



## Shaping Mediterranean landscapes: The cultural impact of anthropogenic fires in Tyrrhenian southern Tuscany during the Iron and Middle Ages (800-450 BC / AD 650-130)

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

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21

22 **Abstract**

23 Charcoal analysis, applied in sediment facies analysis of the Pecora river palaeochannel (Tyrrhenian  
24 southern Tuscany, Italy), detected the occurrence of past fire events in two different fluvial  
25 landforms at 800–450 BC and again at AD 650–1300. Taking place in a central Mediterranean  
26 district adequately studied through palaeoenvironmental and archaeological research, the  
27 investigation determined land changes, time phases and socio-economic driving forces involved in  
28 dynamic processes of fire. The fire sequences had purely anthropogenic origins and was linked to  
29 forest opening and reduction by local communities. Introduced by the Etruscans, fires dated to 800–  
30 450 BC involved mainly the forest cover on the hilly slopes, ensuring agricultural exploitation.

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

#### 41 **Keywords**

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

#### 45 **Introduction**

46 The history of traditional rural landscapes can be considered a recent research priority, widely  
47 stimulated by the policies of supranational and state communities (Brouwer, 2004; Pedrolí et al.,  
48 2007). The term ‘cultural landscape’ is illustrative of the interaction and co-existence between  
49 humankind and its natural environment. Cultural landscapes often reflect the evolution of human  
50 society and settlement patterns over the course of time, influenced by the natural environment as  
51 well as by social, economic and cultural forces (Rössler, 2006; Sodano, 2017). Cultural landscapes  
52 embrace traditional forms of land-use, considering the characteristics and limits of the natural  
53 environment they are established in, and they show specific ecosystems and biological diversity  
54 (Fowler, 2003). In 1992 the UNESCO World Heritage Centre began to recognize ‘cultural  
55 landscapes’ as a category of site within the Convention’s Operational Guidelines. In this sense, the  
56 Mediterranean basin holds a unique and privileged role. Its physical morphology, abundance of  
57 environmental and bio-cultural diversity, and millenary history, favoured the rise of a remarkable  
58 mosaic of widely distributed and diversified habitats (Blondel, 2006; Horden and Purcell, 2000;  
59 Hughes, 2005).

60 The dual essence of the Mediterranean landscapes, environmental and anthropic, has been  
61 investigated over the course of time with approaches based on the often contrasting social and  
62 natural sciences (Holmgren et al., 2016; Mercuri, 2014). Palaeoenvironmental researches are the  
63 fundamental resources used by natural sciences to investigate cultural landscape progression. The

64 study approaches make use of data garnered from pollen and charred wood fragments, with the  
65 contribution of other biostratigraphical, geomorphological and isotopic studies, in order to  
66 reconstruct the evolution of the past vegetation landscape and affecting fire sequences (Bevan et al.,  
67 2019; Conedera et al., 2009; Mercuri and Sadori, 2014; Scott and Damblon, 2010; Zanchetta et al.,  
68 2013).

69 The most common approach is largely based on the analysis of pollen, non-pollen palynomorphs  
70 and macro/microscopic charcoal particles from high-resolution Holocene marine, lake or peat cores.  
71 These researches, initially focused on reconstructing localized landscape, in the last 20 years have  
72 assumed a broader interest, increasing large-scale land cover narratives (Berger et al., 2019;  
73 Bottema and Sarpaki, 2003; Carrión et al., 2010a, 2010b; de Beaulieu et al., 2005; Fyfe et al., 2019;  
74 Jalut et al., 1997, 2000, 2009; Jimenez-Espejo et al., 2007; Mercuri et al., 2013; Pérez-Obiol et al.,  
75 2011; Pons and Quézel, 1998; Roberts et al., 2011b; Sadori et al., 2011, 2015; Stoddart et al., 2019;  
76 Weiberg et al., 2019; Willis, 1994; Woodbridge et al., 2019).

77 More than pollen, macroscopic wood charcoal fragments are a ubiquitous proxy in  
78 palaeoenvironments, due to their resistance to microbial decomposition and are therefore commonly  
79 found in both soil and sediment archiving contexts (Robinson et al., 1997; Scott et al., 2000b; Talon  
80 et al., 1998). Since the end of 1970s, soil/sediment charcoal analyses have been widely used in  
81 Central Europe to investigate the occurrences of fire events and the correlated burnt woody  
82 vegetation (Nelle et al., 2013). In the Mediterranean environment, these researches are currently  
83 limited to local contexts and lack a macro-regional narrative (Carcaillet et al., 1997; Delhon et al.,  
84 2009, 2013; Henry et al., 2010; Moser et al., 2017; Piqué et al., 2018).

85 The aim of both pollen and soil/sediment charcoal analyses is to obtain long-term ecological  
86 research with in-depth details of land cover and fire events, in order to explore the role of climate or  
87 anthropogenic impact in the recorded changes. In the genesis of the Mediterranean landscapes, the  
88 climate is considered as the first-scale factor influencing and determining the natural environment at  
89 least until ca. 6500 cal. yr BP, when the biological archives start responding to both climate change  
90 and human impact (Roberts et al., 2011a). For the last 6000 years, the evaluation of causes and  
91 effects has been a common and problematic issue, subject to debates often polarized between those  
92 supporting a climatic origin and those favouring an anthropogenic explanation (Di Pasquale et al.,  
93 2004; Mercuri and Sadori, 2014; Roberts et al., 2011a).

94 Recently, an important review involving pollen records (past vegetation), stable isotopes (climate),  
95 archaeological site surveys and C14 dates (long-term population change), has highlighted landscape  
96 changes in seven different Mediterranean regions by human and natural agencies during the past ten

97 millennia (Bevan et al., 2019). This study suggests that human actions were relevant on land cover  
98 after ca. 3500 cal. yr BP and the dominant landscape trajectory differed in the eastern and western  
99 Mediterranean during the past 1500 years, following the distinctive historical events of different  
100 regions (Roberts et al., 2019). In fact, while the sum of human activities has produced measurable  
101 effects at a global scale, locally investigations require regional, sub-regional and also micro-  
102 regional approaches with the perspective of historical and archaeological sources, adopting a socio-  
103 cultural analysis rather than deterministic approach in order to avoid simplistic causal relationships  
104 (Carrión et al., 2010a; Pyne et al., 1996; Roberts et al., 2019). At present, there are few territories  
105 with high-quality datasets that allow the comparison of high-resolution paleoecological records with  
106 historical documents and archaeological data (Jouffroy-Bapicot et al., 2016; Kaal et al., 2011;  
107 Mensing et al., 2018; Moser et al., 2017; Sadori et al., 2015). More research is needed to integrate  
108 the three sources so as to understand how sociopolitical and economical changes influenced local  
109 land use (Holmgren et al., 2016; Scott and Damblon, 2010).

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

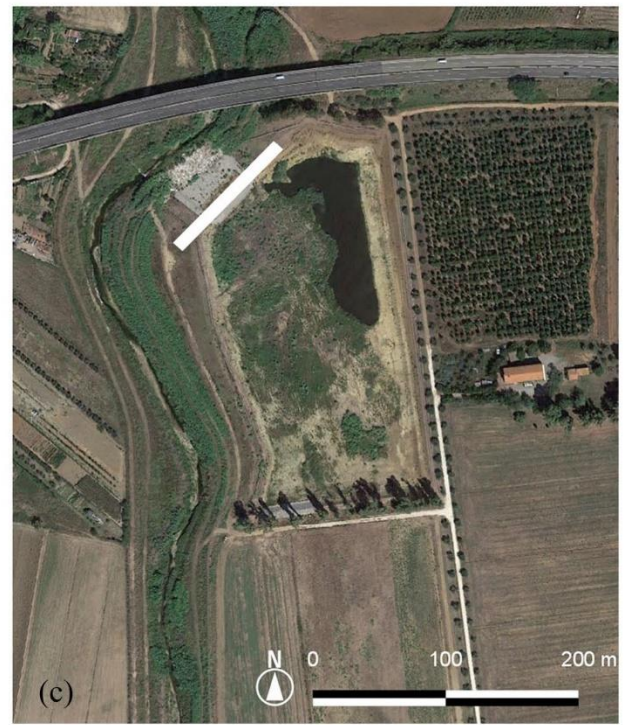
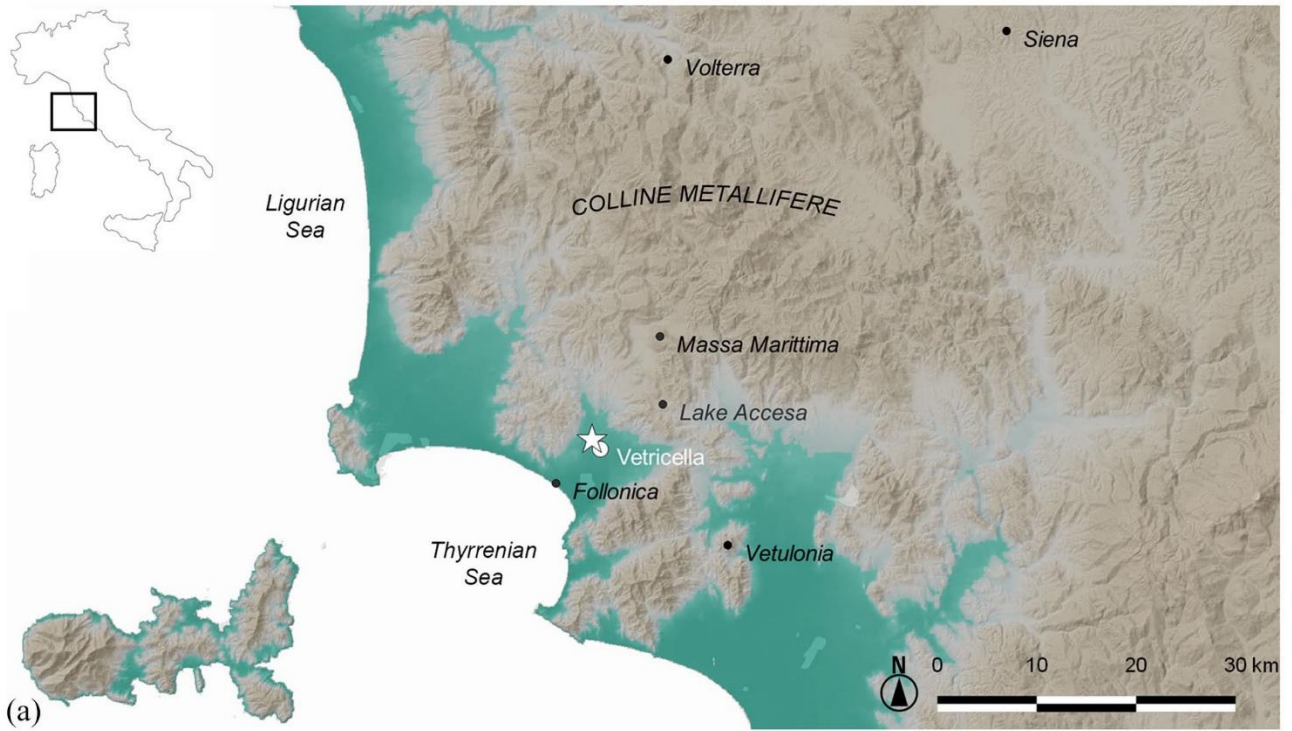
118 The recording of macroscopic charred wood remains contained in the alluvial sediment started  
119 quantitative analysis and taxonomic identification of extracted charcoal pieces, combined with  
120 radiocarbon dating. Sediment charcoal records detect the occurrences of fire events and the  
121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

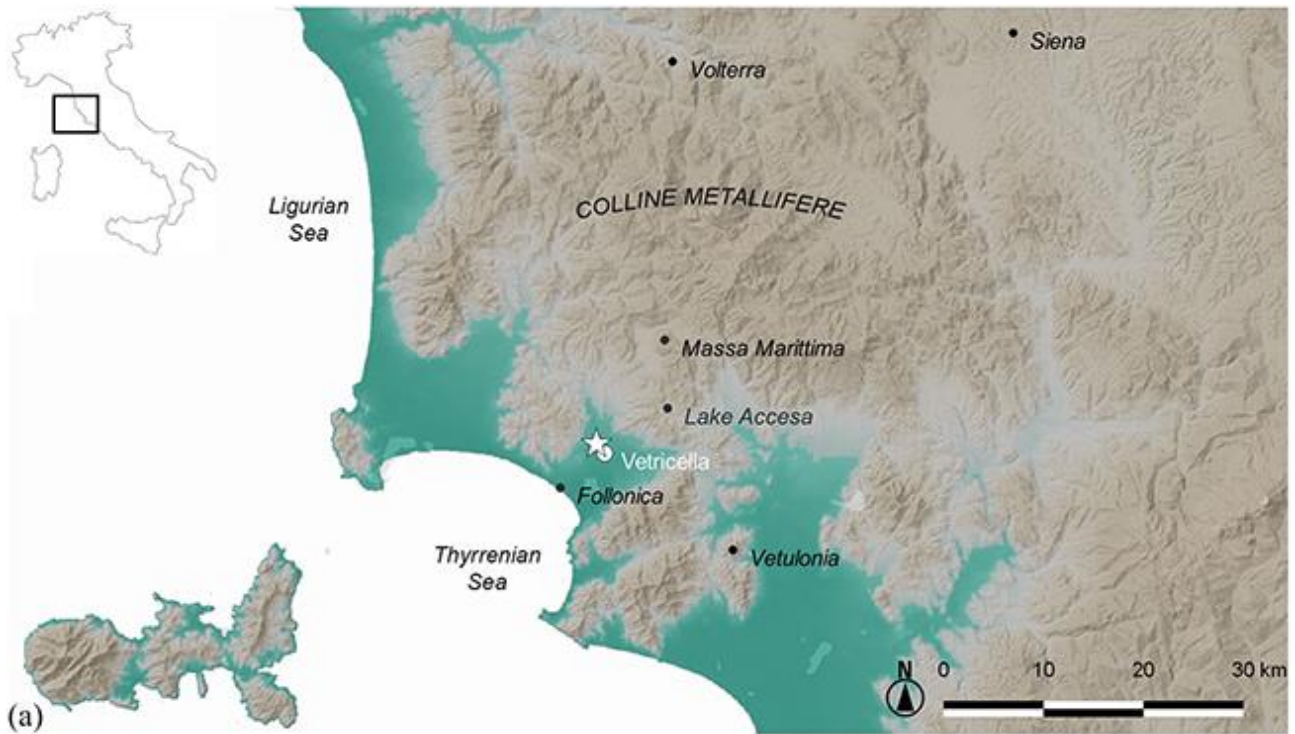
130 Fire is a fundamental ecological stress factor and selective force in Mediterranean ecosystems, as  
131 independent climatic stress or ancient technique for land management, and played a fundamental  
132 role in the present mosaic-like pattern (Barbero et al., 1990; Naveh, 1975; Quézel, 1983). To answer  
133 the question concerning climate and cultural aspects during fire events (Pyne and Goldammer,  
134 1997), the study considers 3) the late-Holocene sedimentary charcoal and pollen records from Lake  
135 Accessa in southern Tuscany, as proxies of changes and variability in fire regimes, past vegetation  
136 and land cover (Drescher-Schneider et al., 2007; Vanni re et al., 2008), and 4) archaeological site  
137 patterns, as proxies for population changes. This ‘biodiverse’ multiproxy approach proved to be  
138 useful at tracing the fire history, detecting climate or anthropogenic causes and evaluating the  
139 effects of fire impact on past forest environments (and the landscape in general). Our research  
140 determines land changes, time phases and driving socio-economic forces that modified the coastal  
141 area of southern Tuscany, marking the progression of a cultural landscape that still characterises  
142 Tyrrhenian central Italy.

### 143 **Study area**

#### 144 *Environmental setting*

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





151

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



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

160 Set between the town of Massa Marittima to the NE and the Gulf of Follonica to the SW, the Pecora  
161 river basin is one of the natural links between the southern slopes of the Colline Metallifere (here  
162 ca. 480 m asl) and the Tyrrhenian coast (Figure 1b). The river is ca. 20 km long and has a catchment  
163 of about 250 km<sup>2</sup>. The basin originated after the definitive emersion of the area occurred at the end  
164 of the Pliocene and the interaction between vertical uplift and climatic changes during the  
165 Quaternary that led to the erosion of valleys and deposition of alluvial and slope deposits interacting  
166 also with karst processes (Benvenuti et al., 2009). The present-day mostly hilly landscape is  
167 characterized by erosional processes along the steep valley slopes and limited deposition along the  
168 valley floors. Staircases of flat alluvial terraces bear witness of depositional processes acting in the  
169 past.

170 Karst processes deeply influenced landscape evolution as indicated by the presence of wide  
171 coalescent karst depressions, karst springs and typical terraced calcareous tufa sediments associated  
172 to cool-water physio-chemical and microbiological carbonate precipitations in fluvial-swampy  
173 environments (Capezzuoli et al., 2014; Ford and Pedley, 1996; Pedley, 2009). Today, the uppermost  
174 part of the basin is artificially drained by means of hanging channels, to bypass karst depressions,  
175 and trench-cut channels, to bypass the main barrage. The karst processes are also at the origin of the  
176 unique historically attested lake in the area. The Lake Accessa (UTM 654508 E, 4761263 N,  
177 WGS84/UTM zone 32N, 157 m a.s.l.) is a small lake located 10 km to the south of the town of  
178 Massa Marittima, beyond the western watershed of the mid Pecora river valley (Figure 1a and b).  
179 Surrounded by hills reaching a height of ca 300 m, the lake covers a surface of ca. 14 ha (39 m max.  
180 water depth) with a catchment area of ca. 5 km<sup>2</sup>.

181 According to the weather station of Follonica (15 m a.s.l., UTM 644053 E, 4754898 N,  
182 WGS84/UTM zone 32N, data source <http://www.sir.toscana.it/>), the area is characterized by a  
183 Mesomediterranean climate, with a minimum average temperature of 3.1°C during the coldest  
184 months and an annual precipitation of 592 mm. Arable crops, vineyards and olive groves are present  
185 in the flat valley floors and/or on the gentler slopes. The Mediterranean evergreen forest, dominated  
186 by *Quercus ilex* L. with *Arbutus unedo* L., abounds on the steeper slopes of the Pecora river basin.  
187 Small stands of thermophilous deciduous broadleaved species, such as *Q. cerris* L., *Q. pubescens*  
188 Willd. and *Fraxinus ornus* L. are scarcely present, whereas the deciduous oak forest, dominated by  
189 *Q. cerris* L., is located only on the cooler north-western slopes of the basin.

190 *Historical land-use: archaeological and palaeoenvironmental data*

191 The rich mineral deposits present in the Colline Metallifere and subsequent mining activities deeply  
192 influenced human activities and settlements since the Eneolithic/Bronze Age (Aranguren and Sozzi,  
193 2005; Corretti and Benvenuti, 2001). With the spread of Etruscan tribes in the 9th and 8th centuries  
194 BC, the coastline became the main metal-working area of central Italy (usually known as Etruria)  
195 with the establishment of towns involved in the trade of artefacts (Acconcia and Milletti, 2009;  
196 Chiarantini et al., 2009). In the 3rd century BC, Roman political expansion started to exercise its  
197 control on Etruria (Harris, 1971) and between the 1st century BC and 1st century AD the region  
198 reached the peak of its settlement and economic development during the Classical Age (Cambi and  
199 Botarelli, 2004; Citter, 1996; Dallai, 2003a; Vaccaro, 2008). Following the collapse of the Roman  
200 Empire at the end of the 5th century AD, few settlements continued to exist in the coastal alluvial  
201 plains, while new sites were founded thanks to the spontaneous relocation of small units of  
202 population on higher ground (Dallai, 2003b).

203 In AD 574, the Lombards conquered Etruria, creating the duchy of Tuscia as part of their kingdom  
204 (Wickham, 1981). After Charlemagne's occupation of the Lombard Kingdom in AD 774, the duchy  
205 was transformed into the Carolingian March of Tuscia from the AD 797. In the 10th century AD  
206 this region (and its natural resources) became a strategic and political cornerstone of the Kingdom  
207 of Italy and the later Ottonian kings of the Holy Roman Empire (Vignodelli, 2012). In time, this led  
208 to direct control by local aristocratic families during the 11th century AD, evident in the  
209 construction of hilltop stone castles, with a clear economic strategy aimed at exploiting metal  
210 bearing deposits (Bianchi, 2015). In the 12th and 13th centuries AD, the autonomy gained by  
211 families and the subsequent development of towns, politically organized as Communes, launched a  
212 new historical phase, determining the definitive success of both castles and towns and crystallizing  
213 the settlement landscape until the modern era (Gaggio, 2017).

214 Anthropogenic pressure obviously played an important and fundamental role in shaping the current  
215 forest cover of the southern Colline Metallifere. According to the high-resolution pollen and  
216 sedimentary charcoal sequences of the Lake Accesa, human presence became significant already ca.  
217 8000 cal. yr BP at the Mesolithic-Neolithic transition (Colombaroli et al., 2008, 2009). Land use  
218 became even more significant and constant in the late-Holocene (ca. 4300 cal. yr BP) at the  
219 beginning of the Bronze Age (Drescher-Schneider et al., 2007). The impact of Etruscan settlement  
220 on forest cover can be dated from ca. 2600 to ca. 2500 cal. yr BP, 750–650 BC (Drescher-Schneider  
221 et al., 2007; Stoddart et al., 2019; Vannièrè et al., 2008). Archaeological research has identified the  
222 fundamental importance of both the Etruscans and (late Republican and early Imperial) Romans  
223 played in the development of rural Etrurian landscapes between the 3rd century BC and 1st century  
224 AD, especially as they favoured olive and vine cultivation (Barbieri, 2010; Carandini, 1994; Manca

225 et al., 2016; Santangeli Valenzani and Volpe, 2012; Zifferero, 2015). Local archaeobotanical data  
226 indicate traces of greater human control over productive landscapes with the occasional presence of  
227 vines and olives (Aversano et al., 2017; Bowes et al., 2015; Langgut et al., 2019; Mariotti Lippi et  
228 al., 2002, 2020) and scholars highlighted the heritage of this agrarian land use in local traditions as  
229 well as its presence in northern Maremma up to few decades ago (Bowes et al., 2015). Recent  
230 comparison between pollen and local archaeo-anthracological data have however suggested  
231 additional phases of forest reduction with intensive agriculture and livestock grazing during the 2nd  
232 and 3rd centuries AD, followed after a hiatus by intensive olive orcharding between the 11th and  
233 13th centuries AD (Di Pasquale et al., 2014). The evidence now shows that the steps to define the  
234 rural landscape of southern Tuscany were more complex than was hypothesized in the past.

## 235 **Materials and methods**

### 236 *Field work*

237 Investigation has been carried out mainly in a retention basin (UTM 647378 E, 4757710 N,  
238 WGS84/UTM zone 32N, 16 m a.s.l.) located on the hydrographic left of the Pecora river, at ca.  
239 500 m to the NW of the archaeological site of Vetricella (Figure 1b and c). The retention basin,  
240 featuring a length of ca. 400 m and width of ca. 100 m perpendicular to the Pecora river flow  
241 direction, allowed for the observation of 4 sections. A palaeochannel, ca. 50 m wide and 3 m deep,  
242 was identified in the NW Section (Figure 1c), characterized by different depositional environments  
243 suggesting changes in the geomorphological conditions and alluvial plain landscape.

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

### 251 *Laboratory treatments*

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

257 Although fluvial depositional environments are a different type of context, laboratory treatments  
258 followed the standard procedure of soil charcoal analysis (Carcaillet and Thinon, 1996; Robin et al.,  
259 2013; Talon, 2010). Sediment samples were firstly air-dried and weighed, and successively wet-  
260 sieved through 0.4, 1, 2 and 5 mm sized mesh. Charcoal concentration and taxonomical  
261 identification were performed for macroscopic charcoal remains >1 mm (Robin et al., 2014).  
262 Charcoal concentration is expressed as specific anthracomass per sampled layer (SAL) in  
263 milligrams of charcoal and per kilogram of dried soil (Talon, 2010).

264 Charcoal remains were divided in three classes of size: 1–2, 2–5, >5 mm. Taxonomical analysis was  
265 conducted up to a maximum of 100 fragments for charcoal remains >2 mm, whereas between 1 mm  
266 and 2 mm a maximum of 20 charcoal pieces per sediment sample were identified. Taxonomical  
267 identification was carried out by an incident light microscope at magnifications of 100×, 200× and  
268 500× and supported with wood anatomy atlases (Abbate Edlmann et al., 1994; Schweingruber,  
269 1990; Vernet et al., 2001) and the reference collection in the Laboratory of Plant and Wood  
270 Anatomy at the Department of Agricultural Sciences of the University of Naples ‘Federico II’.

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

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

### 285 *Radiocarbon dating*

286 AMS radiocarbon dating was performed on nine charcoal remains selected according to location  
287 and taxonomical interest and in relation to the spectrum of identified taxa in each layer. Chemical  
288 pre-treatments for the extraction of the organic part of the samples by way of acid-alkali-acid  
289 (AAA) protocol (Mook and Streurman, 1983) were carried out in the Department of Environmental,

290 Biological and Pharmaceutical Sciences and Technologies of the University of Campania ‘Luigi  
291 Vanvitelli’. Samples were dated by AMS at the INFN-LABEC CHNet in Florence (Fedi et al.,  
292 2007). Radiocarbon dates have been calibrated using OxCal 4.3 (Bronk Ramsey, 2017) and the  
293 Reimer et al. (2013) calibration curve.

#### 294 *Pollen analysis*

295 For pollen analysis five sediment samples were collected and prepared in the pollen laboratory at  
296 the Institute of Plant Sciences of the University of Bern using standard preparation methods (Moore  
297 et al., 1991). This first test run revealed very low pollen concentrations and poor pollen  
298 preservation. In a second run, the samples were prepared again using sediment sample volumes of  
299 2 cm<sup>3</sup> instead of 1 cm<sup>3</sup>. This, together with a slightly adapted pollen preparation method  
300 (hydrofluoric acid in big centrifuge tubes), revealed enough pollen grains for palynological analysis,  
301 although ultimately pollen preservation remained poor. Nevertheless, at least 100 identifiable pollen  
302 grains per sample were counted under a light microscope, which is sufficient for calculation of  
303 pollen percentages and main trends (Heiri and Lotter, 2001).

### 304 **Results**

#### 305 *Sedimentology and facies analysis*

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

#### 309 *U3*

310 The unit fills the bottom of the palaeochannel and is considerable the oldest stratigraphic unit  
311 (Figure 2a). U3 is made of loose planar cross-bedded, poorly sorted, rounded to subrounded fine to  
312 coarse-grained gravels (Gp), variable amount of sandy matrix. Minor planar or low angle cross-  
313 bedded sands (Sp) and lenses and blankets of massive to finely laminated silts and clays (Fm, Fl)  
314 are also present. The composition of the gravels includes also rare clasts of calcareous tufa. The  
315 facies association is typical of a gravel-sand sinuous-meandering river with a westward lateral  
316 accretion of gravel and sand bars.



317

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

324 *U4*

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

335 Although the sedimentary characteristics of U4 are homogeneous, a further subdivision in sub-units  
 336 (SU) has been made according to the presence of minor unconformities related to minor changes of  
 337 the internal architecture. SU4.1, dominated by sands and fine gravels, is observed in the western  
 338 part of the section, covering a shallow and almost flat unconformity (Figure 2a); SU4.2, located

339 towards the east and gravelly dominated, fills a deeper channel cutting SU4.1; both SU4.1 and  
340 SU4.2 are cut by a further shallow and slightly undulated unconformity buried under SU4.3 finer-  
341 grained sediments.

#### 342 *Sediment charcoal analysis*

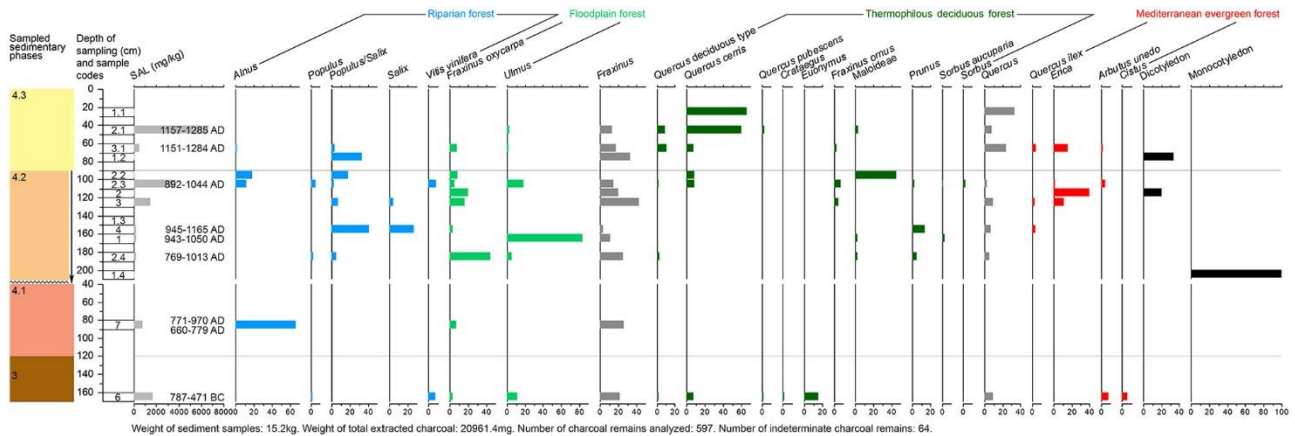
343 Preliminary results from the U4 have already been reported by Pieruccini et al. (2018) and  
344 Buonincontri et al. (2018). In the current study the complete dataset of fifteen sediment samples is  
345 presented (Supplementary Table 1, available online): one sediment sample collected in the upper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

351 Of the total quantity of extracted charcoal, 597 remains were taxonomically analyzed, including 178  
352 pieces from the 1 mm to 2 mm size class, 177 from the 2 mm to 5 mm size class and 242 pieces that  
353 were larger than 5 mm in size (Supplementary Table 1, available online). This allowed to identify  
354 23 different taxa. For 64 charcoal remains (13.7% of the analyzed charcoal pieces from all class  
355 sizes) the identification was not possible due to bad preservation or vitrification.

356 Regarding the identified taxa, the most represented belong to thermophilous deciduous vegetation:  
357 *Fraxinus* (17.4%), with *F. cf. ornus* (2.4%) and *F. cf. oxycarpa* (7.5%), *Quercus cf. cerris* (16.5%),  
358 and *Ulmus* (13.3%) prevail. *Populus/Salix* (4.7%), with *Salix* (2.5%) and *Populus* (1.7%), *Alnus*  
359 (5.3%), *Vitis vinifera* (2.6%), and *Euonymus* (1.5%) are also present. *Crataegus*, *Q. cf. pubescens*,  
360 and *Sorbus*, with *S. cf. aucuparia*, don't exceed 1%. *Erica* (3.6%), *Arbutus unedo* (1.9%), *Q. cf. ilex*  
361 (0.9%) and *Cistus* (0.6%) represent the Mediterranean evergreen vegetation. Unidentifiable  
362 dicotyledons and monocotyledons constitute 0.4% and 0.6% of the total identified charcoal.

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

371 and *Q. cf. cerris*. In contrast, *Q. cf. cerris* dominates two out of the four layers from the SU4.3,  
 372 whereas it co-occurs in one layer with *F. cf. oxycarpa* and *Erica*.



373  
 374 **Figure 3.** Pecora river NW section, sediment charcoal data. From left to right: unit and sub-unit  
 375 sedimentary facies in stratigraphic sequence; sediment samples ordered by depth; value bars of SAL  
 376 (in grey) with indication of AMS radiocarbon dates; percentage bars of identified taxa. The  
 377 identified taxa are grouped and colored on the basis of their ecological significance.

378 *Carpological analysis*

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

383 *Radiocarbon datings*

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

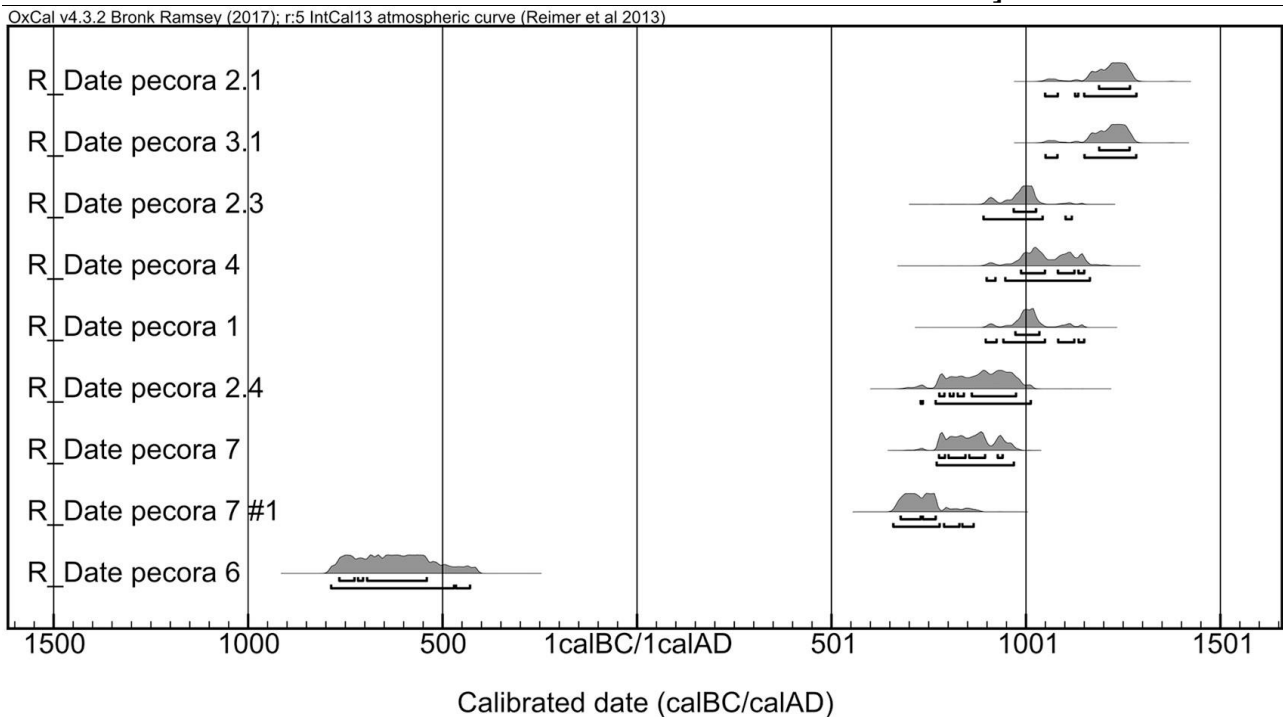
388 **Table 1.**

389 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	<i>Ulmus</i>	Fi3451	808 ± 50	<b>[1185–1268]</b> [1050–1083] [1127–1135] <b>[1151–1285]</b>
	3.1	<i>Alnus</i>	Fi3274	809 ± 49	<b>[1189–1267]</b> [1051–1082] <b>[1151–1284]</b>



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



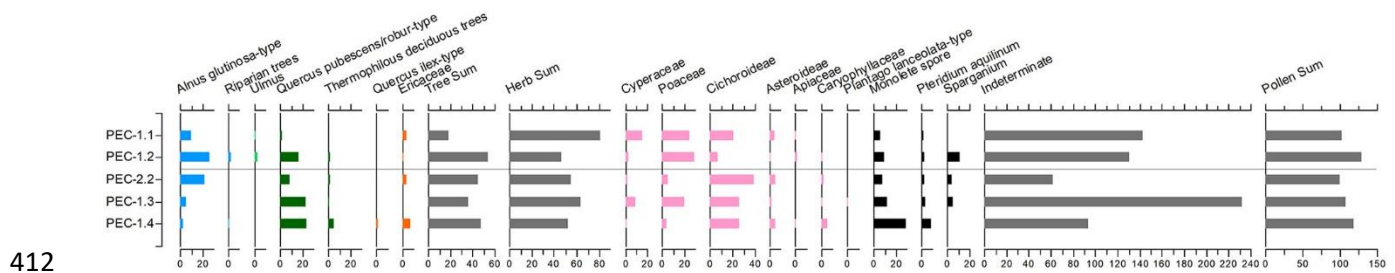
390

391 **Figure 4.** Multiplot graph of calendar ages.

392 The depositional phase recorded in U3 facies association (gravel-sand sinuous-meandering river) is  
 393 dated from the 8th century BC to the mid-5th century BC (Sample Id 6, Fi3497, 2 sigma), although  
 394 the top of the unit is eroded by the subsequent depositional events (see below). The later  
 395 depositional U4 sediments (braided gravel-bed river) gradually took shape between the end of the  
 396 7th century AD and the end of the 13th century AD. In detail, the SU4.1 is dated from the late 7th to  
 397 the second half of the 10th century AD (Sample Id 7, Fi 3554, Fi3171, 2 sigma). The SU4.2 is the  
 398 larger and deeper deposition facies. Samples collected at different depths and considerable distances  
 399 (Figure 2a) show a constant chronological pattern. The facies began in the second half of the 8th  
 400 century AD (Sample Id 2.4, Fi3452, 2 sigma) but was a depositional event mainly from the mid-  
 401 10th to the mid-11th century AD (Sample Id 1, Fi3004, Sample Id 4, Fi3005, Sample Id 2.3,  
 402 Fi3496, 2 sigma). From the SU4.3, the two dated samples collected at the same height but at a  
 403 distance of several metres one from the other (Figure 2a), have an equal time range between the  
 404 mid-12th century AD and last part of the 13th century AD (Sample Id 3.1, Fi3274, Sample Id 2.1,  
 405 Fi3451, 2 sigma).

406 *Pollen analysis*

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



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

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

418 **Discussion**

419 *Taphonomical processes*

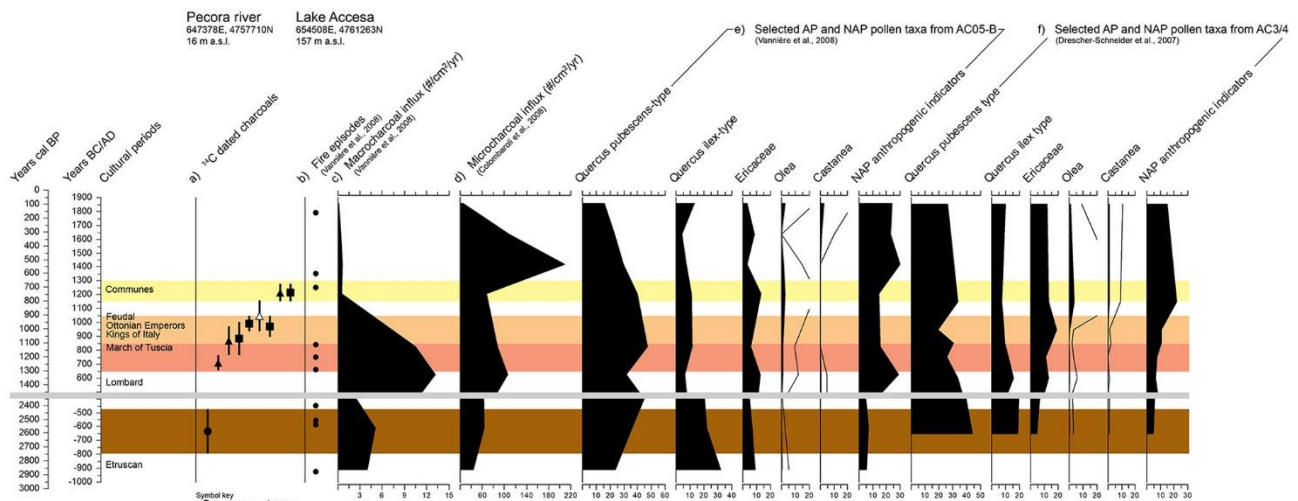
420 The abundance of charcoal within the geological sediments is the result of incomplete combustion  
421 of vegetation fuel (Forbes et al., 2006). The main sources of charcoal were generally generated by  
422 forest fires occurring naturally or man-ignited in relation to anthropogenic activities (Clark,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

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

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

450 The discontinuous chronological depth, focused on two historical periods (800–450 BC, AD 650–  
451 1300), prevents us from reconstructing the fire history of the area and obtaining a detailed sequence  
452 of land cover changes following the impact of fire events. However, previous palaeoenvironmental

453 studies carried out in the nearby Lake Accessa can be compared through sedimentary pollen and  
 454 macro/microcharcoal records providing evidence of the fire regime and vegetation history  
 455 (Colombaroli et al., 2008; Drescher-Schneider et al., 2007; Vanni re et al., 2008). The evidence that  
 456 fires in the Pecora river basin initially occur in a phase of slight regional fire increase (800–450  
 457 BC), subsequently matching local and regional fire events (AD 650–850) that coincide with  
 458 disturbances and changes in plant cover as well as land use (Figure 6), suggests that the episodes  
 459 noted for the Pecora river can be integrated and discussed in a wider regional picture.

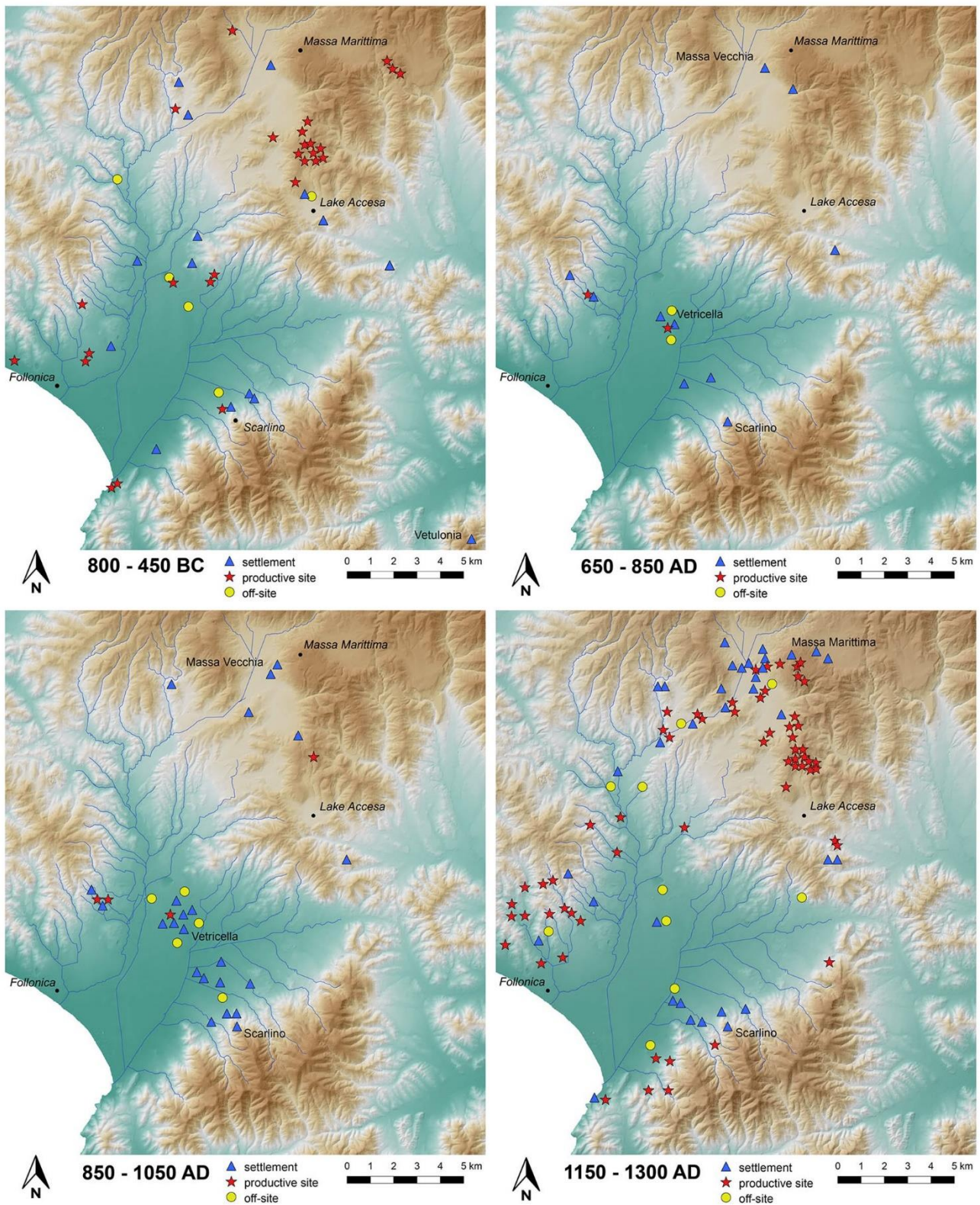


460

461 **Figure 6.** Proxy data from the northern Maremma area positioned in local historical and cultural  
 462 periods. A comparison is proposed between (a) the concentrations of radiocarbon ages (2 sigma) for  
 463 the Pecora river palaeochannel and proxy records from Lake Accessa: (b) local to regional fire  
 464 episodes (Vanni re et al., 2008); (c) sedimentary macroscopic charcoal influx (Vanni re et al.,  
 465 2008); (d) sedimentary microscopic charcoal influx (Colombaroli et al., 2008); (e) from AC05-B  
 466 profundal core (Vanni re et al., 2008) and (f) AC3/4 littoral core (Drescher-Schneider et al., 2007),  
 467 selected arboreal pollen curves (AP), representing local deciduous forest (*Q. pubescens*-type),  
 468 evergreen forest (*Q. ilex*-type and Ericaceae), plantations (*Olea* and *Castanea*), and selected non-  
 469 arboreal pollen curves (NAP) of anthropogenic indicators (sum of *Apium*, *Artemisia*, Cerealia-type,  
 470 Chenopodiaceae, Cichorioideae, *Plantago lanceolata*-type, Poaceae, *Pteridium*, *Rumex*). Coloured  
 471 bars (according to unit and sub-unit sedimentary facies from Figure 2) represent the supposed fire  
 472 use periods in the Pecora river valley. The grey bar marks the time interval missing in the  
 473 stratigraphic sequence of the Pecora river palaeochannel.

474 In addition, the centuries examined in our research were strongly influenced by human activities in  
 475 this regional district. Although the anthropogenic phases with maximum fire activity corresponded  
 476 to a greater sensitivity of the vegetation, triggering significant changes in vegetational communities  
 477 (Vanni re et al., 2008), the available Lake Accessa records lack accurate comments and analysis for

478 the last 2500 years. In fact, an in-depth cause/effect analysis needs to be interfaced with  
479 archaeological proxies that have deduced the anthropic occupation in the study area, the main  
480 activities carried out by human communities along with economic and social dynamics. The district  
481 of the Colline Metallifere has been the focus of archaeological research and systematic surveys  
482 carried out by the Department of Historical Sciences and Cultural Heritage (University of Siena),  
483 the Archaeological Superintendency of Tuscany, and other organizations, for the past 35 years. The  
484 recorded sites have been listed, mapped and discussed in articles (Cucini, 1985; Dallai, 2003b),  
485 unpublished Degrees (Casini, 1992; Dallai, 1993; Pestelli, 1993) and PhD theses (Dallai, 2003c;  
486 Marasco, 2013a; Ponta, 2019). Consequently, the area is a privileged case study for evaluating the  
487 level of anthropic presence and land use (Figure 7). The time frame covered by the sediment  
488 charcoal analysis allows to shed light on the relationship between the human population and the  
489 transformation of the northern Maremma environment.



490

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

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

499 *Men and fire: cultural impact in northern Maremma*

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

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

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

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

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

528 Steingraber, 1983). Vetulonia's catchment comprised the hilly slopes (Figure 7) and engaged in  
529 crop management (Mariotti Lippi et al., 2002), mining and salt production (Aranguren et al., 2007,  
530 2009) rather than exploitation of the alluvial plain. Local archaeobotanical analysis showed that  
531 Etruscan settlements altered the natural state of the pre-existing deciduous *Quercus* forest through  
532 cutting and farming enhancing the xeric features of the vegetation (Mariotti Lippi et al., 2000;  
533 Sadori et al., 2010). The woods supplied the timber to realize buildings and handcrafted items  
534 (Mariotti Lippi et al., 2002). After logging, the use of fire was thus part of the forest opening and  
535 clearing activities, providing Vetulonia with access to the mineral resources as well as agricultural  
536 exploitation of the hills. However, the significant persistence of deciduous woodland (in Pecora  
537 river and Lake Accessa records) would appear to imply a localized presence of cultivated and open  
538 degraded habitats (Figure 6). Despite significant anthropogenic pressure, the impact of fire clearing  
539 was probably contained and restricted to the settled and productive areas.

#### 540 *Swamp reclamation (AD 650–850)*

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

549 US4 sediments contain abundant charcoal remains, concentrated within the troughs and beds.

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

556 The up-valley calcareous tufa environments are typically made of wide flat swampy areas alternated  
557 with barrages or waterfalls (Pieruccini et al., 2018), where calcium bicarbonate-rich waters  
558 precipitate the carbonate by physio-chemical processes such as turbulence (waterfalls and steps) and  
559 micro-biological activity (swamps and ponds) (Capezzuoli et al., 2014). The erosion of these  
560 deposits can be justified only by the drying of the ponds due to important climatic changes or



561 human interference. From 1200 cal. yr BP (mid-8th century AD) the northern Maremma underwent  
562 a period of decreasing moisture, reducing river erosion potential (Magny et al., 2007). The local  
563 climatic signal was not strong enough to generate a rapid fluvial system response. Therefore, only  
564 artificial deep trenches cutting the barrages played the most important role for draining the upper  
565 valley wetland, diverting the natural course of the river and reclaiming the flat calcareous tufa-  
566 deposited terraces (Figure 2c). The subsequent river down-cut led to the transport and deposition of  
567 a large amount of calcareous tufa clasts. Coupled with the onset of the fluvial erosional events from  
568 the end of the 7th century AD, the presence of charcoal remains suggests that the drainage and  
569 reclamation of the wet environments was also associated with clearance of the local waterlogged  
570 and flooded vegetation by way of fire activity.

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

583 In the Pecora river valley, the population was scarce, with only a few scattered sites across the  
584 hilltops and on the alluvial plain, occupied by modest-sized communities (Figure 7). The finding of  
585 charred cereal caryopses in the palaeochannel sediments, identified as *T. monococcum*  
586 (Supplementary Table 2, available online), confirms the presence in the valley, from at least the  
587 end-7th century AD, of a cereal type, highly resistant to pests and diseases. In northern Maremma,  
588 archaeobotanical investigations argued the cultivation of minor cereals in the early Middle Age to  
589 minimize the risks of environmental adversities, in response to the involution of the state  
590 (Buonincontri et al., 2017). Nonetheless, control exercised by the Lombard authorities appears to  
591 have strongly influenced the local economy within the valley (Cucini, 1989; Marasco, 2013b). It is  
592 interesting to note that *T. monococcum* is a cereal considered ‘cultural’ element of Lombard  
593 farming (Buonincontri et al., 2014). The Pecora river from the mid-8th century AD was known as  
594 *Teupascio*, which translates as the ‘King’s water’, a toponym which further emphasizes the role

595 played by public authorities in the management of this valley (Bianchi and Collavini, 2018). In the  
596 9th century AD, administration of this fluvial corridor became part of the March of Tuscia.  
597 Regulation of the river as well as the clearing interventions on the coastal lowlands tends to imply  
598 planning and management by the public Lombard and Carolingian rulers. Drainage, reclamation  
599 and clearing by fire were carried out to control the fluvial hydraulic force and to obtain flat, open  
600 lands upstream. Therefore, while man-induced fires contributed to the significant change of the  
601 fluvial erosional processes, the still marginally developed cultural areas would have prepared the  
602 landscape for the introduction of a primitive fiscal system.

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

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

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

619 Starting from the end of the 7th century AD, the erosional processes continued with greater  
620 emphasis and the palaeochannel deepened. The arrival of sediments coming from the erosion of the  
621 calcareous tufa becomes more rapid and abundant, rated up to 0.7 cm/yr and concentrated in a very  
622 short time span, excluding any climate-related cause. The increasing thickness of the sedimentary  
623 sequence and its deposition indicates that this main depositional phase was associated with the  
624 major land reclamation effort and related environmental changes occurring upstream. Charcoal was  
625 contextual to this phase, therefore the use of fires was again associated with artificial river  
626 regulating measures. Land clearing interventions in this period affected not only the swampy flat

627 terraces but also the flooded low-lying areas as well as the higher lands of the river valley,  
628 encompassing the whole river basin. The presence of new and different habitats represents the  
629 intention of enlarging the anthropic activities across the valley.

630 Interestingly, from the mid-9th century AD (1100 cal. yr BP), the decreasing microscopic and  
631 macroscopic charcoal accumulation rates in the Lake Accessa sediment testify to the use of fire  
632 centred in the Pecora river valley (Figure 6). However, the pollen sequences of Lake Accessa  
633 recorded the progressive or suddenly concurrent collapse of the deciduous *Quercus* forest (until the  
634 modern age) and the rise of xeric shrubland (Figure 6). This is in agreement with other  
635 pollen/sediment charcoal time series showing in northern Tuscany the spread of low Mediterranean  
636 maquis and shrublands following land-use intensification, rather than climate (Colombaroli et al.,  
637 2007). In northern Maremma, local deciduous *Quercus* forest supplied fuelwood and timber  
638 suggesting the exploitation of hilly habitats mostly for harvesting wood (Di Pasquale, 2004; Di  
639 Pasquale et al., 2014; Rossi, 2016). Within the Pecora river valley, the use of fire could be  
640 combined with wood cutting in order to clear logging waste, shrubs, dead and standing biomass  
641 (Gabrielli, 1964; Piussi and Redon, 2001). On the whole, the decline of the hilly Medieval forest  
642 confirms the increasing anthropic interest to exploit woodland and to open areas by harvesting  
643 timber and fire clearing from the mid-9th century AD. This is strongly consistent with the 1 sigma  
644 interval of  $Fi_{3452}$  dating both the fires and the beginning of the deeper depositional events of  
645 calcareous tufa gravels in SU4.2 at least to the second half of the 9th century AD (AD 862–975).

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

655 From the mid-10th century AD to the mid-11th century AD, the continuous consumption of  
656 woodland triggered an increase in erosion and downstream sediments. A consequence of post-  
657 timber-harvesting and fire clearing is the consumption of the forest floor, which led to erosion rates  
658 of greater magnitude, increasing velocities and sediment transport capacity of the overland or rill

659 flow (Borrelli and Schütt, 2014; Scott et al., 2009). The increased amount of sediments in the  
660 palaeochannel from the erosion of calcareous tufa suggests the improvement of the reclamation and  
661 hydrological management upvalley, possibly due to more strict control on the drainage. This led to  
662 the deep incision of the calcareous tufa terraces and barrages and the subsequent transport  
663 downvalley of big amount of sediments. Today, the Pecora thalweg is still deeply entrenched (up to  
664 10 m) within the original surface of the calcareous tufa, down to the bedrock (Pieruccini et al.,  
665 2018).

666 Public interest in the Pecora river valley increased from the 10th century AD. At the same time,  
667 new areas for the storing of resources appeared in rural settlements and higher quality agri-food  
668 resources were collected in the form of crops producing large-kernelled cereals, such as naked  
669 wheat, and new edible fruits, such as chestnuts (Bianchi and Grassi, 2013; Buonincontri et al., 2015,  
670 2017). The discovery of charred glume fragments and cereal caryopses in the palaeochannel  
671 deposits, identified as *H. vulgare* and *T. cf. dicocum* (Supplementary Table 2, available online), are  
672 consistent with the concurrent pollen analyses (Figure 5) showing cultural indicators (i.e. Cerealia-  
673 type, *Plantago lanceolata*-type). These point to human interference and open habitats used for  
674 agricultural practices. Drainage and fires continued in the Pecora river valley in order to reclaim  
675 new open areas and increase food production. The use of fire clearing aimed to fertilize soil both in  
676 new tillage and in coppice forest for temporary crops (the so-called *cetine*; Piuissi and Redon, 2001).  
677 These events created progressively more arable lands that would become the future agricultural  
678 landscape after the mid-10th century AD, as recorded in the pollen sequence AC3/4 of the Lake  
679 Accessa (Figure 6). The simultaneous rise of NAP, *Castanea* and *Olea* (for the first time in two  
680 thousand years) would pinpoint this precise strategy aimed at the improvement and cultivation of  
681 new agri-food resources (Buonincontri et al., 2015; Di Pasquale et al., 2014).

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

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

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

691 *cerris* and *Fraxinus* with *F. cf. ornus*) with scant Mediterranean evergreen plants (*Erica* and *Q. cf.*  
692 *ilex*). Riverbanks (*Salix* and *Populus*) and lowlands (*Fraxinus* with *F. cf. oxycarpa*) were the second  
693 areas affected by the fires (Figure 3). The presence of deciduous *Quercus* woodland and riparian  
694 vegetation is confirmed by the contextual pollen analysis (Figure 5). However, the highest  
695 percentage record of herbs and cultural indicators suggest the remarkable presence of an open  
696 landscape with fields. Two radiocarbon dates set the deposition and fire phase between the mid-  
697 12th and end of the 13th century AD (Fi3451 and Fi3274, 2 sigma) (Table 1). These were the  
698 responses of the fluvial system to the changes started in the mid-7th century AD in the upper  
699 catchment which lasted for ca 650 years.

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

711 From the end of the 10th century AD, a gradual transition from the public fiscal authorities to more  
712 localized control took place, stimulated the socioeconomic development of castles and encouraging  
713 the leading role of towns such as Massa Marittima (Bianchi, 2015; Dallai et al., 2005). From the  
714 mid-12th century AD, the valley was subjected to a strong recorded anthropic presence (Figure 7).  
715 New fortified hilltop settlements and castles absorbed gradually the previously smaller sites  
716 scattered across the plains. Production sites proliferated exploiting natural resources (Cortese, 2008;  
717 Cucini Tizzoni and Tizzoni, 1992). The role played by Massa Marittima in the inland increased  
718 both politically and economically, going through a period of development and architectural growth  
719 (Dallai, 2014). Affecting deciduous forest on well-drained and hilly areas, the presence of fires  
720 appears to be strongly linked to demographic increase and control within the district of the Colline  
721 Metallifere. Decreases in sedimentary and associated environmental dynamics in the palaeochannel  
722 of the Pecora river are consistent with limited interventions in the lowlands, suggesting the presence  
723 of a more stable landscape, less susceptible to erosion. The agrarian revolution, previously

724 established and affirmed, persisted under local feudal control, whereas the new impact of  
725 settlements, mining and metallurgical activities spread across the hilltops. The new settlements and  
726 growing production sites reclaimed more lands and exploited the woods for harvesting fuel and  
727 timber. Therefore, the use of fire was consequent to the practices of removing undergrowth, stumps  
728 and waste biomass after clearcutting or coppicing (Redon, 1987).

## 729 **Conclusion**

730 The use of fire is the most ancient anthropogenic technique for the management of vegetation,  
731 playing a fundamental role in present Mediterranean cultural landscapes, both in term of vegetation  
732 structure and composition (Colombaroli et al., 2008; Colombaroli and Tinner, 2013; Connor et al.,  
733 2019). The interaction between the socio-cultural aspects involved in fire management decisions  
734 and the natural environment determined the underlying dynamic processes of Mediterranean  
735 ecosystems.

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

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

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

753 3) The Pecora river fire sequences had purely anthropogenic origins. The use of fires was linked to  
754 forest opening and reduction by local communities. Introduced by the Etruscans, fire events dated to  
755 800–450 BC ensured agricultural exploitation on the hilly slopes. From AD 650, fire contributed to  
756 the Medieval upstream reclamation and vegetation clearing of flat swamplands. From AD 850 to  
757 1050, the use of fire spread over a wider area in the valley, increasing potentially arable lands.  
758 Between AD 1150 and 1300, fires belonged to a regional forest clearance phase.

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

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

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

778 Historically, the role of Etruscans and Romans has often been discussed in promoting the  
779 development of rural landscapes with olive and vine cultivation in central Tyrrhenian Italy,  
780 highlighting the heritage of this agrarian land-use in local traditions and its presence, up until a few  
781 decades ago (Bowes et al., 2015; Mercuri et al., 2013). However, our research in the Colline  
782 Metallifere indicates that the historical relevance of the Etruscans should be downscaled. Events  
783 that can be attributed to the Roman period are not recorded. The open-habitat landscape (with crops  
784 and orchards) began in AD 850 through public intervention and spread from the mid-10th century

785 in a well-defined policy aimed at creating key strategic and economic sites. Such a pattern appears  
786 to reflect local as much as regional land cover changes (Colombaroli et al., 2007). In the northern  
787 Latium Anti-Apennines and the Rieti basin (respectively, 87 and 350 km to the south-east), a more  
788 permanent forest reduction and cultivation occurred only during Medieval and post-Medieval times  
789 (Mensing et al., 2018; Sadori, 2018), with the latter area pointing to late-Carolingian sociopolitical  
790 transformations between AD 850 and 900 (Schoolman et al., 2018). However, by focusing on a  
791 micro-regional case study, our research has permitted us to verify and investigate causal  
792 relationships, avoiding oversimplifications by means of a valuable proxy (sediment charcoal data)  
793 that reconstruct the history of fire events both in terms of a detailed space-time definition, and  
794 provides a better integration of local human history. Medieval fire clearing activities in northern  
795 Maremma, we conclude, represented a considerable impulse for new land usage, determining the  
796 definitive success of local cultural landscape strategies until the modern era.

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