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Human-induced fires and land use driven changes in tree biodiversity on the northern Tyrrhenian coast

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ABSTRACT

The history of fires in southwestern Tuscany (Italy), from the Colline Metallifere to the coast of northern Maremma, is presented with an observational perspective at local and regional scale. The area was studied as part of the nEU-Med project, which investigates resources management, agricultural practices and political strategies in two coastal plains, the Cornia and Pecora valleys, between the 7th and 12th centuries AD. Four cores, selected for palaeoenvironmental studies, were analysed for microcharcoals (C3 and C7 - Cornia Valley, ~last 7500 years; P3 and P4 - Pecora Valley, ~last 3200 years). Microscopic charcoal particles are ubiquitous and particularly high in the most recent pollen zone of the diagrams: most records belong to the 10–50 μm size class (>90%), followed by the 50–125 μm size class (<7%) and the rest are records of size >125 μm. The last size class includes large microcharcoals indicating local fires. Several *potential fire activity increases* (PFAIs) are visible as peaks in the diagrams. In the Cornia Valley, ancient phases of local fires were recorded at ~5600 BC; not strictly local fires were scattered in the valley at ~4600 BC, ~3500 BC, and until ~400-1450 AD, when the peaks testify to the spread of fires with increasing human activity. In the Pecora Valley, scattered local fires are observed at ~900 BC, between ~300 BC and ~50 BC, and in the later phases from ~400 AD to ~1050 AD. Therefore, the increase in fires is visible in the last millennium in both valleys. Fire was probably used to open the landscape, as fluctuations of pollen curves of mixed oakwood (mainly deciduous *Quercus*) and *Erica* suggest. The extensive presence of shrubby heather vegetation testifies to the occurrence of repeated fires. In the Cornia Valley, besides oaks, the main fuel source were *Corylus avellana* and *Ostrya carpinifolia/Carpinus orientalis*. In the Pecora Valley, cores show a synchronous increase in AP and NAP pyrophytes until ~400-500 AD, followed by a decrease in AP pyrophytes. Considering forest dynamics, a too short return time for fires affects the biodiversity of woody plants, as woods could not fully recover and several tree species may not have reach sexual maturity, resulting in less sprouting and recolonization. In these valleys, the recovery of large-sized microcharcoals, the presence of heather shrub vegetation, and the trend of AP/NAP pyrophytes suggest that fires have increased significantly in the last ~1200 years (~800-1400 AD).

1. Introduction

The Mediterranean landscape is the product of both climatic events and human action, and a variety of approaches, including both social and natural sciences, have been used to understand what forces modelled its traits over a long term of environmental transformations (Holmgren et al., 2016; Mercuri, 2014; Mercuri et al., 2011; Rick et al., 2020). One of the main forces influencing landscapes is fire, since it affects plant biodiversity and vegetation cover and can have anthropogenic and climatic triggers. It has been observed that fires vary in magnitude and speed depending on the subsistence of populations (Vannière et al., 2008). Fire induced socio-environmental changes when its regime intensified as a tool (and effect) of land use and forest clearance.

In vegetation history, local data are particularly useful for modeling a heterogeneous Mediterranean landscape such as Italy (Conedera et al., 2018; Millington et al., 2009). Reconstructing the history of fire in a given region helps shed light on the natural-fire component and on anthropogenic fires that lead to changes in vegetation. Although initially used for small-scale investigation, it later became common for larger

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environmental reconstructions (see Buonincontri et al., 2020 and references therein).

The most common approach to understanding fire history is the combined study of microcharcoals and pollen from sedimentary cores, which should also include data on flammability and other land cover variables. In addition, it is important to combine palaeoecological data to assess human impact on past vegetation and thus its effects on current vegetation (Marignani et al., 2017; Mercuri et al., 2015; Rull, 2010). For this reason, several studies include microcharcoals in the palaeoenviromental reconstruction for the Mediterranean basin (central: Colombaroli et al., 2008; Kaltenrieder et al., 2010; Sadori et al., 2015; western: Carracedo et al., 2018; Reddad et al., 2013; eastern: Masi et al., 2013; Turner et al., 2008). Charcoals, like pollen, can be used as proxies in palaeoecological reconstructions because of their resistance to decomposition, which allows them to be preserved in sediments and soils (Robinson et al., 1997; Scott et al., 2000; Talon et al., 1998).

Charcoals, usually classified by size classes (e.g., Marquer, 2010) – from macro (>500 μm) and meso (500–160 μm) to micro (<160 μm) – can be found in both sediments and archaeological layers (macrocharcoals: Carracedo et al., 2018; Fiorentino and Magri, 2008; Mercuri et al., 2019; meso- and microcharcoals: Cui et al., 2009; Damnati and Reddad, 2017; Peresani et al., 2018; Sadori, 2018). Macrocharcoals are usually visible during archaeological excavations or in sedimentary records, but they represent only a minor part of the anthracological materials produced by human or natural fires (Marquer, 2010). They allow taxonomical identification, giving information on local flora, and can be directly radiocarbon dated (Bal et al., 2023; Buonincontri et al., this issue). Microcharcoals are particularly interesting because their size can affect the transport distance from the combustion site in any sedimentary basin (Jones et al., 1997; Sadori et al., 2015; Verardo, 1997), with large-sized microcharcoals being transported far less than small particles in terrestrial and marine cores (Genet et al., 2021).

The main objective of this paper is to study microcharcoals for the reconstruction of the history of fires and how they have contributed to shape the landscape on a local and regional scale in the area between the Colline Metallifere (Metalliferous Hills) and the coast of northern Maremma region, Italy. This is the southwestern Tuscany area studied within the nEU-Med project (Bianchi and Hodges, 2018), which investigates the resources, agriculture, and political strategies that developed in two coastal plains, the Cornia and Pecora valleys, between the 7th-12th centuries AD. The centres of many economic and productive activities were represented by the site of Vetricella (Scarlino, Grosseto) located in the middle of the Pecora Valley, and Carlappiano (Pimobino, Livorno) located near the coast in the Cornia Valley. The area has been the subject of archaeological research for several decades (Bianchi and Hodges, 2020; Marasco, 2009). The region has always been influenced by human presence since the Bronze Age (Stoddart et al., 2019) and during the Roman Age (Bowes, 2020). The main economic vocations of the territory were iron and salt (Bianchi and Hodges, 2020; Dallai, 2018). These were made possible by the presence of an area associated with metallurgical activities in the hinterland of the Colline Metallifere and by the optimal conditions for evaporative salt-works on the coast of the Gulf of Follonica. The history of fires in the region can contribute to the reconstruction of environmental dynamics and economic scenario of the study area. Microcharcoals and pollen of pyrophytes from cores collected in the Cornia Valley and in the Pecora Valley were specifically investigated as part of the nEU-Med project (Clò et al., 2023). These new data will help corroborate knowledge on the use of fire and its effect on vegetation on a long-term perspective, with particular attention to the study period underlying the project (7th-12th centuries AD).

2. Regional settings: the flora and the fire

The study area is in the southern part of Tuscany called northern "Maremma". It includes the Cornia and Pecora valleys, which occupy the territory between the Colline Metallifere and the Tyrrhenian Sea, near the municipalities of Piombino and Follonica.

According to Blasi and Biondi (2017), the hill slopes are mostly covered by woods of *Quercus cerris* L., *Q. petraea* (Matt.) Liebl., *Q. robur* L., *Castanea sativa* Mill., and *Ilex aquifolium* L., with sometimes the presence of *Fagus sylvatica* L. Another type of mixed oakwood in the region includes *Q. cerris* L. with *Carpinus betulus* L., *Acer campestre* L., *Prunus avium* (L.) L., and *Q. petraea* (Matt.) Liebl. At lower altitudes, where climate conditions become more Mediterranean, *Q. cerris* L., *Q. pubescens* Willd., and *Q. ilex* L. become dominant together with *Erica arborea* L., *Arbutus unedo* L., *Phillyrea latifolia* L., and *Viburnum tinus* L.

Data from the weather station of Follonica describe a meso-Mediterranean climate, with average annual temperature of 16.3 °C and annual precipitation of 420 mm in 2022, referring to an increase in temperatures and decrease in precipitation compared to 2020 (15.8 °C and 573 mm respectively). The climatic conditions are such that, on the one hand, vegetation characterised by species particularly sensitive to flammability can develop and, on the other hand, biomass can be produce in the summer months with low humidity and high temperatures (Blasi et al., 2004; Keeley et al., 2011).

Tuscany is considered one of the Italian regions where fire problems are most significant. The summer of 2021 ended with a trend consistent with the number of events recorded in the last 5 years: 91 forest fires that covered a total area of approximately 174.68 ha (July 2016–2021 month averages; Regione Toscana, 2021). July 2017 saw the worst situation with about 200 events and nearly 900 ha involved (Regione Toscana, 2021). In forest formations, where fires have been and still are recurrent events, fire exerts a selective pressure that determines adaptive features at the level of individuals, populations, and communities (Corona et al., 2004). On this basis, Bertacchi and Borgia (2020) explain the presence of three distinct post-fire vegetation types in northwest Tuscany: pinewood, Ericaceae scrub, and cork scrub. The spread of active pyrophytes

Table 1
Main pyrophytes in the study area and their adaptations to fire and post-fire response mechanisms. Fire ecology and post-fire restoration approaches according to Bertacchi and Borgia (2020), Blasi and Biondi (2017), and Mazzoleni and Esposito (2004a).

Species	Fire adaptations
Arbutus unedo L.	Vegetable sprout at the collar
Cistus incanus L.	High seed dissemination
	Fire promotes germinaton by splitting of tegumetes that increases water absorption
Cistus monspeliensis L.	High seed dissemination
	Fire promotes germinaton by splitting of tegumetes that increases water absorption
Calluna vulgaris (L.) Hull.	Develops in thin soils and areas highly impacted by fire events
Erica arborea L.	Vegetable sprout at the collar
Myrtus communis L.	Vegetative regrowth
Phillyrea angustifolia L.	Vegetative regrowth
Pinus pinaster Aiton	Seed germination
	Seedling emergence
Quercus suber L.	Fire resistance
	Vegetative regrowth

species with vegetative regeneration (e.g., *Arbutus unedo*, *Erica arborea*, *Myrtus communis*, and *Phillyrea angustifolia*) together with other species with passive adaptations (e.g., *Quercus suber* and *Pinus pinaster*) is favoured in case of repeated fires (Bertacchi and Borgia, 2020, Table 1). Massive fire-induced germination is observed in several woody species belonging to the genus *Cistus* (e.g., *C. incanus* and *C. monspeliensis*) and is also common to many herbaceous species, among which *Calluna vulgaris* is dominant (Blasi and Biondi, 2017; Mazzoleni and Esposito, 2004a, Table 1).

3. Materials and methods

3.1. Selected cores and chronology

After the coring campaign performed by the GAMMA GeoServizi company in the Cornia and Pecora valleys with the collection of twelve sediment cores, four cores were selected for palaeoenvironmental analyses (Fig. 1): C3 and C7 (Cornia 3 and Cornia 7), and P3 and P4 (Pecora 3 and Pecora 4). The same cores were analysed for palynological (Clò et al., 2023), geomorphological, sedimentary, and geochemical analyses (see Volpi et al., this issue). Core chronology was calculated using sedimentary rate, ^{14}C dates, and stratigraphic correlations. A total of 17 AMS 14C ages were measured on organic sediments and woody-charred macroremains collected along the stratigraphic sequence of the cores (four dating for C3, six for C7, three for P3 and four for P4; Volpi et al., this issue). The AMS radiocarbon dates, measured at the Beta Analytic Laboratory (Miami, Florida-USA) in 2018, were calibrated using BetaCal 3.21 with IntCal13+NHZ2 calibration curve and database (Bronk Ramsey, 2009; Hua et al., 2013; Reimer et al., 2013).

The interpolation of dates and depths to create the calibrated age-depth models is based on correlations presented and discussed in Volpi et al. (this issue). Deposition occurred in a stable environment with few hiatus events or changes in accumulation rate. Deposition times were calculated by linear interpolation age-depth models using the 'classic' age-depth modelling software Clam (Blaauw, 2010; statistical software package R) and the IntCal20 calibration curve (Reimer et al., 2020). Age-depth models are showed in Fig. 2 with outlying dates plotted in red.

3.2. Pollen samples, treatment, and analysis

The 76 samples selected for microcharcoal analysis are the same ones selected for the pollen counts thus assuring the correct comparison between forest cover and fire. Microcharcoals analysis was carried on slides already prepared for palynological analyses. The extraction process used is the standard one adopted by the Laboratory of Palynology and Palaeobotany of the University of Modena and Reggio Emilia (Florenzano et al., 2012; van der Kaars et al., 2001; also described in Clò et al., 2023). The *Lycopodium* spores added during the preparation allowed the calculation of the CHAC (concentration expressed as number of microcharcoals • cm^{-3} = $\#/cm^3$) and CHAR (= CHAC values corrected using the sedimentation rate; number of microcharcoals • cm^{-2} $years^{-1}$ = $\#/cm^2/y$). While CHAC and CHAR are both presented in the results section, in the discussion we report only on CHAR since it's more significant for reconstructing the fire history. Microcharcoal particles were observed at 400× magnification. They were divided in three size classes, based on the maximum axis (small-sized microcharcoals: 10–50 μm; medium-sized microcharcoals: 50–125 μm; large-sized microcharcoals: >125 μm), chosen in order to disentangle evidence for regional or local fires. Microcharcoals <10 μm were not considered due to the possible fragmentation that occurs during the extraction procedure (Carcaillet et al., 2001). In general, taphonomic and sedimentary processes can also cause microcharcoal particles fragmentation. However, no fragmentation was observed during standard pollen procedures after quantitative comparisons between thin-section and pollen-slide charcoal series of the same core, while very large particles (>0.2 mm) are eliminated by the pollen-slide method (Tinner and Hu, 2003).

For each sample, four selected lines were read on a slide. Tilia software (Grimm, 2004) was used for data elaboration and diagrams combined with pollen curves selected to discuss the presence of fires: in fact, Arboreal Pollen and herbaceous pyrophytes are useful to reconstruct main flora and vegetation changes following the local/regional fire history.

To study the relationship between woody vegetation and fire in this specific context, a different study than the paleoenvironmental reconstruction already performed (Clò et al., 2023), the percentages of woody pollen taxa were calculated on the arboreal pollen sum (the AP sum includes only trees, shrubs, and lianas). Selected sums consisting of

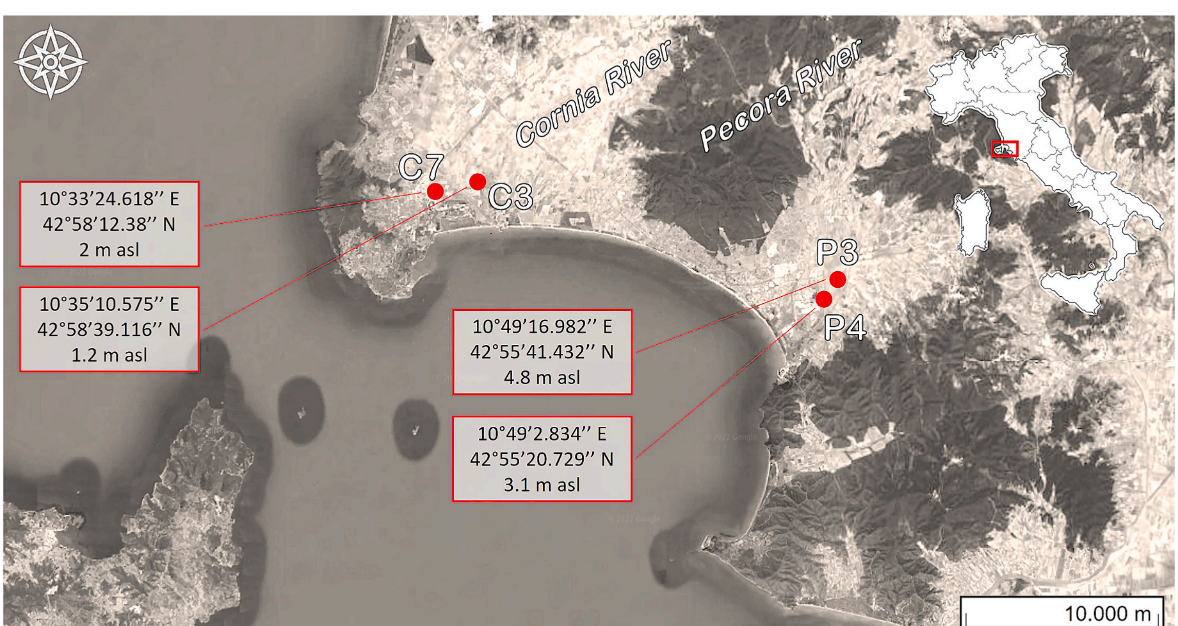

Fig. 1. Location of the cores analysed for microcharcoals (C3: Cornia 3; C7: Cornia 7; P3: Pecora 3; P4: Pecora 4) on GoogleEarth™.

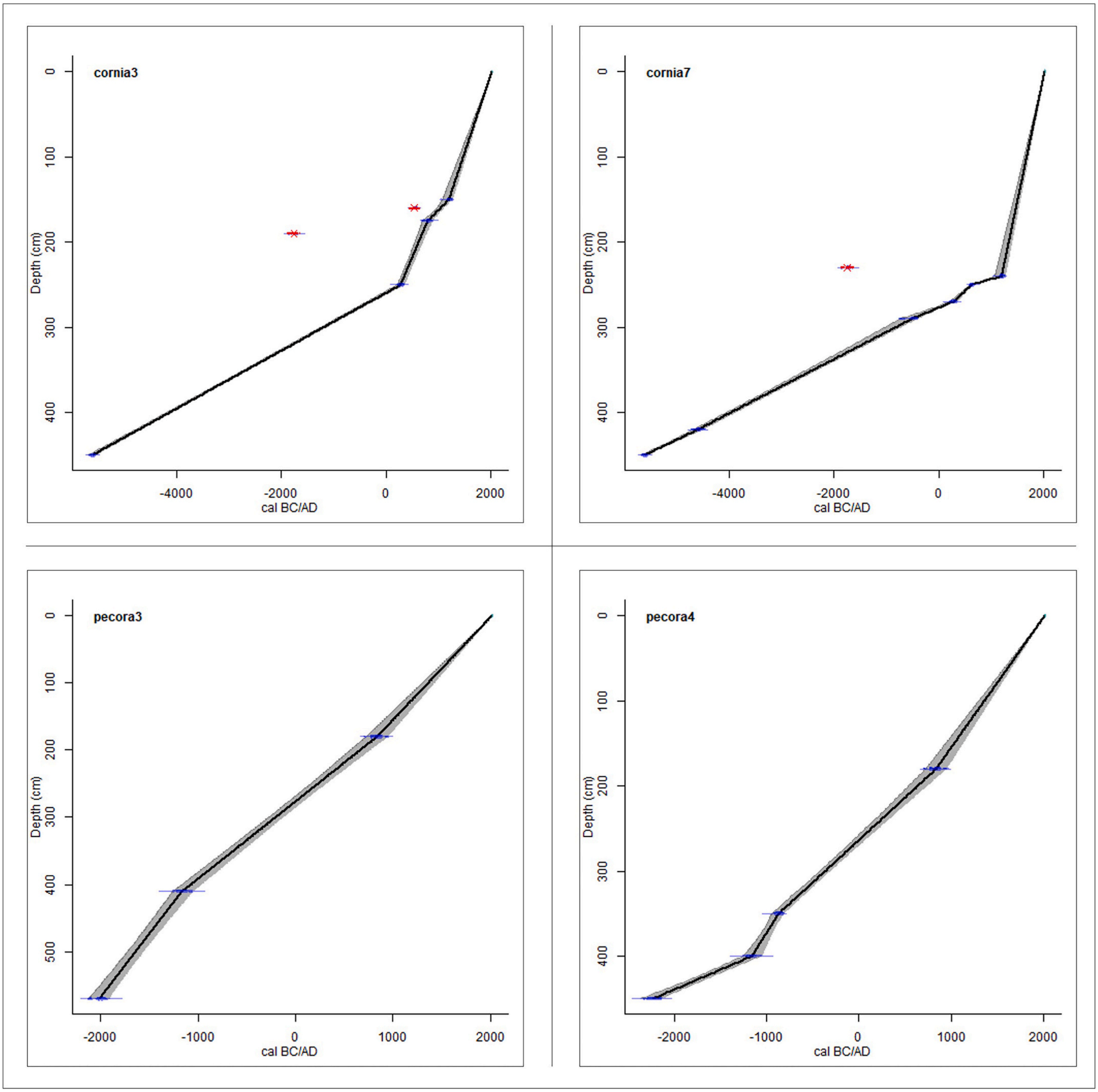

Fig. 2. Age-depth models for Cornia 3 and Cornia 7 (top) and Pecora 3 and Pecora 4 (bottom). The 95% confidence intervals are shown as gray shading. The calibrated radiocarbon distributions used to develop the models (in black) are shown in blue, and outlying dates are plotted in red.

woody pollen taxa were considered for the interpretation: i) woody pyrophytes (*Rhamnus*, *Myrtus*, deciduous *Quercus*, *Quercus ilex*, *Cytisus*, *Erica*), ii) mixed oakwood (*Acer campestre* type, *Carpinus betulus*, *Corylus*, *Fraxinus excelsior* type, deciduous *Quercus*, *Fraxinus excelsior* type, *Ostrya carpinifolia/Carpinus orientalis*, *Ulmus*, *Tilia*), and iii) hygrophilous trees (*Alnus*, *Populus*, *Salix*). Pollen sums of herbaceous plants were calculated on the total pollen sum (see Clò et al., 2023): iv) herbaceous pyrophytes (*Mentha* type, Cichorieae, Rosaceae, *Plantago lanceolata* type, *Plantago* undiff., Poaceae, Caryophyllaceae, *Asparagus*, *Lotus*, *Trifolium*, *Medicago*). The botanical terminology follows the APG IV (The Angiosperm Phylogeny Group, 2016) and The Plant List Version 1.1 (The Plant List, 2013). The names of *Corylus*, *Myrtus*, and *Olea* refer respectively to the species *Corylus avellana*, *Myrtus communis*, and *Olea europaea*. Pollen zones were labelled as in the pollen diagrams: C3-1 to 4, and C7-1 to 4; P3-2 to 4, and P4-2 to 4. They were established based on pollen data and on CONISS, visual examination and correlation among cores, and zones with low number of samples have been identified thanks to the correlation with the other core of the same valley (Clò et al., 2023).

4. Results

Microscopical charcoal particles are ubiquitous in the samples and especially high in the most recent pollen zone of the diagrams (mainly in C3-4 and C7-4). The total values of T CHAC (microcharcoal concentration) and T CHAR (microcharcoal accumulation rate) in each core are shown in Table 2 The trend for both CHAC and CHAR is similar, except for the lower half of the C7 core that has a very low sedimentation rate (from 440 to 280 cm: 0.3 cm yr–1, and at 245 cm: 0.16 cm yr–1). In general, according to Volpi et al. (this issue), the cores from the Cornia Valley show quite variable sedimentation rates ranging from 0.08 cm yr to 1 in C3 to 8 cm yr–1 in C7. The estimated sedimentation rate is almost steady (1 cm yr–1 on average) in the Pecora Valley. Several *potential fire activity increases* (PFAIs) are visible as peaks of microscopical charcoals in the diagrams.

4.1. Size classes

Most microscopical charcoals belong to the 10–50 μm size class, while less records belong to the 50–125 μm size class. An amount <0.5% of microcharcoals belonging to the size class >125 μm was observed in each core (C3: 0.3%, C7: 0.1%, P3: 0.2%, P4: 0.2%): we cannot exclude that these data are underestimated because some large-sized microcharcoals may have occasionally been fragmented during chemical extraction. Nevertheless, the large records are highly valuable indicators of local fire presence without precise quantitative evaluations.

4.2. Trend of microcharcoal particles in pollen zones

Microcharcoal particles are present in all zones, described below from the bottom of the cores (C3 and C7 from the Cornia Valley, P3 and P4 from the Pecora Valley).

4.2.1. Cornia Valley (Figs. 3 and 4; Table 3 and 4)

Four zones were found in C3 and C7. The CHAR values of all size classes are higher in C3 than in C7, and in both cores the values increase in the most recent levels (Zone 4).

4.2.1.1. Zone 1. **C3-1 and C7-1 (C3: samples 22–20, 450–410 cm; C7: samples 19–18, 440–410 cm) –** In C3-1, large-sized microcharcoals show a peak at ~5600 BC and fall at ~4700 BC. They are less abundant in C7 and, with an inverse trend, have a minor increase at ~4650 BC that suggest local fires. The 50–125 μm size class has a high CHAR throughout the zone in both cores. *Pinus*, *Carpinus betulus*, *Ostrya carpinifolia/Carpinus orientalis*, *Abies*, and *Fagus* (only present in C7-1) maintain stable values or tend to increase, while *Quercus ilex* has its highest values in the spectra.

In C3, the mixed oakwood decreases due to the reduction of deciduous *Quercus*, *Corylus*, and *Fraxinus excelsior* type. The same type of vegetation tends to increase in C7, largely driven by deciduous *Quercus*, while local fires seem to have affected mainly hygrophilous wood and riparian vegetation. In fact, the fall of *Alnus*, *Salix*, and *Ulmus* coincides with the peak in large-sized microcharcoals. Fires probably also affected the shrub component (e.g., *Corylus*). The trend of *Erica* seems less affected by local fires in C3, while it decreases with the increase in microcharcoals at the end of this zone in C7. Herbaceous pyrophytes (NAP pyrophytes) increase immediately after the decline in (mainly local) fires in C3 at ~4700 BC.

4.2.1.2. Zone 2. **C3-2 and C7-2 (C3: samples 19–14, 409–290 cm; C7: samples 17–10, 409–295 cm) –** This zone is divided into two subzones (2a, 2b).

In C3-2a there is a small peak in >125 μm microcharcoals that marks the presence of local fires at ~3500 BC, coinciding with a decrease in deciduous *Quercus*, *Erica*, *Ostrya carpinifolia/Carpinus orientalis*, and *Quercus ilex*. However, the recovery of both mixed oakwood and arboreal pyrophytes (AP pyrophytes) is rather rapid in C3-2a. Considering the whole zone, in C3-2, >125 μm microcharcoals are scattered, while the other two size classes show significant values. Small and medium-sized microcharcoal particles begin to decrease at ~1800 BC, then >125 μm microcharcoals increase with stable values until the end of C3-2b. *Pinus* spreads widely in C3-2b, together with *Erica* and *Quercus ilex*. *Quercus* deciduous decreases with increasing local fires at ~1200 BC.

This is slightly different in C7-2a where the CHAR of all size classes of microcharcoal particles is low and a significant drop in the 50–125 μm size class is observed. *Abies alba* starts to decrease at ~4000 BC, and *Olea* is present with low overall microcharcoal values. In this subzone, the spread of *Erica* from ~3350 BC matches with the decrease in deciduous *Quercus*; then the recovery of deciduous *Quercus* in C7-2b has abrupt oscillations, alternated with *Erica*, *Quercus ilex*, and other pyrophytes. The small-sized microcharcoal particles increase in C7-2b, and the medium-sized ones increase at ~2100 BC and remain constant until ~1750 BC. The low presence of >125 μm microcharcoals and high percentages of trees and shrubs suggest low impact of local fires in C7-2b.

4.2.1.3. Zone 3. **C3-3 and C7-3 (C3: samples 13–11, 289–230 cm; C7: samples 9–8, 294–263 cm) –** Low values of all microcharcoals size classes are recorded. In C3-3, a relatively high *Buxus* precedes the large-sized microcharcoal peak (~400 AD) that corresponds to a slight decrease in hygrophilous trees (mainly *Alnus*) and a simultaneous increase in mixed oakwood and AP pyrophytes. *Erica* is steady. In C7-3, a slight peak of all size classes of microcharcoal particles at ~500 BC corresponds to a general fall of shrubs (*Corylus* and *Myrtus*) and *Abies*. *Erica* shows an increasing trend throughout the zone, while *Quercus ilex* begins to rapidly decline. This suggests local and regional fire events during a period of wood clearing, which favoured a rapid diversification of shrub biodiversity, with the simultaneous presence of *Corylus*, *Sambucus nigra*, *Cytisus*, *Myrtus*, and *Juniperus* type at the end of C7-3 (after ~500 BC). *Olea* and *Vitis* are present in the same levels.

4.2.1.4. Zone 4. **C3-4 and C7-4 (C3: samples 10–1, 229–100 cm; C7: samples 7–1, 262–190 cm) –** This zone is divided into two subzones (4a, 4b; the subzone 4a is absent in C7, but it is shown in Fig. 4 to facilitate comparison with the other cores).

Both C3-4 and C7-4 show the highest CHAR peaks of all microcharcoal size classes, especially in subzones 4b, as evidence of cyclical strong fires in the area, both on a local and regional scale, during the last 1150 years. Fluctuations are documented in most of the arboreal pollen taxa (e.g., *Pinus*, deciduous *Quercus*, *Carpinus betulus*, *Ostrya carpinifolia/Carpinus orientalis*, *Alnus*, *Salix*, *Quercus ilex*, and *Erica*), suggesting that fires were common and involved a wide diversity of trees and shrubs. The expansion of herbaceous and arboreal pyrophytes is particularly evident following strong local fires starting from ~1200 AD.

4.2.2. Pecora Valley (Figs. 5 and 6; Table 5 and 6)

The same zonation was followed but, in accordance with the most recent chronology, the pollen zones identified in the Pecora cores start from subzone 2b. Despite the trends of microcharcoals being different, revealing local differences, the CHAR for small and medium size classes increases in the top cores.

4.2.2.1. Zone 2. **P3-2 and P4-2 (P3: samples 20–16, 430–350 cm; P4: samples 15–13, 370–330 cm) –** In P3-2b, a peak of the >125 μm and 50–125 μm size classes, together with a slight increase in small-sized microcharcoals, is visible during a decrease in hygrophilous wood affected by local fires at ~900 BC. The peak of microcharcoals matches a decline in mixed oakwood although deciduous *Quercus* remains steady and *Fraxinus excelsior* type shows an isolated peak. *Erica* shows high values even if with fluctuations throughout the subzone, with an

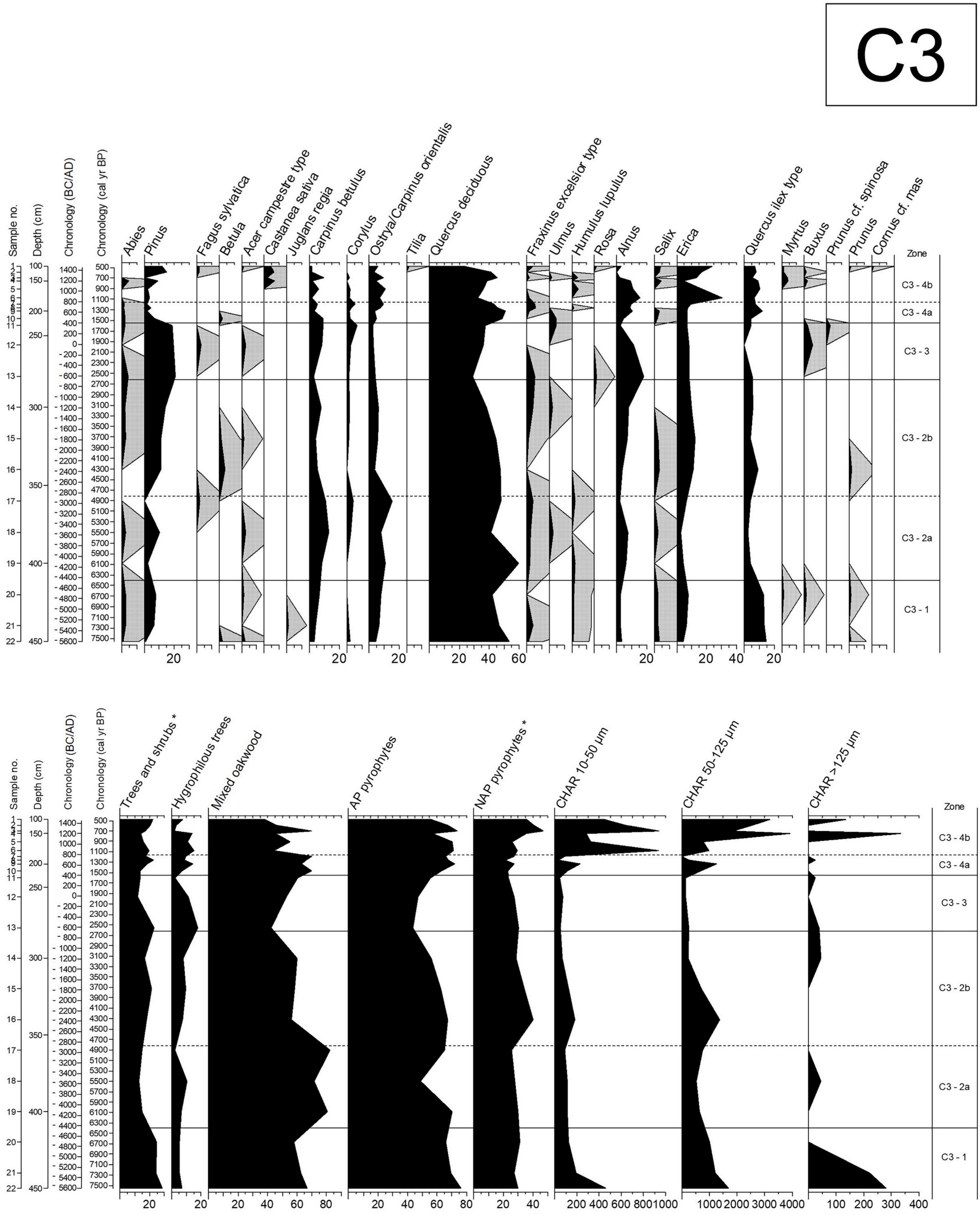

Fig. 3. Arboreal pollen percentage diagrams of Cornia 3 - C3 (AP = 100%). Top: arboreal pollen; Bottom: selected sums and CHAR. Enhanced curves x 10. The * marks the NAP pollen percentage calculated on AP + NAP sum. Pollen zones and subzones are based on pollen analyses (see Clò et al., 2023).

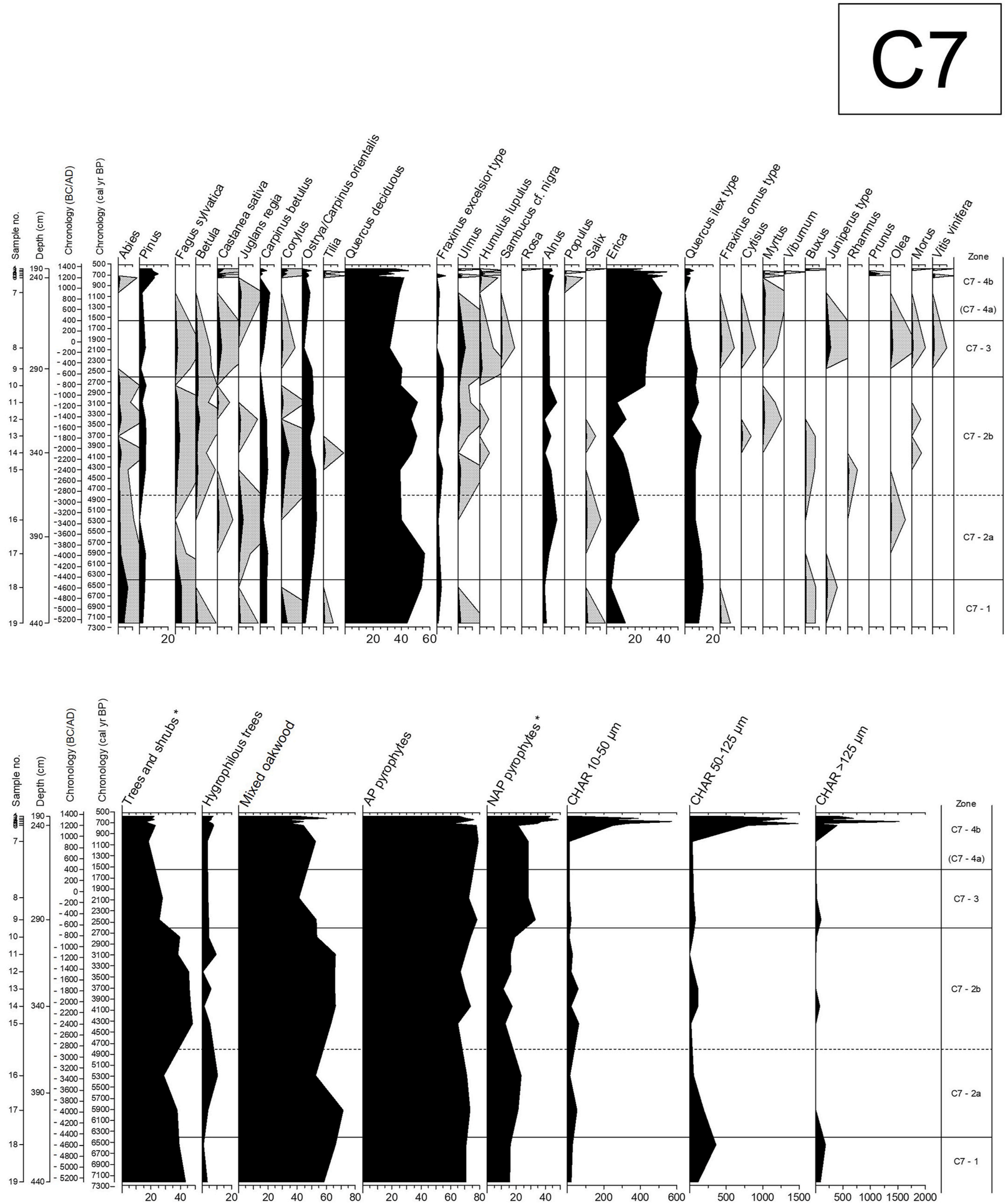

Fig. 4. Arboreal pollen percentage diagrams of Cornia 7 - C7 (AP = 100%). Top: arboreal pollen; Bottom: selected sums and CHAR. Enhanced curves x 10. The * marks the NAP pollen percentage calculated on AP + NAP sum. Pollen zones and subzones are based on pollen analyses (see Clò et al., 2023); subzone C7-4a is shown in brackets as no sample falls within the sub-zone range.

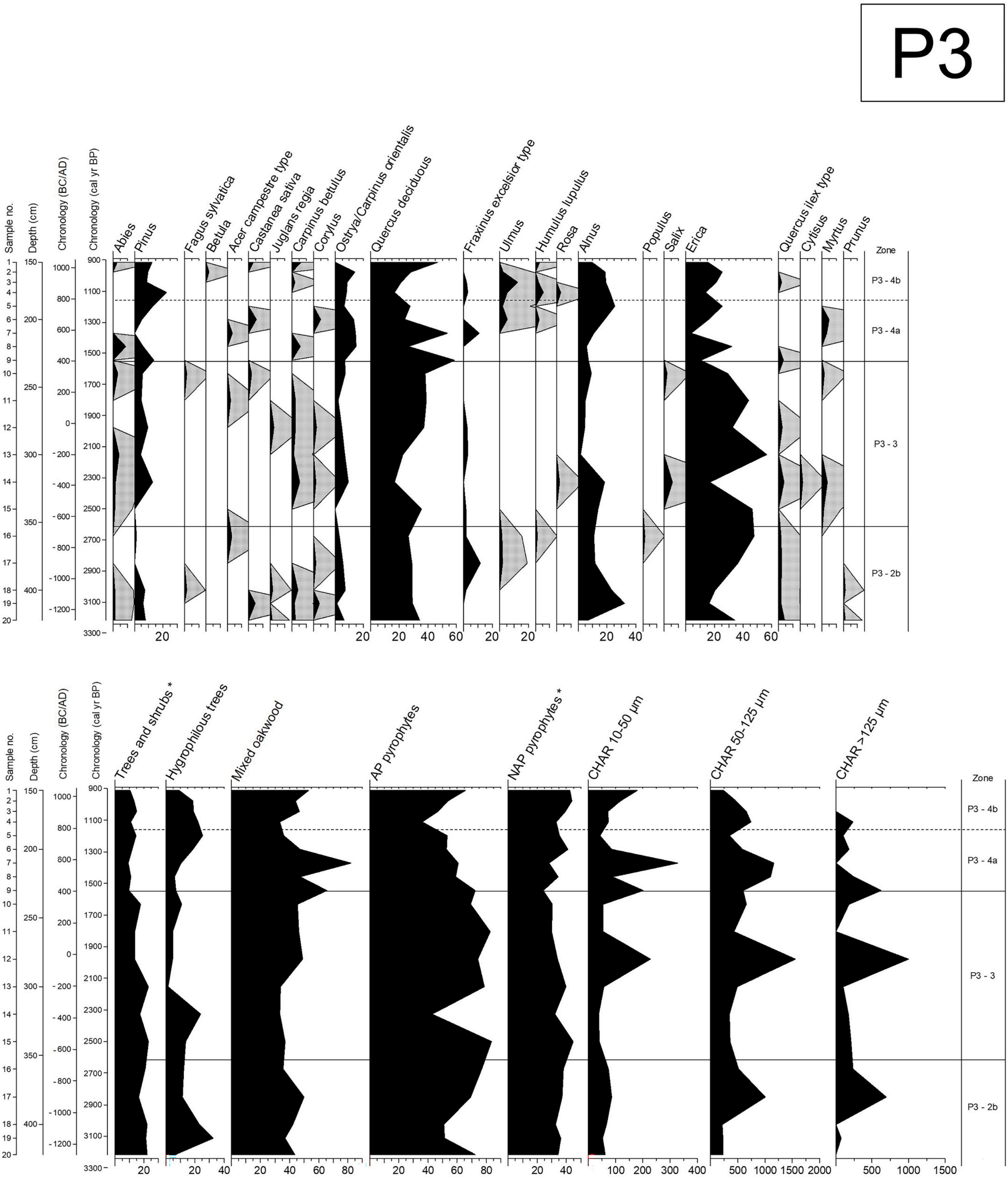

Fig. 5. Arboreal pollen percentage diagrams of Pecora 3 - P3 (AP = 100%). Top: arboreal pollen; Bottom: selected sums and CHAR. Enhanced curves x 10. The * marks the NAP pollen percentage calculated on AP + NAP sum. Pollen zones and subzones are based on pollen analyses (see Clò et al., 2023).

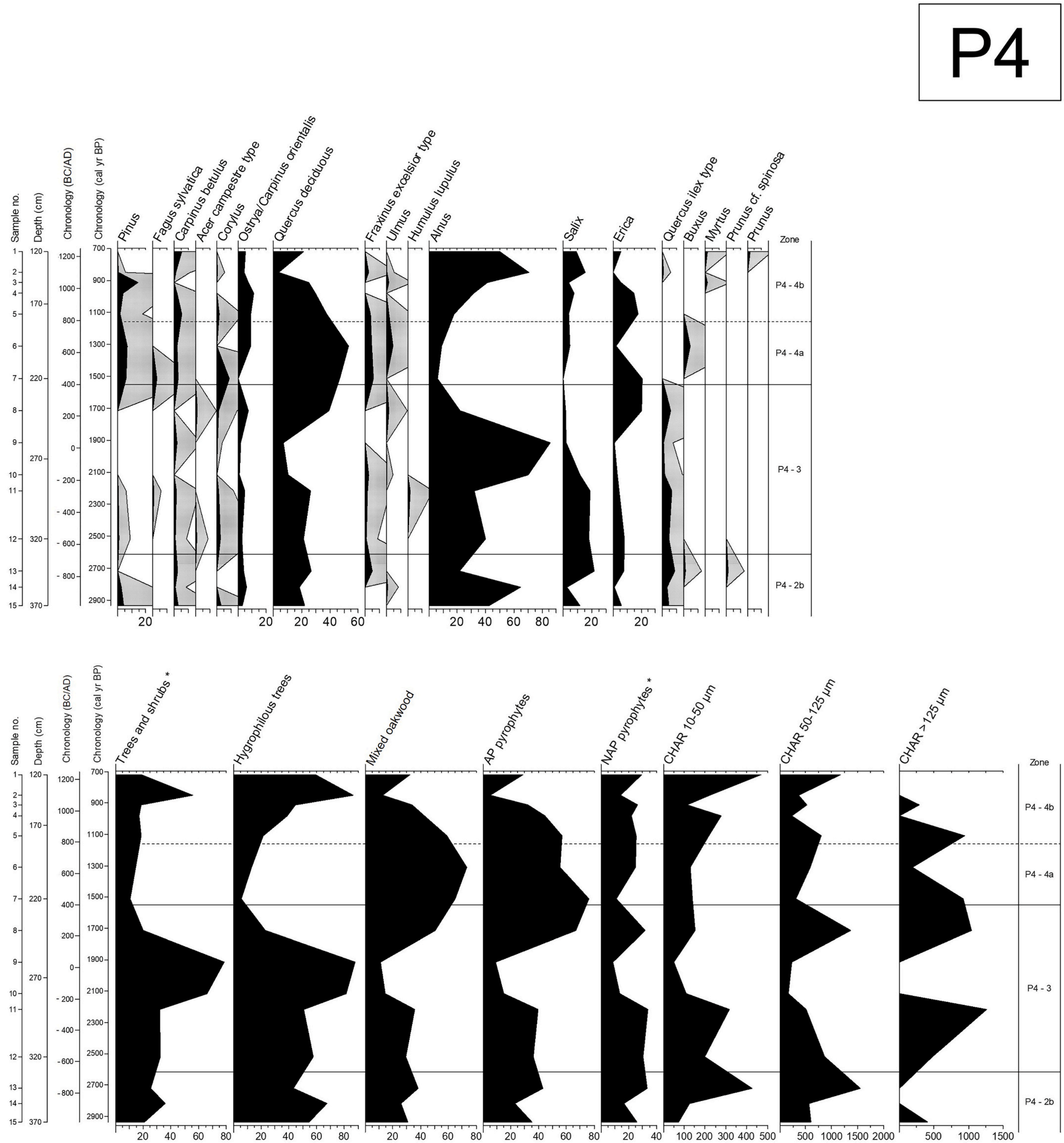

Fig. 6. Arboreal pollen percentage diagrams of Pecora 4 - P4 (AP = 100%). Top: arboreal pollen; Bottom: selected sums and CHAR. Enhanced curves x 10. The * marks the NAP pollen percentage calculated on AP + NAP sum. Pollen zones and subzones are based on pollen analyses (see Clò et al., 2023).

increase right after the peak of microcharcoals. P4-2b shows a lower incidence of local fires but reflects the presence of regional fires at ~750 BC. In P4-2b, *Alnus* shows the same trend as described for P3-2b, but *Salix* is abundant especially at the end of the subzone when *Alnus* declines. *Erica* is scarce.

4.2.2.2. Zone 3. **P3-3 and P4-3 (P3: samples 15–10, 349–235 cm; P4: samples 12–8, 329–230 cm) –** P3-3 shows a peak in all the microcharcoals size classes at ~50 BC, coinciding with the decrease in *Erica*. Alongside the heather, *Alnus* and *Salix* also decrease in the zone, though before the microcharcoals peak. *Erica* presents fluctuations in P3-3 with opposite trend to the mixed oakwood and shows two peaks right before

Table 2
CHAC and CHAR values (maximum, minimum, mean), depth (cm) and frequencies of >125 μm microcharcoals (%) of the studied cores (C3; C7; P3; P4).

Core	T-CHAC (#/cm^3) (min-max)	T-CHAC max: sample no./depth (cm)	T-CHAR (#/cm^2/y) (min-max)	T-CHAR max: sample no./depth (cm)	Frequency of charcoals >125 μm
C3	7206–118,455	6 (170)	3219–96,060	3 (140)	40.9%
C7	27,912–205,443	15 (350)	10,840–580,673	4 (220)	52.6%
P3	35,436–280,211	7 (210)	42,878–339,056	7 (210)	65.0%
P4	53,121–440,734	13 (340)	53,121–480,481	1 (120)	53.3%

and after the microcharcoals peak. This seems to indicate some fire activities, both locally and regionally, mostly consuming the mixed oakwood and heather shrubby vegetation. In this context, the presence of *Pinus* in the territory increases with higher percentages observed in P3 than in P4.

In P4-3, the very high presence of 50–125 μm and >125 μm microcharcoals (~300 BC and ~250 AD) does not coincide with low forest cover, which is still well represented by hygrophilous woods, mixed oakwood, and arboreal pyrophytes. The absence of strictly local fires (~150 BC/~50 AD) favours the rapid spread of *Alnus*.

Table 3
Cornia 3: main features of the arboreal/charcoal pollen zones (charcoal particles: large = > 125 μm; medium = 50–125 μm; small = 10–50 μm).

Cornia 3										
Zone	No. of samples	Depth (cm)	AP pollen		Microcharcoals		Subzone	No. of samples	Depth (cm)	Notes
			Pollen taxa	%	CHAR	Conc.				
C3-1	3	450-410	broadleaved *Quercus* ; *Quercus ilex* type; *Ostrya carpinifolia/ Carpinus orientalis* ; *Pinus*	47.3 13.7 6.3 5.2	10-50 μm 50-125 μm >125 μm	25917.1 1306.7 167.7				• High large CHAR; • Low and decreasing medium+small CHAR; • broadleaved *Quercus* , *Quercus ilex* , *Pinus* high; • *Ostrya carpinifolia/ Carpinus orientalis* increases
C3-2	6	409-290	broadleaved *Quercus* ; *Ostrya carpinifolia/ Carpinus orientalis* ; *Carpinus betulus* ; *Quercus ilex*	49.4 11.1 10.7 3.7	10-50 μm 50-125 μm >125 μm	10520.2 640.6 14.6	C3-2a	3	409-350	• Low large CHAR; • Low and steady medium+small CHAR; • broadleaved *Quercus* , *Ostrya carpinifolia/Carpinus orientalis* fluctuating; • *Carpinus betulus* increases;
			broadleaved *Quercus* ; *Pinus* ; *Erica* ; *Quercus ilex* type	43.2 12.0 11.1 6.4	10-50 μm 50-125 μm >125 μm	12364.1 775.1 15.3	C3-2b	3	349-290	• Low and steady high CHAR; • Low peak in small+medium CHAR; • *Quercus ilex* fluctuating; • *Erica* , *Pinus* increase; • broadleaved *Quercus* decreases
C3-3	3	289-230	broadleaved *Quercus* ; *Pinus* ; *Alnus*	34.0 19.5 10.4	10-50 μm 50-125 μm >125 μm	5444.8 177.3 20.8				• Low and steady CHAR; • *Pinus* constant; • broadleaved *Quercus* increases; • *Alnus* decreases
C3-4	10	229-100	broadleaved *Quercus* ; *Quercus ilex* type; *Pinus*	47.1 8.6 3.7	10-50 μm 50-125 μm >125 μm	11424.6 555.2 6.4	C3-4a	4	229-175	• Small peak in small+medium CHAR; • Low large CHAR; • broadleaved *Quercus* , *Quercus ilex* high and constant; • *Pinus* decreases
			broadleaved *Quercus* ; *Erica* ; *Quercus ilex* type; *Alnus*	36.1 17.5 7.9 6.6	10-50 μm 50-125 μm >125 μm	59683.4 2212.5 78.2	C3-4b	6	174-100	• High peaks in CHAR; • broadleaved *Quercus* , *Quercus ilex* , *Alnus* fluctuating; • *Erica* increases

Table 4
Cornia 7: main features of the arboreal/charcoal pollen zones (charcoal particles: large = > 125 μm; medium = 50–125 μm; small = 10–50 μm).

Cornia 7										
Zone	No. of samples	Depth (cm)	AP pollen		Microcharcoals		Subzone	No. of samples	Depth (cm)	Notes
			Pollen taxa	%	CHAR	Conc.				
C7-1	2	440-410	broadleaved *Quercus*; *Quercus ilex* type; *Erica*	48.7 11.3 8.1	10-50 μm 50-125 μm >125 μm	24863.7 2300.5 137.7				• High large+medium CHAR; • Low and constant small CHAR; • broadleaved *Quercus* increases; • *Erica* decreases; • *Quercus ilex* constant
C7-2	8	409-295	broadleaved *Quercus*; *Erica*; *Quercus ilex* type	47.9 14.1 9.4	10-50 μm 50-125 μm >125 μm	33584 1210 0	C7-2a	2	409-365	• Low and decreasing CHAR; • broadleaved *Quercus* fluctuating; • *Erica* increases; • *Quercus ilex* constant
			broadleaved *Quercus*; *Erica*; *Quercus ilex* type	45.7 12.8 8.3	10-50 μm 50-125 μm >125 μm	33306.5 536.7 14.8	C7-2b	6	364-295	• Low and steady CHAR; • broadleaved *Quercus* fluctuating; • *Erica* decreases; • *Quercus ilex* constant
C7-3	2	294-263	broadleaved *Quercus*; *Erica*; *Quercus ilex* type	35.7 27.8 6.7	10-50 μm 50-125 μm >125 μm	15564 602.2 58.7				• Low and constant CHAR; • broadleaved *Quercus*, *Quercus ilex* decrease; • *Erica* increases
C7-4	7	262-190	broadleaved *Quercus*; *Erica*; *Pinus*	34.3 30.4 9.2	10-50 μm 50-125 μm >125 μm	259533.1 8888.2 434.9	C7-4b	7	262-190	• High peaks in CHAR; • broadleaved *Quercus*, *Erica*, *Pinus* increase; • *Quercus ilex* decreases

Table 5
Pecora 3: main features of the arboreal/charcoal pollen zones (charcoal particles: large = > 125 μm; medium = 50–125 μm; small = 10–50 μm).

Pecora 3										
Zone	No. of samples	Depth (cm)	AP pollen		Microcharcoals		Subzone	No. of samples	Depth (cm)	Notes
			Pollen taxa	%	CHAR	Conc.				
P3-2	5	430-350	*Erica*; broadleaved *Quercus*; *Alnus*	30.9 29.5 16.8	10-50 μm 50-125 μm >125 μm	68290 4367 199.1	P3-2b	5	430-350	• Low peaks in medium+large CHAR; • Low and constant small CHAR; • *Alnus* decreases; • *Erica* increases; • broadleaved *Quercus* constant
P3-3	6	349-235	*Erica*; broadleaved *Quercus*; *Alnus*	37.5 31.5 8.7	10-50 μm 50-125 μm >125 μm	79450 6398.5 277.2				• High peak in CHAR; • broadleaved *Quercus* increases; • *Erica* fluctuating; • *Alnus* decreases
P3-4	9	234-150	broadleaved *Quercus*; *Erica*; *Alnus*	38.0 17.5 13.4	10-50 μm 50-125 μm >125 μm	149720.1 7622.4 228.8	P3-4a	5	234-185	• Peaks in CHAR; • broadleaved *Quercus* decreases; • *Erica* fluctuating; • *Alnus* increases
			broadleaved *Quercus*; *Erica*; *Alnus*	28.1 19.1 17.3	10-50 μm 50-125 μm >125 μm	110438.2 5287 59.9	P3-4b	4	184-150	• Low peak in small+medium CHAR; • Decreasing high CHAR; • broadleaved *Quercus* increases; • *Erica* fluctuating; • *Alnus* constant

Table 6
Pecora 4: main features of the arboreal/charcoal pollen zones (charcoal particles: large = > 125 μm; medium = 50–125 μm; small = 10–50 μm).

Pecora 4										
Zone	No. of samples	Depth (cm)	AP pollen		Microcharcoals		Subzone	No. of samples	Depth (cm)	Notes
			Pollen taxa	%	CHAR	Conc.				
P4-2	3	370-330	*Alnus*; broadleaved *Quercus*; *Salix*; *Erica*	42.9 22.3 11.9 4.7	10-50 μm 50-125 μm >125 μm	207556.3 9018.7 136.3	P4-2b	3	370-330	• Peaks in small+medium CHAR; • Low high CHAR; • Peak in *Alnus*; • *Salix* increases; • broadleaved *Quercus* constant
P4-3	5	329-230	*Alnus*; broadleaved *Quercus*; *Erica*	49.8 20.8 7.1	10-50 μm 50-125 μm >125 μm	165183.1 6268.4 558.4				• Peaks in CHAR; • Peak in *Alnus*; • broadleaved *Quercus, Erica* increase
P4-4	7	229-120	broadleaved *Quercus*; *Erica*; *Alnus*	50.1 11.4 7.3	10-50 μm 50-125 μm >125 μm	133651.9 4458.6 556	P4-4a	2	229-190	• Fluctuations in CHAR; • *Alnus*, *Erica* decrease; • broadleaved *Quercus* constant
			Alnus; broadleaved *Quercus*; *Erica*	42.2 23.4 8.6	10-50 μm 50-125 μm >125 μm	260342.4 6143.6 245.5	P4-4b	5	189-120	• Peaks in CHAR; • Decrease in large CHAR; • *Alnus* increases; • *Erica* fluctuating; • broadleaved *Quercus* decreases

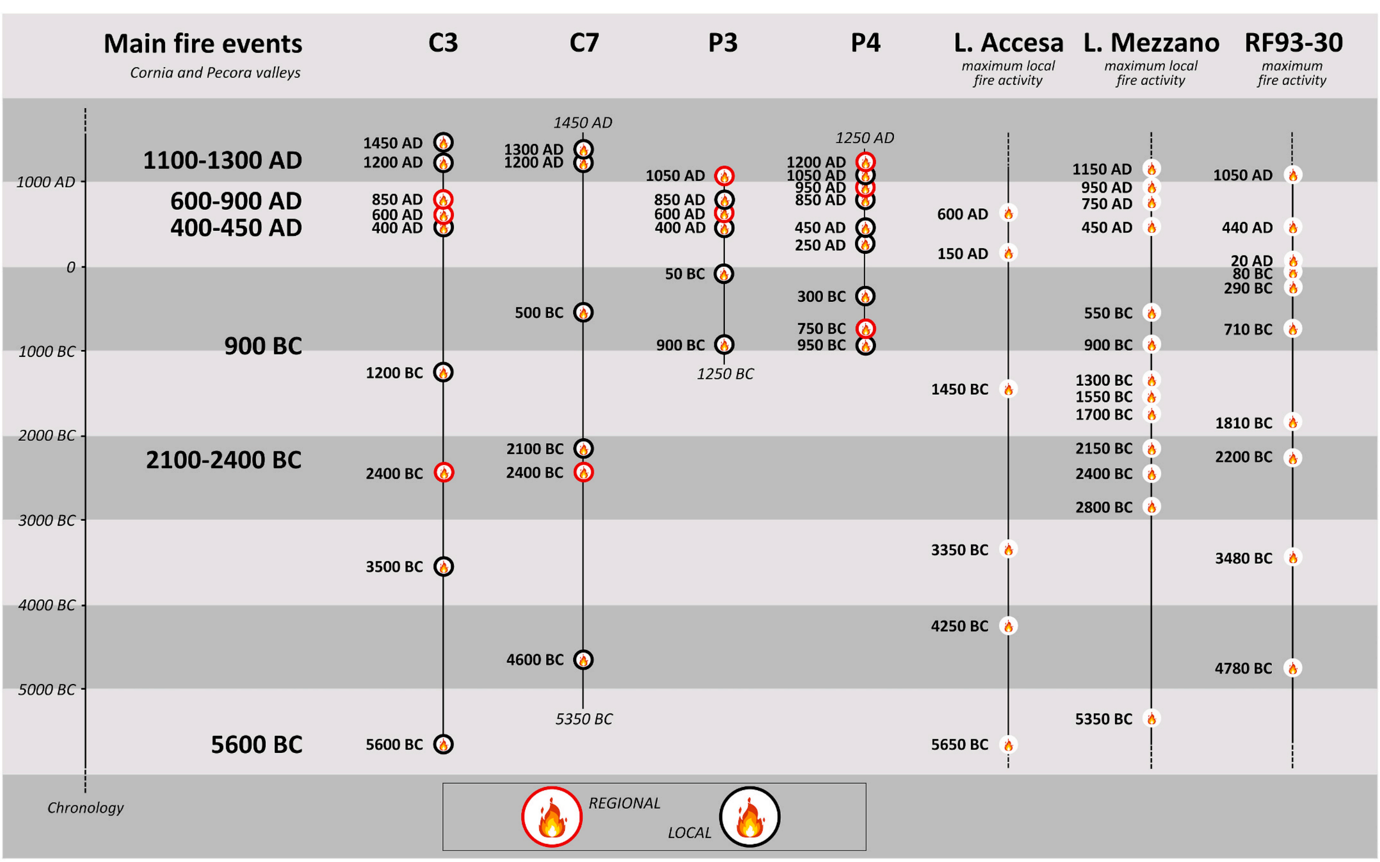

Fig. 7. Main fire events recorded in the Cornia (C3, C7) and Pecora (P3, P4) valleys and reference cores from Lake Accesa (Vannière et al., 2008), Lake Mezzano (Sadori, 2018), and the marine core RF93-30 (Mercuri et al., 2019).

4.2.2.3. Zone 4. **P3-4 and P4-4 (P3: samples 9–1, 234–150 cm; P4: samples 7–1, 229–120 cm) –** This zone is divided into two subzones (4a, 4b). The >125 μm microcharcoals size class presents high percentages and some peaks at the bottom of the zone in both cores. Small and medium-sized microcharcoals especially increase in the upper part of the zone suggesting fire episodes mostly on a regional scale and a local increase in trees. In P3-4, the mixed oakwood has low values from ~650 AD to ~850 AD probably due to the presence of local fires. *Erica* is also present with significant fluctuations. The situation is very similar in P4-4, although this core also shows a strong increase in *Alnus* and *Salix*, together with an increase in mixed oakwood in recent levels.

5. Discussion

The most striking evidence emerging from these sedimentary records is the widespread presence of microscopical charcoals, which testifies to the presence of fires or phases of *potential fire activity increases* (PFAIs) in the two valleys during the last eight millennia (Fig. 7). In both valleys, microcharcoal particles show a similar trend with the highest values at the top of the diagrams. Large-sized microcharcoals (>125 μm), indicating local fires, were more common in the Pecora Valley: fire events would have been more widespread in this valley than in the Cornia Valley. In fact, the human activities may have favoured the repeated occurrence of fires, with the aim of opening the forest to obtain space for buildings, expand agricultural practices, and improve mining activities in the Pecora Valley.

In the Cornia Valley, evidence of local fires is observed at ~5600 BC and in recent phases until ~1200-1450 AD (C3, C7; Figs. 3 and 4). An increase in fires, suggested by the significant presence of small and large-sized microcharcoals, is clearly visible in the last millennium. Fires occurred mostly in the Medieval period, probably because of the expansion of human activities in the area. Fire was probably used to open landscape as suggested by the oscillations of pollen curves of mixed oakwood and *Erica*. The main biomass for fires largely consisted of deciduous *Quercus* complemented by other trees. In the Cornia Valley, the main source of fuel were oaks together with *Corylus* and *Ostrya carpinifolia/Carpinus orientalis*.

In the Pecora Valley, there is clear evidence of scattered local fires from ~900 BC, at ~50 BC and ~400 AD (P3-3; Fig. 5), and until ~1200 AD (P4-3; Fig. 6). Similarly, data obtained from charcoal macroremains from a retention basin of the Pecora River, near the archaeological site of Vetricella, show a local assessment of woody plants in two main periods dated between ~800 and 450 BC and ~650-1300 AD (Buonincontri et al., 2020). Charcoals showed a different use of fire during the two periods, linked to forest opening.

In P4 a slight shift in the growth of the mixed oakwood is almost contemporaneous with the highest presence of microcharcoals from ~250 AD to ~1050 AD; the increase in microcharcoal particles is related to the decrease in *Alnus* and other hygrophilous trees with also a slight increase in large and medium-sized microcharcoals. Alder was most likely the main fuel consumed by the fires.

5.1. The dynamics of pyrophytes

Fire-tolerant arboreal and non-arboreal species have evolved two main strategies to withstand burning and, depending on which of the two they adopt, they can be divided in passive or active pyrophytes. Passive species have anatomic structures (e.g., thick bark) or biological processes that allow them to resist fire or reduce damage. Active species have evolved vegetative (resprouters) or seed (seeders) response strategies. Blasi et al. (2004) divide pyrophytes according to whether the response to fire disturbance increases seed propagation, vegetative reproduction or growth, or all of them. Most trees and shrubs represented in these pollen spectra, such as *Quercus* and *Myrtus*, react to fire disturbance with a vegetative regrowth. Pines and most non-arboreal plants, such as *Medicago* and *Trifolium*, use seed reproduction to ensure regrowth after fire episodes. Shrubs like *Cistus* can react with both behaviours, and *C. salvifolius* is an active pyrophyte by seeds. Indeed, *Quercus pubescens*, *Q. ilex*, *Castanea sativa*, *Myrtus communis*, *Phillyrea angustifolia* and *P. latifolia*, *Arbutus unedo*, *Cytisus scoparius,* and *Rhamnus alaternus* can regenerate from underground parts (Blasi et al., 2004).

The aerial parts of *Erica*, including *E. arborea* and *E. scoparia*, can be easily burned but these species are able to give out suckers and can disseminate very high quantities of seeds with medium-to-high germination capability. *Erica multiflora* is also a resprouting shrub (Bertacchi and Borgia, 2020). AP pyrophytes are frequent in the Cornia diagrams, with some fluctuations and an increase in the upper part of the cores (C3-4b and C7-4b), coinciding with the strong increase in microcharcoals. Fluctuations of NAP pyrophytes mostly follow those of AP pyrophytes, although trees and shrubs have higher percentages (AP pyrophytes: 65%, NAP pyrophytes: 28%, on average). This can be interpreted as the presence of strong fires destroying great part of the vegetation in the area, with the simultaneous removal of many plants.

The P3 diagram seems to fit this pattern, with high percentages of AP pyrophytes (especially *Erica*, which has high values, 49% on average) and similar percentages of NAP pyrophytes (29%). Instead, in the P4 diagram, pyrophytes follow the CHAR curves much more strictly compared to the other cores, with a peak at ~300 BC, ~250 AD, ~850 AD, and ~1050 AD corresponding to peaks in AP and NAP pyrophytes (Fig. 6). They should have been influenced mainly by alder burning: their curve decreases when *Alnus* increases, and the abundance of trees possibly masked the arrival of other pollen in the sediment.

Both Pecora cores show a synchronous trend of AP and NAP pyrophytes until ~400-500 AD, and an opposite trend after this phase with a visible decreasing trend of AP pyrophytes. Considering forest dynamics after fire events, it is probable that if the return time of a fire was too short, woods encountered difficulty to recover and trees may not have reached sexual maturity, did not spread sufficient seeds, and after the fire there was not large sprouting and recolonization. In the Pecora Valley, the large presence of shrubby heather vegetation suggests the presence of repeated fires in this region. The development of this vegetation is especially evident in P3, suggesting that fires have continuously affected that area in the last three millennia.

5.2. Climate and anthropogenic influences on fire regime

Increasing evidence demonstrates that wildfires, closely related to biomass burning, have increased continuously since the last 21,000 years (Last Glacial Maximum). The available vegetation/biomass and climate changes have triggered the occurrence of wildfire globally. Moreover, this phenomenon has been amplified by the long-term human exploitation of natural resources. These events became particularly evident during the Holocene, albeit with great spatial heterogeneity in fire activity from one region of the Earth to another (Carrión et al., 2003; Power et al., 2008; Vannière et al., 2021).

In the Cornia Valley, a phase of local fires was recorded at ~5600 BC (C3-1; Fig. 4), and similarly local fires occurred at Lake Accesa at 5650 BC (Vannière et al., 2008). Regional fires slightly increase at ~4600 BC (C7-1; Fig. 5), when some *potential fire activity increases* (PFAIs) are visible in Lake Accesa (Vannière et al., 2008) until 4250 BC, and in the Adriatic core RF93-30 (~4780 BC) in southern Italy (Mercuri et al., 2019).

A second interesting peak of local fires is visible at ~3500 BC (C3-2a; Fig. 3), when a large fire affected deciduous *Quercus*, *Ostrya carpinifolia/Carpinus orientalis*, and *Quercus ilex*. This phase includes the Late Neolithic and Copper Age in central Italy (Dolfini, 2020; Radi and Petrinelli Pannocchia, 2018), and could be related to the presence of Neolithic settlements that used fire for forest clearing, field cultivation, and other agricultural purposes. Anthropogenic and climate-induced fires allowed the development of macchia, dominated by *Erica* and *Quercus ilex* in the Mediterranean vegetation from ~4000 to ~1300 BC

(Di Rita et al., 2022). A sharp vegetational change occurred just after ~4000 BC at the Lake Massaciuccoli, and the fire activity increased causing a strong decline in the highly fire-sensitive *Abies alba*; then, during 100 years of higher fire incidence, evergreen and other forest communities were converted to low-diversity fire-prone shrub communities (Colombaroli et al., 2007). A comparable decrease of *Abies* is also visible in the Cornia Valley (C7-2a). Many records show the concomitant increase in microcharcoal records and Bronze Age settlements (e.g., Mezzano, ~1700-1550 BC; Sadori, 2018). The development of heather shrubs was probably stimulated by Etruscan metallurgy in the region (Sadori et al., 2010).

A regional fire is recorded in the Cornia Valley starting from ~2400 BC, with local evidence in C7 at ~2100 BC. Small and medium-sized microcharcoals testify to the presence of widespread fire events in the region, with local events also attested in the Lake Mezzano record at ~2400 BC and ~2150 BC (Sadori, 2018) and in the marine core RF93-30 at ~2200 BC (Mercuri et al., 2019). Then, the Cornia Valley seems to have been mostly undisturbed by local fires until ~1200 BC (C3-2b), when a short fire episode mainly affected the mixed oakwood leaving space to pines and hygrophilous wood. Small and not strictly local fires were recurring from ~400 AD with the maximum spread at ~1450 AD, when high peaks testify to the spread of fires with the increase in human activity in the area. The land use favoured the development of a Mediterranean macchia, with *Buxus* and *Myrtus* (C3-4b, C7-3b,4b), and the exploitation of *Quercus ilex* woods.

The Pecora Valley presents some differences compared to the Cornia Valley, and local peculiarities that makes the fire history of the two cores quite different.

In the P3 diagram, local fire events are recorded at ~900 BC that should have mainly affected *Alnus*. Then, shrubby vegetation was frequently burned from ~50 BC, with evidence of both local and regional fires that had probably still anthropic origin. Then, fire events alternated with recovery of AP pyrophytes continued until ~850 AD (P3, Fig. 5). In the last centuries, the diagrams highlight mainly regional fires under the pressure of management regimes.

In P4, major fire episodes were evident until ~1200 AD (P4, Fig. 6). The oldest one was at ~950 BC and probably affected *Fraxinus* and *Acer* in the mixed oakwood, while the hygrophilous wood dominated by *Alnus* persisted. In the same period, local fires are attested also at Lake Mezzano, suggesting an anthropogenic influence on the fire regimes in the region (Sadori, 2018). Then, at ~300 BC and at ~250-450 AD, the fire seems to have mostly consumed hygrophilous trees, since the peaks in large-sized microcharcoals correspond to the decrease in *Alnus* and the increase in mixed oakwood. A decrease in water level and dry conditions could explain the evidence. An inverse trend of deciduous oaks and alder interested the period between the two fire peaks. The later episode was probably also caused by human activities considering the proximity of the core to archaeological site of Vetricella. Reclamation activity is among the most invoked causes for the reduction of alder habitats and its spread. According to Magri et al. (2019), the disappearance of *Alnus* swamps is a relatively recent phenomenon that has produced a severe loss of biodiversity, but the vanished alder forests proved to be able to rapidly recover several times through the Holocene, and therefore they may still have some potential to be restored in the Mediterranean.

Interestingly, at ~400-450 AD several fire events occurred in central Italy, as attested by records from the Cornia (C3) and Pecora (P3, P4) valleys, Lake Mezzano, and marine core RF93-30. Deciduous *Quercus* began to decline especially after ~650 AD, with widespread fires in the region (C3, P3, and Lake Accesa). Local fires occurred at 850 AD and 1050 AD in the Pecora Valley. Similarly, a fire event is recorded at ~1050 AD in the core RF93-30 (Mercuri et al., 2019). Then, the regional fire image is evident until ~1200 AD in P4, with local evidence in the Cornia Valley.

6. Conclusions

Fire is one of the main ecological factors shaping the Mediterranean environment and influencing the structure of the landscape, with a mosaic of stages undergoing regeneration and degradation. In recent years, in most of the Mediterranean, fires have become more extensive and more frequent with important negative effects from an ecological point of view. Palaeoenvironmental data confirm that fire events have occurred in southern Tuscany during the whole Holocene. The *potential fire activity increases* (PFAIs), visible as peaks in the diagrams, were of local or regional relevance. The main events can be summarised as follows (Fig. 7):

- A big event at ~5600 BC has occurred in the Cornia Valley and in the Lake Accesa. This event was followed by the successful recovery of oaks in the Cornia Valley (Clò et al., 2023).
- In the Cornia Valley, fire events also occurred at ~4600 BC and ~3500 BC, the last one probably linked to Neolithic activity; moreover, in this valley fire events can be observed between ~2400 BC and ~2100 BC, and similarly are recorded at Lake Mezzano. This phase slightly precedes the maximum expansion of cereal fields in the Cornia Valley (2000–1900 BC; Clò et al., 2023), so the fire may have been used intentionally to open spaces for cultivation.
- Then, a period of several fire events is detected between ~1450 BC (in Lake Accesa), ~1200 BC (in the Cornia Valley), and ~900 BC in the Pecora Valley indicating phases of the Late Bronze Age and Etruscan land use. In particular, different land use is evident in the change of pollen spectra in the Cornia Valley, towards a predominantly pastoral economy (Clò et al., 2023).
- Fire events during the Iron/Roman Age are evident in the Pecora Valley at ~300 BC and ~50 BC.
- A new series of fires is recorded at ~150 AD (Lake Accesa) and at ~250-450 AD (Pecora Valley) that marks the Empire/Late Roman period. Pollen spectra reflect a decline of deciduous *Quercus* that could indicate human control of forest cover in the Pecora Valley (Clò et al., 2023).
- From ~600 AD, fire events occurred in the two valleys with clear evidence of repeated regional and local fires at ~1050-1200 AD, also evident in the marine core RF93-30.

The vegetation and cultural contexts (Bianchi and Hodges, 2018, 2020) are very different in the two valleys. Pollen spectra show a vegetation characterised by Mediterranean plants, hygrophilous wood, and pasturelands. However, the two valleys were characterised by great environmental stability without significant vegetation changes (Clò et al., 2023). The comparison of vegetation dynamics of the cores, recovery of large-sized microcharcoals, high presence of heather shrub vegetation, and trend of AP/NAP pyrophytes suggest that the frequency of fires notably increases in the studied valleys during the last ~1200 years (~800-1400 AD). Among the causes of such increase there are demographic growth and soil occupation (Stoddart et al., 2019). Changes in the land use and vegetation cover have altered the structure of the landscape with the formation of shrublands with heather and dense macchia also including myrtle and box, resulting in more favourable conditions for fire ignition than in the past (Marchetti and Ricotta, 2004; Mazzoleni and Esposito, 2004b).

Data availability

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

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CRediT authorship contribution statement

Elisa Furia: Investigation, Writing – original draft, preparation, Pollen analysis, Formal analysis. **Eleonora Clò:** Investigation, Writing – review & editing, Map design, Visualization, All authors have read and agreed to the published version of the manuscript. **Assunta Florenzano:** Investigation, Writing – review & editing. **Anna Maria Mercuri:** Conceptualization, Methodology, Supervision, Investigation, Writing – original draft, preparation.

Declaration of competing interest

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

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