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ARTICLE

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Historical ecology identifies long-term rewilding strategy for conserving Mediterranean mountain forests in south Italy

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Abstract

In the context of global decline in old-growth forest, historical ecology is a valuable tool to derive insights into vegetation legacies and dynamics and develop new conservation and restoration strategies. In this cross-disciplinary study, we integrate palynology (Lago del Pesce record), history, dendrochronology, and historical and contemporary land cover maps to assess drivers of vegetation change over the last millennium in a Mediterranean mountain forest (Pollino National Park, southern Italy) and discuss implications in conservation ecology. The study site hosts a remnant beech–fir (*Fagus sylvatica–Abies alba*) mixed forest, a priority habitat for biodiversity conservation in Europe. In the 10th century, the pollen record showed an open environment that was quickly colonized by silver fir when sociopolitical instabilities reduced anthropogenic pressures in mountain forests. The highest forest cover and biomass was reached between the 14th and the 17th centuries following land abandonment due to recurring plague pandemics. This rewilding process is also reflected in the recruitment history of Bosnian pine (*Pinus heldreichii*) in the subalpine elevation belt. Our results show that human impacts have been one of the main drivers of silver fir population contraction in the last centuries in the Mediterranean, and that the removal of direct human pressure led to ecosystem renovation. Since 1910, the Rubbio State Forest has locally protected and restored the mixed beech–fir forest. The institutions in 1972 for the Rubbio Natural Reserve and in 1993 for Pollino National Park have guaranteed the survival of the silver fir population, demonstrating the effectiveness of targeted conservation and restoration policies despite a warming climate. Monitoring silver fir populations can measure the effectiveness of conservation measures. In the last decades, the abandonment of rural environments (rewilding) along the mountains of southern Italy has reduced the pressure on ecosystems, thus boosting forest expansion. However, after four decades of natural regeneration and increasing biomass, pollen influx and forest composition are still far from the natural attributes of the medieval forest ecosystem. We conclude that long-term forest planning encouraging limited direct human disturbance will lead toward rewilding and renovation of carbon-rich and highly biodiverse Mediterranean old-growth forests, which will be more resistant and resilient to future climate change.

KEYWORDS
conservation, European beech (*Fagus sylvatica* L.), historical ecology, land cover, land use, old-growth forests, palynology, Pollino National Park, rewilding, silver fir (*Abies alba* Mill.)

INTRODUCTION

Ecological planning for forest landscapes requires sustainability criteria that address long-term vulnerability and management-related impacts in a global change context (Beller et al., 2020; Bergès & Dupouey, 2019; Whitlock et al., 2018). To achieve, for example, the United Nations' Sustainable Development Goals (SDGs) will require significant efforts aimed at enhancing the knowledge of mechanisms governing life on Earth with special regard to biodiversity conservation and natural resource dynamics (Nakamura et al., 2019). Evaluating forest continuity, the degree of naturalness of modern ecosystems and their disturbance history resulting from socioeconomic and climatic change is essential for developing a strategic baseline of management policies (Bergès & Dupouey, 2019; Piovesan, Mercuri, & Mensing, 2018; Szabó et al., 2017; Whitlock et al., 2018) and can provide a tool to align stakeholders viewpoints toward common and concrete objectives (McAfee et al., 2019). However, before attempting to achieve any realistic ecological planning of forest landscapes, we need an in-depth understanding of their past composition, structure, and functions, along with their land-use history (Whitlock et al., 2018).

Although it is broadly acknowledged that paleoecology can actively contribute to nature conservation (Beller et al., 2020; Brown & Pasternack, 2005; McAfee et al., 2019; Swetnam et al., 1999; Szabó et al., 2017; Whitlock et al., 2018), few studies have integrated the palaeoecological perspective with documentation of historical humanities/social change (Izdebski et al., 2016; Swanson et al., 2021). Such a cross-disciplinary analysis of local landscape history can be extremely beneficial for developing on-the-ground management decisions, given legacies of vegetation differ radically from place to place due to local-scale dynamics (e.g., environmental complexity, natural, and anthropogenic disturbances, land-use change, climate change) (Fraterrigo, 2013; Mensing et al., 2020).

Historically, silver fir (*Abies alba* Mill.) has undergone a dramatic decrease throughout Europe (Abraham et al., 2021; Cruise et al., 2009; Di Pasquale et al., 2014; Guido et al., 2020; Klopcic & Boncina, 2011; Pini et al., 2017; Vitasse et al., 2019). Silver fir is a key species for maintaining biodiversity and ecological functioning of Mediterranean mountain forests and its accelerated decline in modern times makes it of particular conservation interest (Büntgen et al., 2014; Dobrowolska et al., 2017). Paleoecology-based modeling studies suggest an interesting potential capacity of silver fir to recover across large areas of Europe, and indicate anthropogenic pressures as the main drivers of silver fir decline (Di Pasquale et al., 2014; Morales-Molino et al., 2020; Tinner et al., 2013; Vitasse et al., 2019). Many of these studies documented the declining trend and local extinction of silver fir, but none of them explored the ecological history of a mixed silver fir stand that persisted until today.

The Apennine's mixed beech–fir forests and southern Apennine's pure silver fir stands constitute two priority habitats of European interest for biodiversity conservation (Natura 2000 Network, Annex II, codes 9220, 9510). The mountains of southern Italy contain well preserved metapopulations of silver fir. This is partially due to the high environmental heterogeneity (climate, lithology and geomorphology) that creates sharp and complex ecological gradients and many different ecological niches. Furthermore, lands of southern Italy host Quaternary refugia for temperate tree species with a unique genetic differentiation in the Mediterranean basin. The large genetic distance of silver fir and European beech populations growing in the southern Apennines testify to the isolation of such populations in the Late Quaternary (de Beaulieu et al., 2017; Liepelt et al., 2009; Magri et al., 2006; Piotti et al., 2017). Southern Italy has also experienced a long history of human settlement and developing cultures dating back to the Neolithic period (Guilaine, 2003; Manzi et al., 2011). These Mediterranean mountain forests present a lively history marked by ecosystem dynamics that are not yet fully described and understood (Birks & Tinner, 2016), involving the persistence of silver fir through periods of climate change (Piotti et al., 2017; Terhürne-Berson et al., 2004) and human-altered ecological niches. Mountain areas of southern Italy represent a complex mosaic of natural and cultural landscapes with a long history of land use, where, surprisingly, ancient trees and large patches of old-growth forests have survived over time (Piovesan et al., 2020; Piovesan, Biondi, et al., 2018; Piovesan, Biondi, Baliva, De Vivo, et al., 2019). Conserving and restoring old-growth stands is an urgent and effective nature-based strategy to protect biodiversity and to counter climate warming. Natural forests represent a solution to multiple problems associated with global environmental change. The high ecological integrity of old-growth forest stands provides habitat for threatened species, creates a climate refugia that buffers extreme climatic events, and contributes to global carbon stocks (Carroll & Ray, 2021).

In this study, we discuss the last millennium ecological history of a remnant *Abies–Fagus* mixed mountain forest in Pollino National Park (southern Italy). We present a cross-disciplinary approach using pollen and nonpollen palynomorphs (NPPs) analyses, compared with historical narratives at the local and regional scale, demographic fluctuations, local tree-ring records, climate anomalies and trends, and land cover maps. Our aim is to describe the last millennium of vegetation history of a remnant fir–beech forest at the southernmost limit of its distribution and to provide a perspective for the ecological restoration of mixed Mediterranean mountain forests. Specifically, we (1) discriminate between the human and climate drivers that shaped today's forest vegetation and led to silver fir persistence; (2) investigate the effectiveness of silver fir's conservation policies by comparing a high-resolution palaeoecological reconstruction during the last century with the reconstructed fir distributions derived from historical maps and remote sensing data; (3) contextualize findings within the large-scale ecological processes currently ongoing in Mediterranean mountains; and (4) discuss implications in conservation ecology.

METHODS

Study site: Vegetation and climate

The study site, named "Lago del Pesce" by locals (40°0′32″ N 16°13′28″ E; elevation ~1200 m above sea level [asl]), is a small mountain lake in Pollino National Park (Basilicata, Italy) (Figure 1). The area belongs to the Francavilla in Sinni (PZ) municipality. The geological substrate is mainly composed of flysch. The pond is partially surrounded by a dense seminatural European beech (*Fagus sylvatica* L.) forest that is interrupted toward the east by a grassland with scattered trees. European beech forests dominate the mountain elevation belt of the Apennine mountain chain and are a widespread and competitive forest type in Europe, often creating monospecific stands despite different ecological conditions (Ellenberg, 1988; Pignatti, 1994; Willner et al., 2017). There is no riparian forest (i.e., alder stands; *Alnus glutinosa*) along the lakeshore (Figure 1); a band of Cyperaceae separates the water body and the forest edge. Nearby, the Rubbio State Forest, first established in 1910 and then designated as a Natural Reserve in 1972, includes an *Abies–Fagus* mixed forest with centuries-old specimens. Today the Reserve is part of the Natura 2000 Network (code: IT9210300) given its high natural value and conservation status. The forest currently has a volume stock of 460 m^3 ha^{-1} and a growth rate of ~10 m^3 ha^{-1} $year^{-1}$. At lower elevations, deciduous oaks (*Quercus cerris* L. and *Quercus pubescens* Willd.) become the dominant component of the landscape.

The area lacks a meteorological station close by; climate data are extracted from the management plan of the Rubbio Natural Reserve (https://webgate.ec.europa.eu/life/publicWebsite/project/details/2309). Precipitation and temperature were estimated by interpolating data from 60 meteorological stations scattered in the region of Basilicata. Average precipitation is ~1200–1300 mm $year^{-1}$ with an annual average temperature of ~10–12°C (20–22°C in the warmest month; 2–4°C in the coldest month). Fog is frequently formed in the area, especially during spring and autumn.

The palynological survey

Core recovery and pollen processing

Three ~250-cm long sediment cores were recovered from the edge of the lake in July 2017 using a modified square-rod Livingstone corer. The most complete core (PES17-1E) was composed of three sections (Appendix S1: Figure S1) and bottomed out on gravel. Each section was split, photographed, and subsampled at ~10-cm intervals for pollen processing. The upper part of the core was subsampled at higher resolution to reconstruct forest dynamics and analyze the effectiveness of conservation measures applied during the last century. In total, 22 levels were analyzed from the core.

The extraction of pollen and NPPs was carried out in the Nevada Paleoenvironmental Analysis Laboratory (NevPal, University of Nevada, Reno, USA) during summer 2018. The standard method proposed by Faegri and Iversen (1964) was used for pollen processing, and a known quantity of exotic spores

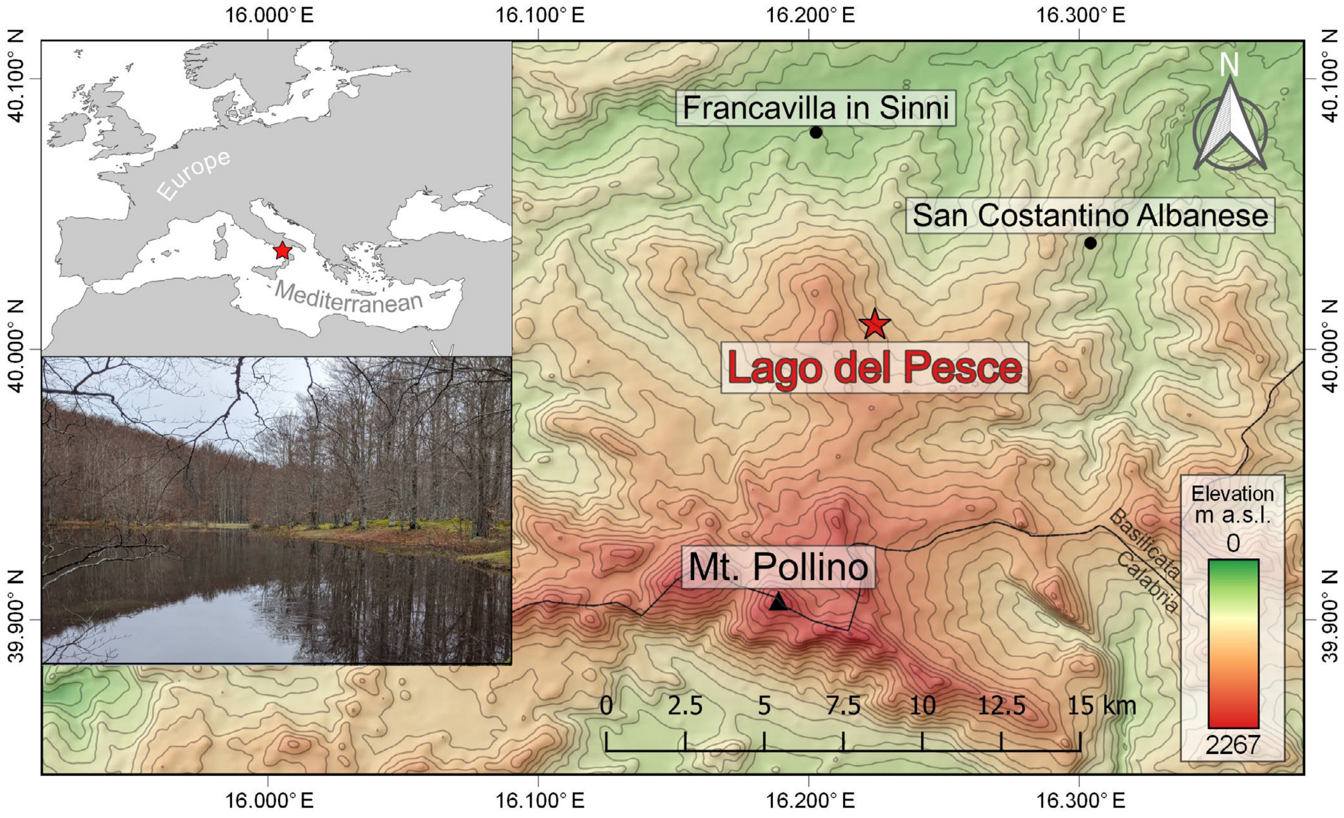

FIGURE 1 Study site map showing the position of Lago del Pesce, Mt. Pollino and the two nearby modern urban centers cited in the text. Insets in the upper-left corner: the study site location in the Mediterranean basin (top); a photograph of Lago del Pesce (bottom). Photograph credited to Edward M. Schoolman.

(*Lycopodium* spp.) was added for calculating pollen concentration (Stockmarr, 1971).

Age–depth model

The age–depth model is based on six ^{14}C accelerator mass spectrometry (AMS) ages from plant remains and charcoal particles (Table 1) using the R package *RBacon* (Blaauw & Christen, 2018; R Core Team, 2017). Radiocarbon dates were calibrated using the IntCal20 calibration curve (Reimer et al., 2020) within the *RBacon* package. The sediment of the upper 20 cm was dated using the fallout of ^{137}Cs associated with the atmospheric nuclear tests (~1950 to ~1980); the ^{137}Cs peak was attributed to 1963 (Foucher et al., 2021).

Palynological analysis

Terrestrial and aquatic palynomorphs were identified using reference material provided by the Nevada Paleoenvironmental Analysis Laboratory, along with manuscripts and published dichotomous keys (e.g., Beug, 2004; Chester & Raine, 2001; Reille, 1992). Pteridophyte spores were clustered into two groups—monolete and trilete—based on morphological features (Erdtman, 1943). Nonpollen palynomorphs surveyed for this study were: (1) spores of coprophilous fungi, particularly *Sporormiella* type and *Sordaria* type (van Geel et al., 2007); (2) green algae of the genus *Pediastrum* (Jankovská & Komárek, 2000); and (3) chlamydospores of *Glomus* sp. (van Geel et al., 1989). Microcharcoal particles were counted along with pollen on the same slides and assigned to two size groups—50–125 and >125 μm—according to Sadori and Giardini (2007).

Concentration for pollen and charcoal was calculated in grains cm^{-3} using added *Lycopodium* sp. spores (Stockmarr, 1971). Pollen accumulation rates (hereafter pollen influx) were obtained by dividing concentration values by $year^{-1}$ cm^{-1} given by the age–depth model.

A cluster analysis was carried out on the percentages data to investigate the principal pollen zones. Only terrestrial taxa present in at least three samples were included in the clustering. We used the Unweighted Pair Group Method with Arithmetic (UPGMA) (paired group) algorithm and the Bray–Curtis similarity index to compute the hierarchical clustering. The same similarity index

TABLE 1 Accelerator mass spectrometry radiocarbon dates of six plant macro-remains from Lago del Pesce.

Label	Depth (cm)	Fraction modern (±)	$D^{14}C$ (±)	^{14}C age (BP) (±)
Surface	0	n/a (n/a)	n/a (n/a)	−67 (5)
179602	50	0.9611 (0.0039)	−38.9 (3.9)	320 (35)
179603	122	0.9211 (0.0038)	−78.9 (3.8)	660 (35)
7003 (*)	196	0.8129 (0.0019)	−187.1 (1.9)	1665 (20)
7004	226	0.8666 (0.0016)	−133.4 (1.6)	1150 (15)
7005 (*)	239	0.8890 (0.0020)	−111.0 (2.0)	945 (20)
179604	247	0.8805 (0.0035)	−119.5 (3.5)	1020 (35)

Note: The surface sample was arbitrarily set on the coring year (AD 2017 = −67 BP) (Blaauw & Christeny, 2011). Ages marked with (*) were rejected by the model.

(Bray–Curtis) was also used to perform nonmetric multidimensional scaling (NMDS) on the pollen influx data. Calculations were carried out using the software Past (Hammer et al., 2001).

Reconstructing vegetation history

Differences in pollen and spore production and dispersal among species can bias the reconstruction of past plant communities (e.g., richness and composition) based on pollen percentages. Due to the small size of Lago del Pesce (0.25 ha) and its isolation, it was not possible to use models based on pollen productions, pollen fall speeds and dispersal modalities (e.g., Sugita, 2007; Theuerkauf et al., 2016; Theuerkauf & Couwenberg, 2021) for estimating the past vegetation composition. Thus, to understand the extent of the bias, we compared influx pollen data with GIS-derived data (see below) of the areas occupied by different forest types.

In this study, we supported the interpretation of pollen spectra and the transition from one pollen zone to another through independent proxies, including historical narratives, tree-ring data paleoclimate data, and land-use maps. These independent proxies are briefly presented in this section and then used to discuss the results of the palynological survey.

Historical narratives

Historical narratives represent a key pillar of studies in historical ecology. In this study, the detailed historical narratives were considered as part of the environmental context that constrained forest landscape dynamics. We considered the historical outline of the area focusing on the foundation of settlement, monasteries, and towns nearby the site, changes in the way land were used and managed (e.g., monks and Bourbon regulations), major regional events described by secondary literature (e.g., the Unification of Italy). A special focus on the medieval regional history is presented in the Appendix S1: Section S1.

Tree-ring data

Apart from the palynological survey, we reconstructed a tree recruitment history for Bosnian pine (*Pinus heldreichii* H.Christ) of the subalpine belt in the Pollino National Park with the aim of comparing pollen-based forest reconstruction with an independent proxy able to describe past vegetation dynamics and responses (Sangüesa-Barreda et al., 2020). Details on the dendrochronological methods can be found the Appendix S1: Section S2, and in the original publication (Piovesan, Biondi, Baliva, Dinella, et al., 2019).

Paleoclimate sources

The biological and ecological evidence coming from the palynological survey, and the reconstructed recruitment history of subalpine pine trees, have been placed in a climatic context inferred by paleoclimate studies. We considered North Atlantic Oscillation (NAO) phases (Franke et al., 2017), a sea surface temperature (SST) reconstruction from the Sicily Channel based on Mg/Ca ratios measured on planktonic foraminifer (Margaritelli et al., 2020), and a tree ring-based summer temperature reconstruction from Mt. Smolikas (Greece) (Esper et al., 2020). Mt. Pollino and Mt. Smolikas lie at the same latitude ∼400 km apart, in the Italian and Balkan peninsula, respectively. We also considered the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) (Lüning et al., 2019) as part of the broader climatic context. Furthermore, we considered phases of increased fluvial activity recorded at a regional scale (Basilicata, Italy) (Piccarreta et al., 2011). The detailed climate context of the area in the last millennium is presented in Appendix S1: Section S3.

Land cover maps and remote sensing analyses

The historical distribution of silver fir was reconstructed using the Rubbio State Forest parcel map of 1914 and the historical topographic map of the Italian Military Geographic Institute (IGM, 1956/58) in raster format. The current landscape around Lago del Pesce was analyzed by customizing the land-use/land cover (LU/LC) classes from CORINE Land Cover 2018 data. Last, the current distribution of silver fir in the study area was obtained as raster pixel-based analysis from optical satellite images of the Sentinel constellation (https://www.copernicus.eu/en) of the European Space Agency (ESA). Further information on the development of land cover maps and remote sensing analyses is in given Appendix S1: Section S4.

RESULTS

Palynological results

Chronology

Six radiocarbon ages were obtained on plant macrofossils and charcoal fragments (Table 1). A surface age was arbitrarily set based on the coring year, 2017 (Blaauw & Christeny, 2011). ^{137}Cs analysis revealed elevated ^{137}Cs in the 6–20 cm depth section of the core (Appendix S1: Figure S2). Nearly identical ^{137}Cs activities in the 6–14 cm core interval suggest that the ^{137}Cs in this core is primarily derived from surface run off and terrestrial erosion. We assumed that the 1963 peak bomb due to atmospheric fallout was present at the 13–14 cm section when the increasing trend of ^{137}Cs moved to an asymptote (Appendix S1: Figure S2). Two radiocarbon dates were rejected by the model as outliers (Figure 2). The final output defines a chronology that covers ~1100 years (from approximately AD 900 to the present day), with a nearly constant sedimentation rate (4.40 ± 1.50 year^{-1} cm^{-1}). The model highlights that a higher sedimentation rate occurred in the upper 20 cm of the core (Figure 2).

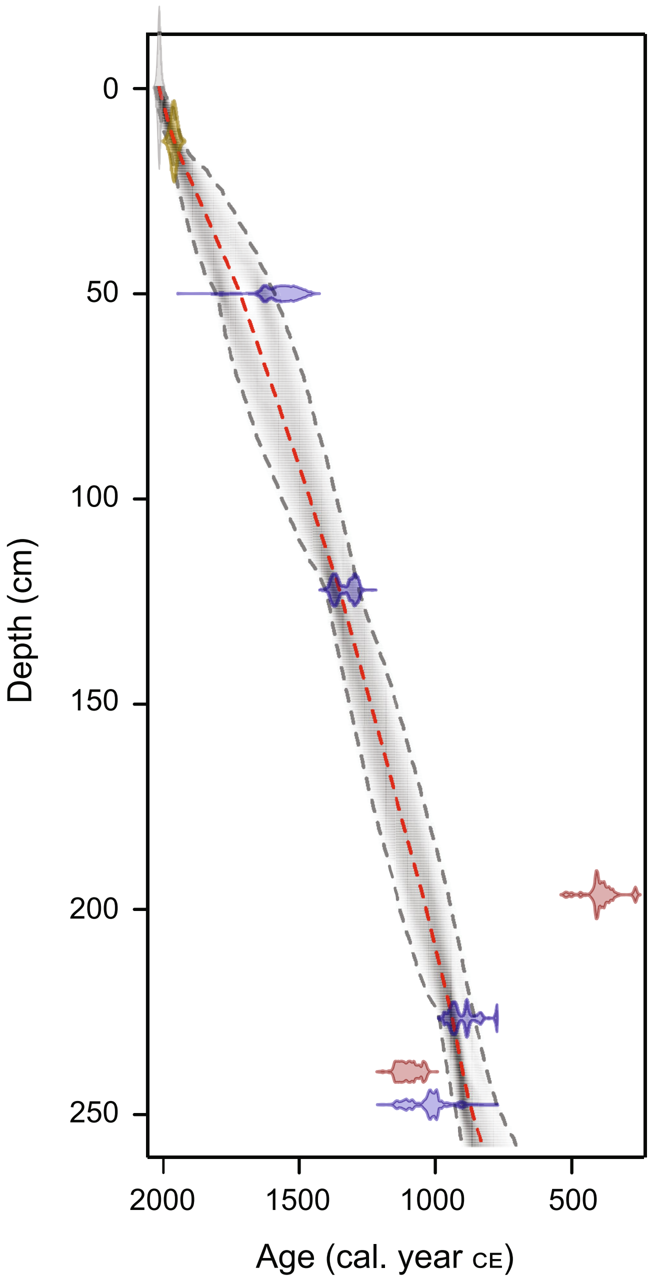

FIGURE 2 Age–depth model based on six accelerator mass spectrometry calibrated ages and the ^{137}Cs peak. In yellow, the ^{137}Cs date (1963). In blue, radiocarbon dates included in the model. In red, radiocarbon ages rejected by the model. The gray area represents the 95% confidence interval and the red dotted line represents the best estimate (median values). See Table 1 for details on radiocarbon dates.

Pollen zones

Pollen diagrams describe the relevant turnover of vegetation cover over time (Figures 3–5). Three main pollen zones were interpreted from the cluster analysis performed on pollen percentages (Figure 3). Zone 2 was further subdivided into three subzones supported by different historical events. The transitions among different environments along our chronology are supported by nonmetric multidimensional scaling performed on pollen influx data (NMDS, Figure 4). The pollen dataset from Lago del Pesce is available in the Neotoma Paleoecology Database repository: Neotoma Paleoecology Database repository at https://doi.org/10.21233/QRZ8-H393.

Zone 1 (900–1070 CE)

In Zone 1, the dominant pollen/spore types were ferns (45%) and herbs/grasses (40%) whose main components

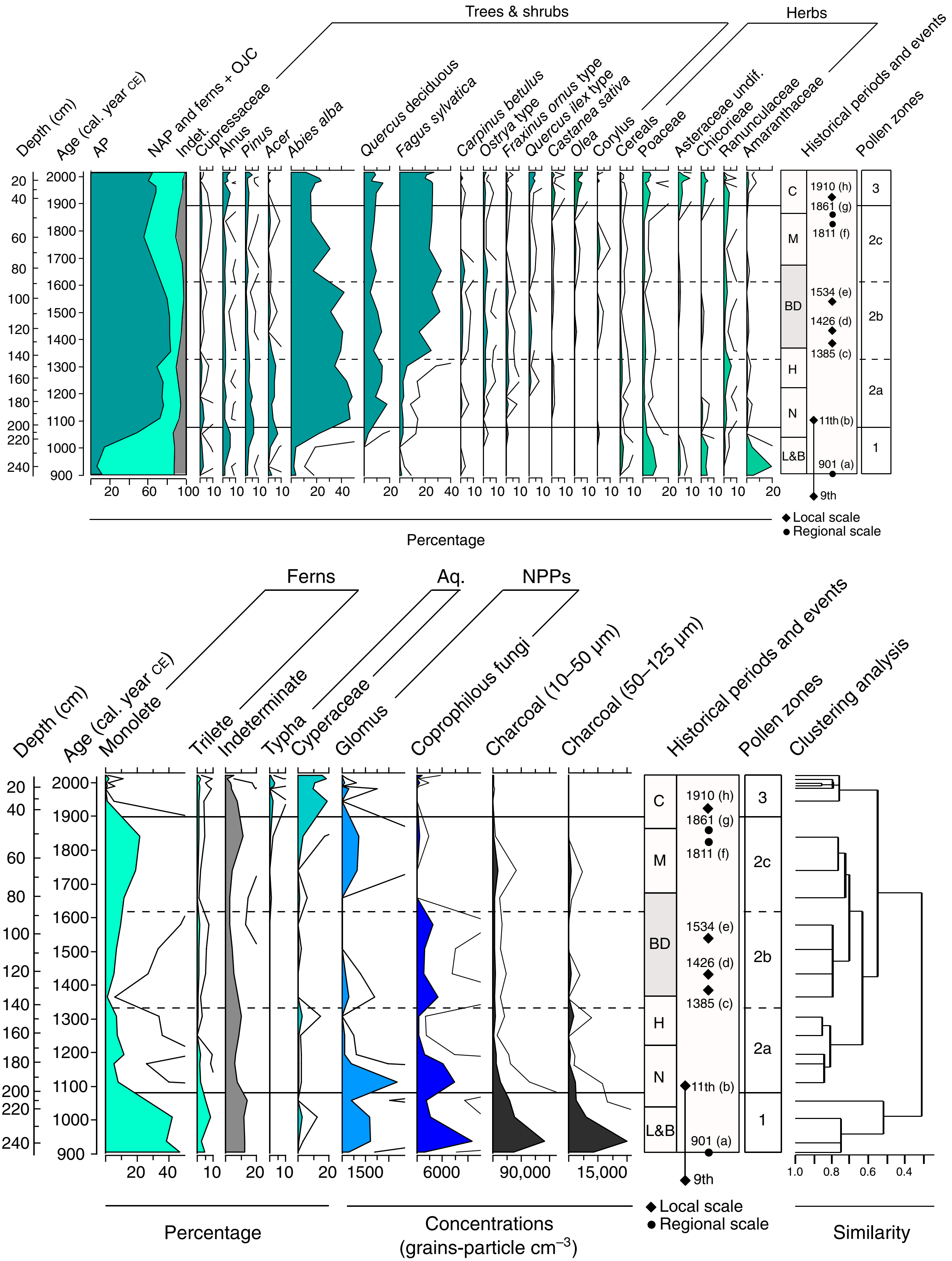

FIGURE 3 Legend on next page.

were Amaranthaceae, Asteraceae (Asteroideae and Cichorioideae), and Poaceae (Figures 4 and 5). Cereals were found in lower quantities than weedy types, and numerous herbaceous taxa were present along with spores of coprophilous fungi (*Sporormiella* type and *Sordaria* type), *Glomus* sp. chlamydospores and charcoal particles (Figure 3). Woody vegetation was present in trace amounts, largely represented by pioneer and disturbance-related arboreal taxa such as pine (*Pinus* subg. *Diploxylon*), alder (*Alnus*), juniper (Cupressaceae), and maple (*Acer*). Late-successional *taxa* such as silver fir (*A. alba*) and beech (*F. sylvatica*) were present in low percentages (<5%).

Zone 2 (1070–1890 CE)

During this time period, forest species become a dominant pollen type. Vegetation change within Zone 2 was primarily due to relative abundance of each taxon. Arboreal species showed a shift from early successional pioneer (e.g., *Acer*, *Alnus*, *Pinus*, Cupressaceae) to mixed forest dominated by late-successional species (*Abies* and *Fagus*). The clustering supported the presence of three subzones that show a different balance of taxa (Figure 3):

1. Subzone 2a (1070–1330 CE). The first pollen subzone is characterized by a rapid increase and persistence in the percentage of silver fir (Figures 4–6). Starting from an average value of ~5% in Zone 1, *Abies* increases to 45% in less than a century. The floristic composition abruptly changes from a grassland to a forest ecosystem. Forest taxa, such as oak, beech, and maple, European hop-hornbeam (*Ostrya* type) as well as early pioneer species such as south European flowering ash (*Fraxinus ornus* L.) increase much more slowly than silver fir. Disturbance taxa such as ferns, herbs, and shrubby plants (Cupressaceae) have lower percentages than in Zone 1. Following this trend, charcoal particles have an abrupt decrease as well, whereas coprophilous fungi and *Glomus* sp. halve their percentages (Figure 3). The total arboreal pollen sum shows amounts of up to 80%. Other than *A. alba* (50%), the forest community was composed of deciduous *Quercus* (showing a peak of ~20%), *F. sylvatica* L. (5%–10%), *Acer* sp. (5%–10%), *Alnus* sp. (~5%), *Pinus* sp. (~5%), and Cupressaceae, Rosaceae, *Ostrya* type, *Fraxinus ornus* L., *Ulmus* sp., *Carpinus betulus* L., and *Quercus ilex* L. (<5%). Although the composition became more complex, the landscape is dominated by *A. alba* that appears to yield little space for the spread of other woody species. Herbs and ferns kept decreasing their percentages followed by coprophilous fungi, *Glomus* sp., and charcoal particles that fell to values of a few percent (Figure 3).
2. Subzone 2b (1330–1615 CE) is characterized by the rise of beech (up to 34%) along with deciduous oaks (up to 14%) and persistence of silver fir (30%–40%). Beech and silver fir show a dynamic complementary balance, in which an increase of one corresponds to a decrease in the other. Herbaceous taxa are poorly represented, although ferns (monolete) consistently increase their percentage values, accounting for ~11% at the end of Zone 2b.
3. Subzone 2c (1615–1890 CE) is characterized by the beginning of a decline in silver fir that decreases to as low as 16% (Figure 3). Beech became dominant (25%–35%), while deciduous oaks are stable at ~10%. Herbaceous taxa, particularly ferns, slowly but consistently increase their percentage values, reaching ~20% by ~1840 CE before declining to near zero.

Zone 3 (1890–2017 CE)

Beech and deciduous oaks showed stable percentages values—respectively 20%–25% and 8%—up to recent times (Figure 3) when silver fir marked an oscillating trend in alternation with the other tree species (Figure 3). The total sum of herbs and grasses reaches values higher than seen in the previous centuries (20%). The main weedy taxa found in this zone are Ranunculaceae, Poaceae, Asteraceae, and Caryophyllaceae. Cultivated plants, that is, cereals, *Cannabis sativa* L., *Castanea sativa*, and *Olea europaea* L., are present as well (Figures 4 and 5). Aquatic plants (*Typha* sp. and Cyperaceae) first appear at the end of Zone 2c and increase in Zone 3. Finally, the current compositional arrangements are distinguished by a greater abundance of Mediterranean evergreen species (*Quercus ilex* type) and cultivated trees (*Olea*).

FIGURE 3 Pollen diagram of selected pollen percentages and palynomorphs concentrations. Blank unfilled lines are 5× exaggeration. On the right side, the historical periods and events cited in the text. BD: Black Death; C: Contemporary; H: Hohenstaufen; L&B: Longobard and Byzantine; M: Modern; N: Normans. (a) Conquest of Reggio Calabria by Muslims; (b) rise of several monasteries in the region of Basilicata; (c) foundation of San Nicola in Valle monastery; (d) foundation of Francavilla in Sinni; (e) foundation of San Costantino Albanese; (f) Bourbons role on forest management; (g) unification of Italy; (h) establishment of the State Reserve. Hierarchical clustering (on the right) was performed using the Unweighted Pair Group Method with Arithmetic Mean (UPGMA) (paired group), Bray–Curtis similarity index.

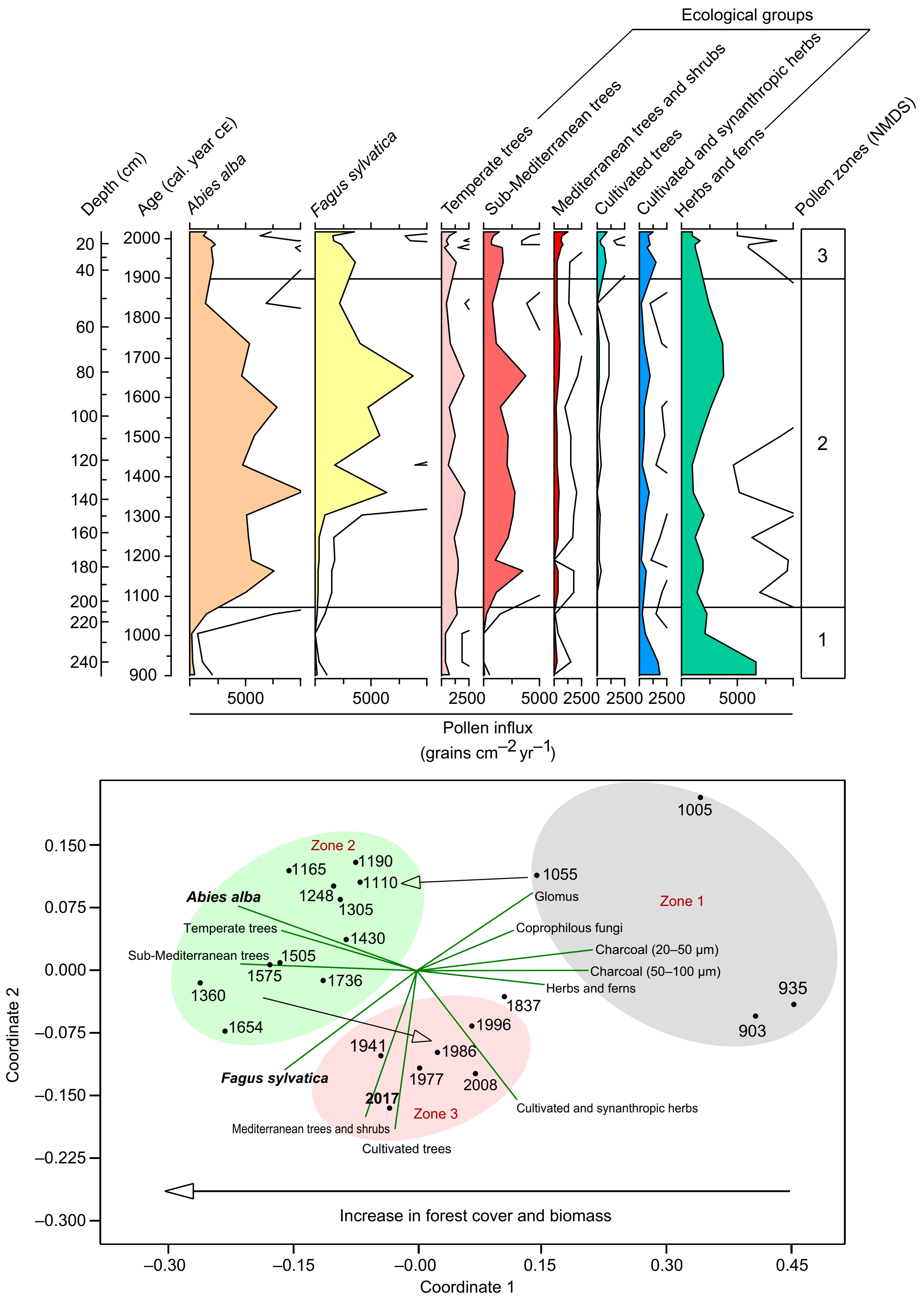

FIGURE 4 Legend on next page.

Palynological evidence versus tree recruitment and forest composition

Selected tree pollen influxes from Lago del Pesce show a very similar long-term trend with the reconstructed recruitment density of Bosnian pines from the nearby subalpine elevation belt (Figure 5a,b). Both feature a bell-shaped distribution coincident with the recurrent plague period up to the first half of the 17th century, and then decreasing toward the present. Whereas tree-ring records resulted in phase with the forest pollen influx from Lago del Pesce, arboreal taxa percentages increased much earlier due to the massive expansion of silver fir (Figure 3). The longevity of Bosnian pine is quite remarkable, with one tree (*Italus*, 1233 years old; Piovesan, Biondi, Baliva, Dinella, et al., 2019) older than the basal age of the sediment core from Lago del Pesce.

Lago del Pesce is located in a clearing inside a beech forest. The mixed forest dominated by large silver fir extends upstream over an area of 55.20 ha in the southwest area (1197 m average distance, minimum distance 578 m from the lake). Analysis of historical maps with the current distribution of silver fir shows that the fir population is present only inside Rubbio State Forest (Figure 6). However, whereas the area occupied by silver fir has been stable since the 1950s, the map of 1914 suggests a different distribution of silver fir, likely to be closer to the lake (Figure 6).

The comparison between the current vegetation cover of the forest types (percentage of the total area analyzed in a given radius) and pollen influx of the dominant forest species shows a good correlation that culminates in a radius of between 1.5 and 2 km from the lake's center (Appendix S1: Figure S3). As expected, beech dominates the pollen rain. Fir pollen shows the highest pollen influx-vegetation cover ratio compared with the other forest types (Appendix S1: Figure S3).

DISCUSSION

Drivers of vegetation change in Lago del Pesce

900 to 1070 CE: Managed pastureland

In southern Italy, pastoralism has a long history dating back more than 2500 years and has been described by continuous records until modern times (Florenzano, 2019). In this context, human-induced fire was used to clear forests and to manage pastures and agricultural fields (slash and burn agriculture) (Montanari & Stagno, 2015). The pollen record from Lago del Pesce during the 10th century shows evidence of a landscape characterized by grasslands, livestock, and fire. This pollen assemblage, with high frequencies of *Glomus*, Amaranthaceae, and Asteraceae, low pollen concentrations, high amounts of indeterminate pollen grains, and high amounts of charcoal could represent taphonomic processes with deterioration and loss of susceptible palynomorphs, however given the local historical records we hypothesize intensive land-use practices associated with periodic burning.

Muslim raids along the coast of southern Italy, along with the warm climate phase of the ninth century, contributed to moving agricultural laborers toward the use of middle–high elevation mountain lands. Nearly all the earliest records from the monastery of Sant'Elia, which were preserved as single documents confirming the monastery's ownership of property holdings through the records of sales and donations, describe the improvements undertaken on the land and especially the clearing of forests (Appendix S1: Section S1). These improvements may have drawn more people to settle in the inner mountain land of Basilicata during this period. People were also potentially drawn by the hospitality of several monastic communities that settled in the inner mountain land of Basilicata, as well as the robust economy and connections that existed

FIGURE 4 Upper panel: Pollen influx (grains^{-1} cm^{-2} year^{-1}) of *Abies alba* and *Fagus sylvatica* compared with the following ecological groups: Temperate trees (*Fraxinus excelsior* type, *Tilia*, *Pinus*, *Ulmus*, *Acer*, *Alnus*, *Carpinus betulus*, *Corylus*), sub-Mediterranean trees (*Quercus* deciduous, *Fraxinus ornus* type, *Ostrya* type, Rosaceae), Mediterranean trees and shrubs (*Quercus ilex* type, Cupressaceae, *Phillyrea*, Ericaceae, *Pistacia* type, *Rhamnus* type), cultivated trees (*Castanea sativa*, *Olea*, *Vitis*, *Juglans*), cultivated and synanthropic herbs (Poaceae, cereals, *Urtica*, *Plantago lanceolata*, *Plantago* sp., *Chicorieae*, *Trifolium*, *Rumex*), herbs and ferns (*Artemisia*, Asteraceae undiff., Ranunculaceae, Amaranthaceae, *Galium*, *Salvia*, Caryophyllaceae, Apiaceae, Scrophulariaceae, Brassicaceae, *Primula*, Fabaceae, *Sanguisorba*, *Polygonum*, Monolete, Trilete). Blank unfilled lines are 5× exaggeration. Pollen zones from Figure 3 are shown on the right. Lower panel: nonmetric multidimensional scaling (NMDS) performed on pollen influx data in the upper panel, based on the Bray–Curtis similarity index (stress = 0.07; axis 1 = 0.82; axis 2 = 0.07). Black circles represent the location in biplot space of pollen levels. Associated numbers represent ages (cal year AD) for each pollen level. The direction and relative length of taxon vectors should be considered as the relative contribution of each record considered. Color ellipses include levels defined by pollen zones from Figure 3. cal. year = calibrated year.

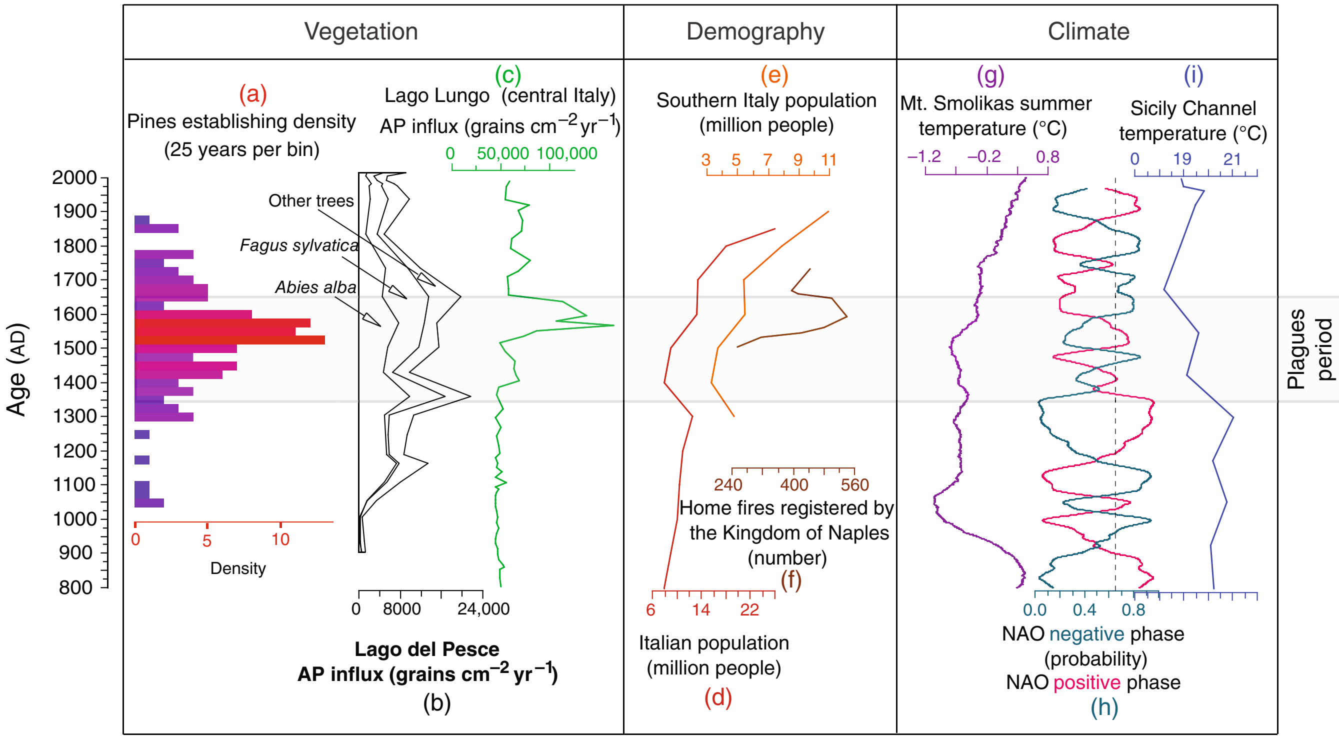

FIGURE 5 Comparison among vegetation, demography and climate data included in the study. (a) Bosnian pines' establishing density; (b) Lago del Pesce selected pollen influx (*Abies*, *Fagus*, total trees); (c) Lago Lungo (central Italy) tree and shrub pollen (AP) influx (from Mensing et al., 2015); (d) Italian population (from Lo Cascio & Malanima, 2005); (e) southern Italy population (from Malanima, 2016); (f) number of home fires registered by the Kingdom of Naples (from Fusco, 2009); (g) summer temperature reconstruction from Mt. Smolikas (Greece) smoothed by moving average filter, 150 points (from Esper et al., 2020); (h) North Atlantic Oscillation (NAO) positive and negative phase reconstruction smoothed by moving average filter, 30 points. The dashed line indicates the reliability threshold, that is, ≥0.66 degree of belief (from Franke et al., 2017); (i) Sicily Channel temperature reconstruction (from Margaritelli et al., 2020). The plague period (in gray) refers to a period of recurring plagues outbreaks spanning from 1346 (Black Death) to 1658 CE (the Naples Plague).

between the neighboring region of Apulia and the rest of the Byzantine Empire (Arthur, 2021). Monks allowed wayfarers (or people fleeing from violence in nearby regions) to establish small villages close to the monastery, and the resulting workforce played a key role in the reclamation of the wild and inaccessible mountain lands of Basilicata (Sogliani, 2015). The reclamation process could have caused the severe anthropogenic disturbances that degraded the forest ecosystem around Lago del Pesce in the 10th century. There are no other high-resolution pollen records from the inner mountain of Basilicata to be compared with Lago del Pesce. During the same period (10th century) a high anthropogenic impact on forest vegetation has been identified in an inner valley of central Italy (Mensing et al., 2018).

1070 to 1330 CE: Establishment of silver fir forest

At the passage of the 10th century into the 11th century, the abrupt decline in charcoal, coprophilous fungi and herbaceous taxa, and the exponential increase of silver fir could be linked to a cool wet climatic phase characterized by flood events and increased snowpack persistence in the mountains supported by independent paleoclimate sources (Esper et al., 2020; Franke et al., 2017; Piccarreta et al., 2011) (Figure 5g,h). Alternatively, the rapid conversion from grassland to silver fir-dominated forest in the 11th century could be the result of new priorities of forest management introduced by the Normans at a time when a cooler, wetter climate facilitated forest expansion. In the 11th century, the Normans arrival brought a new set of sociopolitical priorities to the region, activities captured in medieval Latin narrative texts (Appendix S1: Section S1). Local Norman rule introduced new restrictions on the exploitation of forests, as the Normans recognized the valuable resources that could be taken from woods (e.g., carts, agricultural tools, beams for buildings) (Pasquarello, 1998). Most of the royal woodlands were managed by a *magister foresterii*, a professional role thought to supervise activities carried out in the woods (including, e.g., tree cutting, deadwood harvesting,

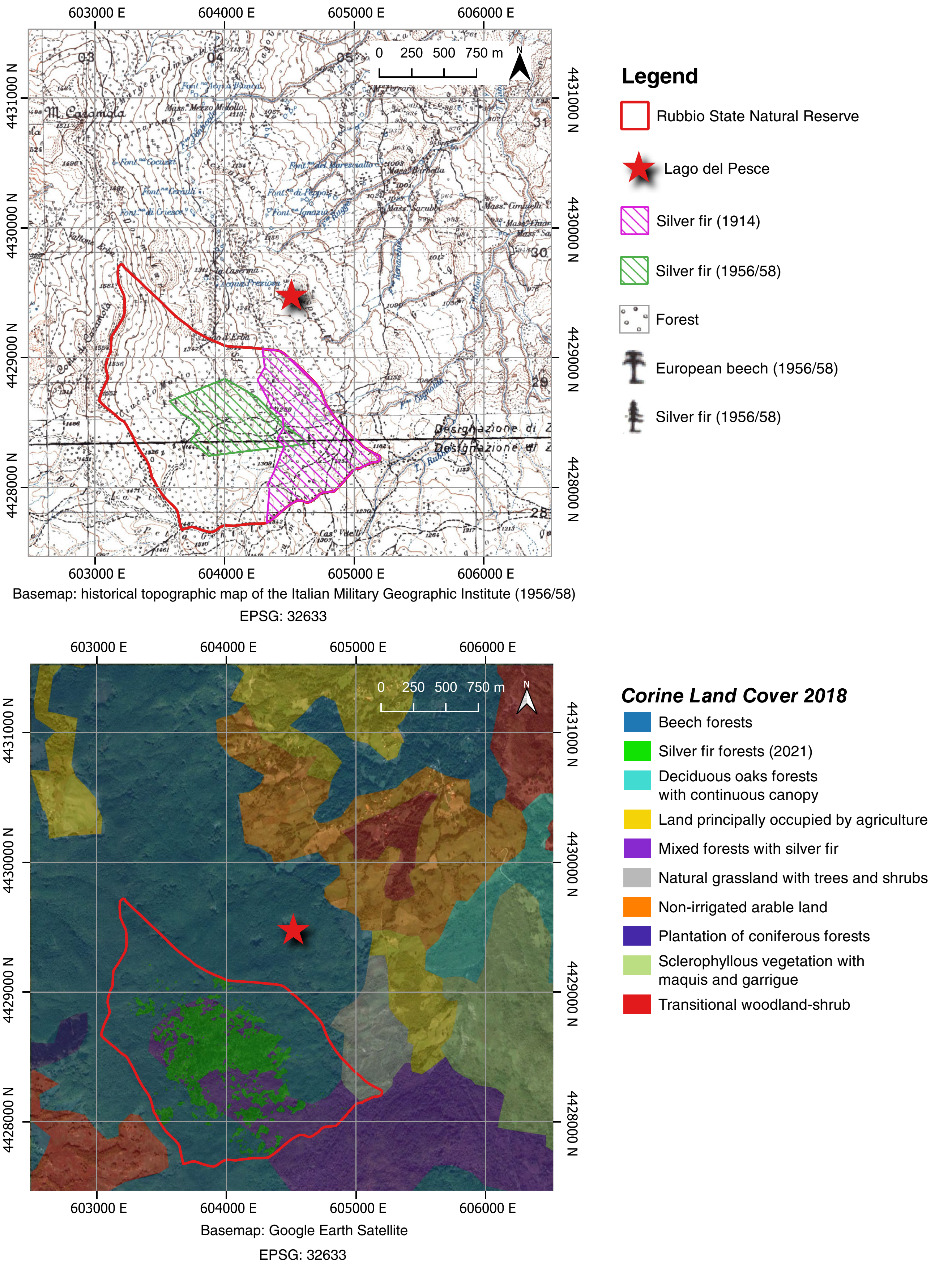

FIGURE 6 Land use and forest cover maps. Upper map: the historical distribution of silver fir (IGM plus the 1914 distribution). Lower map: the current landscape around Lago del Pesce (CORINE). The current boundaries of the Rubbio Natural Reserve are shown.

hunting, livestock management) (Cascella, 1991; Musca, 1987; Pasquarello, 1998). The payment of a tax was required to use forest resources, and specific regulations were enforced on valuable forest species such silver fir, elm, or cypress, species of particular interest because their size allowed them to be used for beams (Pasquarello, 1998). Fir, in particular, had long been noted for its "fast" development and straight growth (Musca, 1987). In these stands (often under a royal or later imperial reserve status) cutting activities and grazing of livestock were forbidden and wildlife that were capable of damaging young trees were controlled (Musca, 1987). The outcomes of this new socioeconomic pattern are corroborated by our palynological record from Lago de Pesce. Changes in climate and human activity appear to have operated in a synergistic fashion resulting in fast forest landscape expansion.

Our hypothesis on the role that Normans played in supporting a natural forest recovery needs further attention. The first written evidence of humans supporting silver fir regeneration comes from the 13th century, when a monastic Benedictine community settled in Camaldoli (northern Apennines) began to protect and promote silver fir over other species for spiritual purposes (Bottacci, 2012). In the following centuries, this practice evolved into a silvicultural system based on clear-cutting followed by sapling plantations aimed at creating an even-age structure of the silver fir stands (Bottacci, 2012). As far as we know, this represents the first evidence of forestry in Europe along with the pinewood plantations around Nuremberg of the 14th century (Radkau, 2012). The singular silver fir expansion occurring at the beginning of the 11th century in Lago del Pesce could be interpreted as a natural process (i.e., rewilding), a human-driven process (i.e., forest management and/or special cares toward silver fir), or more likely a combination of the two. Of note, in the pollen record of the nearby Tyrrhenian coastal mountains of Calabria (southern Italy) (Joannin et al., 2012), silver fir did not recover in the last 1000 years and the reasons for this difference should be investigated further.

Once established, silver fir held its dominance in the area for almost three centuries. Our pollen record reveals an *Abies*-centered landscape in the period of the 11th through 13th centuries coinciding with evidence of continued human activity, a growing population, and climate stability. In synthesis, the brief cool wet climate associated with a negative NAO (Figure 5h) between the 10th and the 11th centuries may have contributed to the initial fir establishment in such a short time. However, during the following two centuries, the forest (and in particular silver fir) seems to have been protected by local land-use priorities.

1330 to 1615 CE: Succession to beech–fir forest

Not until the 14th century, after the end of the Norman–Hohenstaufen dynasty in southern Italy (Appendix S1: Section S1), and the outbreak of the Black Death epidemics across Italy and Europe, did beech finally become a major component of this forest. By AD 1350 the forest ecosystem became characterized by varying co-dominance of *Abies* and *Fagus* conforming to a pattern of beech–silver fir alternation (Petritan et al., 2015).

Our results suggest the beginning of a long-term plague-related rewilding phase, beginning with the Black Death of 1346–1352 and finishing in coincidence with the Naples plague of 1656–1658, supported by a cooler wetter climate consistent with studies from across much of Europe (Ljungqvist et al., 2018; Mensing et al., 2020; Piovesan, Biondi, Baliva, Dinella, et al., 2019; Sangüesa-Barreda et al., 2020; van Hoof et al., 2006; Yeloff & van Geel, 2007) (Figure 5g–i). A steady increase in tree pollen influx along with the increased recruitment density of pine trees in the subalpine elevation belt (Figure 5a,b) supports the interpretation of expanded forest cover in the area of Lago del Pesce. This period of rewilding and forest expansion coincides with a major period of forest recruitment in different Mediterranean subalpine forest ecosystems (Sangüesa-Barreda et al., 2020). These parallel insights suggest that the rewilding event started in the middle of the 14th century was a large-scale process in the Pollino massif, potentially involving lands from the foothills to the subalpine environment. The high mortality during the Black Death pandemic (Figure 5d,f) caused a decline in the population of southern Italy (Figure 5e) that was followed by land abandonment and rewilding mountain landscapes in agreement with central Italy (Izdebski et al., 2022).

In the period from the 14th to the first half of the 17th century, the forest ecosystem gained its greatest tree density on record, as inferred from the forest pollen influx (Pidek et al., 2010; Seppä & Hicks, 2006). This interpretation is also supported by historical documentation of dense and wild forests around the San Nicola in Valle monastery, which was founded in 1395 and located immediately below our study site (Giganti, 1978). Even livestock were described as completely absent in these mountains because they were devoid of roads and inhabited by wild predators (e.g., wolves) considered dangerous for people (Giganti, 1978). Archaeological surveys in the Sinni valley (below our study site) found that several fortified centers were abandoned between the end of 14th and the onset of the 15th centuries due to the fall of the Angevin Kingdom of Naples and the ensuing sociopolitical instability in southern Italy (Vitale, 2018).

1615 to 1890 CE: Intensified forest exploitation

In the Modern Era, population growth might have contributed to the shrinkage of forest cover that has also been recorded southern and central Italy (Allen et al., 2002; Joannin et al., 2012; Mensing et al., 2018). As a population grows and the demand for natural resources rises, we can assume that the foundation and expansion of the large San Nicola Abbey and local rural villages of Francavilla in Sinni (established in 1426) and San Costantino Albanese (established in 1534) (Figure 1) gradually began to reclaim the wildlands of the area and to exploit local wood resources. Woods were heavily exploited for building construction, home heating, and the manufacture of wood products by the monks (e.g., hand-inlaid cabinets to be traded; Giganti, 1978). The human footprint is suggested by evidence of a less dense forest with an increased presence of cultivated plants in the last century, including increased cereal and olive cultivation, likely to have come from the foothills (Figure 4). The decline of forest species increased in the 18th century, as highlighted by both the tree pollen percentage trends and tree pollen influx. However, the introduction of forest laws in the first half of the 19th century that governed timber harvesting and prohibited deforestation appear to have halted the degradation of the forest ecosystem (Figures 4–6b).

Century-long conservation practice targeted at silver fir

From intensive exploitation to nature conservation

Silver fir was characterized by an important decline, although it never left the area of Lago del Pesce in the last 1000 years. At this site, fir pollen influx resulted in high values in respect to the European silver fir's average values (see Figure 6 in Abraham et al., 2021). Today the local fir population is limited to the upper mountain belt inside the Rubbio Natural Reserve (Figure 6).

Our pollen record is the first example of silver fir ecosystem renovation following phases of intensive land exploitation in a Mediterranean mountain context. In the Middle Ages, forests were heavily exploited throughout Europe, especially at the expense of mesic species that were widespread in the lowlands (Fyfe et al., 2015; Mensing et al., 2015; Piovesan, Mercuri, & Mensing, 2018). Many studies have attributed silver fir site-specific adaptions to Mediterranean climate conditions to either gene diversity or phenotypic plasticity (Büntgen et al., 2014; Čater & Levanič, 2019; Dobrowolska et al., 2017; Dorado-Liñán et al., 2019; Tinner et al., 2013). For example, silver fir metapopulations of the southern Apennine (subsp. *apennina*, Giacobbe, 1973) are able to regenerate and grow in bright light and are less affected by drought stress with respect to central Europe populations (Dobrowolska et al., 2017; Giacobbe, 1975), although silver fir remains a late-successional shade-tolerant species. However, these distinctive ecological and genetic traits (Piotti et al., 2017) were not enough to prevent the silver fir population from rarefaction and local extinction. The persistence of silver fir in the area of Lago del Pesce until modern times could be the legacy of past land-use priorities as argued in Mensing et al. (2020). Several authors have agreed that nonclimate factors such as frequent fires, ungulate grazing/browsing, intensive harvesting (e.g., clear-cutting, coppicing, selective extractions, short regeneration period) were major drivers of silver fir population contraction (Büntgen et al., 2014; Di Pasquale et al., 2014; Dobrowolska et al., 2017; Morales-Molino et al., 2020; Py-Saragaglia et al., 2017; Rey et al., 2019; Ruosch et al., 2016; Tinner et al., 2013; Valsecchi et al., 2010; Vitasse et al., 2019). Moreover, in modern times, emissions of acidic sulfates and nitrates have aggravated the shrinking trend of silver fir populations (Büntgen et al., 2014). Most of these drivers are directly or indirectly anthropogenic in nature.

In the Apennine, silver fir has been selectively harvested for a long time (at least since the Roman period) for the quality of lumber. Furthermore, many forests were converted to coppices for charcoal making and beech/oaks were favored over silver fir. In the last centuries the decreasing trend of silver fir around the Lago del Pesce, could be attributed to increasing harvesting through clear-cuttings and expanding coppicing area, which are among the major drivers of silver fir decline in Europe (Dobrowolska et al., 2017). Even the fir forests of Pollino did not escape the clear-cuts carried out in the 1800s and the first half of the 1900s (Iovino & Menguzzato, 1993).

The establishment of Rubbio State Forest in 1910 represented a milestone in the conservation of the fir population (Figure 6). The National Forest Service protected most of the surviving firs, continuing to harvest beech trees until the establishment of the Natural Reserve in 1972, when the management was focused on nature protection. The State Forest conserved the fir population, whereas most of the fir forests in the Pollino area were destroyed by extensive logging campaigns beginning in the early 1900s. In the 1930s, a sawmill specialized in processing fir and pine board, was installed in the vicinity of Lago del Pesce and was in operation until the 1970s. These harvesting campaigns around the lake, supported by an intensification of mechanization, in turn accelerated erosion in the 20th century. Soil erosion as a consequence of the perturbed forest is registered in the sediment with persisting high levels of ^{137}CS after the 1963 peak bomb (Appendix S1: Figure S2). Today, the protected areas support the establishment of wide rewilding areas interconnected with small patches of forest managed with a close-to-nature silviculture, mimicking natural processes.

Silver fir and land-use abandonment: What should we expect?

The landscape history of Lago del Pesce highlights the capacity of silver fir to colonize abandoned lands and to be part of the early-succession stages of forest development in an Oro-Mediterranean environment (Figure 7). This scenario fits perfectly with the ecological succession model proposed for the Carpathians by Volařík and Hédl (2013). Even though these findings come from two different biogeographical contexts, the establishing and developing dynamics of silver fir appear to have been quite similar. The silver fir population expanding upward above the typical upper altitudinal limit of the species in abandoned subalpine pasturelands is further proof that supports the capacity of silver fir to occupy abandoned pastures (Chauchard et al., 2010). In Pollino, silver fir and Bosnian pines populations are making contact in the subalpine elevation belt.

In unmanaged woodlands, the positive effects of abandonment are corroborated by recent studies focusing on tree species richness and balance in mixed stands, also involving soil nutrition and deadwood features (Sitzia et al., 2012). As suggested by our reconstructed Mediterranean landscape history, the abandonment of montane woodland practices does not lead to the complete dominance of beech over silver fir. The high shade tolerance of silver fir ensures its competitiveness under mature stands of beech (Petritan et al., 2015) where, in the absence of specific pressures from external physical and biological agents (i.e., fires, excessive browsing/grazing, intensive forestry), regeneration establishes vigorously (Figure 7; Appendix S1: Figure S4). In fact, thanks to the rewilding regime guaranteed in recent decades by the National Park, silver fir saplings are spreading in the pure beech stands surrounding Lago del Pesce with a greater abundance toward the Rubbio reserve (Figure 7; Appendix S1: Figure S4). However, the growth of fir under the closed canopy is a very slow process, taking up to 100 years or more to achieve sexual maturity (Piovesan & Lüttge, 2018). This "silent" diffusion of fir seedlings and saplings under the closed canopy of beech (Figure 7; Appendix S1: Figure S4) limits palaeoecological reconstructions of rewilding forest landscapes. The pollen of this new generation of silver fir will be recorded in the sediment when natural disturbance events allow their release into the upper canopy. Ideally, in old-growth forests, silver fir regeneration would be favored by natural tree fall. In old-growth forests, the natural fall of large trees creates gaps in the canopy layer, provides downed wood that can be colonized by tree seedlings and, in the case of uprooting, generates a pit and mound microtopography and the associated ecological niches suitable for silver fir (and other mesic species) regeneration (Habashi, 2019). At lower altitudes, silver fir seems to be capable of associating with sub-Mediterranean tree species, provided that anthropogenic disturbances are minimal (Di Pasquale et al., 2014; Vitasse et al., 2019). Although palaeoecological studies have demonstrated the landscape domination of mixed fir forest during dry and warm climate phases of the Holocene (e.g., Morales-Molino et al., 2020), drought events can lead to growth declines in Mediterranean sites (Gazol et al., 2015) and further studies are needed to investigate the impacts of global warming on fir growth and reproduction.

Implications for ecosystem restoration

According to our results, in the Pollino area the highest forest biomass was reached in coincidence with the severe plague phase that dramatically reduced the human population and consequently decreased human pressure on the land (Figure 5d,e). This is a testament to the legacy role past land-use practices have played and will continue to play in shaping Mediterranean ecosystems. Landscape legacies are the baseline for understanding past and future vegetation trajectories and interpreting contemporary ecosystem patterns (Fraterrigo, 2013). In many Mediterranean areas, forest ecosystem functioning and biodiversity is still affected by past land use (e.g., Pedrotta et al., 2021; Tinner et al., 2016).

This historical ecological process is similar to the rewilding that is currently taking place throughout Mediterranean mountains due to the urbanization and relative abandonment of rural land-use practices (Navarro & Pereira, 2015). Our evidence suggests that Mediterranean forests would benefit from the current rewilding episode. Restoration approaches that favor natural regeneration and structural complexity can be highly successful for conserving biodiversity and increasing the carbon stock held in the wooden biomass and soils (Pugh et al., 2019). Forests re-growing as a result of land-use changes would contribute to the melding of fragmented forest ecosystems (Sánchez de Dios et al., 2020) and the recovery of ecosystem functioning (Pugh et al., 2019). For example,

FIGURE 7 Silver fir spreading and regeneration in Mediterranean mountains of southern Italy. (a) Sila National Park: Saplings established under a mature mixed stand; (b) temperate and Mediterranean tree taxa (*Abies alba*, *Fagus sylvatica*, *Quercus petraea*, *Quercus ilex*) in a high-naturality mixed stand in a mountain valley of Aspromonte National Park; (c) light-demanding and shade-tolerant seedlings (*Abies alba*, *Fagus sylvatica*, *Quercus petraea*, *Quercus ilex*) regenerating together in a sunny-dry exposure; (d) silver fir (*Abies alba*) and *Acer opalus* subsp. *obtusatum* regenerating alongside a stone wall in a highly dry and sunny exposure; (e) silver fir nuclei in a rewilding beech forest glade.

the forest growing stock of mixed beech–fir stands recovering toward old-growth status is expected to reach up to 900 m^3 ha^{-1} on fertile soils, with an average value of ~800 m^3 ha^{-1} (Diaci et al., 2007; Lábusová et al., 2019). Old-growth mixed forests where large and tall (40–60 m) silver firs overcome the beech canopy layer create a multilayered vertical profile with structural complexity, canopy roughness, and high carbon stock. The actual growing stock of the Rubbio Natural Reserve is currently half of this benchmark and still far from the attributes shown in late medieval times. Structural and compositional features shown in medieval times represent a target for future forest restoration and conservation efforts.

The restoration of relic beech–fir woods of the Lucano-Calabrian Apennines (Pollino, Sila, Serre, Aspromonte) would also preserve many endemic species belonging to the Arcto-Tertiary geo-flora (Di Pietro & Fascetti, 2005) and wildlife of conservation interest (e.g., the black woodpecker). This represents a special case of ecological planning because of the convergence of carbon sink—and storage—and biodiversity priorities (Reside et al., 2017).

CONCLUSIONS

Our palynological analysis identified landscape dynamics that corroborated strongly with historical sources of sociopolitical changes at the regional scale, in which climate forces have played more of a supporting role in vegetation dynamics over the last millennium. As in the case of the Rieti Basin (Mensing et al., 2018), each historical period is characterized by a unique landscape composition (Figure 4). Today's landscape is dominated by seminatural temperate and sub-Mediterranean forests with a more appreciable contribution of Mediterranean trees. The increase in Mediterranean pollen since the 1980s could be in response to global warming (López-Orozco et al., 2021) and/or less intensive management/rewilding of hilly coppices. Although during most of the 20th century forest harvesting severely impacted forest functioning, structure, and composition, the institution of the Rubbio State Forest (1910), the Rubbio Natural Reserve (1972) and the Pollino National Park (1993) locally conserved silver fir and restored the forest ecosystem (see the recent increase of pollen influx in Figure 5b). Forest composition is today moving toward the ecological space of the late medieval mixed old-growth forest. This study underlines the importance of long-term forest ecological planning for conserving highly biodiverse beech–fir ecosystems (e.g., Alba-Sánchez et al., 2019). However, after four decades of rewilding, pollen influx, and forest composition are still far from the natural attributes of the medieval mixed forest ecosystem. Pollen data and the yet localized silver fir distribution indicate that the return to the natural forest composition will be a long process. Following severe human impacts, the recovery of a mature mixed forest takes only a few centuries (1–3) in a Mediterranean montane context, but returning to a natural demography characterized by old and ancient trees needs a longer time (likely to be more than 500 years; Cannon et al., 2022).

The restoration of mixed stands should be the primary goal toward sustainable forest management (indicator 15.2 of Agenda 2030) and protection of biodiversity in Mediterranean mountains (indicator 15.4). Mixed stands and old-growth forests are also more resistant and resilient to changing climate conditions, especially when characterized by a long forest continuity (Colangelo et al., 2021; Mausolf et al., 2018). This case study could be representative of other protected areas of southern Italy (Sila and Aspromonte National Parks), where particular care has been given to protect and restore mixed forests toward old-growth status. Silver fir is very sensitive to direct anthropogenic disturbances (e.g., fire, grazing, selective forest harvesting), so that monitoring its population can measure the effectiveness of conservation measures. In this sense, silver fir becomes an umbrella species in conservation ecology of Mediterranean mountains. Here, the rewilding represents an opportunity to enlarge the protected areas and their strict protected cores (Agenda 2030, indicator 15.1.2), creating new spaces where natural dynamics can take place without further human interference. Rewilding proved to be a successful tool for forest renovation first in late medieval times, when recurring episodes of plague dramatically affected land-use practices and the local forest gained its greatest biomass and compositional complexity of the last thousand years, and then again in contemporary times, when the establishment of protected areas have contributed to protect and restore the local remnant beech–fir mixed forest.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The pollen dataset utilized for this research is available from the Neotoma Paleoecology Database repository at https://doi.org/10.21233/QRZ8-H393.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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