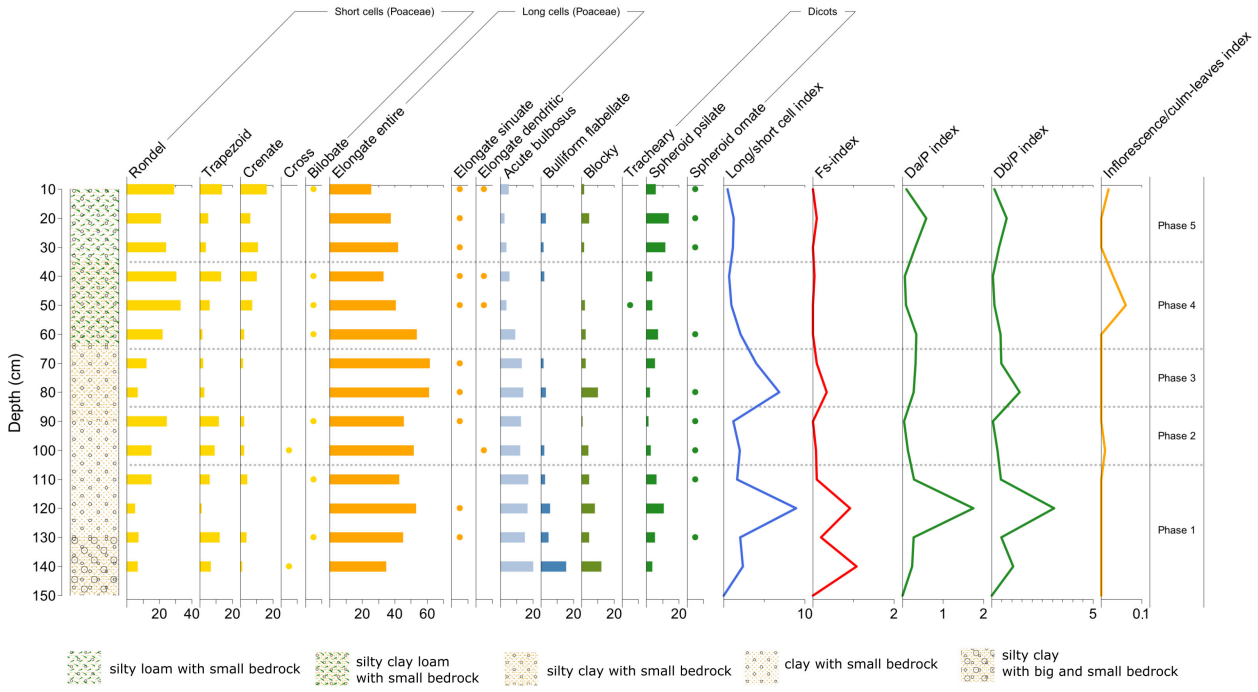

FIGURE 13
Phytolith diagram showing percentages of morphotypes from Malìa – Profile 5. See diagram legend in Figure 11 (Image source: Ferrara, 2024).

short cell index, D/P index), while there is an increase in the presence of inflorescence phytoliths, which may attest the use of the site for cultivation purposes.

The presence of inflorescence, associated with phytoliths indicating the clearing out of other grasses (cf. the long/short cell index decrease) and bushes (cf. the D/P index decrease), may be highly indicative of specific cultivation practices that kept certain grasses (crops)? reaching their maturation stage, while removing/clearing out some other types of grasses and bushes.

In between Phase 2 and 4, Phase 3 is on the contrary characterized by simultaneous peaks in long/short cells index, Fs-index and Db/P index, accompanied by a decrease in the inflorescence index. This may be linked to mature grasses being harvested or grazed before reaching their inflorescence stage.

In the last and more recent phase of Profile 5 (Phase 5), there is an increase in dicots (0.5) and long grass cells, followed by their reduction associated with an increase again in inflorescence, which may attest first an abandonment phase and then a re-use of the site (possibly for the combination of olive cultivation and grazing, based on the owners´ information on the land use since last century).

4.3.2 Profile 4

The location of this profile is a large open space among olive trees. Phases of use and abandonment, similar to Profile 5, can be deduced also here from the phytolith analysis (Figure 14). The oldest Phase 1 displays peaks in both the long/short cell index, Fs-index and D/P index, followed by their decrease in Phase 2. A second peak in all these three indices occurs in Phase 3, characterized also by the presence of inflorescence phytoliths that continues in Phase 4. Phase 3 shows a potential abandonment of the site, suggested by an increase in late-season grasses (i.e., in their year of growth; cf. long/short cell index) and in the presence of dicots (indicated by peaks in the long/short cell index, inflorescence index and D/P indices).

In Phase 4, the phytoliths from dicots decrease, thus these dicot plants were not likely to be olive trees. The increasing (in Phase 3) and then decreasing trend of the D/P indices (in Phase 4) could signify that the dicot vegetation present in Phase 3 was rather the result of abandonment (e.g. shrubs), successively cleared out for cultivation purposes around the existing olive trees (visible in Phase 4 and potentially a similar shift also took place in the previous Phase 2).

5 Discussion

As shown from our results, phytolith assemblage analysis provides the possibility to distinguish between close and open environment in historical olive agroecosystems and, furthermore, to differentiate between periods of anthropogenic occupation and abandonment of a site. Phytoliths as biocultural traces can also reveal previously unknown dimensions of local land use, linked to traditional ecological practices of the past. Phytolith assemblage analysis can then allow us to understand how land uses in diverse historical times

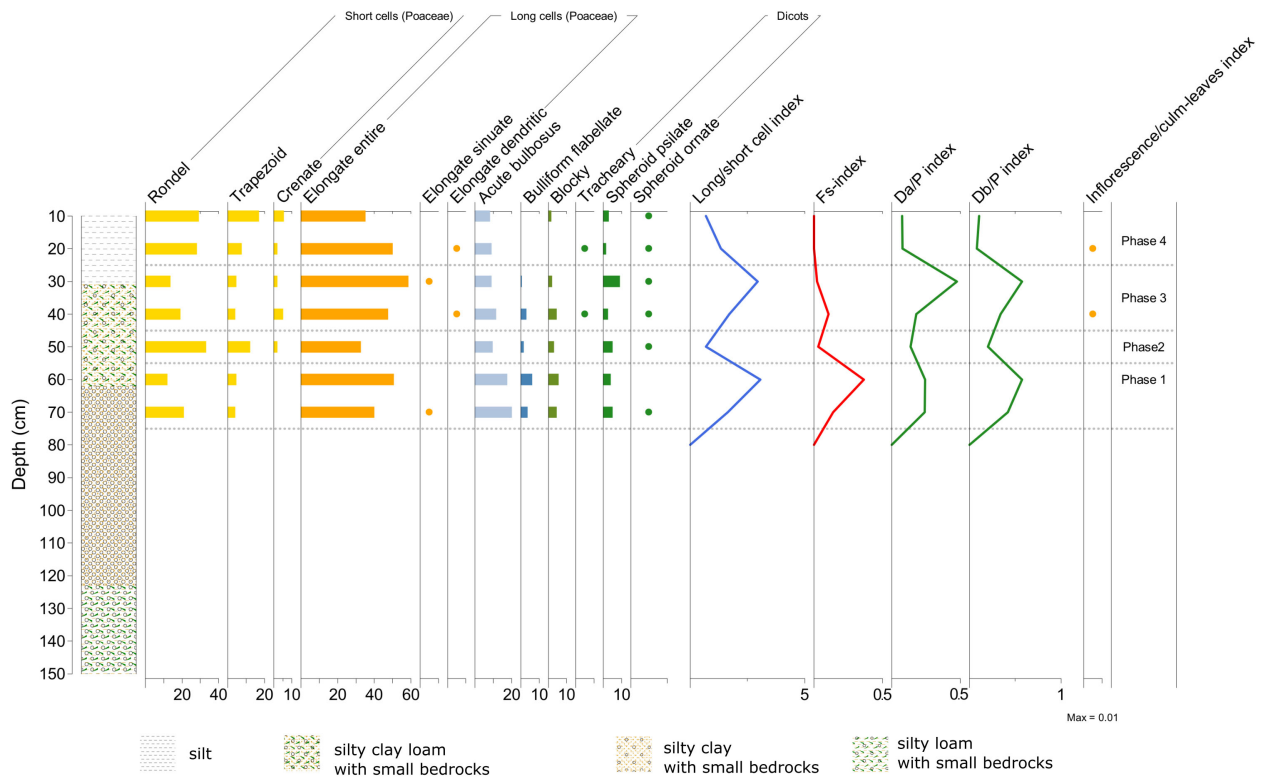

FIGURE 14
Phytolith diagram showing percentages of morphotypes from Malìa – Profile 4. See diagram legend in Figure 11 (Image source: Ferrara, 2024).

have contributed to shape the current configurations of ancient olive trees in present space.

The results from Bosco Pisano are reference for comparisons with the other study areas based on the agricultural use of *Olea*, since they can be representative of the tree cover density typical of an olive woodland. In the case of Bosco Pisano, phytolith assemblage analysis aimed to establish a reference for the local calibration of the threshold in tree cover density calculated by the D/P index, which was applied to interpret evidence from the other sites.

In Cozzo del Lampo, the results from phytolith analysis have shown that the site transitioned – through at least six millennia – from a shrubland into the olive orchard we see today. A similar transition is also shown in the Malìa site, where we gain further knowledge into how biological diversity in plant composition was positively correlated with human practices and negatively affected by anthropogenic abandonment. Phytoliths as biocultural proxies in the soil can therefore allow us to gain new knowledge on the land use and management of a site happening as a historical process, helping see more clearly how different historical phases are interlinked and dependent to each other.

The results presented here also suggest both shifts and maintenance in land use. In Malìa, the phytolith results show that a predominant grass vegetation cover has been the norm, as in the phytolith diagrams we see no drastic change from natural or semi-natural grassland to today´s olive orchards. This result suggests that a grass layer was maintained, either via grazing (thus we could advance also the hypothesis that phytoliths may have been introduced through the dung of grazing livestock) or by cutting grass (meadowing). This could have been probably also a practice in other olive agroecosystems in the Madonie Mountains. In this area of Sicily, olive orchards were organized to provide grazing and fodder, alongside cultigens; a multifunctional land use which may have been necessitated by the local extremely harsh topography. Moreover, the Malìa phytolith records, if compared with other proxies, may shed light on the correlation between certain land use practices and specific cultural phases in local history. In Profile 5, the peaks of the inflorescence/culm-leaves index are simultaneous with the presence of C4 phytoliths (bilobate and cross), indicative of certain plant varieties that may have been associated with specific cultural land use practices. This is the case, for instance, of the introduction of C4 plants for both humans and animals' diet during early Medieval times (as attested in the archaeological record elsewhere in Sicily, cf. Egli et al., 2013), which in the Madonie Mountains may be linked to the Islamic settlers´ agricultural practices reshaping the local landscape during the 9^{th}–11^{th} centuries BCE (cf. Barbera, 2013). The Malìa case is therefore inspiring for further integrated investigations into correlation dynamics between plant diversity traced from soil layers of the past and the diverse historical phases of cultural contaminations on the island. Furthermore, since peaks in inflorescence with C4 grasses (thriving in more warm and wet environments) occur together with a decreasing trend of water stress (cf. Fs-index) in Profile 5, we may infer that these grasses reaching an inflorescence stage could have been favored somehow by local access to water.

In conclusion, our work demonstrates that phytoliths assemblages conceived as biocultural traces stored in soil layers can be analyzed for the investigation of past land uses in historical agroecosystems. Phytoliths in the soil reflect local plant communities and, studied as biocultural heritage and within a historical perspective, they can be interpreted as the accumulated outcomes of local plants´ responses to both external and internal inputs/stresses. Even though the deposition and preservation of phytoliths in agricultural soils are affected by several environmental and anthropogenic disturbances over time, the analysis presented here shows that phytoliths assemblages can be informative on how land use practices in a place at different periods are correlated to the alternate states and historical conditions of these agroecosystems over time. In such respect, results show that these historical agroecosystems have experienced significant shifts in both conditions and compositions of local vegetation over the past millennia (as indicated in particular in Cozzo del Lampo, where chronology is available). Such historical dimension can be highly informative not only to better understand past land use practices, but also to advance knowledge about how local plants (and humans managing them) have acted and re-acted in front of changing environmental circumstances (e.g., climate). In Cozzo del Lampo and Malìa profiles, the oldest changes in land cover, driven probably by environmental shifts (i.e., climate), have preceded and potentially partly driven the coming land use and its further changes. The phytolith records presented in this paper inform us of an initial shrubland, which could have been favored by certain climatic and environmental conditions. Among the local xerophilous taxa occurring naturally in this environment, the selection of *Olea* was surely shaped by pragmatism alongside cultural influences, since it is one of the most resistant trees/shrubs for agricultural and silvo-pastoral use. In simple words, the phytolith record in Cozzo del Lampo, when combined with local palynological and paleoclimatic data, suggests the hypothesis that, without the environmental conditions favoring a certain type of vegetation to spread at ca. 5550–4050 BCE (cf. Cozzo del Lampo, Profile 1), we would not have had the beginning of olive-linked land use. Furthermore, an herbaceous undergrowth has been the local land cover in these olive agroecosystems for centuries, until most recent phases in which grasses are present in their young stage.

The analysis of phytolith assemblages stored in the soil as biocultural heritage can, therefore, be used to infer land use dynamics at the whole agroecosystem level, particularly in remnants of old systems. This method opens up the possibility of expanding phytoliths research as proxies to understand past land use practices in historical agricultural soils. This allows for a better understanding of not only past land uses but, what is even more important, their ecological legacies on current soils and ecosystem conditions. Information on the silica cycle in agroecosystems over the long term is important to reconstruct long-term anthropogenic drivers and their impacts of land use practices. The analysis of phytoliths as biocultural evidence can thus operationalize the investigation of past land uses in historical agroecosystems to address current management issues, since along the (deep) history of a site we may find past analogues to future scenarios of local

environmental changes. These we may want to bear in mind when reflecting on how future adaptations of land use and agriculture could be shaped. Knowing how these agroecosystems have locally responded to similar shifts and challenges we face today or we may face in the future, can provide us with crucial evidence that we can immediately operationalize in our current management. This could be the case, for instance, of ecosystems´ reaction to an increase in local temperatures and progressive dryness, or to the anthropogenic abandonment of a site. More importantly, we may start noticing the evidence of an incredible interdependence between gradients of variation along millennia (in microclimatic conditions, land cover, land use, biodiversity, occupation) and longer stability trends (represented by the maintenance of certain vegetation elements, i.e. century-old olive trees); and advance the interpretative hypothesis that exactly such persistence could have been the prolonged response to disturbances. The novel contribution of our work relies on showing that agriculture in itself is an ecological practice, which over the long term have contributed to maintain certain agroecosystems structures and functions, including their biocultural diversity. Such a historically informed perspective can inspire us practitioners for present day management and future adaptation, as well as inform public policies on the urgent need to promote the conservation of these historical agroecosystems.

Data availability statement

The original contributions presented in the study are publicly available. This data can be found here: Zenodo, https://doi.org/10.5281/zenodo.15367550.

Author contributions

VF: Data curation, Writing – original draft, Investigation, Formal analysis, Resources, Visualization, Conceptualization, Writing – review & editing, Methodology. GS: Investigation, Writing – review & editing, Resources, Methodology. GG: Writing – review & editing, Investigation, Resources. TM: Methodology, Writing – review & editing, Investigation, Formal analysis, Resources. AE: Methodology, Investigation, Resources, Conceptualization, Project administration, Funding acquisition, Supervision, Writing – review & editing.

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Supplementary material

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SUPPLEMENTARY MATERIAL S1
Stratigraphy of the study areas.

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