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Alpine Glacier Reveals Ecosystem Impacts of Europe's Prosperity and Peril Over the Last Millennium

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Key Points:

- Novel ice core microfossil data reveal large-scale dynamics among ecosystems, land use, and climate in Europe
- Proxies preserved in ice cores link land-use change to societal challenges caused by climate events and epidemics
- Agricultural reforms and industrialization disrupted links between climate and land use and led to current environmental challenges

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Information about past ecosystem dynamics and human activities is stored in the ice of Colle Gnifetti glacier in the Swiss Alps. Adverse climatic intervals incurred crop failures and famines and triggered reestablishment of forest vegetation but also societal resilience through innovation. Historical documents and lake sediments record these changes at local—regional scales but often struggle to comprehensively document continental-scale impacts on ecosystems. Here, we provide unique multiproxy evidence of broad-scale ecosystem, land use, and climate dynamics over the past millennium from a Colle Gnifetti microfossil and oxygen isotope record. Microfossil data indicate that before 1750 CE forests and fallow land rapidly replaced crop cultivation during historically documented societal crises caused by climate shifts and epidemics. Subsequently, with technology and the introduction of more resilient crops, European societies adapted to the Little Ice Age cold period, but resource overexploitation and industrialization led to new regional to global-scale environmental challenges.

Plain Language Summary Sophisticated microscopy and geochemistry analyses of glacier ice from the Monte Rosa Massif in the Swiss Alps reveal close linkages among European climate, vegetation, agriculture, pollution, pests, and fire during the past millennium. Our novel time series shows that societal and environmental dynamics were mainly controlled by climate, pandemics, and technological innovations. By placing the glacial information into historical context, we reveal some of the mechanisms that created prosperity and peril in Europe's past. Industrialization and import of maize and other new crops enabled European societies to transcend the crop failures and famines of the Little Ice Age climate period during the 19th century, but unintended environmental consequences resulted, which are now culminating in global warming and species loss.

1. Introduction

Narrative sources written by chroniclers and diarists along with land estate accounts have precise chronologies but are often limited in the covered period and space and do not usually allow extrapolation to an extended region (Brönnimann et al., 2018; Pfister et al., 2015). Most microfossil records from lake sediments documenting ecosystem change lack the chronological precision, temporal resolution, spatial scale, and ecosystem complexity to relate them to short-term historical events that affected a large area (Kidwell, 2015). Ice core studies can address continental-scale climate and pollution impacts with high resolution (Eichler et al., 2017; Loveluck et al., 2018). More recently, microfossils preserved in ice cores (Brugger, Gobet, & Blunier, 2019; Brugger, Gobet, & Osmont, 2019; Liu et al., 2005; Vasil'chuk & Vasil'chuk, 2020) showed the strength to provide vegetation and land use-reconstructions over a large spatial scale with unrivaled chronological precision—and simultaneous access to climate proxies measured in the same ice core (Sigl et al., 2018). However, the potential of microfossil records from ice cores to document vegetation responses to environmental and societal events has largely been unexplored. Here, we provide the first investigation of a glacier ice core from the European Alps to serve as a high-resolution vegetation, land use, and climate archive. We examine how extreme weather, human innovation, crop failures, and pollution shaped European

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ecosystems and how these societies adapted to technological advances in a rapidly changing world. Our approach provides a long-term past analog for ongoing and expected changes, such as societal and ecosystem responses to droughts or warming in Europe (Fischer et al., 2018).

The ice core was retrieved from Colle Gnifetti in the Monte Rosa massif, which forms part of the alpine border between Switzerland and Italy and is located in the heart of the European continent (Jenk et al., 2009; Sigl et al., 2018), where agriculture and other human activities shaped vegetation for thousands of years (Figure 1; Lang, 1994; Rey et al., 2019; Roberts et al., 2018). The Colle Gnifetti glacier saddle, located at an altitude of 4,450 m a.s.l., is an old natural ice archive that has resisted melting due to its high elevation for the past 10,000 year (Jenk et al., 2009). In the ice, microfossils, such as pollen from plants, charcoal from burning biomass, and pollution particles have been preserved. They were brought up to the glacier by atmospheric transport from the surrounding lowlands. Atmospheric transport simulations estimate that the catchment of the Colle Gnifetti site encompasses primarily large areas of northern and central Italy, northern Spain, France, and Switzerland but also includes minor contributions from more distant areas in Europe within a radius of several hundred kilometers, and therefore reflects subcontinental scale vegetation composition and land-use dynamics (Figure 1).

Here, we use this information to decipher large-scale vegetation and land-use dynamics in response to biological, environmental, and societal drivers, such as succession, invasion, pathogen infestation, disturbance, climate change, and technological innovation. By comparing the continuous long-term ice core data to historical evidence on specific events, we comprehensively assess the main ecological and environmental forcings of European ecosystem dynamics during the past 1,000 year. Such a holistic view into past processes and mechanisms of ecosystem change may contribute to a better understanding of reorganizations of European ecosystems in response to global change. Specifically, we address to what extent ongoing global change response processes are rooted in the past with an emphasis on long-term processes that may have started decades or even centuries ago. We briefly discuss the implications of such insights for ecosystem and societal developments in Europe.

2. Materials and Methods

The two ice cores from Colle Gnifetti (45°55′45.7″N, 7°52′30.5″E) investigated in this study were recovered in 2003 (CG03B) and 2015 (CG15) and span the entire glacier thickness of 82 and 75 m from the surface to the underlying bedrock, respectively (Sigl et al., 2018). We transported the frozen ice cores to cold storage (−20°C) before sampling and preparing for analysis (see Supporting Information S1 for details on methodology).

The ice was dated by annual layer counting of seasonally varying signals, constrained by the presence of absolute time markers such as sulfate peaks from well-established volcanic eruptions, prominent dust layers associated with known major Saharan dust storm events, and the 1963 peak from nuclear weapons tests reflected in radioactive isotopes. Confirmation of the chronology and dating of the oldest ice core section was achieved by independent absolute dating methods such as nuclear dating with lead (^{210}Pb) and carbon (^{14}C) isotopes (Jenk et al., 2009; Sigl et al., 2018, Figure S1).

The ice core was cut in contiguous sections of ca. 500–1,000 g (original sampling thickness of 0.08–0.73 m or 0.07–0.63 m weq) of ice for microfossil analyses, and the samples were prepared following a new microfossil extraction protocol for ice samples (Brugger et al., 2018). We optically analyzed pollen, spores, and other microfossils to infer vegetation and land-use dynamics, charcoal for fire activity, and spheroidal carbonaceous particles (SCPs) to reconstruct industrial air pollution from fossil fuel combustion (Brugger, Gobet, & Osmont, 2019), at contiguous intervals of once every decade spanning the period 1050–2015 CE (corresponding to 0–56.6 m depth of the ice core). As an additional nonspecific burning tracer, we supplement our new analysis by including a highly resolved black carbon (BC) record (Sigl et al., 2018) and an oxygen isotopes ($\delta^{18}O$) record as an indicator of past temperatures, both retrieved previously from the same ice core and here averaged to the same decadal resolution as the microfossil records. The $\delta^{18}O$ record suggests similar centennial temperature trends over the past millennium, including a warm medieval period followed by a cooler LIA, as previously inferred from a Colle Gnifetti $\delta^{18}O$ record that was measured with a continuous flow analyzing system (Bohleber et al., 2018; Figure S5). Optimal sum-of-squares partitioning was applied

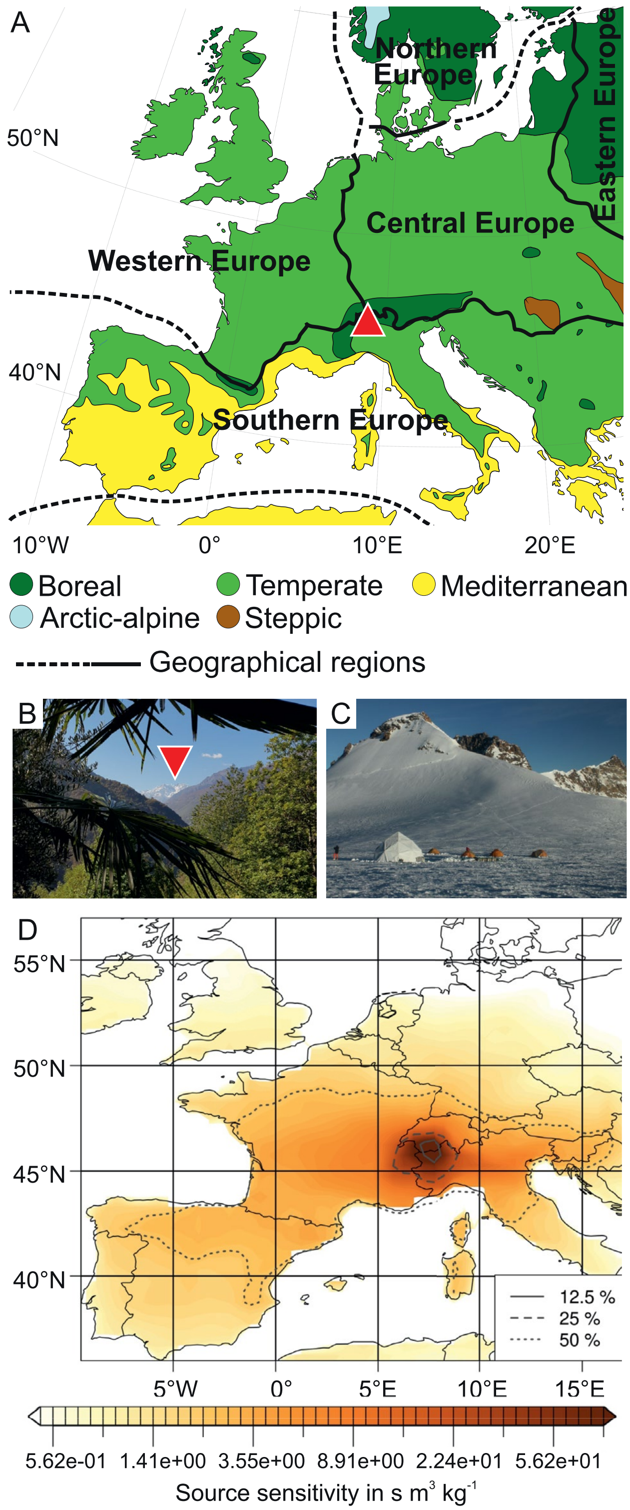


Figure 1. Study site in the Monte Rosa massif. (a) European biomes and geographical regions (Lang, 1994), as well as the study region of Monte Rosa in the European Alps (red triangle). (b) Southern view from Italy toward Monte Rosa and the Colle Gnifetti glacier saddle (red triangle; Photo: Willy Tinner). (c) Drilling camp in summer 2015 on the Colle Gnifetti glacier saddle (Photo: Michael Sigl). (d) Source sensitivity of Colle Gnifetti to different land areas are based on the atmospheric transport model FLEXPART. Source sensitivity was calculated as air mass residence time in a given grid cell divided by air density and as such is given in units (s m^3 kg^{-1}). Isolines encompass areas with the largest source sensitivity that contribute the given percentage to the total source sensitivity.

for zonation of the pollen data including all taxa >5% (= 27 taxa; Bennett, 1996; Birks & Gordon, 1985). Subsequently, we inferred statistically significant local pollen assemblage zones (LPAZ) with the broken stick approach (Bennett, 1996). We identified gradients in ecosystem composition over time with linear ordination techniques (i.e., principal component analysis [PCA]) applied to the pollen data (Brugger, Gobet, & Osmont, 2019) due to low species turnover as identified by the short gradient length of the first axis (= 1.734 SD) of a detrended correspondence analysis (DCA, detrended by segments; Ter Braak & Prentice, 1988). We addressed the sample-to-sample noise in the pollen record deriving from the large microfossil catchment in combination with changing wind directions by a combination of smoothing methods (i.e., moving average calculations for the tree pollen percentages) and ordination analyses incorporating the entire pollen assemblage for interpretation (Figure S3).

To investigate the catchment areas of the Colle Gnifetti ice core, we used the atmospheric transport model FLEXPART (Pisso et al., 2019) in time-reversed mode and for a passive atmospheric tracer, calculating source sensitivities to surface sources. The calculations encompass the year 2017 CE, for which high-resolution meteorological input data were available. We assume that atmospheric transport during the past millennium was similar to the simulated year 2017 CE, but we are aware that climate variability may have altered source sensitivities during the investigated past millennium. The use of a passive tracer compared to an aerosol tracer that undergoes settlement and deposition may result in larger source sensitivities at larger transport distances.

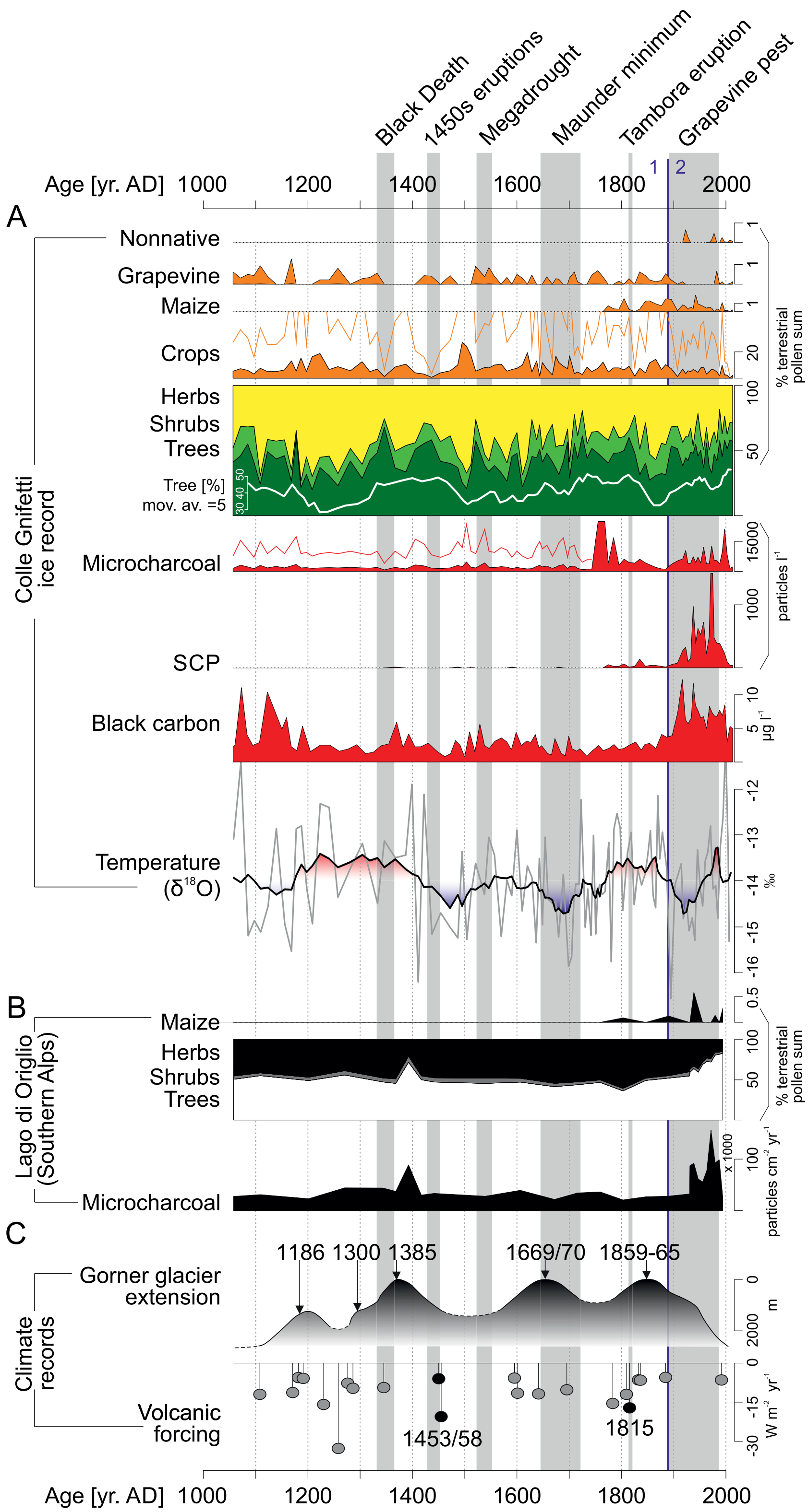
3. Results and Discussion

3.1. General Vegetation and Climate Dynamics

The microfossil record contains a big variety of pollen types and shows some inherent sample-to-sample noise in the pollen signal, which likely reflects the site location and its strong exposure to changing air masses as well as the large microfossil catchment with diverse vegetation, land use, and fire regimes. See Table S1 for complete pollen taxa list and their assignment to summary groups. Occasional pollen of *Lygeum spartum*, a wild grass of dry environments that grows in North Africa and southernmost Europe, correlates with visible orange dust layers in the ice (Sigl et al., 2018), indicating small contributions of microfossils from distant areas. Overall, the pollen assemblage with a high portion of mediterranean pollen (see Figure S2) is consistent with the FLEXPART results (Figure 1) indicating a large catchment that is composed of a variety of vegetation types. The PCA for the pollen data indicates that expansions of forest species (e.g., *Fagus sylvatica*, beech; deciduous temperate *Quercus*, oaks; and evergreen Mediterranean *Quercus*) alternated with grassland and crop plants (e.g., Poaceae, wild grass species; *Vitis vinifera*, grapevine; Cerealia-type, cultivated cereals) over time. Intensified land-use phases occurred synchronously across biomes as indicated in the PCA by separating natural plants from field crops, weeds, and fruit trees (e.g., *Olea europaea*, olive tree; *Castanea*, sweet chestnut; PCA in Figure S3). The pollen record contains one statistically significant pollen assemblage zone delimiting the 20th century vegetation composition from the older part of the record (Figure S4). Additionally, the ice core's stable oxygen isotope data show past temperature oscillations at decadal to centennial scales, which allow us to directly compare and assess the impact of climate dynamics and variability over the past 1,000 year across different European biomes in the following (Figure 1).

3.2. Climate Impacts on Preindustrial Societies

Our microfossil record begins in the medieval period where the herb and crop pollen suggests increasing arable and pastoral activities with large-scale deforestation (declining tree and shrub pollen to <50%), promoted by relatively mild and stable conditions (ca. 1000–1300 CE; Pfister, 1990) as also indicated by the high $\delta^{18}O$ values around −13.5‰ reflecting warmer temperatures (Figure 2). This is in accordance with documentary data describing that the clearing of forests, new crop rotations, and favorable conditions in the growing season led to increased crop yields, allowing the population to grow, mainly between 1170 and 1300 (Pfister, 1990). Forests delivered timber for construction and fuel for heating or iron smelting (e.g., in the lowlands of the Southern Alps), to accommodate growing demands (Radkau, 2012; Smil, 2017). These vegetation changes agree with regional lake-sediment records around the Alps suggesting open landscapes (Colombaroli et al., 2010; Gobet et al., 2003; Tinner et al., 2003).


Black Death
1450s eruptions
Megadrought
Maunder minimum
Tambora eruption
Grapevine pest
Age [yr. AD] 1000 1200 1400 1600 1800 2000
1
2
A
Colle Gnifetti ice record
Nonnative
Grapevine
Maize
Crops
Herbs
Shrubs
Trees
Tree [%] mov. av. =5
Microcharcoal
SCP
Black carbon
Temperature (δ18O)
% terrestrial pollen sum
particles l-1
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B
Lago di Origlio (Southern Alps)
Maize
Herbs
Shrubs
Trees
Microcharcoal
% terrestrial pollen sum
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1186 1300 1385
1669/70 1859-65
m
Volcanic forcing
1453/58
1815
W m-2 yr-1
Age [yr. AD] 1000 1200 1400 1600 1800 2000

Figure 2.

Our data show that around 1300 CE, the LIA cooling (Holzhauser et al., 2005) – in the CG03 A $\delta^{18}O$ record reflected with lower values (around −14.5‰) from 1400 to 1850 CE–resulted in declines of crop cultivation and pastoral activities, while forests at least partly recovered seen as an increase of tree and shrub pollen to >60% (Figure 2). A series of events is documented in written sources. Rainy years in 1315–1317 CE made crop storage in winter difficult (Campbell, 2016) and forests expanded in northern and southern Europe. The Black Death raged after 1348 CE, which decimated population until 1500 CE (Aberth, 2005; Benedictow & Benedictow, 2004; Campbell, 2016; More et al., 2017, 2018). Due to population decline, the demand for grain plummeted whereby marginal land was converted to permanent pasture or to forest (Figures 2 and 3). Two major volcanic eruptions in 1453 and 1458 CE (Esper et al., 2017; Sigl et al., 2015) caused extensive famines as reported in documentary data (Camenisch, 2018), resulting again in a substantial reduction in crop pollen in our ice record (Figures 2 and 3). A large peak in crop pollen (20%) at around 1500 CE composed mainly of *Beta*-type associated with the root crop *Beta vulgaris* as well as an increase in Cerealia-type (Figure S4) suggests either a short-term increase in agriculture activities, unreported in documentary data, or favorable microfossil transport during crop pollen flowering season, creating this striking feature in the pollen record. About half a century later, the pronounced drought in 1540 CE is documented in more than 300 written documents as low river flows and lake levels, crop failures, and continental-scale forest and settlement fires affected most parts of Europe from the southern British Isles to southern Italy and from the Iberian Peninsula to Poland (Brönnimann et al., 2018; Cook et al., 2015; Pfister et al., 2015; Wetter et al., 2014). In our ice core from Colle Gnifetti, this event is preserved in both the charcoal and BC -derived fire records as one of the largest fire peaks during the preindustrial era (i.e., charcoal concentrations >4,800 particles L^{-1}; Figure 2). The high-resolution Colle Gnifetti ice core record provides strong proxy evidence of this weather event in a natural archive. This finding suggests that other preindustrial fire episodes observed in the ice core, such as the charcoal and BC peaks e.g., during the medieval period and around 1510 CE, may correspond to other hitherto unknown historically important dry periods that markedly increased fire incidents in Europe in the past. Finally, the harsh climate conditions of the LIA culminated during the Late Maunder Minimum from 1675 to 1715 CE (Holzhauser et al., 2005) following plague waves of the 17th century (Alfani & Percoco, 2019; Curtis, 2016; Malanima, 2009), when our ice core record reveals a series of crop cultivation minima (e.g., gaps in the crop pollen curve, Figure S3) contemporaneous with the lowest $\delta^{18}O$ values reflecting these cold conditions (Figure 2). Wet summers with poor harvests were recurrently followed by extended rain in autumn and winter that hampered sowing of winter cereals and crop storage during the cold months, causing famines and societal unrest (Hoffmann, 2014).

The preindustrial ice core evidence supported by documentary data show that agricultural dynamics on a subcontinental scale reacted synchronous to climatic and societal factors. Thus, the characteristic small-to medium-scale subsistence systems of preindustrial societies show a high sensitivity to large-scale forcing of ecosystem change (Tinner et al., 2003).

3.3. Industrialization of Land Use

The ice record becomes more complex after 1750 CE. Agrarian innovations and population growth from 1750 CE transformed the subsistence economy into industrialized production with huge energy demands (Malanima, 2016) mirrored in the Colle Gnifetti microfossil record. *Zea mays* (maize) pollen, first detected after 1750 CE, documents for the first time the wide introduction of maize agriculture south of the Alps in a natural archive (Figure 2). More productive crops such as maize (south of the Alps) and potatoes (its counterpart north of the Alps), first introduced as garden cultures in Europe from the Americas in the late

Figure 2. Comparison of the Colle Gnifetti glacier record (a) with independent data (b and c). (a) Colle Gnifetti record shows the sum of nonnative plants (*Nothofagus, Pterocarya, Fallopia, Heliotropium*), *Vitis* (grapevine), *Zea mays* (maize), sum of crop, tree, shrub, and herb pollen as a proxy for vegetation and land use, microcharcoal concentrations for fire activity, spheroidal carbonaceous particles (SCP) for fossil fuel combustion, black carbon for nonspecific burning averaged to the microfossil resolution and oxygen isotopes ($\delta^{18}O$) for temperature averaged to microfossil resolution (gray) and as a 9-point moving average (black line). The complete pollen taxa list is in Table S1. 5X exaggeration for crops and 10X exaggeration before 1750 CE for microcharcoal (red). White curve in pollen summary graph shows 5-point moving average for tree pollen percentages. (b) Vegetation and fire reconstruction from Lago di Origlio, south of the Alps (Tinner et al., 2005). (c) Gorner glacier advances (low values) and retreats (high values) ca. 5 km northwest from Colle Gnifetti (Holzhauser et al., 2005) and cumulative global volcanic aerosol forcing (Sigl et al., 2015). Gray boxes indicate palynological signals during the Black Death, volcanic eruptions 1453/1458 CE (1450s eruptions), "Megadrought," Maunder minimum, Tambora eruption, and the grapevine pest *Phylloxera*. Blue vertical line delimits statistically significant local pollen assemblage zones (LPAZ 1 and 2). Vertical dashed lines delimit 200 year intervals.

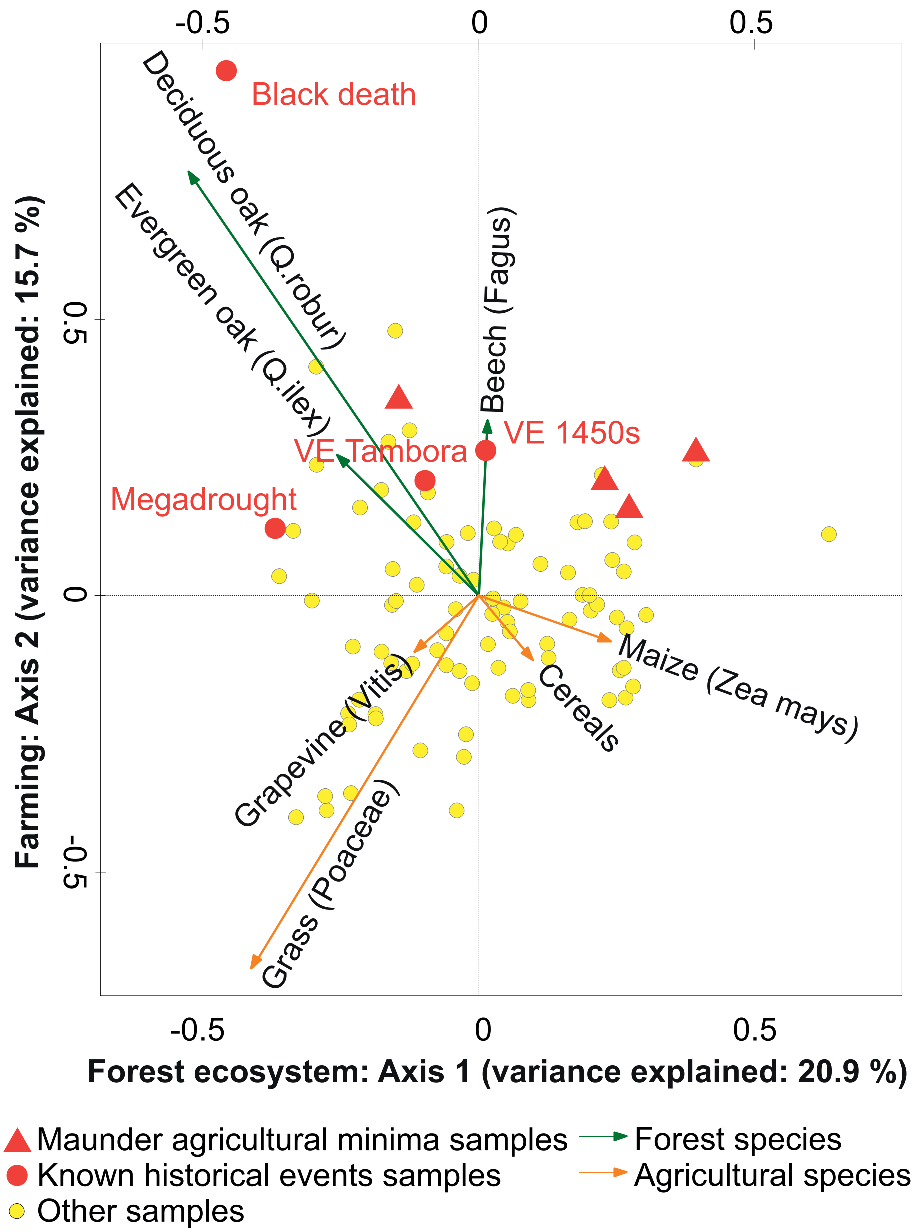

Figure 3. Sample scores for principal component analysis (PCA) for the ice pollen record. PCA based on percentages of the pollen sum. Sample scores of the following historical events are highlighted: Black Death CE 1347–1352, the volcanic eruptions CE 1453/1458 (VE 1450s), the megadrought CE 1540, volcanic eruption (VE) Tambora CE 1815. Selected taxa scores indicate the importance of farming vs. forest over the period recorded by the ice core: temperate beech oak forests (*Fagus* and *Quercus robur*), Mediterranean evergreen oak forest (*Quercus ilex*), crop cultivation (Cerealia, *Vitis*, *Zea mays*), and open landscape (Poaceae). The complete taxa list for PCA analysis is shown in Table S1.

16th century, were rapidly incorporated into regional production in the mid-18th century in the context of the rearrangement of agriculture (Malanima, 2009). The wet and cold climate conditions during the LIA (especially the Maunder Minimum; Holzhauser et al., 2005) led to a rapid shift from traditional crops (e.g., *Triticum*, *Panicum*, and *Hordeum*) to these more productive and resilient new crops in Europe (Montanari, 1996). Maize provided a much-needed cheap starch source, which would soon result in a new tragedy. The widespread mono diet of maize among Mediterranean peasants induced the malnutrition disease *Pellagra* that caused skin maladies and dementia in the 18th century (Montanari, 1996).

The devastating Tambora eruption in 1815 CE (Sigl et al., 2015) is preserved in the ice core as a sulfate peak (see Figure S1; Jenk et al., 2009) but its impact is less pronounced in the pollen record than the volcanic eruptions in the 1450s (Figure 3) despite documented crop failures (Luterbacher & Pfister, 2015). According to documentary data, the subsequent weather anomalies attributed to this eruption largely affected potato production in western and northern Europe (Luterbacher & Pfister, 2015). While the detailed history of *Zea mays* (maize) and most native crops is preserved in our pollen record, we fail at detecting *Solanum tuberosum* (potato) because it has a weak pollen dispersal (Lang, 1994) and its signal is therefore not recorded on this large scale. This example of *Solanum tuberosum* pollen reveals some limitations of natural archive data if documentary data are not also considered.

In the 18th century, the rapid increase of fire activity in our record (charcoal concentration maximum of ca. 35,000 particles L^{-1}) may reflect a change in land use (Montanari, 1996) connected to the burning of maize residues after harvests to increase soil fertility, as well as the increased demand for firewood. Rare written reports from Upper Austria (Sombart, 1919) confirm our findings that timber and charcoal were exported from the forested Alps for the energy-demanding salt extraction in Austria, and for heating, mining, metallurgy, and smelting in northern Italy. Many forest fires ignited due to widespread charcoal production, contributing to the fire signal in the ice core. Our pollen record does not demonstrate major changes in forest cover (i.e., tree pollen remains stable around 50% until 1820 CE; Figure 2) while maize pollen appears contemporaneously; suggesting that instead the signal derives from fires on crop fields and/or burning or collection of young trees (Conedera et al., 2004). Our record shows a large-scale deforestation (reduced tree pollen to 30%) beginning 1820 CE, displaying that increasing timber demands finally exceeded the sustainable use of the resource (Summermatter, 2012). These forest clearings resulted in a series of environmental catastrophes around the Alps such as floods and avalanches in the 19th century that are reported in documentary data (Summermatter, 2012).

The ice core contains frequent SCP and slightly increasing BC concentrations (Sigl et al., 2018) after 1770 CE that delimit the beginning of wide anthropogenic atmospheric pollution from fossil fuel combustion about two decades after the onset of maize plantation and the associated fire activity increase (Figure 2). Large-scale burning of coal is documented from Great Britain in the 17th and 18th century where shipping documents report massive coal transport as energy demands exceeded timber availability much earlier than on the European continent (Malanima, 2016).

The 20th century is marked by a statistically significant change in the pollen assemblage of our ice core (i.e., LPAZ boundary zone 1 and 2) including a rapid expansion of forest species to >50% at around 1890 CE (Figure 2). At that time, the transition to fossil energy allowed natural wood resources to recover. These forest recoveries were supported by new forest protection paradigms that were enacted in response to avalanches and flooding, such as the first mountain forest protection laws of Switzerland and Italy in 1876 CE and 1877 CE, respectively (Summermatter, 2012).

The availability of fossil energy accelerated the exchange of goods over large distances (Crosby, 2003), which is strongly reflected in our data by a spectacular shift in the pollen assemblage. For example, the ice record shows a decline of *Cannabis* (hemp) cultivation from 2% to mostly below the detection limit in the 19th century associated with the import of new fibers (van der Knaap et al., 2000). On the other hand, the sudden appearance of nonnative pollen taxa such as *Nothofagus*, *Pterocarya*, *Fallopia*, and *Heliotropium* after 1910 CE suggests the spread of exotic species across Europe (Figure 2, see Table S1 for assignment of nonnative pollen taxa). The ease of fossil fuel-operated transport facilitated the exchange (Crosby, 2003) of neophytes imported for botanical gardens (Davis, 2003; McAleer, 2016). These new plants set the start of an unprecedented global ecosystem alteration with invasive species in the 20th century (Mack & Lonsdale, 2001) widely recorded in vegetation reconstructions from the Neotropics with a sudden spread of exotic trees (Brugger, Gobet, & Osmont, 2019; Niemann et al., 2013; Simberloff et al., 2010). Finally, *Vitis* (grapevine) pollen disappears in the early 20th century in our data, reflecting decreasing grapevine cultivation (Figure 2). In 1860 CE, the grapevine pest *Phylloxera* was introduced with American grapevine species in France and spread rapidly across western Europe, destroying many vineyards in and around the Alps (Daux et al., 2012; Gale, 2011). The Colle Gnifetti ice core contains the first unambiguous evidence from a natural archive documenting the introduction of overseas crops such as maize, as well as the subsequent shift to a fossil-fuel economy that led to serious subcontinent-wide environmental consequences, including increasing pollution and widespread pathogens that intensified after the beginning of industrialization in Europe.

3.4. Implications for Modern and Future European Ecosystems

Our ice core record shows the scale to which preindustrial societies in Europe were affected by climatic events (Camenisch, 2018; Cook et al., 2015; Esper et al., 2017; Pfister et al., 2015) and epidemics (Aberth, 2005; Campbell, 2016) with continuous data during the past thousand years. Synchronous, short-term recoveries of forest ecosystems occurred across large areas, expressed, for example by *Fagus*-deciduous *Quercus* (beech-temperate oak) forest expansions and crop cultivation alternating during documented societal events (Figure S3). Europe's production systems adapted to adverse climate conditions during the LIA with innovations and industrialization of land use in the 18th century (Malanima, 2016; Montanari, 1996; Sombart, 1919). Ultimately, the rapid impact from industrial land use and amplified energy consumption resulted in unsustainable resource exploitation (Pfister, 1990), for instance, visible as the historic minimum of forests in the 19th century that resulted in environmental changes such as floods and avalanches (Summermatter, 2012), as well as increasing pollution. These massive changes confirm steady increases in unspecific land use and pollution tracers measured previously in Colle Gnifetti ice cores such as ammonium (NH_4), sulfate (SO_4), nitrate (NO_3), lead (Pb) and other heavy metals, radioactive isotopes, and polycyclic aromatic hydrocarbons (Barbante et al., 2004; Döscher et al., 1995, 1996; Gabrieli & Barbante, 2014; Gabrieli et al., 2010, 2011; More et al., 2017; Schwikowski et al., 1999, 2004; Sigl et al., 2018).

Industrialized agriculture with fossil fuel-based heavy machinery is nowadays concentrated in central areas (lowlands with fertile soils), which are most profitable for large-scale production (MacDonald et al., 2000). The only remnants of original, quasi-natural ecosystems in these fertile areas are currently under high pressure from urban sprawl and industrialized agriculture (MacDonald et al., 2000). On the other hand, the 19th century shift from agricultural to industrialized and centralized societies in Europe triggered the abandonment of subsistence cultivation on less favorable land or led to their transformation to pasture or forests for instance mountain terraces (MacDonald et al., 2000; Schwörer et al., 2014).

European history since the Neolithic age shows that agrarian societies are vulnerable to extreme climates and that innovation is the key to adapt to such adverse conditions (Lemmen & Wirtz, 2014). During the LIA, it took many generations to establish a new industrial system adapted to floods, droughts, and other environmental risks with innovative technologies and land-use practices. Past industrialization and introduction of new plant species left a strong continental-scale imprint on the ice. Recent land abandonment and forest successions may trigger recoveries of ecosystems in marginal areas as suggested by our ice record for the past decades. Prolonged droughts together with increased fuel availability associated with forest expansions may, however, enhance fire risks in Europe and the Mediterranean, counteracting current public efforts of fire prevention (Schwörer et al., 2014; Tinner et al., 2005; Vannière et al., 2008). Other effects of modern land use in Europe such as the spread of invasive species (Davis, 2003; Mack & Lonsdale, 2001; McAleer, 2016), diseases, pollution from high-temperature combustion (traffic, industry, and energy production), and eutrophication may continue to impact vegetation and ecosystems and hence augment societal risks.

Our holistic, microfossil-inferred view of a thousand years of European history suggests that adaptations and innovations were key to breaking the historical cycle of societal expansion and retreat during periods of favorable and adverse climate. Continued adaptations and technological innovations may allow society to find sustainable land use approaches to reduce climate warming and the associated threats.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data will be stored in Neotoma Database (www.neotomadb.org) and Zenodo (https://doi.org/10.5281/zenodo.5519059).

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