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Medieval forest land use along the Tyrrhenian coast (Tuscany, central Italy): The archaeo-anthracological signal (AD 750–1250)

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ABSTRACT

Charcoal analysis, applied in archaeological excavation of Vetricella site in the distal reach of the Pecora river (Tyrrhenian southern Tuscany, Italy), detected the exploitation, management, and ecology of forest land cover between mid-8th century AD and mid-13th century AD. Taking place in a central Mediterranean district adequately studied through palaeoenvironmental and archaeological research, the investigation determined times and modalities of Medieval human impact on forest ecosystem. The fuelwood supply areas were characterised by *Quercus cerris* forest, in the past much larger and extended than Mediterranean evergreen forest. The collection of fuelwood was based on the traditional method of coppice woodland management, including the release of decade-year-old standard trees for the production of larger timber assortment, useful for building activities (testified by the numerous post-holes). The silvicultural system, known as compound coppice, produced a forest landscape characterised by multi-storied stands ensuring production of fruit and spreading of acorns for feeding pigs. Changes in the forest ecosystem were particularly detectable from mid-10th century AD, when accessory pioneer woody species, resilient to cut clearance, spread. It was the Ottonian period of activities in sequence aimed at radically changing the site of Vetricella along with land use in the Pecora river valley. The resulting forest land cover management, depending on the political strategies adopted by Medieval authorities, marked the progression of a cultural landscape still characterizing central Tyrrhenian Italy.

1. Introduction

The history of forest land use straddles the boundary between human, social, and ecological sciences. On a territory, human practices and actions are consequent to its forest cover, but also the biodiversity and functioning of forest landscapes are connected to human factors and history (Hermy and Verheyen, 2007). How forest ecosystems have changed over time and how past human activities impacted on these dynamics are long-standing questions that have involved, as interdisciplinary research, historians, geography, ecologists, anthropology (first) and archaeologists (later), with their sources and working methods (Hughes, 2005; Harris, 2013; Mercuri and Sadori, 2014; Szabó et al., 2015; Conedera et al., 2017; Whitlock et al., 2018; Mensing et al., 2020).

In the debate, which started in the second half of the 19th century, the disciplines proceeded in parallel, occasionally encroaching on their fields of influence. Points of contact and collaboration were not missing, but the first critical issue to overcome was the time scale. Historians, geographers, ecologists and forest scientists focus on historical and ethnographic archives, inorganic and biological, identifying the landscape as a human-made structure, in which visible anthropic signs - cultivation methods and rural artefacts - reflect production and silvicultural techniques with precise chronologies and historical correlations (Moreno, 1982, 1986; Piussi, 1982; Wickham, 1994; Grove and Rackham, 2001; Szabó, 2005; Agnoletti, 2006; Rackham, 2006; Squatriti, 2013; Montanari and Stagno, 2015; Decocq, 2022). Archaeological and, in particular, landscape archaeology research, with the focus on material sources, sites and artefacts altering the natural environment, has extended research into time periods far beyond the limits of historical and ethnographic archives (Darvill, 2008; Campana, 2018). A fundamental contribution has come from ecology and, more precisely, the field of palaeoecology, which has refined the analytical tools useful to reconstruct past ecosystem and their dynamics in response to natural

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and anthropogenic drivers, using plant proxies. In a very short time, the favourite tool of (palaeo)ecology unequivocally becomes the biostratigraphic pollen analysis from Holocene marine, lake or peat cores, that have contributed greatly to the debate on human activity as an ecological factor on forest structures (Roberts et al., 2011, 2019; Mercuri, 2014; Mercuri and Sadori, 2014; Kouli et al., 2015; Sadori et al., 2016).

Crossed the boundary between environmental sciences and historical-anthropological sciences, it is not unusual to observe long-term research perspectives in environmental history texts, from topographic archaeological surveys of sites and landscapes to time series from palaeoenvironmental palynological proxies, which summarise records of changes in populations, ecosystem, disturbance frequencies, trends and periodicities (Walsh, 2013; Bottema, 2016; Schoolman et al., 2018). Nevertheless, the quality of the palaeoenvironmental palynological proxy resulted in interpretations essentially on a regional (and larger) scale and long times inevitably smoothed the local complexities of human-induced changes. The identification of a simple correlation of historical phases/environmental changes was often the anthropogenic explanation of events (Mercuri et al., 2013; Mercuri, 2014), far from socio-cultural interpretations that require instead regional, sub-regional and also micro-regional approaches with the perspective of historical and archaeo-logical sources (Roberts et al., 2019). In the mainstream of palaeoecological studies, the use of historical and archaeological sources has led to a deterministic approach and the formulation of simplistic causal relationships (Holmgren et al., 2016). Instead, it is essential to recognise the role of human activity in the transformation of forest landscapes in order to identify what, who and when produced those environmental changes that shaped the structure, organisation, management and economics of forest land use (Mensing et al., 2020).

A tool between palaeoecology and archaeology is charcoal analysis (anthracology), defined as the study of wood fuel remains derived from archaeological sites. Charcoal is of high interest due to its widespread use and provides insights into the use of wood by people in all archaeological situations (Chabal, 1992, 1994; Théry-Parisot et al., 2010). Anthracological assemblages therefore represent the material residues of human-forest interactions and, being of essentially anthropogenic production and dispersal, investigate the complexity of palaeoecological and cultural signals in the archaeological remains of a community (Kabukcu, 2018). Research in environmental archaeology conducted on fuelwood remains is the most useful for defining forest areas, because it is possible to carry out a socio-cultural analysis with the perspective of the sources from the archaeological settlements that shaped the woodland. If the forest is a space integrated into the life of a community, then it is within the space of the community that traces of this integration are preserved.

Anthracology provides a unique set of analytical tools disentangling the various phases of the complex relationships between vegetation, climatic conditions and forest management and land use in the past. Our research paper presents an anthracological strategy adopted to understand habitat, use, management, activities, features and development of a forest area by a medieval community that between the mid-8th and mid-13th century was settled in the lower reach of the Pecora river valley, on the edge of the upper Tyrrhenian coast (Gulf of Follonica) in the northern Maremma of the Italian peninsula. The research was carried out as part of a European project, funded under the ERC-Advanced 2015 programme, entitled *nEU-Med: Origins of a new economic union (*7th-12th *centuries): resources, landscapes and political strategies in a Mediterranean region*. The project focused on the form and timeframe of economic growth between the early and late Middle Ages in the central Mediterranean. Here, extensive archaeological investigations have indicated the site of Vetricella, in the distal reach of the Pecora river valley, as the centre of the royal court of *Valli*, which between the second half of the 9th and the mid-11th century AD gradually became the core of the entire territory, both in terms of administrative control and the management of economic and productive resources (Marasco and Briano, 2020; Bianchi, 2022).

Our research paper present and discusses the aspects most closely related to the interactions between the forest ecosystem and human activities of management and exploitation. In fact, the forest changes and modifies the quality and quantity of tree and shrub species because of certain human activities. In the absence of these activities, the forest would have a composition, physiognomy and characteristics linked to the climate, substratum and morphology of the land, in order to achieve complete equilibrium with the natural environmental conditions. The disturbing activities of human communities, such as the harvesting and cutting of firewood and timber, and the grazing of animals, directly and indirectly change the forest stand by altering the local ecological factors, leading to the gradual replacement of species by others better adapted to the new environmental conditions. The forest takes the direction and shape given to it by the human community.

2. Regional settings

2.1. Topography, climate and current landscape

The archaeological site of Vetricella (Scarlino, GR) is located in the distal reach of the Pecora river floodplain in northern Maremma (central Italy), on a terrace formed by the alluvial fan of the river about 6 km from the coast on the Tyrrhenian Sea. Set between the Montioni ridge (265 m asl) and Monte Arsenti (536 m asl) from N to NW, the hilly ridges of Massa Marittima and Scarlino to the NE, and the Gulf of Follonica from W to SW, the Pecora river basin is one of the natural links between the southern slopes of the Colline Metallifere and the Tyrrhenian coast (Fig. 1). The river is ca. 20 km long and has a catchment of about 250 km^2.

The proximal part of the basin is characterised by wide karst features such as karst depressions, active and unactive karst springs, and calcareous tufa terrace systems (Pieruccini et al., 2021). Here, the tributaries of the Pecora river are characterised by deep valleys, although the bottoms of the valleys are flat, terraced and narrow. During the Quaternary, associated subaerial processes drove the deposition of continental sediments (Benvenuti et al., 2009; Coltorti et al., 2017), including alluvial deposits and continental fresh-water carbonate sediments, such as calcareous tufa. According to the historical cadastre of Tuscany (drawn up in the year 1821), the coastal plain opened at ca 6 km from the present-day coastline and widen up to 5 km in the distal part (Fig. 1a). In this area an open lagoon was present only in the southeastern part, directly opening to the sea, whereas a locally densely vegetated swamp extended up to 4 km inland (Londi et al., 2007). In the proximal and distal portions, the present-day surface hydrology is mainly related to artificial drainage and reclamation works occurred in Medieval times (Buonincontri et al., 2020b; Pieruccini et al., 2021) and in the last two centuries (e.g. Canale Allacciante in Fig. 1; Tongiorgi, 1957; Londi et al., 2007).

According to the weather station of Follonica (4.34 m a.s.l., UTM 643775 E, 4753770 N, data source http://www.sir.toscana.it/), the area is characterized by a mesomediterranean climate, with a minimum average temperature of 3.1 °C during the coldest months and an annual precipitation of 592 mm. The steeper slopes of the proximal portion of the basin are characterised mainly by the Mediterranean evergreen forest of *Quercus ilex* L. and *Arbutus unedo* L., with small, scattered stands of thermophilous deciduous broadleaved, such as *Quercus pubescens* Willd. and *Fraxinus ornus* L. (Fig. 1c). Here, scattered stands of deciduous oak forest of *Quercus cerris* L., mixed with *Quercus pubescens* Willd., *Ostrya carpinifolia* Scop., *F. ornus* L. and *Q. ilex* L., are present on the eastern slopes of the basin. *Q. cerris* forest dominate instead the northern Montioni ridge, while the southern and distal part of the valley is covered by *Q. ilex* forest with *F. ornus* L., *Erica* sp., and, occasionally, *Quercus suber* L. Land use of the gentler hilly slopes of the middle and distal portions and the valley floor is designated instead for the cultivation of arable crops, vineyards, and olive groves.

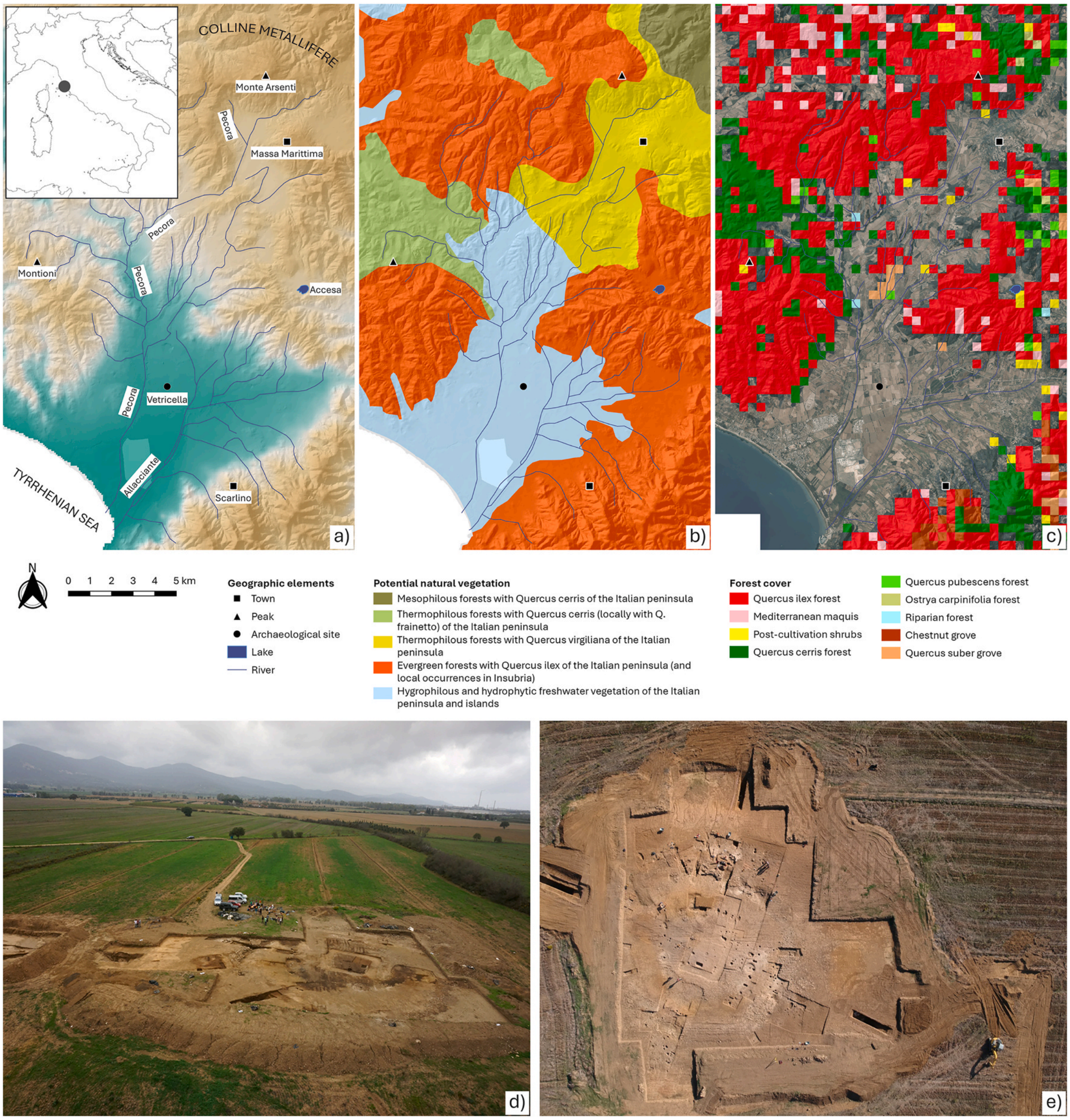

Fig. 1. (a) Location of the study area in the broader context of the central Mediterranean. The Colline Metallifere (Metalliferous Hills) and the course of the Pecora river (blue line) with the archaeological site of Vetricella and locations cited in the text. Map source: pcn.minambiente.it - Dtm Italia; geodati.gov.it - Reticolo Idrografico (QGIS 3.22.14-Białowieża). (b) Potential natural vegetation map of the Pecora river valley. Data sources: va.mite.gov.it - Carta delle serie di vegetazione d'Italia, legend from Blasi et al. (2017) (QGIS 3.22.14-Białowieża). (c) Forest vegetation map of the Pecora river valley. Data sources: dati.toscana.it - Inventario Forestale Toscano; www502.regione.toscana.it - OFC 2013 (QGIS 3.22.14-Białowieża). (d) view from the drone of the archaeological excavation of Vetricella and the distal reach of the Pecora river plain towards the coast (elaboration by Giulio Poggi, Department of History and Cultural Heritage, University of Siena). (c) UAV orthophoto - 2018 campaign (elaboration by Giulio Poggi, Department of History and Cultural Heritage, University of Siena). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.2. *Palaeoecological and historical background*

The geographical area of the Colline Metallifere is a relevant mining district, where numerous ore deposits of pyrite, Fe, Cu-Pb-Zn, Ag, Sb, Hg, Sn and Au were exploited from Eneolithic/Bronze Age (Corretti and Benvenuti, 2001; Aranguren and Sozzi, 2005). On the southern side, the anthropic pressure played an important and fundamental role in shaping the current forest cover. According to the high-resolution pollen and sedimentary charcoal sequences of the Lake Accesa, human presence became significant already ca. 8000 cal yr BP at the Mesolithic-Neolithic transition (Colombaroli et al., 2008, 2009). Land use became even more significant and constant in the late-Holocene (ca. 4300 cal yr BP) at the beginning of the Bronze Age (Drescher-Schneider et al., 2007). The impact of Etruscan civilization on forest cover can be dated from ca. 2600 to ca. 2500 cal yr BP, AD 750–650 (Drescher-Schneider et al., 2007; Vannière et al., 2008; Stoddart et al., 2019).

Archaeological research identified centuries of intense occupation linked to the natural resources of the hills and the coast, both in the form of settlements and production sites. In the protohistoric period, salt production activities on the coast were performed (Aranguren and Castelli, 2011; Aranguren et al., 2014; Sevink et al., 2021). Between the 6th and 5th century BC, Etruscan civilization engaged in mining and crop management on the hills of the proximal reach of the Pecora river (Mariotti Lippi et al., 2002; Aranguren et al., 2007; Giuntoli, 2018), iron smelting and salt production on the coast (Aranguren et al., 2009). Local archaeobotanical analysis showed that Etruscan settlements altered the natural state of the pre-existing deciduous *Quercus* forest through cutting and farming enhancing the xeric features of the vegetation (Mariotti Lippi et al., 2000; Sadori et al., 2010). The woods supplied the timber to realize buildings and handcrafted items (Mariotti Lippi et al., 2002).

With the spread of Roman civilisation in the 3rd century BC, villas, farms and smaller agricultural settlements spread to the distal area, expanding agricultural exploitation around the swamp (Marasco, 2013a), while production sites continued metallurgical work (Cucini, 1985; Aranguren and Castelli, 2011; Sevink et al., 2021). Despite signs of decline from the 2nd-3rd century AD, the Late Antique period showed a relative survival of some of the main sites on the coastal plain, with the continuity of ironworking and the vitality of the maritime routes (Marasco, 2013a; Vaccaro, 2018). At the end of the 5th century AD, with the beginning of the Middle Ages, the socio-economic network was still quite solid.

After a marked decline in material evidence between the 6th and 7th centuries AD, more organised human activity becomes visible from the 9th century AD onwards (Marasco, 2013a). In the 10th century AD this district (and its natural resources) became a strategic and political cornerstone of the Kingdom of Italy and the later Ottonian kings of the Holy Roman Empire (Vignodelli, 2012).

In these centuries, anthropogenic fire sequences affected the proximal portion of the Pecora river valley, linked at first to reclamation and vegetation clearing of flat upstream swamplands (Buonincontri et al., 2020b). In particular, from mid-9th century AD the use of fire spread over a wider area in the valley, increasing potentially arable lands. The Medieval fire episodes played an active role in changing the fluvial landforms of the Pecora river into a braided gravel-bed course, influencing also regional vegetation history and the decline of the dominant deciduous *Quercus* woodland (Buonincontri et al., 2020b). From mid-10th century AD, open habitats became the new form of clearly detectable agricultural landscape.

In the Late Middle Ages, local aristocratic families took over control of the Colline Metallifere, building hilltop stone castles with a clear economic strategy aimed at exploiting metal bearing deposits (Bianchi, 2015). In the 12th and 13th centuries AD, the autonomy gained by families and the subsequent development of towns, politically organized as Communes, launched a new historical phase, determining the definitive success of both castles and towns and crystallizing the settlement landscape until the modern era.

2.3. Vetricella, an Early Medieval royal property on Mediterranean sea

In the Pecora river valley, the archaeological site of Vetricella (Fig. 1) and its surrounding area have been the subject of extensive archaeological research for many years (Marasco, 2013b; Marasco et al., 2018) and has recently been included among the contexts investigated within the European Research Council Advanced Project *nEU-Med* (2015–2021). The project, aiming to study the mechanisms and timing of Medieval economic growth (7th-12th centuries AD) in this part of the Mediterranean prior to the great developments of the 12th century AD, has selected the so-called historical region of northern Maremma as a study area due to the variety of natural landscapes and the presence of important resources (Hodges, 2018).

Vetricella appears to have been either the centre or a major unit of the royal court of Valli, set by Medieval historical sources in the distal reach of the valley (Bianchi and Collavini, 2018). During the European Middle Ages, Valli was a property of the Kingdom of Italy and assigned to Adelaide (AD 931–999), widow of the last king Lothair II, and later wife of Otto I (founding Emperor of the Holy Roman Empire), mother of Otto II and grandmother of Otto III (Vignodelli, 2012).

The site holds a significant place in Italian archaeological research, being the only royal court on the peninsula that has been extensively excavated. The archaeological site is characterised by a close series of phases of life (Supplementary Table 1) that, especially between the second half of the 9th century and the mid-11th century AD, marked its progressive development as the core of the entire district, both in terms of administrative control and the management of economic and productive resources (Marasco and Briano, 2020).

The first phase of occupation (period 1) falls between the 7th/8th century and the mid-9th century and characterises a consistent settled site related to metallurgical workings. In the second half of the 9th century (period 2), a fortified settlement is created, defended by three concentric ditches, a central artificial mound, on which a tower is built of perishable material (period 3).

The historical moment expressing the greatest development of the site, in relation also to the economic system in which it was included, can be dated to the Ottonian dynasty (AD 919–1024), when a profound structural transformation took place (Supplementary Table 1). Between the second half of the 10th century AD and the beginning of the following century (period 4.1), the innermost ditch was filled in, the central tower rebuilt with a stone base and delimited by a palisade. In this new and larger area, a small religious structure made of perishable material was also built, around which a cemetery was distributed (Viva et al., 2021a, 2021b). In the first half of the 11th century AD, the site is frequently renovated and preserved (period 4.2). Around the tower there was an important administrative centre, connected to the presence of the king's emissaries and their entourage. Here, agricultural products, iron objects related to textile, forging, leather, woodworking, and equestrian activities, were stored (Bianchi, 2022). The community was also engaged in horse and pig farming, butchering and agricultural work (Aniceti, 2020; Viva et al., 2021a, 2021b). In fact, a great movement of products and people around the core of this alluvial plain.

With the end of the Ottonian era, the last two life periods of Vetricella, although still indicating the site as the focal point of a smaller territorial system, are an expression of a changed political and economic framework (Supplementary Table 1). Between mid-11th and mid-12th AD (period 5), the great movement of people, storage, and products of the previous period ceases. The site is sparsely frequented, religious oratory and cemetery abandoned, and some areas are temporary deposits of cereal and legume crops in small pits from neighbouring fields. Between mid-12th and mid-13th AD (period 6), the site is now defunctionalised.

3. Materials and methods

3.1. Selected archaeological contexts and charcoal remains

In accordance with the fieldwork anthracological methods, archaeological contexts were carefully selected considering the origin of charred wood deposits (Chabal, 1994, 1997; Théry-Parisot et al., 2010). In archaeological horizons, scattered and dispersed charcoal are resulting from long-term accumulated fuelwood consumption and accounts for the entire – or almost the entire – supply area characteristic of a time period. This kind of charcoal is present in both occupation levels and floors and are sampling to state the composite and diachronic characterization of the past vegetation landscape.

A total amount of 31 sampled stratigraphic units (SU) provided dispersed charcoal from 18 activities (Table 1). The SU were selected because they were deposits of scattered charcoal, resulting from the long-term accumulation of fuelwood, and they were well related to activities carried out at the site and to known structures. No particular contexts of burnt structures or buildings were found during the excavation, so the risk of mixing charcoal fragments with timber or wooden furniture was unlikely. The chronological periodization (Supplementary Table 1), built on the archaeological stratigraphic analysis, was strictly followed (Marasco and Briano, 2020). Charcoal record from Vetricella ranges from the mid-8th (AD 750) to the mid-13th century AD (AD 1250), corresponding to the long-time span investigated during the extensive archaeological research. A preliminary archaeo-anthracological report was published, however this research paper presents and discusses the revised and more complete dataset, integrating and consolidating the assertions of the

Table 1
Archaeological soil samples from Vetricella providing dispersed charcoal. Sequence of the stratigraphic units (SU), grouped by chronological period and activities, with information on the archaeological context and the type of activities and fireplaces that produced the anthracological assemblages. Absolute values of charcoal remains under taxonomic analysis for each activity are reported.

Period	Cal yr AD	Activities	Main features	SU	Interpretation	Charcoal
1	750â€“850	1	Building structures in perishable materials	1228	Occupation levels and floors near open hearths and kilns	21
		12		1144		112
2	850â€“900	38	First construction activities for the fortification system	506	Scattering from open hearths and kilns	36
		49	Occupation inside the main central building	1500, 3007	Occupation levels and floors near domestic open hearth.	90
		50		215a, 1490, 3006		325
3	900â€“950	78	Waste discard into the inner ditch	519, 636	Scattering from open hearths and kilns (also for forging)	197
4.1	950â€“1000	88	Occupying and preparing for the new construction phase	844	Occupation levels and floors near open hearths and kilns (also for forging)	31
		89		968, 1311		94
		113	Mortar lining of the now filled inner moat	572	Occupation level and floor near open hearths and kilns (also mortar kiln)	40
		116	Waste discard into the inner ditch	446	Scattering from open hearths and kilns (also for forging)	114
4.2	1000â€“1050	198	Levelling after dismantling of the wooden enclosure	112, 426, 459	Occupation levels and floors near open hearths and kilns	215
		236	Dismantling of the cemetery with a small oratory	384	Levels and floors with iron forging furnaces	40
		237		132	Scattering from open hearths and iron forging furnaces	34
5	1050â€“1150	249	Grain storage activities	838	Occupation levels and floors near open hearths	119
		254		3021		62
		260		1289		69
		266		622, 1464, 1465, 1466, 1467, 1469		322
6	1150–1250	294	Abandonment of structures	491, 496	Occupation levels and floors near open hearths	34
						1955

previous report (Buonincontri et al., 2020a).

The archaeological sediments were filtered by way of a flotation machine with mesh-size sieves of 4 mm, 2 mm and 0.5 mm. Considering the exponential trend of charcoal fragmentation, charcoal remains greater than 2 mm were preferred for the sake of a more rapid identification and statistical accuracy (Chabal, 1992; Figueiral and Mosbrugger, 2000; Asouti and Austin, 2005; Kabukcu, 2018). Charcoal fragments were identified using an incident light microscope working between 100x, 200x, and 500x magnification, referring both to wood atlases (Schweingruber, 1990; Abbate Edlmann et al., 1994; Vernet et al., 2001) and the reference collection in the Department of History and Cultural Heritage, University of Siena (Supplementary Table 2).

Taxonomic identification reached the species (e.g. *Ostrya carpinifolia*) or genus level (e.g. *Alnus* sp.) thanks to the fragments' good state of preservation. Botanical nomenclature follows Pignatti (1982). In some cases, grouped taxonomic references have been used according to anatomical types on a morphographic basis, such as deciduous *Quercus* type (Vernet et al., 2001). In addition, precise anatomical criteria were used to distinguish certain species, as reported in atlases, by applying them to those fragments with better shaped and larger growth rings. In particular, *Fraxinus* cf. *ornus* and *Fraxinus* cf. *angustifolia* were distinguished by recording and comparing the diameter of the initial and final pores (Abbate Edlmann et al., 1994; Vernet et al., 2001). To distinguish between the various species of *deciduous* Quercus, the characteristics listed in Cambini (1967) were observed. Regarding the evergreen *Quercus*, *Quercus* cf. *ilex* is reported to be the only evergreen *Quercus* present in the study area. Partial, uncertain or even distorted anatomical views did not allow us to identify occasionally the samples, or limited identification to the family level.

For a good statistical outcome, dispersed charcoal remains should be 200–250 per activity. These numbers were collected in activities related to periods 2, 3, 4.2 and 5 (Table 1). The counted charcoal remains (Supplementary Table 2) were then processed by calculating the percentage frequencies of each determined taxon on the total amount of determined taxa per period (Table 2). Indeterminate fragments were not included in the percentage calculation. The frequencies were then showed on a horizontal bar graph (Fig. 2), plotted by using the software C2 (Juggins, 2022). Taxa are grouped based on their ecological significance, according to the local potential natural vegetation (Fig. 1b).

3.2. Selected postholes and diameter ranges

An important feature of the Vetricella excavation is the presence of postholes with lime, mortar and stone fillings, related to the construction of defensive palisades, walkways, mortar mixers and buildings such as the tower. The presence of conglomerates and hydraulic binders allowed for the perfect preservation of the negative diameter of the wooden element in the elevation. An analysis of the diameters of the postholes was performed on a sample of negative SU, considering, in addition to the diameter, the age and function above all (Supplementary Table 3). The diameters were grouping into classes of 4 cm and the absolute values and percentage frequency were calculated (Table 3). In Fig. 3, bar graphs shows the absolute value frequency of all periods and in detail of the period 4 (4.1 + 4.2).

Table 2
Charcoal remains from Vetricella. Absolute values (No) and percentage frequency (%) of determined plant taxa grouped by chronological period.

Period	1		2		3		4.1		4.2		5		6			
Cal yr AD	750-850 AD		850-900 AD		900-950 AD		950-1000 AD		1000-1050 AD		1050-1150 AD		1150-1250 AD			
Taxa	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	Total amount	%
Alnus sp.			4	0.9%					4	1.4%	11	2.0%			19	1.0%
Arbutus unedo			1	0.2%							1	0.2%			2	0.1%
Erica sp.			16	3.7%	6	3.0%	3	1.1%	3	1.0%	6	1.1%			34	1.8%
Fraxinus cf. *angustifolia*					1	0.5%	3	1.1%	1	0.3%					5	0.3%
Fraxinus cf. *ornus*	7	5.3%	28	6.5%	11	5.6%	25	9.0%	62	21.5%	123	21.8%	2	5.9%	258	13.4%
Ostrya carpinifolia	1	0.8%	1	0.2%											2	0.1%
Pinus sp.			1	0.2%	1	0.5%									2	0.1%
Quercus sp.	38	28.6%	142	32.9%	23	11.7%	29	10.4%	29	10.0%	60	10.7%	2	5.9%	323	16.8%
Quercus cf. *cerris*	34	25.6%	133	30.8%	101	51.3%	149	53.4%	164	56.7%	138	24.5%	25	73.5%	744	38.6%
Quercus cf. *ilex*			2	0.5%	1	0.5%	6	2.2%	3	1.0%	4	0.7%			16	0.8%
Quercus cf. *pubescens*	7	5.3%	14	3.2%	7	3.6%	7	2.5%	5	1.7%	12	2.1%			52	2.7%
Quercus deciduous type	36	27.1%	81	18.8%	30	15.2%	47	16.8%	12	4.2%	164	29.1%	5	14.7%	375	19.5%
Maloideae	4	3.0%	2	0.5%	8	4.1%	2	0.7%			4	0.7%			20	1.0%
Rhamnus/Phillyrea									1	0.3%						0.0%
Ulmus sp.	6	4.5%	7	1.6%	8	4.1%	8	2.9%	5	1.7%	40	7.1%			74	3.8%
Total determined taxa	133		432		197		279		289		563		34		1927	

4. Results

4.1. Taxonomic identification results

The anthracological analysis involved 1955 charcoal remains related to activities dated from the mid-8th to the mid-13th century AD. Samples had good charred status, which favoured conservation and therefore the determination of 1927 charcoal remains in fifteen taxa – according to the different levels of taxonomic resolution (Supplementary Table 2).

In Fig. 2, the determined taxa are displayed in horizontal percentage bars and pooled in forest types, based on their ecological significance and the local potential natural vegetation, to highlight the habitats involved during wood collection.

- Thermophilous deciduous *Quecus* forest: deciduous *Quercus* type (including *Q.* cf. cerris and *Q.* cf. *pubescens*), *F.* cf. *ornus*, *O. carpinifolia*, Maloideae, *Ulmus* sp.;
- Mediterranean evergreen forest: *Arbutus unedo*, *Erica* sp., *Pinus* sp., *Q.* cf. *ilex*;
- Hygrophilous and hydrophytic trees: *Alnus* sp., *F.* cf. *angustifolia.*

Percentage data from the scattered charcoal highlights the clear predominance of the deciduous *Quercus* type (60.8%), over the total chronological periods analysed, showing a strong presence of *Q.* cf. *cerris* (38.6%), determined by anatomical features such as better shaped and larger growth rings (Table 2). This is followed by other thermophilous deciduous taxa, *F.* cf. *ornus* (13.4%) and *Ulmus* sp. (3.8%). Hygrophilous and hydrophytic trees of floodplain and riparian habitats (*Alnus* sp. 1% and *F.* cf. *angustifolia* 0.3%), as well as the Mediterranean sclerophyllous trees and shrubs (*Erica* sp., 1.8%, *Q.* cf. *ilex*, 0.8% and *A. unedo*, 0.1%) are scarcely represented in the anthracological record.

From the first period (AD 750–850), 133 scattered charcoals were identified (Table 2; Fig. 2). Deciduous *Quercus* type (57.9%) is the most recorded group (including *Q.* cf. *cerris*, 25.6%, and *Q.* cf. *pubescens*, 5.3%), followed by thermophilus deciduous plants, *F.* cf. *ornus* (5.3%), *Ulmus* sp. (4.5%), Maloideae (3.0%) and *O. carpinifolia* (0.8%).

In period 2 (AD 850–900), analysis determined 432 dispersed charcoal remains (Table 2; Fig. 2). Deciduous *Quercus* type (52.8%) is the most recorded group (including *Q.* cf. *cerris*, 30.8%, and *Q.* cf. *pubescens*, 3.2%), followed by *Quercus* sp. (32.9%). *F.* cf. *ornus* (6.5%) and *Ulmus* sp. (1.6%) represent other deciduous taxa together with *Alnus* sp. and *O. carpinofolia* not exceeding 1%. Regarding the Mediterranean evergreen vegetation, *Erica* sp. is present (3.7%), along with *Q.* cf. *ilex*, *A. unedo* and *Pinus* sp. <1%.

Attributed to P3 (AD 900–950) are 197 dispersed charcoals determined from long-term firewood activities (Table 2; Fig. 2). Of these, 70.1% were classified as deciduous *Quercus* type (of which *Q.* cf. *cerris*, 51.3%, and *Q.* cf. *pubescens*, 3.6%). Other deciduous taxa are also part of the anthracological record: *F.* cf. *ornus* (5.6%), *Ulmus* sp. (4.1%), Maloideae (4.1%), and *F.* cf. *angustifolia* (<1%). Of the evergreen vegetation, *Erica* sp. is the most attested (3.0%) considering that *Q.* cf. *ilex* and *Pinus* sp. do not exceed 1%.

Some 279 scattered charcoal remains were determined between AD 950–1000 in period 4.1 (Table 2; Fig. 2). Deciduous *Quercus* type is the most recorded taxon (72.8%), consisting of *Q.* cf. *cerris* (53.4%) and *Q.* cf. *pubescens* (2.5%), followed by *F.* cf. *ornus* (9%), *Ulmus* sp. (2.9%) and *F.* cf. *angustifolia* (1.1%). Concerning evergreen vegetation, *Q.* cf. *ilex* (2.2%) and *Erica* (1.1%) are recorded.

In P4.2 (AD 1000–1050), analysis determined 289 charcoal remains (Table 2; Fig. 2), dominated by deciduous *Quercus* type (62.6%), including *Q.* cf. *cerris* (56.7%) and *Q.* cf. *pubescens* (1.7%). This is followed by thermophilous deciduous taxa *F.* cf. *ornus* (21.5%). Hygrophilous and hydrophytic trees of floodplain and riparian habitats do not exceed 1.7% (*Alnus* sp., 1.4%, and *F.* cf. *angustifolia*, 0.3%), Mediterranean evergreen trees and shrubs reach 2% (*Q.* cf. *ilex*, 1%, and *Erica* sp., 1%).

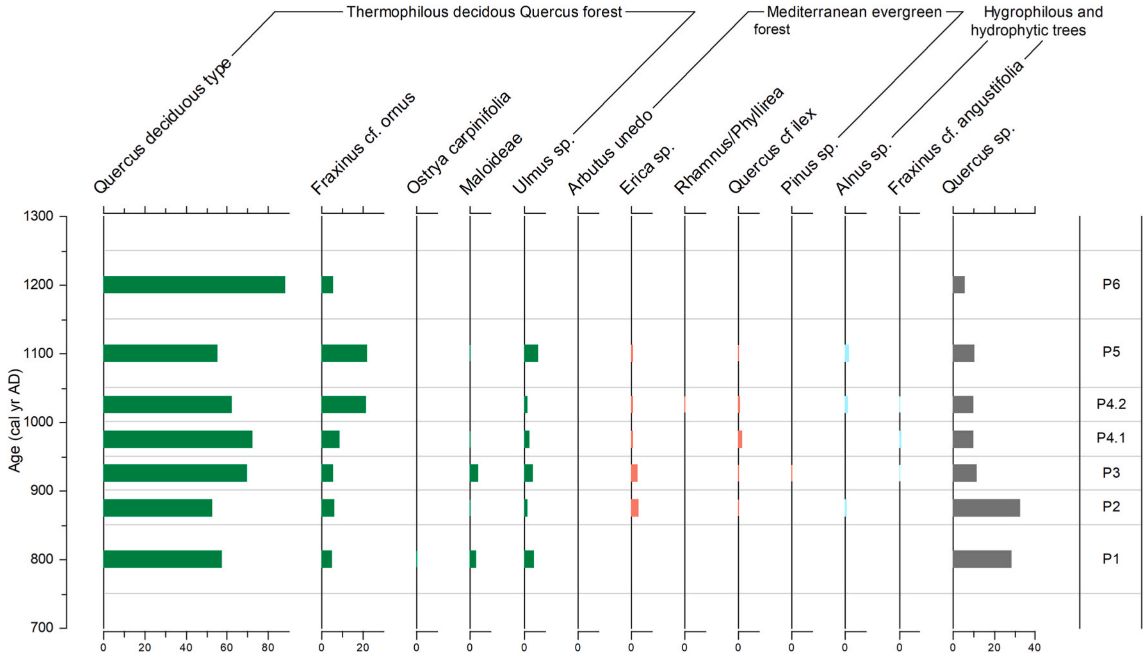

Fig. 2. Charcoal analysis diagram of charcoal remains from Vetricella. On the y-axis, time intervals (calibrated years AD) and chronological period are indicated. On the x-axis, the percentages of each determined taxon, calculated over the total amount of determined charcoal remains analysed in each time interval, are reported. The coloured bars group the taxa as follows: thermophilous deciduous *Quercus* forest (green); Mediterranean evergreen forest (red); hygrophilous and hydrophytic trees (light blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Classes of posthole diameters (in cm) at Vetricella. Absolute values (No) and percentage frequency (%) in chronological periods.

Period	2		3		4.1 + 4.2		5		6			
Cal yr AD	850-900 AD		900-950 AD		950-1050 AD		1050-1150 AD		1150-1250 AD			
Classes of diameters	No	%	No	%	No	%	No	%	No	%	Total amount	%
15–19					2	7.4%					2	5.3%
20–24			3	50.0	14	51.9%			2	66.7%	19	50.0%
25–29			3	50.0	4	14.8%	1	100.0	1	33.3%	9	23.7%
30–34	1	100.0			6	22.2%					7	18.4%
35–39					1	3.7%					1	2.6%
Total	1		6		27		1		3		38	

Anthracological analysis determined in period 5 (AD 1050–1150) an amount of 563 dispersed charcoals (Table 2; Fig. 2). Deciduous *Quercus* type is prevalent (55.8%, including *Q.* cf. *cerris*, 24.5%, and *Q.* cf. *pubescens*, 2.1%) followed by *F.* cf. *ornus* (21.8%), *Ulmus* sp. (7.1%) and *Alnus* sp. (2.0%). There are also many deciduous and evergreen taxa, albeit with very low percentages, among which Maloideae (<1%), whereas evergreen vegetation is comprised by *Erica* sp. (1.1%), *Q.* cf. *ilex* and *A. unedo* (<1%).

From the last period (AD 1150–1250), only 34 scattered charcoals were identified (Table 2; Fig. 2), failing the values indicated by the anthracological methodology. *Q.* cf. *cerris* is the most recorded deciduous taxon (25 remains) followed by deciduous *Quercus* type (5) and *F.* cf. *ornus* (2).

4.2. Distribution of posthole diameters

A total of 38 postholes preserved the negative impression of the wooden element due to the presence of conglomerates and hydraulic binders (Supplementary Table 3). The most numerous element population (19, 50.0%) has a diameter between 20 and 24 cm and is followed by 9 elements (23.7%) of the next population 25–29 cm (Table 3). However, this second group is very close to the major group because it has 7 elements with a diameter of 25 cm and 2 elements with diameters of 26 and 27 cm (Supplementary Table 3). That is, of the 38 postholes, 26 have diameters between 20 and 25 cm.

Moreover, 27 postholes can be attributed between the mid-10th and mid-11th century (Table 3), a period of structural changes at the site of Vetricella in the Ottonian dynasty, when a radical reorganisation took place with new settings and new structures, such as defensive palisades (Marasco and Briano, 2020). In Fig. 3, absolute value bar graph of the larger population of period 4 (P4.1 + 4.2) shows that between 20 and 29 cm is the preferred size (66.7%). The boxplot, showing the distribution of diameters, suggests that three quartiles occurred between 20 and 25 cm in diameter (Fig. 3). In fact, in period 4.1 + 4.2, the largest sizes are selected for the palisade and as a central support for the mortar machine (thus dedicated to setting up structures with specific functions).

5. Discussion

5.1. Forest habitats in the Middle Ages

In 500 years of activities, the community of Vetricella gathered

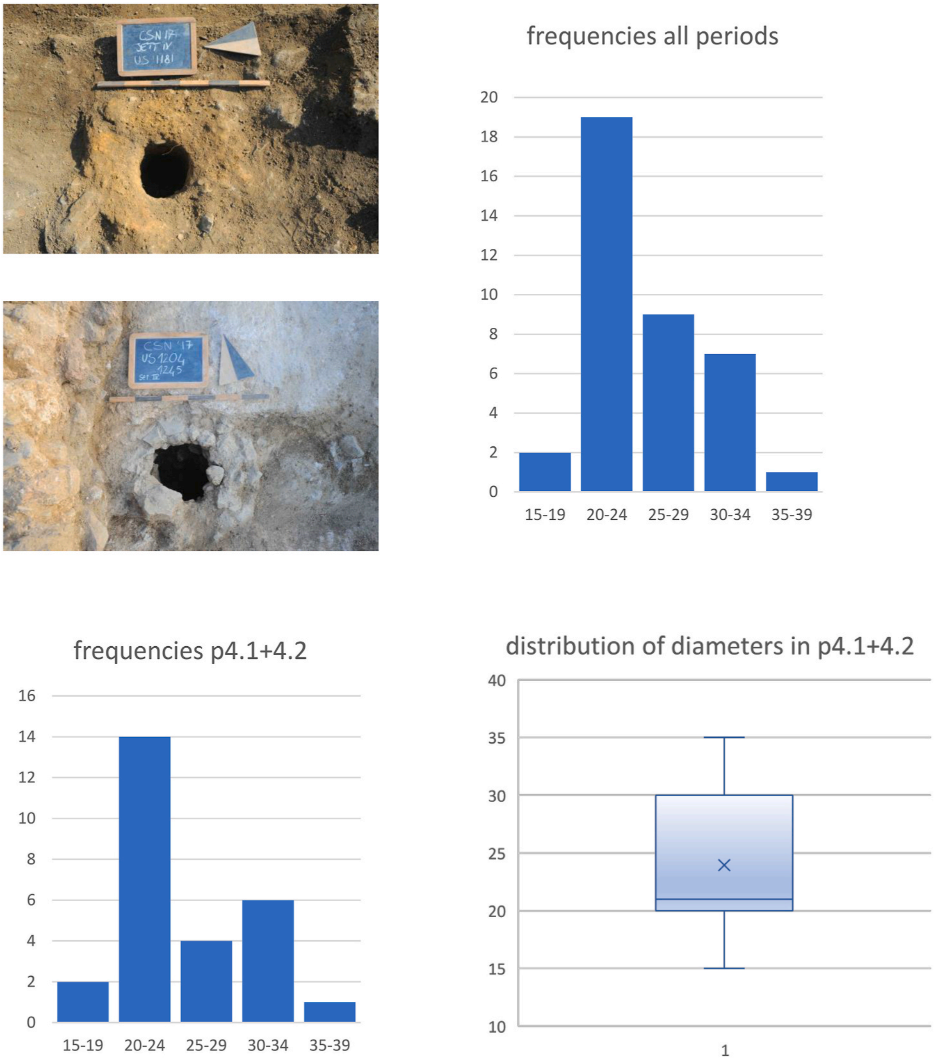

Fig. 3. *In situ* posthole photographs and distribution of posthole diameters. Bar graphs show the distribution of diameters in 4 cm intervals for all chronological periods and, in detail, for period 4.1 + 4.2. The x-axis shows the diameter intervals in cm. On the y-axis are the absolute values of the postholes for each interval. The box plot graph shows the distribution of the sample in the period 4.1 + 4.2 based on the recorded diameters.

continuously firewood from trees (deciduous *Quercus* type, *F.* cf. *ornus*, *Ulmus* sp., Maloideae, and *O. carpinifolia*). The persistent high frequency of deciduous *Quercus* type could suggest its prevalence, especially in the forest cover. Consequently, was this woodland a deciduous *Quercus* forest, or more precisely, a *Q. cerris* forest, considering the abundant presence of the taxon in the anthracological assemblage (Fig. 2)? In the valley of the Pecora river, *Q. cerris* forest are currently located on slopes and hills between 100 and 200 m a.s.l. and at about 6 km from Vetricella, while the evergreen Mediterranean vegetation is widely distributed along the slopes near the archaeological site (approximately 3 km), dominated by *Q. ilex* trees and shrubs of maquis (Fig. 1). According to anthracological data, the presence of Mediterranean evergreen vegetation is mainly limited to *Erica* sp. (shrub), while *Q.* cf. *ilex* and *A. unedo* (trees) are scarcely used. Could this suggest a much wider extension of the *Q. cerris* forest, especially in areas today covered by the Mediterranean evergreen forest? Modelling woodland use and past forest ecology through charcoal analysis has been extensively reviewed and discussed (Théry-Parisot and Meignen, 2000; Asouti and Austin, 2005; Dufraisse, 2014; Kabukcu, 2018; Delhon, 2021). Authors have stressed that the abundant presence of certain species as fuel could originate from on-site availability, productivity and higher levels of biomass recovery, as well as physicochemical features. In the case of Vetricella, the *Q. cerris* forest was probably more distant than the *Q. ilex* trees but it was prevalent in the anthracological record favoured for its higher quality as fuel. However, evergreen shrubs and trees have similar or higher calorific values (Doat and Valette, 1981; Dimitrakopoulos and Panov, 2001; Todaro et al., 2007; Madrigal et al., 2011), therefore excluding the choice of *Q. cerris* on the basis of such properties. A greater extension of the deciduous *Quercus* forest between the Early and Late Middle Ages is also found in the pollen sequences from the nearby Lake Accesa, recording 16,000 years of forest-cover history inside the southern Colline Metallifere (Drescher-Schneider et al., 2007; Vannière et al., 2008). In Medieval time, a constant presence of broadleaved deciduous *Quercus*, associated with floodplain and riparian vegetation, is also attested in the lower reach of the Pecora river alluvial plain, as recorded by recent cores near the coast (Clò et al., 2024). Aside from sudden collapses and fluctuations, the pollen sequences show the dominant and uninterrupted presence of deciduous *Quercus* throughout the Early Middle Ages from the inland to the sea. In our opinion, anthracological data suggests that *Q. cerris* forest would have characterized the slopes around Vetricella from the mid-8th century AD.

The widespread diffusion of the deciduous *Quercus* forest in the central Mediterranean basin, to the detriment of evergreen *Quercus*, has often been considered as the result of climatic events, in particular wet periods during the Holocene's cooler climate phases (Colombaroli et al., 2009). However, pollen increase of deciduous *Quercus* forest along the

Tyrrhenian coast is dated between the end of the Roman Empire and the beginning of the Middle Ages (Drescher-Schneider et al., 2007; Vannière et al., 2008), falling within a dry phase recorded both in Mediterranean region and Europe (Magny et al., 2013; Peyron et al., 2013; Labuhn et al., 2018). In the Colline Metallifere, the lowest Accesa lake-level in the last 2500 years dates precisely to the end of the Roman period (Magny et al., 2007). In fact, favourable climatic phases are to be exlcluded. According to local archaeo-anthracological researches, the expansion of deciduous *Quercus* forest in the southern Colline Metallifere was attributed to anthropic causes, namely the rural depopulation at the end of the Roman Empire and, more generally, the abandoning of cultivated areas (Di Pasquale et al., 2014). Deciduous *Quercus* has, in fact, a greater competitive potential than evergreen *Quercus* in the processes of spatial occupation of abandoned fields (Barbero et al., 1990; Di Pasquale and Garfi, 1998).

The *Q. cerris* forest of Vetricella can therefore be seen as the Early Medieval descendant of a forest condition spread a few centuries before. Descending from the slopes, *Q. cerris* could have extended its colonization to the alluvial plain, in soils that were only occasionally flooded, finding optimal conditions in deep, fertile and moist-rich earths. The tree could mix with the most typical fluvial species such as *Ulmus minor* Mill. and *Fraxinus angustifolia* Vahl subsp. *oxycarpa* (M.Bieb. ex Willd.) Franco & Rocha Afonso, as well as riparian trees in the form of *Alnus glutinosa* (L.) Gaertn. This alluvial plain forest type is still present today in Tuscany, having survived in a few areas to modern land reclamation activities (Mondino and Bernetti, 1998). Considering the comparative evidence of similar woodland taxa in the anthracological record, it seems that these associations were well established during the Middle Ages. The geomorphological conditions identified for the early Middle Ages are in agreement with the definition of floodplain habitats, resulting of alluvial sedimentation of the Pecora river, poorly drained and characterised by the presence of marshes and shallow ponds (Pieruccini et al., 2021). A landscape of wetlands in which the Vetricella site occupied the top of an alluvial fan, sloping towards the south, crossed by little fluvial channels containing small ditches. *Q. cerris* spread across the valley floor, limiting its range to higher grounds away from soils exposed to swamping.

5.2. Forest exploitation, management, and ecology

The anthracological record indicates that deciduous *Quercus* (and, in particular, *Q.* cf. *cerris*) is the predominant wood resource exploited as fuel in Vetricella. Considering that most of the *Quercus* records are attributable to the taxonomic type of deciduous *Quercus*, merging the relative percentages shows an exclusive use of this wood.

In addition to fuel supply, the demand for timber, useful in the construction of buildings, is also of significant importance. Though no preserved poles or beams were found during the excavation, their relevance and possible size are testified by the numerous building features identified in the various chronological periods. The analysis of the negative evidence of poles in the site and the distribution of their diameters, excellently preserved due to the presence of mortar and/or stone fillings, indicated timber with diameters between 20 and 25 cm. In the bibliography, these values can be referred to more than ten-year periodically cut forests. Current surveys in cut *Q. cerris* woods show a growth of shoots with an average 9 cm diameter and 11 m height after 35 years under natural conditions (Amorini et al., 1998). Larger diameters (average 20 cm diameter), requiring more than 40 years in a modern cut wood converted to high forest with the use of thinning techniques (Fabbio and Amorini, 2006). The supply of timber at Vetricella was based on selected wood cuts and the local community would, in fact, have felled trees considered more mature and suitable for the harvesting of woodland resources.

In the aftermath of the felling, new shoots would have sprouted directly from the stumps or roots of deciduous broadleaved species, regenerating the forest resource. It is the fundamental principle of coppicing, a traditional method of woodland management, already recorded by written sources in the Colline Metallifere and southern Tuscany at the end of the Middle Ages (Piussi and Redon, 2001). Coppicing includes periodic felling of the same stump, allowing the shoot to regrow, consequently producing large amounts of timber without the need to replant. With this forest management, the fuelwood harvesting was combined. Coppicing and regrowth, also associated with a wider extension of the deciduous *Quercus* forest, justifies the continuous and predominant exploitation of *Q. cerris* during the entire settlement phase of Vetricella.

In addition to the persistent and important use of *Q. cerris* fuelwood in Vetricella, the community continuously used woody species, accessory in *Q. cerris* coppice, from the earliest centuries of the settlement. If the presence of thermophilous trees and shrubs of the Maloideae is rather sporadic, as is the use of thermo-xerophilous evergreen *Erica* sp. and *Q. ilex*, the exploitation of *F.* cf. *ornus* and *Ulmus* sp. seems higher and more constant (Fig. 2). In particular, the use of *F.* cf. *ornus* after mid-10th century AD increases (period 4.1), up to triple the initial percentages in the 11th century AD (period 4.2) and until to mid-12th c. AD (period 5).

In the Colline Metallifere, *F. ornus* L. occurs typically in mixed deciduous or evergreen forest covering the hills, joining forest types dominated by *Q. cerris* (Mondino and Bernetti, 1998). It is a frugal and fast-growing plant, able to colonise open habitats and lightly forested areas. It thrives on poor soils while suffering the competition of other deciduous trees in richer ones. *Ulmus* sp. can be found in the Colline Metallifere between the alluvial plain, where the deep, humus-rich soils are subject to waterlogging, and the first slopes featuring welldrained soils (Mondino and Bernetti, 1998). Kind of pioneer species, *Ulmus* sp. is characterised by being a light-demanding and fast-growing tree, able to endure different levels of stress. The lack of canopy cover and the decrease in litter due to coppicing greatly reduces the interception of incident radiation, heat and rainfall. The soil system can lose resilience to prolonged periods of summer drought (Tedeschi et al., 2006), rain-splash and wash-out erosion (Borrelli and Schütt, 2014). Coppicing has detrimental effects on the stability of the *Q. cerris* forest, effects that are amplified when the site features unfavourable conditions such as shallow soils, southern exposure and steep slopes (Cutini and Benvenuti, 1998). Due to its specific adaptive abilities, *F. ornus* L. and *Ulmus* sp. are most favoured by these ecological changes, as well as the most competitive at the beginning and over the course of time, becoming the main accessory species in the coppice *Q. cerris* forest (Amorini et al., 1998; Fabbio and Amorini, 2006). The notable increment at Vetricella in the presence of *F.* cf. *ornus* as a fuel from AD 950–1150 (Fig. 2) can be attributed to the spreading of this pioneer species caused by environmental soil degradation and the growth of the *Q. cerris* coppice.

In general, the 10th century AD was a period in which the exploitation of woodland resources led to detectable changes of the hilly forest habitat and where a sequence of activities took place, aimed at radically changing the site of Vetricella along with land use in the river valley (Supplementary Table 1). On-site changes include the building of new fortifications and a stone base for the central tower structure together with the creation of a burial area possibly related to a newfound religious edifice (Marasco and Briano, 2020). In this century the demand for timber had to be important, since most of the postholes belong to this era of structural change and renewal. In the Pecora river valley, land use activities enhanced drainage and the clearing of flat swamplands, expanding also forest clearance on the hilly slopes in order to increase cultivable lands (Buonincontri et al., 2020b; Pieruccini et al., 2021). That resulted in a complex project of large-scale transformations that progressively intensified the exploitation and use of wood, increasing the consumption of the hilly forests.

5.3. The multiple productive use of Q. cerris forests: compound coppice and grazing

The silvicultural management system, derived from the anthracological and posthole record of Vetricella, consisted, therefore, of a *Q. cerris* forest exploited with cutting activities, in whose open and sunny spaces, progressively degraded due to the scarce presence of canopy, heliophilous tree (*F.* cf. *ornus* and *Ulmus* sp.) and shrub (*Erica* sp. and Maloideae) expanded. A type of lower storey to which the coppicing cut created the most favourable conditions for spreading. The coppiced elements (*Q.* cf. *cerris*, *F.* cf. *ornus* and *Ulmus* sp.) were cut by thinning the number of suckers on the stumps, preceded in turn by the removal of the undergrowth shrubs (*Erica* sp. and Maloideae). In order to provide Vetricella with the necessary beam supply, coppice management clearly included the release of standard trees for the production of a larger timber assortment. The standards could take on the form of decade-old plants born from seeds or chosen from selected shoots and preserved for a longer coppice cycle.

This silvicultural system produced multi-storied stands consisting of a low storey even-aged coppice underwood and an uneven-aged partial upper storey of standard trees treated as high forest. The lower storey was regularly cut in order to produce small material whilst the objective of the upper storey was to produce large-sized timber. This system – usually known as compound coppice – is limited in modern silviculture (death of stumps, lower growth of shoots and reduced wood production) and subject to criticism (Cantiani et al., 2006; Fiorucci, 2009; Bernetti and La Marca, 2010). On the other hand, in Early Medieval coppice forests, the release of standard trees largely satisfied a diverse wood production from the requests of the present-day timber market (Zanzi Sulli and Di Pasquale, 1993). Purpose of this practice, in addition to collecting wood, was also to encourage the herbaceous vegetation of the undergrowth, which, together with the shoots of the stumps, represented food for the grazing livestock, and, finally, to allow better growth of the left suckers. The presence of standard trees of *Q. cerris* ensured, moreover, the production of acorns, in addition to timber, supporting the regeneration of the forest from seed and, also, animal feed.

From the 9th to the beginning of the 11th century AD, zooarchaeological data suggests a free-range type of pig husbandry, the so-called *pannage*, occurring in Vetricella (Aniceti, 2020). In fact, the recovery of a considerable quantity of foetal and perinatal pig remains, representing natural losses, would strongly point towards this hypothesis (Aniceti, 2020). The compound coppice structures of the *Q. cerris* forest in the Pecora river valley were an ideal grazing environment for the breeding of pigs. Pastures, of course, would have had the effect of invalidating seed regeneration, but cattle relocation for a few years might activate regrowth (Zanzi Sulli and Di Pasquale, 1993).

6. Conclusion

The research in environmental archaeology conducted on fuelwood and timber remains is the most useful for defining use, management, and ecology of forest areas. It is possible to carry out a socio-cultural analysis with the perspective of the sources from the archaeological settlements working in the local environment. In the lower reach Pecora river valley, the site of Vetricella was the centre of the royal court of *Valli*, a fiscal estate existing since the 8th century AD, controlling and managing economic and productive resources until the mid-13th century AD. Archaeo-anthracological analysis, carried out on 1890 charcoal remains, and the investigation on diameters of 38 postholes explored the interactions between human activities and the forest ecosystem in order to define a composite and diachronic characterization of the Medieval forest landscape as well as to provide information on the forest land-use for harvesting fuelwood and timber.

The fuelwood supply areas were characterised by *Q. cerris* forest, today typical of hilly habitats. In the past, this forest type should have been much larger and extended, especially in areas currently covered by Mediterranean evergreen forest. In fact, *Q. cerris* forest probably reached alluvial plain, in soils only occasionally flooded, finding optimal conditions in deep, fertile and moist-rich soils. From the earliest life centuries of the settlement, the *Q. cerris* forest is characterized by accessory pioneer thermophilous woody plants, *F. ornus* L. and *Ulmus* sp. above all, then Maloideae, and more xerophilous evergreen shrubs such as *Erica* sp.

The collection of fuelwood was based on the traditional method of coppice woodland management, including the release of decade-year-old standard trees for the production of larger timber assortment, useful for building activities (testified by the numerous post-holes). This silvicultural system is known as compound coppice and produced a forest landscape characterised by multi-storied stands.

The exploitation reduced the canopy cover and caused progressive environmental soil degradation that favoured the spread of accessory pioneer species resilient to cut clearance. Changes in the forest ecosystem were particularly detectable from mid-10th century AD, when *F. ornus* L. became well present in the woodland landscape, and more consumed as fuel. It was the Ottonian period of activities in sequence aimed at radically changing the site of Vetricella along with land use in the Pecora river valley. A complex project of large-scale transformations that progressively intensified the exploitation and use of wood, increasing the consumption of the hilly and alluvial plain forests.

The compound coppice structure of *Q. cerris* forest in the Pecora river valley was ideal grazing environment for the breeding of pigs, occurring near Vetricella. Like coppicing, the spread of grazing in woodlands was an important factor in the decline and parallel colonization of the Medieval forest habitat. The forest land use record of Vetricella is the first evidence regarding the capitalization of coppicing and pasture in woodland, dating back to the late-Carolingian period (9th century AD) the beginning of a silvo-pastoral landscape that still today represents a tradition of great importance in central Italy.

CRediT authorship contribution statement

Mauro Paolo Buonincontri: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Marta Rossi:** Formal analysis, Investigation, Writing – original draft. **Gaetano Di Pasquale:** Investigation, Supervision, Writing – review & editing.

Data availability

All the data are included in the article and available on request.

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Declaration of competing interest

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

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Appendix A. Supplementary data

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