Shaping Mediterranean landscapes: the cultural impact of anthropogenic fires in Tyrrhenian southern Tuscany during the Iron and Middle Ages (800-450 BC / AD 650-1300)

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Abstract

Charcoal analysis, applied in sediment facies analysis of the Pecora river palaeochannel (Tyrrhenian southern Tuscany, Italy), detected the occurrence of past fire events in two different fluvial landforms at 800–450 BC and again at AD 650–1300. Taking place in a central Mediterranean district adequately studied through palaeoenvironmental and archaeological research, the investigation determined land changes, time phases and socio-economic driving forces involved in dynamic processes of fire. The fire sequences had purely anthropogenic origins and was linked to forest opening and reduction by local communities. Introduced by the Etruscans, fires dated to 800–450 BC involved mainly the forest cover on the hilly slopes, ensuring agricultural exploitation.

From AD 650, fires contributed to Medieval upstream reclamation and vegetation clearing of flat swamplands. From AD 850 to 1050, the use of fire spread over a wider area in the river valley, increasing arable lands. Between AD 1150 and 1300, fires belonged to a regional forest clearance phase. Medieval fire episodes had a paramount importance in shaping and determining the character of the Tuscan Mediterranean landscape. From AD 850, Medieval fire clearing influenced regional vegetation history contributing to the decline of the dominant deciduous *Quercus* woodland. Open habitats became the new form of a clearly detectable agricultural landscape from AD 950. The use of fire clearing and the resulting landscape changes in the Pecora river valley depended on the political strategies adopted by Medieval authorities and marked, in fact, the progression of a cultural landscape still characterizing central Tyrrhenian Italy.

Keywords

anthropogenic fire clearing, Colline Metallifere, Etruscans, floodplain forest, late-Holocene, marshy waterlogged vegetation, Middle Ages, Mediterranean Cultural Landscape, multiproxy approach, reclamation, sediment charcoal analysis, thermophilous deciduous forest

Introduction

The history of traditional rural landscapes can be considered a recent research priority, widely stimulated by the policies of supranational and state communities (Brouwer, 2004; Pedroli et al., 2007). The term ‘cultural landscape’ is illustrative of the interaction and co-existence between humankind and its natural environment. Cultural landscapes often reflect the evolution of human society and settlement patterns over the course of time, influenced by the natural environment as well as by social, economic and cultural forces (Rössler, 2006; Sodano, 2017). Cultural landscapes embrace traditional forms of land-use, considering the characteristics and limits of the natural environment they are established in, and they show specific ecosystems and biological diversity (Fowler, 2003). In 1992 the UNESCO World Heritage Centre began to recognize ‘cultural landscapes’ as a category of site within the Convention’s Operational Guidelines. In this sense, the Mediterranean basin holds a unique and privileged role. Its physical morphology, abundance of environmental and bio-cultural diversity, and millenary history, favoured the rise of a remarkable mosaic of widely distributed and diversified habitats (Blondel, 2006; Horden and Purcell, 2000; Hughes, 2005).

The dual essence of the Mediterranean landscapes, environmental and anthropic, has been investigated over the course of time with approaches based on the often contrasting social and natural sciences (Holmgren et al., 2016; Mercuri, 2014). Palaeoenvironmental researches are the fundamental resources used by natural sciences to investigate cultural landscape progression. The study approaches make use of data garnered from pollen and charred wood fragments, with the contribution of other biostratigraphical, geomorphological and isotopic studies, in order to reconstruct the evolution of the past vegetation landscape and affecting fire sequences (Bevan et al., 2019; Conedera et al., 2009; Mercuri and Sadori, 2014; Scott and Damblon, 2010; Zanchetta et al., 2013).

The most common approach is largely based on the analysis of pollen, non-pollen palynomorphs and macro/microscopic charcoal particles from high-resolution Holocene marine, lake or peat cores. These researches, initially focused on reconstructing localized landscape, in the last 20 years have assumed a broader interest, increasing large-scale land cover narratives (Berger et al., 2019; Bottema and Sarpaki, 2003; Carrión et al., 2010a, 2010b; de Beaulieu et al., 2005; Fyfe et al., 2019; Jalut et al., 1997, 2000, 2009; Jimenez-Espejo et al., 2007; Mercuri et al., 2013; Pérez-Obiol et al., 2011; Pons and Quézel, 1998; Roberts et al., 2011b; Sadori et al., 2011, 2015; Stoddart et al., 2019; Weiberg et al., 2019; Willis, 1994; Woodbridge et al., 2019).

More than pollen, macroscopic wood charcoal fragments are a ubiquitous proxy in palaeoenvironments, due to their resistance to microbial decomposition and are therefore commonly found in both soil and sediment archiving contexts (Robinson et al., 1997; Scott et al., 2000b; Talon et al., 1998). Since the end of 1970s, soil/sediment charcoal analyses have been widely used in Central Europe to investigate the occurrences of fire events and the correlated burnt woody vegetation (Nelle et al., 2013). In the Mediterranean environment, these researches are currently limited to local contexts and lack a macro-regional narrative (Carcaillet et al., 1997; Delhon et al., 2009, 2013; Henry et al., 2010; Moser et al., 2017; Piqué et al., 2018).

The aim of both pollen and soil/sediment charcoal analyses is to obtain long-term ecological research with in-depth details of land cover and fire events, in order to explore the role of climate or anthropogenic impact in the recorded changes. In the genesis of the Mediterranean landscapes, the climate is considered as the first-scale factor influencing and determining the natural environment at least until ca. 6500 cal. yr BP, when the biological archives start responding to both climate change and human impact (Roberts et al., 2011a). For the last 6000 years, the evaluation of causes and effects has been a common and problematic issue, subject to debates often polarized between those supporting a climatic origin and those favouring an anthropogenic explanation (Di Pasquale et al., 2004; Mercuri and Sadori, 2014; Roberts et al., 2011a).

Recently, an important review involving pollen records (past vegetation), stable isotopes (climate), archaeological site surveys and C14 dates (long-term population change), has highlighted landscape changes in seven different Mediterranean regions by human and natural agencies during the past ten millennia (Bevan et al., 2019). This study suggests that human actions were relevant on land cover after ca. 3500 cal. yr BP and the dominant landscape trajectory differed in the eastern and western Mediterranean during the past 1500 years, following the distinctive historical events of different regions (Roberts et al., 2019). In fact, while the sum of human activities has produced measurable effects at a global scale, locally investigations require regional, sub-regional and also micro-regional approaches with the perspective of historical and archaeological sources, adopting a socio-cultural analysis rather than deterministic approach in order to avoid simplistic causal relationships (Carrión et al., 2010a; Pyne et al., 1996; Roberts et al., 2019). At present, there are few territories with high-quality datasets that allow the comparison of high-resolution paleoecological records with historical documents and archaeological data (Jouffroy-Bapicot et al., 2016; Kaal et al., 2011; Mensing et al., 2018; Moser et al., 2017; Sadori et al., 2015). More research is needed to integrate the three sources so as to understand how sociopolitical and economical changes influenced local land use (Holmgren et al., 2016; Scott and Damblon, 2010).

The ERC-ADG-2014 project: ‘Origins of a new economic union (7th–12th centuries)’, hosted by the University of Siena, aims at analysing the form and timeframe of economic growth during the Middle Ages in Tyrrhenian southern Tuscany (central Italy), through a multidisciplinary approach involving both natural and social sciences. Central to this is an understanding of the processes of change in settlements as well as the natural and agricultural landscapes, in relation to resource exploitation and the implementation of different political strategies. In the framework of the project, a stratigraphic and sedimentological analysis was performed along a palaeochannel of the Pecora river, located in the seaboard of the study area.

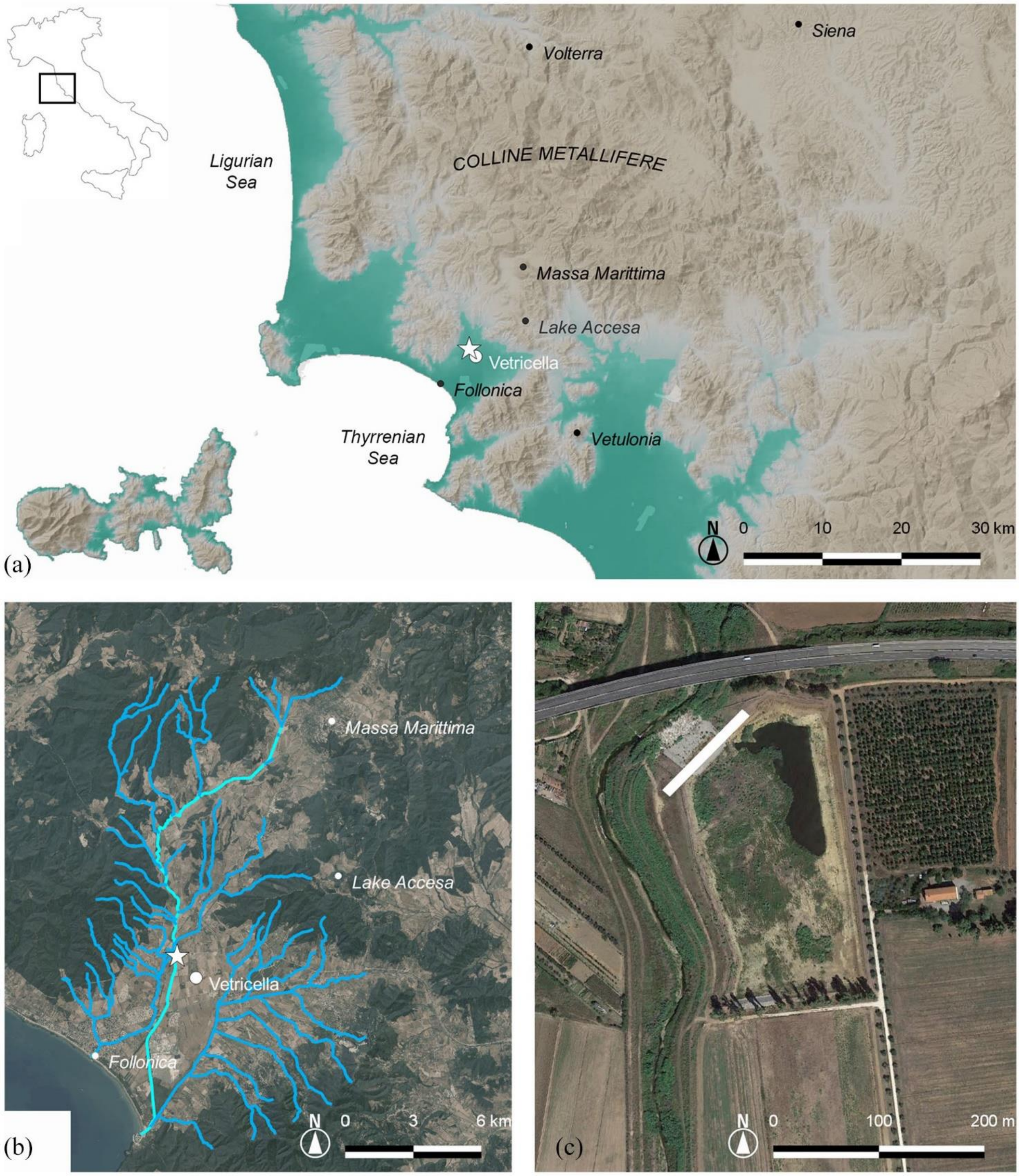
The recording of macroscopic charred wood remains contained in the alluvial sediment started quantitative analysis and taxonomic identification of extracted charcoal pieces, combined with radiocarbon dating. Sediment charcoal records detect the occurrences of fire events and the correlated burnt woody vegetation, revealing the composition of past woody plant communities at a fine spatial scale, often finer than other palaeoecological proxies (e.g. pollen), from few meters to relatively large spatial resolution, depending on the proprieties of the catchment area (Clark and Patterson, 1997; Nelle et al., 2013; Scott, 2010). According to radiocarbon dating, our research investigates the occurrence of past fires between the 8th and the mid-5th century BC and between the mid-7th and 13th century AD. In order to define a valuable reconstruction of fire features and land cover in the Pecora river basin, charcoal data are contextualized with: 1) the sedimentary facies of the palaeochannel, reconstructing fluvial landscapes, alluvial environments and changing dynamics, 2) the pollen analysis as a proxy for past plant communities.

Fire is a fundamental ecological stress factor and selective force in Mediterranean ecosystems, as independent climatic stress or ancient technique for land management, and played a fundamental role in the present mosaic-like pattern (Barbero et al., 1990; Naveh, 1975; Quézel, 1983). To answer the question concerning climate and cultural aspects during fire events (Pyne and Goldammer, 1997), the study considers 3) the late-Holocene sedimentary charcoal and pollen records from Lake Accesa in southern Tuscany, as proxies of changes and variability in fire regimes, past vegetation and land cover (Drescher-Schneider et al., 2007; Vannière et al., 2008), and 4) archaeological site patterns, as proxies for population changes. This 'biodiverse' multiproxy approach proved to be useful at tracing the fire history, detecting climate or anthropogenic causes and evaluating the effects of fire impact on past forest environments (and the landscape in general). Our research determines land changes, time phases and driving socio-economic forces that modified the coastal area of southern Tuscany, marking the progression of a cultural landscape that still characterises Tyrrhenian central Italy.

Study area

Environmental setting

Tyrrhenian southern Tuscany, known also as northern Maremma, is characterized by unique geological resources of fundamental importance in shaping the area's chronological development. The distinctive district of the Colline Metallifere (1060 m asl, along with the nearby island of Elba) stretches from the S and SW of Volterra and Siena to the Ligurian and Tyrrhenian Seas (Figure 1a), representing an important area for the mining of iron, pyrite, copper, silver and lead.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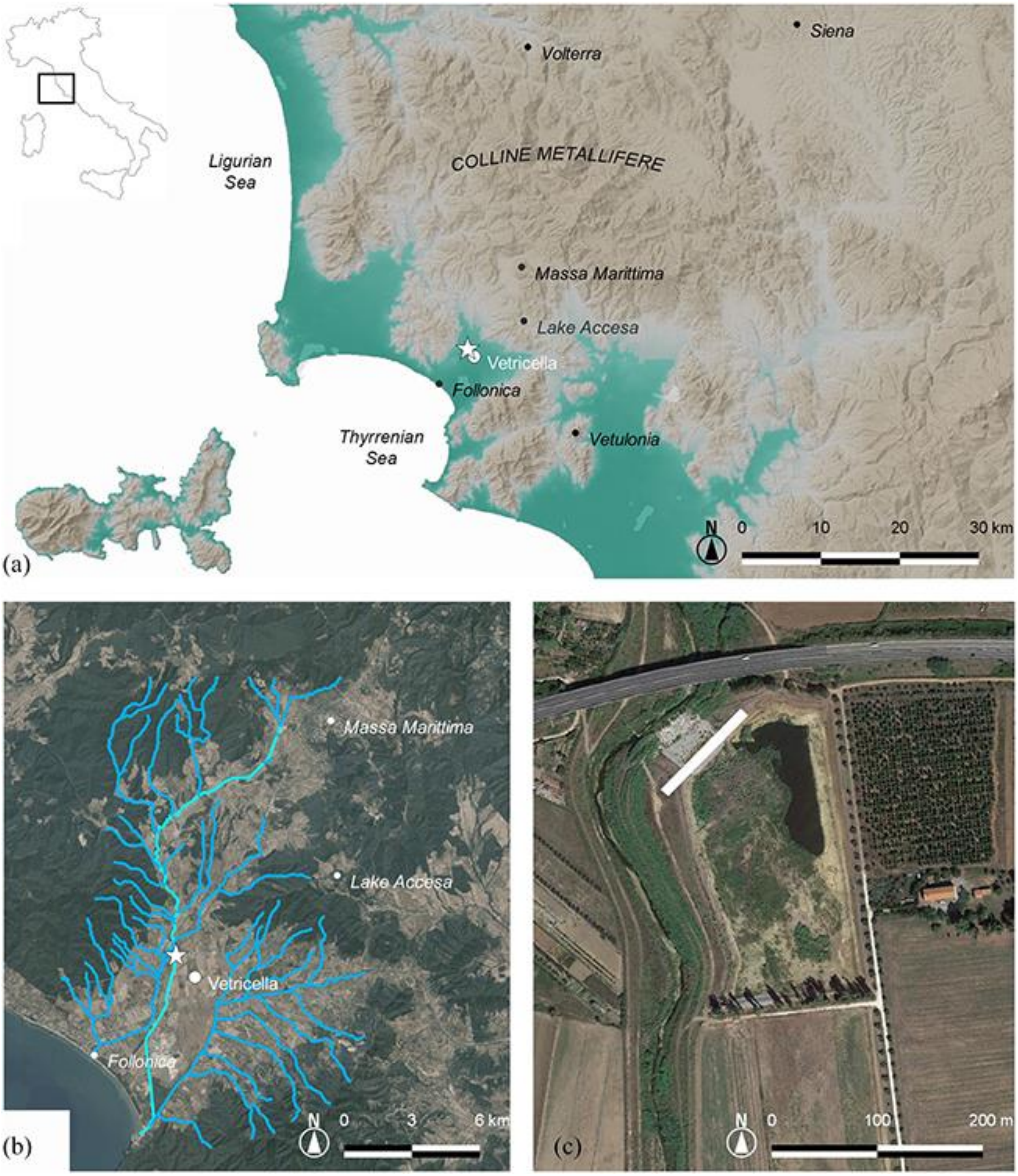

Figure 1. (a) Location map showing the area of the Colline Metallifere with places cited in the text (white circles: archaeological sites; black dots: current locations) and retention basin of the Pecora river (indicated with a star). Map source: SINAnet ISPRA – Dem75 (QGIS 3.10.3 'A Coruña'). (b) Current drainage basin of the Pecora river (light blue: Pecora river course; blue: main hydrography of the valley; white circles: archaeological sites; white dots: current locations; star: retention basin). Map sources: Regione Toscana – Idrografia corsi. Regione Toscana – Ortofoto 2013 (QGIS 3.10.3

‘A Coruña’). (c) Aerial view of the area of the retention basin. White bar indicates the NW section with studied palaeochannel. Map source: Google Satellite 2020 (QGIS 3.10.3 ‘A Coruña’).

Set between the town of Massa Marittima to the NE and the Gulf of Follonica to the SW, the Pecora river basin is one of the natural links between the southern slopes of the Colline Metallifere (here ca. 480 m asl) and the Tyrrhenian coast (Figure 1b). The river is ca. 20 km long and has a catchment of about 250 km2. The basin originated after the definitive emersion of the area occurred at the end of the Pliocene and the interaction between vertical uplift and climatic changes during the Quaternary that led to the erosion of valleys and deposition of alluvial and slope deposits interacting also with karst processes (Benvenuti et al., 2009). The present-day mostly hilly landscape is characterized by erosional processes along the steep valley slopes and limited deposition along the valley floors. Staircases of flat alluvial terraces bear witness of depositional processes acting in the past.

Karst processes deeply influenced landscape evolution as indicated by the presence of wide coalescent karst depressions, karst springs and typical terraced calcareous tufa sediments associated to cool-water physio-chemical and microbiological carbonate precipitations in fluvial-swampy environments (Capezzuoli et al., 2014; Ford and Pedley, 1996; Pedley, 2009). Today, the uppermost part of the basin is artificially drained by means of hanging channels, to bypass karts depressions, and trench-cut channels, to bypass the main barrage. The karst processes are also at the origin of the unique historically attested lake in the area. The Lake Accesa (UTM 654508 E, 4761263 N, WGS84/UTM zone 32N, 157 m a.s.l.) is a small lake located 10 km to the south of the town of Massa Marittima, beyond the western watershed of the mid Pecora river valley (Figure 1a and b). Surrounded by hills reaching a height of ca 300 m, the lake covers a surface of ca. 14 ha (39 m max. water depth) with a catchment area of ca. 5 km2.

According to the weather station of Follonica (15 m a.s.l., UTM 644053 E, 4754898 N, WGS84/UTM zone 32N, 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. Arable crops, vineyards and olive groves are present in the flat valley floors and/or on the gentler slopes. The Mediterranean evergreen forest, dominated by *Quercus ilex* L. with *Arbutus unedo* L., abounds on the steeper slopes of the Pecora river basin. Small stands of thermophilous deciduous broadleaved species, such as *Q. cerris* L., *Q. pubescens* Willd. and *Fraxinus ornus* L. are scarcely present, whereas the deciduous oak forest, dominated by *Q. cerris* L., is located only on the cooler north-western slopes of the basin.

Historical land-use: archaeological and palaeoenvironmental data

The rich mineral deposits present in the Colline Metallifere and subsequent mining activities deeply influenced human activities and settlements since the Eneolithic/Bronze Age (Aranguren and Sozzi, 2005; Corretti and Benvenuti, 2001). With the spread of Etruscan tribes in the 9th and 8th centuries BC, the coastline became the main metal-working area of central Italy (usually known as Etruria) with the establishment of towns involved in the trade of artefacts (Acconcia and Milletti, 2009; Chiarantini et al., 2009). In the 3rd century BC, Roman political expansion started to exercise its control on Etruria (Harris, 1971) and between the 1st century BC and 1st century AD the region reached the peak of its settlement and economic development during the Classical Age (Cambi and Botarelli, 2004; Citter, 1996; Dallai, 2003a; Vaccaro, 2008). Following the collapse of the Roman Empire at the end of the 5th century AD, few settlements continued to exist in the coastal alluvial plains, while new sites were founded thanks to the spontaneous relocation of small units of population on higher ground (Dallai, 2003b).

In AD 574, the Lombards conquered Etruria, creating the duchy of Tuscia as part of their kingdom (Wickham, 1981). After Charlemagne’s occupation of the Lombard Kingdom in AD 774, the duchy was transformed into the Carolingian March of Tuscia from the AD 797. In the 10th century AD this region (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 time, this led to direct control by local aristocratic families during the 11th century AD, evident in the construction of 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 (Gaggio, 2017).

Anthropic pressure obviously played an important and fundamental role in shaping the current forest cover of the southern Colline Metallifere. 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 settlement on forest cover can be dated from ca. 2600 to ca. 2500 cal. yr BP, 750–650 BC (Drescher-Schneider et al., 2007; Stoddart et al., 2019; Vannière et al., 2008). Archaeological research has identified the fundamental importance of both the Etruscans and (late Republican ad early Imperial) Romans played in the development of rural Etrurian landscapes between the 3rd century BC and 1st century AD, especially as they favoured olive and vine cultivation (Barbieri, 2010; Carandini, 1994; Manca et al., 2016; Santangeli Valenzani and Volpe, 2012; Zifferero, 2015). Local archaeobotanical data indicate traces of greater human control over productive landscapes with the occasional presence of vines and olives (Aversano et al., 2017; Bowes et al., 2015; Langgut et al., 2019; Mariotti Lippi et al., 2002, 2020) and scholars highlighted the heritage of this agrarian land use in local traditions as well as its presence in northern Maremma up to few decades ago (Bowes et al., 2015). Recent comparison between pollen and local archaeo-anthracological data have however suggested additional phases of forest reduction with intensive agriculture and livestock grazing during the 2nd and 3rd centuries AD, followed after a hiatus by intensive olive orcharding between the 11th and 13th centuries AD (Di Pasquale et al., 2014). The evidence now shows that the steps to define the rural landscape of southern Tuscany were more complex than was hypothesized in the past.

Materials and methods

Field work

Investigation has been carried out mainly in a retention basin (UTM 647378 E, 4757710 N, WGS84/UTM zone 32N, 16 m a.s.l.) located on the hydrographic left of the Pecora river, at ca. 500 m to the NW of the archaeological site of Vetricella (Figure 1b and c). The retention basin, featuring a length of ca. 400 m and width of ca. 100 m perpendicular to the Pecora river flow direction, allowed for the observation of 4 sections. A palaeochannel, ca. 50 m wide and 3 m deep, was identified in the NW Section (Figure 1c), characterized by different depositional environments suggesting changes in the geomorphological conditions and alluvial plain landscape.

The outcropping sequence was analysed in the field, drawing the sedimentological characteristics in terms of facies analysis (Miall, 1996). The reconstruction of the depositional environment was obtained following the lithofacies characteristics (grain size, composition, shape of clasts, internal geometry and fabric) indicating the flow dynamics. Lithofacies associations or architectural elements correspond, in turn, to the characters of the internal depositional environments. Finally, the associations of architectural elements and the presence of bounding surfaces allow the definition of fluvial models or styles that correspond to the river dynamics and associated landscape.

Laboratory treatments

The sediments filling the channels were characterised by the abundant presence of fine to coarse charcoals. In the NW Section, fifteen sediment samples ranging from 500 ml to 2390 ml of volume were collected, with a depth and width-wise strategy following the identified different depositional environments and aiming at a comprehension of charcoal distribution in response to geomorphological processes (Figure 2a).

Although fluvial depositional environments are a different type of context, laboratory treatments followed the standard procedure of soil charcoal analysis (Carcaillet and Thinon, 1996; Robin et al., 2013; Talon, 2010). Sediment samples were firstly air-dried and weighed, and successively wet-sieved through 0.4, 1, 2 and 5 mm sized mesh. Charcoal concentration and taxonomical identification were performed for macroscopic charcoal remains >1 mm (Robin et al., 2014). Charcoal concentration is expressed as specific anthracomass per sampled layer (SAL) in milligrams of charcoal and per kilogram of dried soil (Talon, 2010).

Charcoal remains were divided in three classes of size: 1–2, 2–5, >5 mm. Taxonomical analysis was conducted up to a maximum of 100 fragments for charcoal remains >2 mm, whereas between 1 mm and 2 mm a maximum of 20 charcoal pieces per sediment sample were identified. Taxonomical identification was carried out by an incident light microscope at magnifications of 100×, 200× and 500× and supported with wood anatomy atlases (Abbate Edlmann et al., 1994; Schweingruber, 1990; Vernet et al., 2001) and the reference collection in the Laboratory of Plant and Wood Anatomy at the Department of Agricultural Sciences of the University of Naples ‘Federico II’.

Charcoal fragments were identified at the species or genus level thanks to their good state of preservation. Botanical nomenclature follows Pignatti (1982). In such cases, grouped taxonomical references have been used, according to the anatomical type, such as Populus/Salix or deciduous *Quercus* type. Sometimes, bad conservation or vitrification allowed for the identification at a family level or the distinction between dicotyledon and monocotyledon wood or no identification at all. Identified remains have been counted and percentage frequency of each taxon calculated on the total amount per sample.

Plant macro-remains, well preserved in charred condition, were recovered in four sediment samples. They were analyzed and separated by way of stereomicroscope observation. Taxonomic identification was carried out using the reference seed collection in the Laboratory of Plant and Wood Anatomy at the Department of Agricultural Sciences (University of Naples ‘Federico II’), atlases and specialist literature (Hubbard, 1992; Maier, 1996; Neef et al., 2012). Botanical nomenclature follows Pignatti (1982). The term *Triticum aestivum/durum* is used in accordance with Jacomet (2006).

Radiocarbon dating

AMS radiocarbon dating was performed on nine charcoal remains selected according to location and taxonomical interest and in relation to the spectrum of identified taxa in each layer. Chemical pre-treatments for the extraction of the organic part of the samples by way of acid-alkali-acid (AAA) protocol (Mook and Streurman, 1983) were carried out in the Department of Environmental, Biological and Pharmaceutical Sciences and Technologies of the University of Campania 'Luigi Vanvitelli'. Samples were dated by AMS at the INFN-LABEC CHNet in Florence (Fedi et al., 2007). Radiocarbon dates have been calibrated using OxCal 4.3 (Bronk Ramsey, 2017) and the Reimer et al. (2013) calibration curve.

Pollen analysis

For pollen analysis five sediment samples were collected and prepared in the pollen laboratory at the Institute of Plant Sciences of the University of Bern using standard preparation methods (Moore et al., 1991). This first test run revealed very low pollen concentrations and poor pollen preservation. In a second run, the samples were prepared again using sediment sample volumes of 2 cm3 instead of 1 cm3. This, together with a slightly adapted pollen preparation method (hydrofluoric acid in big centrifuge tubes), revealed enough pollen grains for palynological analysis, although ultimately pollen preservation remained poor. Nevertheless, at least 100 identifiable pollen grains per sample were counted under a light microscope, which is sufficient for calculation of pollen percentages and main trends (Heiri and Lotter, 2001).

Results

Sedimentology and facies analysis

The retention basins allowed the observation of four well distinguishable stratigraphic units (U) separated by important sedimentary unconformities. Here, two units are presented and described (U3 and U4), the complete description is reported in Pieruccini et al. (2018).

U3

The unit fills the bottom of the palaeochannel and is considerable the oldest stratigraphic unit (Figure 2a). US3 is made of loose planar cross-bedded, poorly sorted, rounded to subrounded fine to coarse-grained gravels (Gp), variable amount of sandy matrix. Minor planar or low angle cross-bedded sands (Sp) and lenses and blanquets of massive to finely laminated silts and clays (Fm, Fl) are also present. The composition of the gravels includes also rare clasts of calcareous tufa. The facies association is typical of a gravel-sand sinuous-meandering river with a westward lateral accretion of gravel and sand bars.

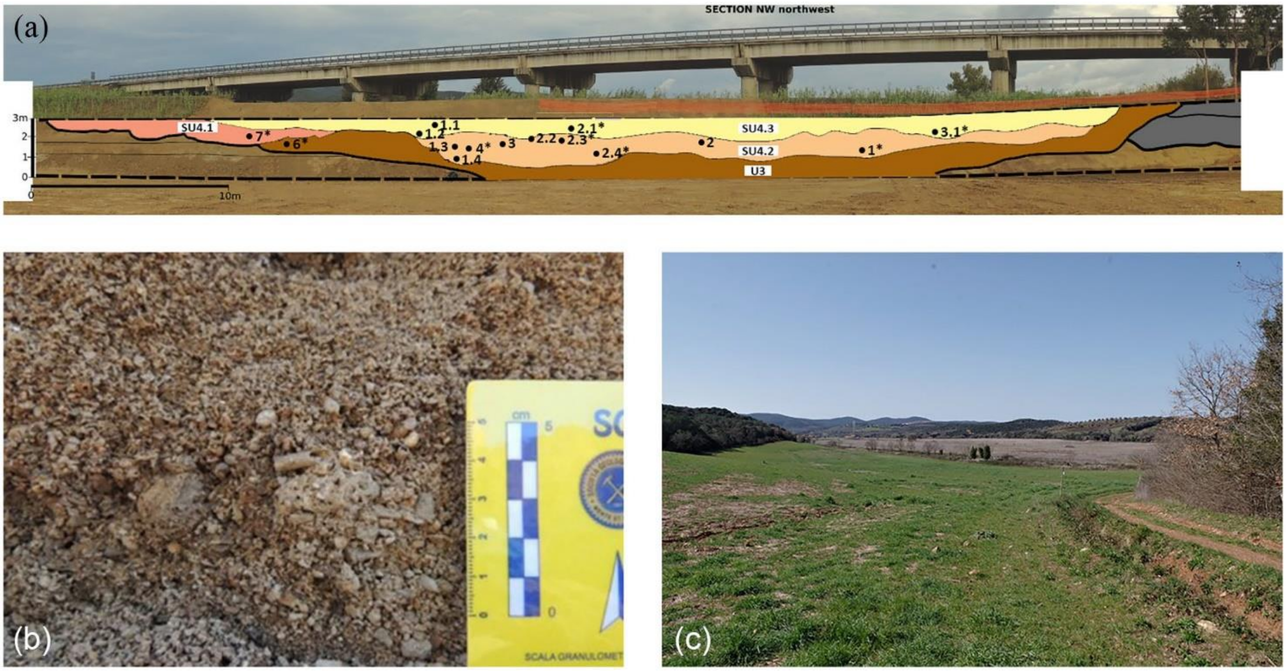

Figure 2. (a) NW section within the retention basin and stratigraphic sequence. Unit (U) and sub-unit (SU) numbering follows the description in the text. Black dots indicate the sediment sampling points; numbers identify the sediment samples; asterisks mark the radiocarbon dated sediment samples. (b) Calcareous tufa clasts in the facies association of the braided gravel-bed palaeochannel (photo: P. Pieruccini). (c) Current flat terraces in the Pecora river valley, originally occupied by swamps with deposition of calcareous tufa (photo: P. Pieruccini).

U4

The channel filled by U3 sediments is unconformably cut by a further channel filled by U4 sediments (Figure 2a). This unit is composed of loose, unsorted, trough crossbedded to massive, fine to medium-grained, rounded to subrounded gravels (Gt, Gh), locally matrix supported (Gsm). Minor trough cross-bedded or massive sands (St, Sh) and lenses and blanquets of massive to finely laminated silts and clays (Fm, Fl) are also present. The gravels' composition is mostly made of very abundant clasts of calcareous tufa, filling troughs and minor channels (Figure 2b). The bedforms are also characterized by the presence of very abundant fine to very coarse charcoals, both scattered within the sediments or concentrated along the base of the beds. The U4 facies association, made of fine-grained gravels and coarse sands, is typical of a braided gravel/sand-bed river environment characterized by downstream accretions.

Although the sedimentary characteristics of U4 are homogeneous, a further subdivision in sub-units (SU) has been made according to the presence of minor unconformities related to minor changes of the internal architecture. SU4.1, dominated by sands and fine gravels, is observed in the western part of the section, covering a shallow and almost flat unconformity (Figure 2a); SU4.2, located towards the east and gravelly dominated, fills a deeper channel cutting SU4.1; both SU4.1 and SU4.2 are cut by a further shallow and slightly undulated unconformity buried under SU4.3 finer-grained sediments.

Sediment charcoal analysis

Preliminary results from the U4 have already been reported by Pieruccini et al. (2018) and Buonincontri et al. (2018). In the current study the complete dataset of fifteen sediment samples is presented (Supplementary Table 1, available online): one sediment sample collected in the upper limit of the oldest U3 of the gravel-sand sinuous-meandering river; one in the SU4.1 of the braided gravel-bed river (stratigraphically older than 4.3 but not related to 4.2); respectively nine and four, including the SU4.3 and SU4.2 of the braided gravel-bed river (Figure 2a). A total of 17 L of sediment were treated with ca. 21 g of extracted charcoal. Sample 1.3 collected in SU4.1 was found to be sterile.

Of the total quantity of extracted charcoal, 597 remains were taxonomically analyzed, including 178 pieces from the 1 mm to 2 mm size class, 177 from the 2 mm to 5 mm size class and 242 pieces that were larger than 5 mm in size (Supplementary Table 1, available online). This allowed to identify 23 different taxa. For 64 charcoal remains (13.7% of the analyzed charcoal pieces from all class sizes) the identification was not possible due to bad preservation or vitrification.

Regarding the identified taxa, the most represented belong to thermophilous deciduous vegetation: *Fraxinus* (17.4%), with *F.* cf. *ornus* (2.4%) and *F.* cf. *oxycarpa* (7.5%), *Quercus* cf. *cerris* (16.5%), and *Ulmus* (13.3%) prevail. *Populus/Salix* (4.7%), with *Salix* (2.5%) and *Populus* (1.7%), *Alnus* (5.3%), *Vitis vinifera* (2.6%), and *Euonymus* (1.5%) are also present. *Crataegus, Q.* cf. *pubescens,* and *Sorbus,* with *S.* cf. *aucuparia,* don’t exceed 1%. *Erica* (3.6%), *Arbutus unedo* (1.9%), *Q.* cf. *ilex* (0.9%) and *Cistus* (0.6%) represent the Mediterranean evergreen vegetation. Unidentifiable dicotyledons and monocotyledons constitute 0.4% and 0.6% of the total identified charcoal.

The quantities of these taxa change considerably between the units and sub-units. The results of the taxonomical identification, together with the SAL and the radiocarbon dating, are presented for each sample in Figure 3. In the U3, *Fraxinus,* attributable to determined *F.* cf. *oxycarpa, Euonymus, Ulmus, Q.* cf. *cerris, Arbutus unedo* and *Cistus* dominate the charcoal assemblages. In the SU4.1, *Alnus* prevails followed by *F.* cf. *oxycarpa.* In the eight layers of the SU4.2, *Fraxinus* (mostly determined *F.* cf. *oxycarpa*) predominates in three samples, in particular together with *Erica*. In this SU, *Populus/Salix* (mostly determined *Salix*) is prevalent together with *Ulmus*; the sub-unit topmost level is dominated by *Ulmus, Alnus, Populus/Salix, Fraxinus* (mostly determined *F.* cf. *oxycarpa*) and *Q.* cf. *cerris*. In contrast, *Q.* cf. *cerris* dominates two out of the four layers from the SU4.3, whereas it co-occurs in one layer with *F.* cf. *oxycarpa* and *Erica*.

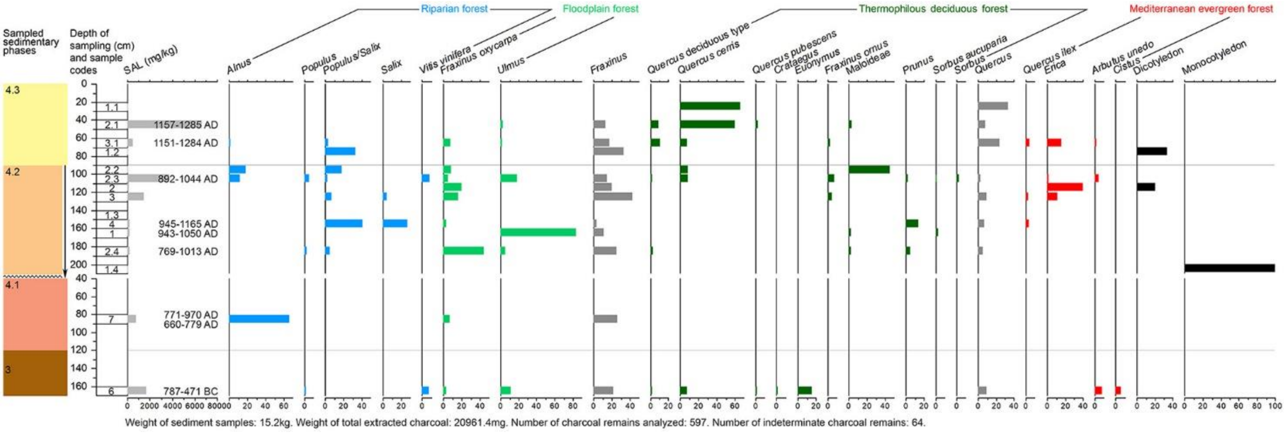

Figure 3. Pecora river NW section, sediment charcoal data. From left to right: unit and sub-unit sedimentary facies in stratigraphic sequence; sediment samples ordered by depth; value bars of SAL (in grey) with indication of AMS radiocarbon dates; percentage bars of identified taxa. The identified taxa are grouped and colored on the basis of their ecological significance.

Carpological analysis

The seven carpological and plant remains were recovered in the U4 facies association (Supplementary Table 2, available online). Sediment sample 2.3 returned the highest number pertaning mainly to cereals, such as *Triticum aestivum/durum*, *H. vulgare* and *T. monococcum*, and field weeds.

Radiocarbon datings

The results of radiocarbon dating are presented in Table 1, where sample ID (sorted by facies and depth), lab code, taxa, radiocarbon age and calibrated age are reported. In the multiplot graph of calendar ages, the range of dates highlights the absence of chronological inversion and confirms the stratigraphic reliability of the palaeochannel (Figure 4).

Table 1.

Radiocarbon and calibrated ages of selected charcoals. In bold, the most probable dating range.

Sedimentary facies	Sample Id	Taxon	Lab code	Radiocarbon age (years BP)	Calibrated age	
					1 sigma	2 sigma
SU 4.3	2.1	*Ulmus*	Fi3451	808 ± 50	**[1185–1268]**	[1050–1083] [1127–1135] **[1151–1285]**
	3.1	*Alnus*	Fi3274	809 ± 49	**[1189–1267]**	[1051–1082] **[1151–1284]**

Sedimentary facies	Sample Id	Taxon	Lab code	Radiocarbon age (years BP)	Calibrated age	
SU 4.2	2.3	*Ulmus*	Fi3496	1042 ± 41	**[969–1027]**	[1103–1119] **[892–1044]**
	4	*Salix*	Fi3005	995 ± 55	**[988–1050]** [1083–1126] [1136–1151]	[895–925] **[945–1165]**
	1	*Ulmus*	Fi3004	1025 ± 40	**[974–1035]**	[895–925] **[943–1050]** [1080–1125] [1135–1155]
	2.4	*Ulmus*	Fi3452	1142 ± 55	[778–791] [805–815] [825–841] **[862–975]**	[730–736] **[769–1013]**
SU 4.1	7	*Alnus*	Fi3171	1165 ± 35	[777–793] **[802–845]** **[855–896]** [928–941]	**[771−970]**
	7	*Alnus*	Fi3554	1275 ± 40	**[679–730]** [736–769]	[837–866] [790–830] **[660–779]**
U 3	6	*Q. pubescens*	Fi3497	2487 ± 48	[766–727]BC [718–705]BC **[695–541]BC**	**[787–471]BC** [466–430]BC

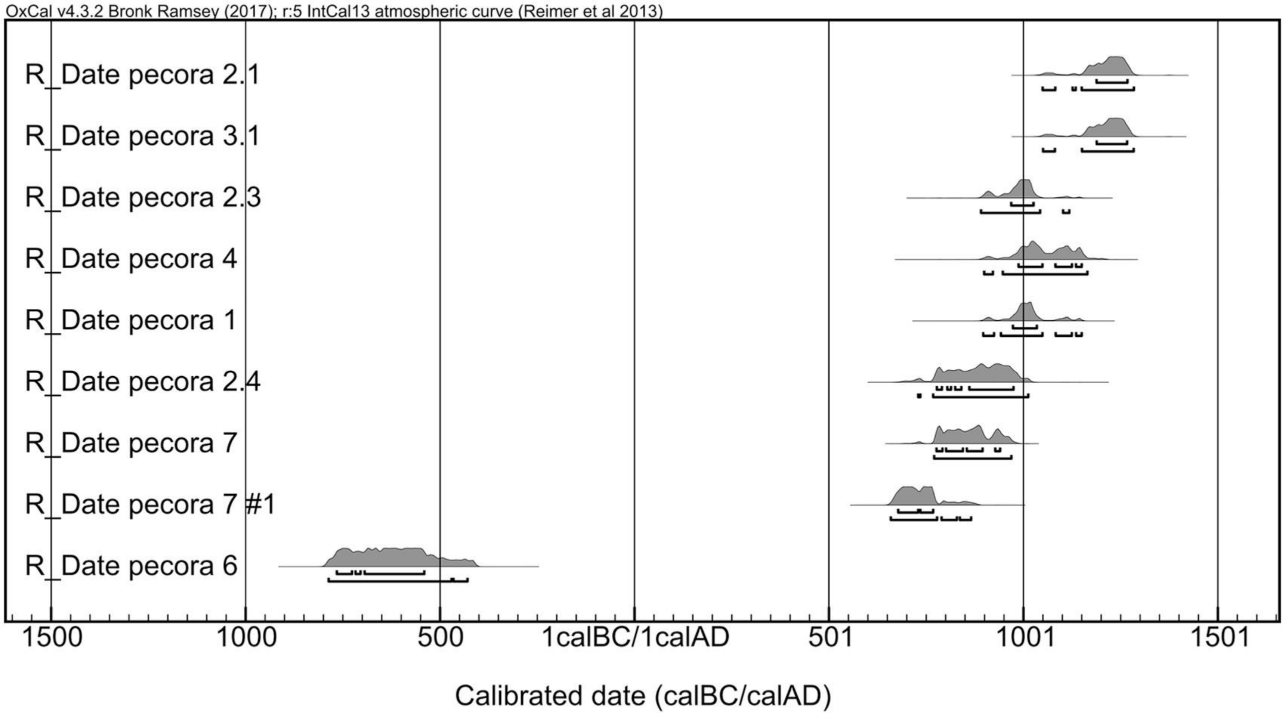

Figure 4. Multiplot graph of calendar ages.

The depositional phase recorded in U3 facies association (gravel-sand sinuous-meandering river) is dated from the 8th century BC to the mid-5th century BC (Sample Id 6, Fi3497, 2 sigma), although the top of the unit is eroded by the subsequent depositional events (see below). The later depositional U4 sediments (braided gravel-bed river) gradually took shape between the end of the 7th century AD and the end of the 13th century AD. In detail, the SU4.1 is dated from the late 7th to the second half of the 10th century AD (Sample Id 7, Fi 3554, Fi3171, 2 sigma). The SU4.2 is the larger and deeper deposition facies. Samples collected at different depths and considerable distances (Figure 2a) show a constant chronological pattern. The facies began in the second half of the 8th century AD (Sample Id 2.4, Fi3452, 2 sigma) but was a depositional event mainly from the mid-10th to the mid-11th century AD (Sample Id 1, Fi3004, Sample Id 4, Fi3005, Sample Id 2.3, Fi3496, 2 sigma). From the SU4.3, the two dated samples collected at the same height but at a distance of several metres one from the other (Figure 2a), have an equal time range between the mid-12th century AD and last part of the 13th century AD (Sample Id 3.1, Fi3274, Sample Id 2.1, Fi3451, 2 sigma).

Pollen analysis

Three sediment samples were collected from the SU4.2 and two sediment samples from the SU4.3. A high number of pollen grains (up to 300% of the terrestrial pollen sum) were not identifiable (Figure 5). Quite a high number of the remaining, identifiable pollen grains generally have thick cell walls (e.g. Cichorioideae, Caryophyllaceae, Asteroideae, Ericaceae) that are more resistant. This could hint to suboptimal preservation (i.e. temporarily oxic conditions).

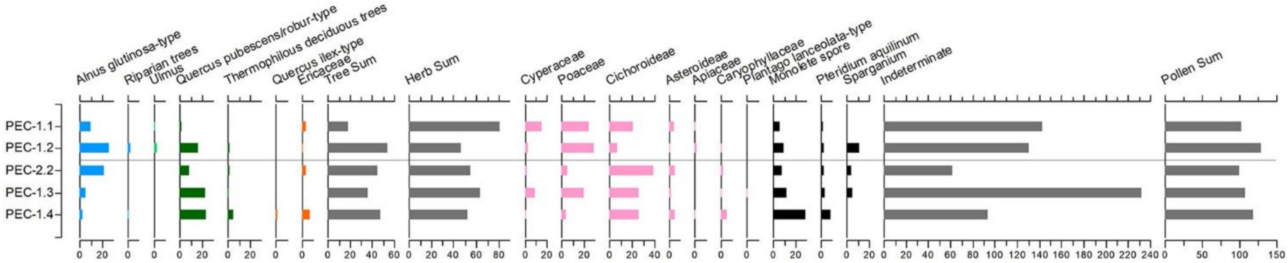

Figure 5. Pecora river NW section, percentages of selected pollen types and fern spores (monolete spores and *Pteridium aquilinum*).

Clearly evident in all samples are the high pollen percentages of herbs, whereas the relatively high number of *Alnus glutinosa*-type and *Quercus pubescens*-type pollen grains indicates the most abundant trees (Figure 5).

Discussion

Taphonomical processes

The abundance of charcoal within the geological sediments is the result of incomplete combustion of vegetation fuel (Forbes et al., 2006). The main sources of charcoal were generally generated by forest fires occurring naturally or man-ignited in relation to anthropogenic activities (Clark, 1988; Clark and Patterson, 1997; Pyne and Goldammer, 1997). The possible provenance of charcoal from nearby human-related contexts, such as archaeological sites or charcoal kilns, has also to be taken into account when interpreting the charcoal record (Moser et al., 2017). Furthermore, in case of forest burning, topographic conditions might influence the dispersion and deposition of charcoal during and after a fire (Scott et al., 2000a). In particular, run-off processes together with the ability of a river to re-distribute sediments down-stream may have facilitated the transport of charcoal by water over long distances as well as mixing of charcoal remains at different sediment depths (Nichols et al., 2000). In such situations, the vertical charcoal distribution is often not chronologically ranged and the quantity of remains may have been altered, having implications for the interpretation of plant assemblages in fluvial sediments. Low density of taxa represented by wood charcoal in fluvial channel deposits may not necessarily reflect the range of tree species burnt in a palaeo-fire (Nichols et al., 2000). Moreover, larger charcoal fragments take longer to waterlog than small pieces and may be transported further than smaller charcoal fragments.

In the case of the Pecora river, charcoals are mixed within the sedimentary record and are part of the sedimentary structure and architecture and their abundance coupled with the absence of human artefacts enables us to exclude an archaeological on-site context. Moreover, such vegetation remains are part of the record of the erosion of the calcareous tufa deposits, permitting us to identify the captured area of the charcoal record in the upstream terraced flat, where the depositional environment of these calcareous tufa was only present. Therefore, charcoal remains provide information on the fire-affected wooded vegetation growing across the Pecora river basin with a high spatial resolution. The large number of radiocarbon dates from the facies association have highlighted the stratigraphic reliability of the palaeochannel without chronological inversion and the absence of perturbation and mixing of the charcoal remains at different sediment depth (Figure 4). The anthracological record is composed of a minimum of two taxa (SU4.1) to a maximum of 13 (SU4.2) and commented according to ecological significance rather than on the proportions of the individual taxa.

Fire history, vegetation changes and population in the southern Colline Metallifere

The discontinuous chronological depth, focused on two historical periods (800–450 BC, AD 650–1300), prevents us from reconstructing the fire history of the area and obtaining a detailed sequence of land cover changes following the impact of fire events. However, previous palaeoenvironmental studies carried out in the nearby Lake Accesa can be compared through sedimentary pollen and macro/microcharcoal records providing evidence of the fire regime and vegetation history (Colombaroli et al., 2008; Drescher-Schneider et al., 2007; Vannière et al., 2008). The evidence that fires in the Pecora river basin initially occur in a phase of slight regional fire increase (800–450 BC), subsequently matching local and regional fire events (AD 650–850) that coincide with disturbances and changes in plant cover as well as land use (Figure 6), suggests that the episodes noted for the Pecora river can be integrated and discussed in a wider regional picture.

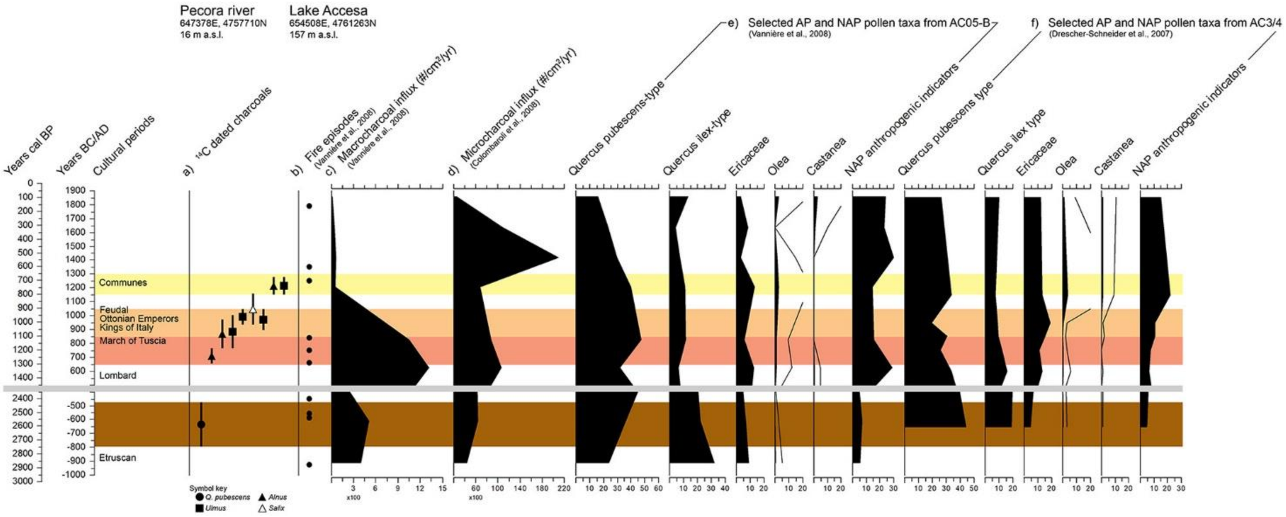

Figure 6. Proxy data from the northern Maremma area positioned in local historical and cultural periods. A comparison is proposed between (a) the concentrations of radiocarbon ages (2 sigma) for the Pecora river palaeochannel and proxy records from Lake Accesa: (b) local to regional fire episodes (Vannière et al., 2008); (c) sedimentary macroscopic charcoal influx (Vannière et al., 2008); (d) sedimentary microscopic charcoal influx (Colombaroli et al., 2008); (e) from AC05-B profundal core (Vannière et al., 2008) and (f) AC3/4 littoral core (Drescher-Schneider et al., 2007), selected arboreal pollen curves (AP), representing local deciduous forest (*Q. pubescens*-type), evergreen forest (*Q. ilex*-type and Ericaceae), plantations (*Olea* and *Castanea*), and selected non-arboreal pollen curves (NAP) of anthropogenic indicators (sum of *Apium*, *Artemisia*, Cerealia-type, Chenopodiaceae, Cichorioideae, *Plantago lanceolata*-type, Poaceae, *Pteridium*, *Rumex*). Coloured bars (according to unit and sub-unit sedimentary facies from Figure 2) represent the supposed fire use periods in the Pecora river valley. The grey bar marks the time interval missing in the stratigraphic sequence of the Pecora river palaeochannel.

In addition, the centuries examined in our research were strongly influenced by human activities in this regional district. Although the anthropogenic phases with maximum fire activity corresponded to a greater sensitivity of the vegetation, triggering significant changes in vegetational communities (Vannière et al., 2008), the available Lake Accesa records lack accurate comments and analysis for the last 2500 years. In fact, an in-depth cause/effect analysis needs to be interfaced with archaeological proxies that have deduced the anthropic occupation in the study area, the main activities carried out by human communities along with economic and social dynamics. The district of the Colline Metallifere has been the focus of archaeological research and systematic surveys carried out by the Department of Historical Sciences and Cultural Heritage (University of Siena), the Archaeological Superintendency of Tuscany, and other organizations, for the past 35 years. The recorded sites have been listed, mapped and discussed in articles (Cucini, 1985; Dallai, 2003b), unpublished Degrees (Casini, 1992; Dallai, 1993; Pestelli, 1993) and PhD theses (Dallai, 2003c; Marasco, 2013a; Ponta, 2019). Consequently, the area is a privileged case study for evaluating the level of anthropic presence and land use (Figure 7). The time frame covered by the sediment charcoal analysis allows to shed light on the relationship between the human population and the transformation of the northern Maremma environment.

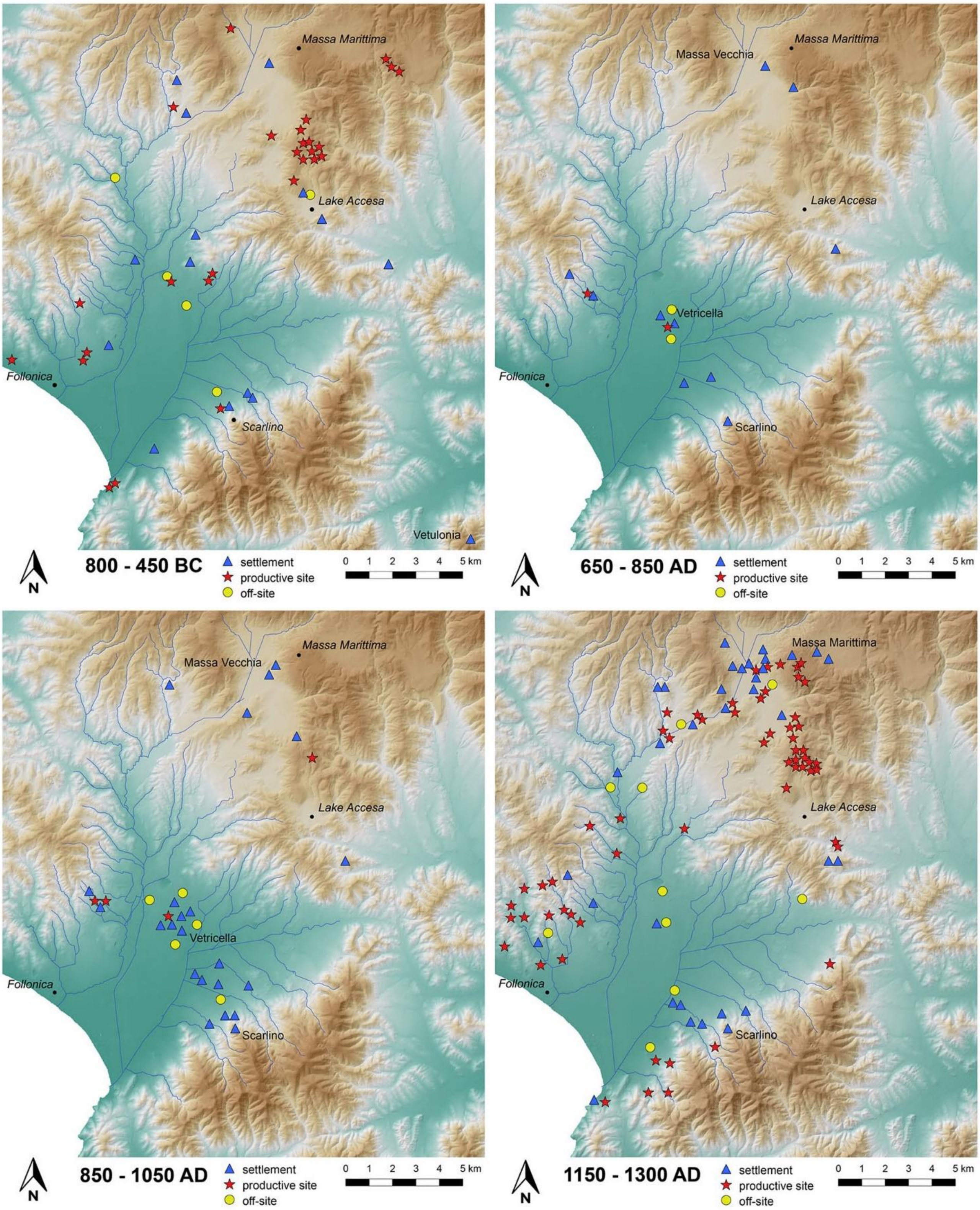

Figure 7. Archaeological settlement patterns in the drainage basin of the Pecora river during the four historical periods discussed through the palaeonvironmental data. The mapping, dating and classification of the archaeological evidences follow those indicated in the references (Casini, 1992; Cucini, 1985; Dallai, 1993, 2003b, 2003c; Marasco, 2013a; Pestelli, 1993; Ponta, 2019). Settlements include villages, farms, buildings, castles and necropolis; artisanal and productive

centres consist of mines, furnaces, slag heaps; off-site records are sporadic forms of occupation. The places and sites cited in the text are reported (black dots: current locations). Map source: SINAnet ISPRA – Dem75 (QGIS 3.10.3 'A Coruña').

Men and fire: cultural impact in northern Maremma

Forest opening for mining and farming activities (800–450 BC)

The older sediment samples of the palaeochannels came from the top of the depositional facies U3 characterized by gravels from the bedrock basin and filling a single channel up to a depth of 3 m (Figure 2a). The depositional environment was typical of a sinuous-meandering river with the presence of periodically flooded distal floodplain or small swamps along the valley floor.

Taxa identification of the sediment charcoal analysis pertains to vegetation of riparian (*Populus* and *V. vinifera*), floodplain (*Ulmus* and *F.* cf. *oxycarpa*) and thermophilous deciduous forests (Figure 3). Fire events affected the vegetation growing on moist low-lying areas, frequently or infrequently flooded by the Pecora river, as well as the vegetation on well-drained lands and valley slopes. Deciduous oaks, *Q.* cf. *cerris* and *Q.* cf. *pubescens*, typified the slope woodland with evergreen shrubs (*A. unedo* and *Cistus*) and small trees, such as *Crataegus* and *Euonymus*, characterizing the understorey vegetation of forest margins and clearings (Figure 3). Radiocarbon dated charcoal (Fi3497, 2 sigma) dates the fires to the beginning of the 8th century BC and the mid-5th century BC (Table 1).

The presence of fire events in the northern Maremma was significant between ca. 2700 and 2500 cal. yr BP (mid-8th–5th century BC). In the basin of the Lake Accesa, a slight increase in the frequencies of fire was recorded by the macro and microscopic charcoal accumulation rates with concentration of local episodes during the 6th century BC (Figure 6). In agreement, strong fire incidence was reconstructed for this period at other sites in southern and central Europe (Tinner et al., 2005, 2009). Thus the fires in the Pecora river valley are attributable to regional episodes affecting the lowlands and the hilly slopes in the southern Colline Metallifere. Locally, Vannière et al. (2008) have attributed such events to the presence in the lacustrine area of Etruscan mining settlements. The pollen sequences of Lake Accesa suggested a minimal impact of these fires on the local vegetation. The deciduous *Quercus* forest did not show any evidence of sudden changes towards more open and degraded xeric formations (Figure 6).

Between the 6th and 5th century BC, the Pecora river valley and the nearby Lake Accesa basin can be considered a single district characterized by the same historical events with an anthropization closely connected to the nearby Etruscan town of Vetulonia (Curri, 1978; Michelucci, 1981;

Steingraber, 1983). Vetulonia’s catchment comprised the hilly slopes (Figure 7) and engaged in crop management (Mariotti Lippi et al., 2002), mining and salt production (Aranguren et al., 2007, 2009) rather than exploitation of the alluvial plain. 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). After logging, the use of fire was thus part of the forest opening and clearing activities, providing Vetulonia with access to the mineral resources as well as agricultural exploitation of the hills. However, the significant persistence of deciduous woodland (in Pecora river and Lake Accesa records) would appear to imply a localized presence of cultivated and open degraded habitats (Figure 6). Despite significant anthropogenic pressure, the impact of fire clearing was probably contained and restricted to the settled and productive areas.

Swamp reclamation (AD 650–850)

The U3 filled channel is in turn cut by a shallower channel (2.5 m deep) filled by sediments (U4) composed of gravelly-sandy bedforms indicating an abrupt change from the sinuous-meandering river to a shallow braided river with fast deposition in an unbound channel system (Figure 2a). The most striking feature is the major presence of unsorted and angular to subangular clasts deriving from the erosion of calcareous tufa (Figure 2b). This is the first evidence of the up-valley calcareous tufa environment erosion and their transportation over short distance (Pieruccini et al., 2018). The SU4.1 facies association is preserved on the right side of the channel and indicates the first phase of the deposition.

US4 sediments contain abundant charcoal remains, concentrated within the troughs and beds. Related to SU4.1, charcoal identifications evidence how fires definitely affected the floodplain (*F.* cf. *oxycarpa*) and marshy waterlogged vegetation (*Alnus*) growing on the frequently flooded low-lying areas in close proximity to the Pecora valley floor (Figure 3). The oldest radiocarbon dated charcoal (from sediment sample 7) dates back the first fire events in the lowlands and the erosion of the calcareous tufa system to the end of the 7th century AD (Fi3554, 2 sigma; Table 1). These events then occur in the 9th century AD (Fi3171, 2 sigma; Table 1).

The up-valley calcareous tufa environments are typically made of wide flat swampy areas alternated with barrages or waterfalls (Pieruccini et al., 2018), where calcium bicarbonate-rich waters precipitate the carbonate by physio-chemical processes such as turbulence (waterfalls and steps) and micro-biological activity (swamps and ponds) (Capezzuoli et al., 2014). The erosion of these deposits can be justified only by the drying of the ponds due to important climatic changes or human interference. From 1200 cal. yr BP (mid-8th century AD) the northern Maremma underwent a period of decreasing moisture, reducing river erosion potential (Magny et al., 2007). The local climatic signal was not strong enough to generate a rapid fluvial system response. Therefore, only artificial deep trenches cutting the barrages played the most important role for draining the upper valley wetland, diverting the natural course of the river and reclaiming the flat calcareous tufa-deposited terraces (Figure 2c). The subsequent river down-cut led to the transport and deposition of a large amount of calcareous tufa clasts. Coupled with the onset of the fluvial erosional events from the end of the 7th century AD, the presence of charcoal remains suggests that the drainage and reclamation of the wet environments was also associated with clearance of the local waterlogged and flooded vegetation by way of fire activity.

Between the mid-7th century AD and mid-9th century AD (1300–1100 cal. yr BP), local fire episodes affected the Lake Accesa basin with high fire frequency (Figure 6). Around 1200 cal. yr BP, drier climatic conditions could have favoured ignition and biomass burning, but later people adopted fire for agricultural and animal husbandry (Vannière et al., 2008). The southern Colline Metallifere were thus involved in regional fire episodes reflecting the need to acquire new land. The impact of land clearing activities was locally contained and only occasionally disturbed the deciduous *Quercus* forest, widely spread and predominant in the lacustrine pollen sequences (Figure 6). In northern Maremma, archaeological and archaeobotanical data have highlighted the subsistence farming economy of the sporadic communities and the marginal role played in the exploitation of timber and local natural resources from the 7th century AD (Bianchi, 2015; Buonincontri et al., 2017; Di Pasquale et al., 2014). The use of fire was thus part of activities aimed at cutting, clearing and opening up forest areas in order to meet with local needs.

In the Pecora river valley, the population was scarce, with only a few scattered sites across the hilltops and on the alluvial plain, occupied by modest-sized communities (Figure 7). The finding of charred cereal caryopses in the palaeochannel sediments, identified as *T. monococcum* (Supplementary Table 2, available online), confirms the presence in the valley, from at least the end-7th century AD, of a cereal type, highly resistant to pests and diseases. In northern Maremma, archaeobotanical investigations argued the cultivation of minor cereals in the early Middle Age to minimize the risks of environmental adversities, in response to the involution of the state (Buonincontri et al., 2017). Nonetheless, control exercised by the Lombard authorities appears to have strongly influenced the local economy within the valley (Cucini, 1989; Marasco, 2013b). It is interesting to note that *T. monococcum* is a cereal considered ‘cultural’ element of Lombard farming (Buonincontri et al., 2014). The Pecora river from the mid-8th century AD was known as *Teupascio*, which translates as the ‘King’s water’, a toponym which further emphasizes the role played by public authorities in the management of this valley (Bianchi and Collavini, 2018). In the 9th century AD, administration of this fluvial corridor became part of the March of Tuscia. Regulation of the river as well as the clearing interventions on the coastal lowlands tends to imply planning and management by the public Lombard and Carolingian rulers. Drainage, reclamation and clearing by fire were carried out to control the fluvial hydraulic force and to obtain flat, open lands upstream. Therefore, while man-induced fires contributed to the significant change of the fluvial erosional processes, the still marginally developed cultural areas would have prepared the landscape for the introduction of a primitive fiscal system.

Widespread forest opening for new agrarian landscapes (AD 850–1050)

The SU4.1 is in turn cut by a minor unconformity indicating the formation of a weakly undulated and deeper channel (Figure 2a). The filling SU4.2 (1 m deep) has the same facies model of SU4.1, with the predominance of cut-and-fill bed-forms again made up of calcareous tufa fine-grained gravels.

According to charcoal analysis in SU4.2 (Figure 3), fire events affected the marshy and riparian vegetation close to riverbanks (*Alnus, Salix* and *Populus*), the alluvial forest on the lowlands (*F.* cf. *oxycarpa* and *Ulmus*), and the vegetation on well-drained areas characterised by thermophilous deciduous forest (*Q.* cf. *cerris* and *F.* cf. *ornus*), with sclerophyllous evergreen trees (*Erica* and *Q.* cf. *ilex*) on degraded soils in the open spaces. The presence of a forest dominated by deciduous *Quercus* with fairly open woodland is strongly suggested by the high pollen percentages of herbs recorded in the concurrent pollen analyses from the sediment samples of the Pecora palaeochannel (Figure 5). Four radiocarbon dates set the historical period of the fires in the SU4.2 fluvial sediment accumulation from the second half of the 8th century AD (Fi3452, 2 sigma) and date the 1 m deep depositional event mainly between the mid-10th and mid-11th century AD (Fi3004, Fi3005, Fi3496, 2 sigma; Table 1).

Starting from the end of the 7th century AD, the erosional processes continued with greater emphasis and the palaeochannel deepened. The arrival of sediments coming from the erosion of the calcareous tufa becomes more rapid and abundant, rated up to 0.7 cm/yr and concentrated in a very short time span, excluding any climate-related cause. The increasing thickness of the sedimentary sequence and its deposition indicates that this main depositional phase was associated with the major land reclamation effort and related environmental changes occurring upstream. Charcoal was contextual to this phase, therefore the use of fires was again associated with artificial river regulating measures. Land clearing interventions in this period affected not only the swampy flat terraces but also the flooded low-lying areas as well as the higher lands of the river valley, encompassing the whole river basin. The presence of new and different habitats represents the intention of enlarging the anthropic activities across the valley.

Interestingly, from the mid-9th century AD (1100 cal. yr BP), the decreasing microscopic and macroscopic charcoal accumulation rates in the Lake Accesa sediment testify to the use of fire centred in the Pecora river valley (Figure 6). However, the pollen sequences of Lake Accesa recorded the progressive or suddenly concurrent collapse of the deciduous *Quercus* forest (until the modern age) and the rise of xeric shrubland (Figure 6). This is in agreement with other pollen/sediment charcoal time series showing in northern Tuscany the spread of low Mediterranean maquis and shrublands following land-use intensification, rather than climate (Colombaroli et al., 2007). In northern Maremma, local deciduous *Quercus* forest supplied fuelwood and timber suggesting the exploitation of hilly habitats mostly for harvesting wood (Di Pasquale, 2004; Di Pasquale et al., 2014; Rossi, 2016). Within the Pecora river valley, the use of fire could be combined with wood cutting in order to clear logging waste, shrubs, dead and standing biomass (Gabrielli, 1964; Piussi and Redon, 2001). On the whole, the decline of the hilly Medieval forest confirms the increasing anthropic interest to exploit woodland and to open areas by harvesting timber and fire clearing from the mid-9th century AD. This is strongly consistent with the 1 sigma interval of Fi3452 dating both the fires and the beginning of the deeper depositional events of calcareous tufa gravels in SU4.2 at least to the second half of the 9th century AD (AD 862–975).

From the mid-9th century AD the strong and incisive role of public authorities aimed at founding key economic and strategic sites across the Pecora river valley, articulated in a more complex pattern of downstream settlements (Figure 7). Here, the site of Vetricella was renewed and fortified with the creation of three concentric ditches enclosing a tower-like structure (Marasco et al., 2018). Initially led by late-Carolingian March of Tuscia (mid-9th century AD) and later by Kings of Italy and Ottonian Emperors in the mid-10th century AD (Vignodelli, 2012), this complex project changed the Pecora river landscape on a large scale using skilled manpower in the sites as well as conspicuous workforce to enhance drainage activities and the clearing of flat swamplands as well as expanding forest use and opening on the hilly slopes.

From the mid-10th century AD to the mid-11th century AD, the continuous consumption of woodland triggered an increase in erosion and downstream sediments. A consequence of post-timber-harvesting and fire clearing is the consumption of the forest floor, which led to erosion rates of greater magnitude, increasing velocities and sediment transport capacity of the overland or rill flow (Borrelli and Schütt, 2014; Scott et al., 2009). The increased amount of sediments in the palaeochannel from the erosion of calcareous tufa suggests the improvement of the reclamation and hydrological management upvalley, possibly due to more strict control on the drainage. This led to the deep incision of the calcareous tufa terraces and barrages and the subsequent transport downvalley of big amount of sediments. Today, the Pecora thalweg is still deeply entrenched (up to 10 m) within the original surface of the calcareous tufa, down to the bedrock (Pieruccini et al., 2018).

Public interest in the Pecora river valley increased from the 10th century AD. At the same time, new areas for the storing of resources appeared in rural settlements and higher quality agri-food resources were collected in the form of crops producing large-kernelled cereals, such as naked wheat, and new edible fruits, such as chestnuts (Bianchi and Grassi, 2013; Buonincontri et al., 2015, 2017). The discovery of charred glume fragments and cereal caryopses in the palaeochannel deposits, identified as *H. vulgare* and *T.* cf. *dicoccum* (Supplementary Table 2, available online), are consistent with the concurrent pollen analyses (Figure 5) showing cultural indicators (i.e. Cerealia-type, *Plantago lanceoloata*-type). These point to human interference and open habitats used for agricultural practices. Drainage and fires continued in the Pecora river valley in order to reclaim new open areas and increase food production. The use of fire clearing aimed to fertilize soil both in new tillage and in coppice forest for temporary crops (the so-called *cetine*; Piussi and Redon, 2001). These events created progressively more arable lands that would become the future agricultural landscape after the mid-10th century AD, as recorded in the pollen sequence AC3/4 of the Lake Accesa (Figure 6). The simultaneous rise of NAP, *Castanea* and *Olea* (for the first time in two thousand years) would pinpoint this precise strategy aimed at the improvement and cultivation of new agri-food resources (Buonincontri et al., 2015; Di Pasquale et al., 2014).

Large-scale reduction of forest for new settlements and mining activities (AD 1150–1300)

Both US4.1 and US4.2 are cut by a further shallow and slightly undulated unconformity buried under US4.3 sediments (Figure 2a). These show the same sedimentary and compositional characteristics of SU4.2 and SU4.1, however with decreasing presence of calcareous tufa fine-grained gravels. Moreover, the thickness of the sedimentary record is very limited, indicating a decrease in sedimentation and associated environmental dynamics in the surrounding landscape.

Due to the amount of charcoal, it can be assumed that during this period fire events continued to affect the vegetation cover (Figure 3). Sediment charcoal analysis revealed the significant presence of taxa indicating vegetation growing in well-drained areas: thermophilous deciduous forest (*Q.* cf.

cerris and *Fraxinus* with *F.* cf. *ornus*) with scant Mediterranean evergreen plants (*Erica* and *Q.* cf. *ilex*). Riverbanks (*Salix* and *Populus*) and lowlands (*Fraxinus* with *F.* cf. *oxycarpa*) were the second areas affected by the fires (Figure 3). The presence of deciduous *Quercus* woodland and riparian vegetation is confirmed by the contextual pollen analysis (Figure 5). However, the highest percentage record of herbs and cultural indicators suggest the remarkable presence of an open landscape with fields. Two radiocarbon dates set the deposition and fire phase between the mid-12th and end of the 13th century AD (Fi3451 and Fi3274, 2 sigma) (Table 1). These were the responses of the fluvial system to the changes started in the mid-7th century AD in the upper catchment which lasted for ca 650 years.

Between 800 and 600 cal. yr BP (mid-12th-mid–13th century AD), the lowest macroscopic charcoal accumulation rate in the sedimentary record of the Lake Accesa is related to a period lacking local fire events (Figure 6). However, an increase in the microscopic charcoal accumulation rate was recorded, suggesting more significant changes in regional fire regimes. The concurrent presence of charcoal sediment in the Pecora river valley would suggest that fire events can be included in the wider fire history involving the Colline Metallifere. The pollen sequences of the Lake Accesa showed the gradually progressive decrease in the presence of deciduous *Quercus* forest, a fixed trend that continued from the previous historical period (Figure 6). While previously fire clearing was used as a means to attack and open the forest landscape mostly in the Pecora river valley, now the whole district of the Colline Metallifere was subjected to reduction of forest area combined with fires.

From the end of the 10th century AD, a gradual transition from the public fiscal authorities to more localized control took place, stimulated the socioeconomic development of castles and encouraging the leading role of towns such as Massa Marittima (Bianchi, 2015; Dallai et al., 2005). From the mid-12th century AD, the valley was subjected to a strong recorded anthropic presence (Figure 7). New fortified hilltop settlements and castles absorbed gradually the previously smaller sites scattered across the plains. Production sites proliferated exploiting natural resources (Cortese, 2008; Cucini Tizzoni and Tizzoni, 1992). The role played by Massa Marittima in the inland increased both politically and economically, going through a period of development and architectural growth (Dallai, 2014). Affecting deciduous forest on well-drained and hilly areas, the presence of fires appears to be strongly linked to demographic increase and control within the district of the Colline Metallifere. Decreases in sedimentary and associated environmental dynamics in the palaeochannel of the Pecora river are consistent with limited interventions in the lowlands, suggesting the presence of a more stable landscape, less susceptible to erosion. The agrarian revolution, previously established and affirmed, persisted under local feudal control, whereas the new impact of settlements, mining and metallurgical activities spread across the hilltops. The new settlements and growing production sites reclaimed more lands and exploited the woods for harvesting fuel and timber. Therefore, the use of fire was consequent to the practices of removing undergrowth, stumps and waste biomass after clearcutting or coppicing (Redon, 1987).

Conclusion

The use of fire is the most ancient anthropogenic technique for the management of vegetation, playing a fundamental role in present Mediterranean cultural landscapes, both in term of vegetation structure and composition (Colombaroli et al., 2008; Colombaroli and Tinner, 2013; Connor et al., 2019). The interaction between the socio-cultural aspects involved in fire management decisions and the natural environment determined the underlying dynamic processes of Mediterranean ecosystems.

The sediment charcoal analysis in a palaeochannel of the Pecora river, located in the south-western coast of Tuscany, offered the opportunity to detect past fire events in the fluvial landforms occurring between 800 and 450 BC and again between AD 650 and 1300 and at a greater spatial resolution. Taking place in a central Mediterranean district adequately studied through palaeoenvironmental and archaeological research, the investigation attested to the paramount importance of Medieval local fire episodes in shaping and determining the character of the Tuscan Mediterranean landscape, as suggested in other records in the region (Colombaroli et al., 2007). The main outcomes can be listed as follows:

1) Four phases of fire events were detected belonging to two major fluvial dynamics and erosional processes. The first phase, dated to the Iron Age (800–450 BC), occurred when the river was characterized by its natural gravel-sand wandering to meandering course. The others dated instead to the Middle Ages (AD 650–850, AD 850–1050, and AD 1150–1300) and occurred during the man-induced braided gravel-bed fluvial phase.

2) In the long history of fires affecting the northern Maremma, the events recorded in the Pecora river valley were included in regional episodes involving the southern Colline Metallifere (850–450 BC and AD 650–850) and more localized events taking place in the river valley (AD 850–1050). From AD 1150 fires reflected again regional fire history.

3) The Pecora river fire sequences had purely anthropogenic origins. The use of fires was linked to forest opening and reduction by local communities. Introduced by the Etruscans, fire events dated to 800–450 BC ensured agricultural exploitation on the hilly slopes. From AD 650, fire contributed to the Medieval upstream reclamation and vegetation clearing of flat swamplands. From AD 850 to 1050, the use of fire spread over a wider area in the valley, increasing potentially arable lands. Between AD 1150 and 1300, fires belonged to a regional forest clearance phase.

4) The Medieval fire episodes played an active role in changing the fluvial landforms of the Pecora river into a braided gravel-bed course. From AD 650, they were a determining factor in the first erosional processes of the upstream calcareous tufa terraces. In AD 850, the widespread fire clearing in the valley increased upstream fluvial erosion rates. From AD 950, the growing consumption of the forest floor increased the downstream gravel-rich deposits of Pecora river.

5) Medieval fire clearing influenced regional vegetation history. Although fires were recorded exclusively within the valley in AD 850, the widespread use contributed towards the decline of the dominant deciduous *Quercus* woodland. From AD 950, open habitats became the new form of clearly detectable agricultural landscape.

6) The use of fire clearing and the resulting landscape changes in the Pecora river valley depended on the political strategies adopted by Medieval authorities and their ability to organize and manage the local communities towards a well-defined objective. From AD 650 (during the lowest phase of human presence) the Lombard political elite induced the first artificial drainage regulation measures and fire clearing of the flat swamplands. From AD 850, the strong and incisive role of the late-Carolingian public authorities intensified fire activities and expanded the open areas to the valley slopes. From AD 950 royal and imperial power focused the fire strategies in order to increase cultivated lands and agri-food production. Between AD 1150 and 1300, the wider regional fire clearing was induced by the strong growth of settlements affecting the natural resources in the hinterland of the Colline Metallifere.

Historically, the role of Etruscans and Romans has often been discussed in promoting the development of rural landscapes with olive and vine cultivation in central Tyrrhenian Italy, highlighting the heritage of this agrarian land-use in local traditions and its presence, up until a few decades ago (Bowes et al., 2015; Mercuri et al., 2013). However, our research in the Colline Metallifere indicates that the historical relevance of the Etruscans should be downscaled. Events that can be attributed to the Roman period are not recorded. The open-habitat landscape (with crops and orchards) began in AD 850 through public intervention and spread from the mid-10th century in a well-defined policy aimed at creating key strategic and economic sites. Such a pattern appears to reflect local as much as regional land cover changes (Colombaroli et al., 2007). In the northern Latium Anti-Apennines and the Rieti basin (respectively, 87 and 350 km to the south-east), a more permanent forest reduction and cultivation occurred only during Medieval and post-Medieval times (Mensing et al., 2018; Sadori, 2018), with the latter area pointing to late-Carolingian sociopolitical transformations between AD 850 and 900 (Schoolman et al., 2018). However, by focusing on a micro-regional case study, our research has permitted us to verify and investigate causal relationships, avoiding oversimplifications by means of a valuable proxy (sediment charcoal data) that reconstruct the history of fire events both in terms of a detailed space-time definition, and provides a better integration of local human history. Medieval fire clearing activities in northern Maremma, we conclude, represented a considerable impulse for new land usage, determining the definitive success of local cultural landscape strategies until the modern era.

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