Palaeogeography, Palaeoclimatology, Palaeoecology 599 (2022) 111051

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

A new indicator approach to reconstruct agricultural land use in Europe from sedimentary pollen assemblages

Mara Deza-Araujo [a,b,*], César Morales-Molino [a,b], Marco Conedera [a], Paul D. Henne [c], Patrik Krebs [a], Martin Hinz [d], Caroline Heitz [d], Albert Hafner [d], Willy Tinner [b]

[a] Insubric Ecosystems, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Cadenazzo, Switzerland
[b] Institute of Plant Sciences and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[c] U.S. Geological Survey, Geosciences and Environmental Change Science Center, Denver, CO, USA
[d] Institute of Archaeological Sciences and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland

ARTICLE INFO

Editor: Howard Falcon-Lang

Keywords:
Cultural indicator pollen types
Human impact
Palynology
Palaeoecology
Archaeobotany
Archaeology
Europe

ABSTRACT

The reconstruction of human impact is pivotal in palaeoecological studies, as humans are among the most important drivers of Holocene vegetation and ecosystem change. Nevertheless, separating the anthropogenic footprint on vegetation dynamics from the impact of climate and other environmental factors (disturbances such as fire, erosion, floods, landslides, avalanches, volcanic eruptions) is a challenging and still largely open issue. For this purpose, palynologists mostly rely on cultural indicator pollen types and related indices that consist of sums or ratios of these pollen types. However, the high environmental and biogeographical specificity of cultural indicator plants hinders the application of the currently available indices to wide geographical settings. Furthermore, the achievable taxonomic resolution of cultural indicator pollen types may hamper their indicative capacity. In this study, we propose the agricultural land use probability (LUP) index, a novel approach to quantify human impact intensity on European ecosystems based on cultural indicator pollen types. From the 'classic' cultural indicators, we construct the LUP index by selecting those with the best indicator capacity based on bioindication criteria. We first train the LUP index using twenty palynological sequences along a broad environmental gradient, spanning from treeless alpine to subtropical mediterranean evergreen plant communities. We then validate the LUP index using independent pollen datasets and archaeological proxies. Finally, we discuss the suitability of the selected pollen types and the potential of the LUP index for quantifying Holocene human impact in Europe, concluding that careful application of the LUP index may significantly contribute to refining pollen-based land-use reconstructions.

1. Introduction

Human transformation of European terrestrial ecosystems accelerated with the emergence of agriculture (Stephens et al., 2019), when agrarian societies opened the woodlands to gain land for arable and pastoral farming. Over the millennia, environmentally transformative human use of land (e.g., land clearance by burning for arable farming) has resulted in the widespread occurrence of 'anthromes' (i.e., anthropogenic biomes) over most of Europe and elsewhere (Ellis, 2011; Ellis and Ramankutty, 2008) that are characterised by varying intensities of human impacts. The assessment of long-term human impacts on the landscape often relies on the use of plants as bioindicators (Burger, 2006), whereby the occurrence or absence of indicator species provides quantitative estimates of the intensity of human disturbance (Diekmann, 2003; Zinnen et al., 2021). Such bioindicator-based methodologies are widely used in plant ecology and rely on the sensitivity of organisms to their environment (Diekmann, 2003; Gerhardt, 2002).

The bioindicator approach can be extended to the past through the analysis of microfossils preserved in lake sediments, peat sequences or other natural archives. For instance, analysing the abundance of crop and weed pollen in fossil assemblages allows reconstructing anthropogenic impacts on ecosystems over long timescales. The most widely used approach in Europe is calculating the abundance of a set of cultural indicator pollen types with demonstrated associations with human activities, especially agriculture (Behre, 1981, 1990). The groundbreaking work by Behre (1981) to select cultural indicator pollen

* Corresponding author at: Insubric Ecosystems, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Cadenazzo, Switzerland.
E-mail address: mara.deza@wsl.ch (M. Deza-Araujo).

https://doi.org/10.1016/j.palaeo.2022.111051
Received 15 December 2021; Received in revised form 4 May 2022; Accepted 5 May 2022
Available online 10 May 2022

types complies to some extent with the bioindicator methodology, although their final definition does not explicitly and fully meet standard bioindication criteria (Gerhardt, 2002). Moreover, human impact indices including the relative abundances of various cultural indicator pollen types have been developed for European pollen assemblages, therefore providing summary evidence for different types of farming (Lang, 1994; Tinner et al., 2003; Mercuri et al., 2013a, 2013b; Kouli, 2015; Roberts et al., 2019; for a summary see Table 1 in Deza-Araujo et al., 2020). Similarly, palynological human-impact ratios such as the 'arable/pastoral index', which considers the proportion of *Plantago* pollen with respect to other cultural indicator pollen types (Turner, 1964), the arboreal pollen to non-arboreal pollen ('AP/NAP') ratio, which aims at reconstructing landscape openness (Berglund, 1991), and the 'Cerealia-t. (t. = pollen type) to *Plantago lanceolata*-t.' index (C/PL index), are used as proxies for the changing relationship of cultivated to fallow land through time (Tserendorj et al., 2021).

Such indices drawing upon cultural indicator pollen types are presently widely used because of their potential to provide a readily interpretable quantification of past human impacts. However, available indices were originally conceived to be used in geographically restricted areas (e.g., Brun, 2011; Mercuri et al., 2013b) or to reconstruct specific land-use practices (e.g., Kouli, 2015), which suggests caution in their widespread application in Europe because of potential shifts in the response of indicator plants along climatic and geographical gradients (Diekmann, 2003). In particular, the selection of cultural indicator pollen types should vary regionally to account for important aspects like the native distribution range and timing of introduction of the concerned species (Deza-Araujo et al., 2020). Moreover, the taxonomic resolution of pollen types (Deza-Araujo et al., 2022) and their relative contribution to the pollen assemblage need to be considered to avoid false attributions and to account for the overrepresentation of certain pollen types (Brun, 2011; Deza-Araujo et al., 2020). In fact, an important issue concerning existing indicator approaches is that they often combine abundant (e.g., high pollen-producer *Olea*) with rare (e.g., low pollen-producer *Vitis*) pollen types without any correction factor (Deza-Araujo et al., 2020). Such biases are typically due to the overrepresentation of wind-pollinated taxa producing large loads of well-dispersed pollen and wetland taxa growing locally (Birks et al., 2016), which may result in misleading estimates and distorted indicator values (Diekmann, 2003; Urban et al., 2012).

In this study, we propose a new agricultural land use probability (LUP) index that aims to assess Holocene human-impact intensity in pollen diagrams in a rigorous and widely applicable manner that makes pollen-inferred reconstructions of past agricultural land use accessible to non-specialists. Our probabilistic approach first identifies a list of cultural indicator pollen types that is suitable for a specific location, and then adjusts their importance as predictors of impact intensity using anthropogenic indicator values (AIV; modified with respect to Birks et al., 1988) that account for the native distribution range, time of introduction and pollen representation. Thus, the LUP index consists of the sum of the weighted pollen abundances of cultural indicator taxa. By incorporating the AIV concept, the LUP index becomes adaptable over wide geographical gradients. Specifically, our probabilistic index emphasises the co-occurrence of indicator taxa in a pollen assemblage and

Table 1
Main features of the palynological records considered in the calibration of the land use probability (LUP) index. MAT, mean annual temperature.

Vegeta-tion belt	Site	Lat (°N), Long (°E)	Eleva-tion (m a.s.l.)	Area (ha)	Age range (cal. yr BP)	MAT (°C) (Fick and Hijmans, 2017)	Reference
Colline/montane	1. Egelsee (Menzingen)	47.183480, 8.582379	770	1.2	50–16,200	8.7	Wehrli et al., 2007
	2. Burgäschisee	47.148056, 7.658333	465	21	−50–18,700	8.9	Rey et al., 2017; Rey et al., 2019b; Rey et al., 2019a
	3. Soppensee	47.090421, 8.080115	596	22.7	−50–14,200	8.6	Lotter, 1999
	4. Moossee	47.021944, 7.480278	521	31	3850–7100	9	Rey et al., 2020; Rey et al., 2019b; Rey et al., 2019a
Subalpine/alpine	5. Bachalpsee	46.670356, 8.023247	2265	8	−50–12,900	0.2	Lotter et al., 2006
	6. Lej da San Murezzan	46.495168, 9.845067	1768	78	−50–11,900	1.9	Gobet et al., 2003, 2005
	7. Lej da Champfèr	46.471268, 9.807297	1791	50	−50–11,850	1.8	Gobet et al., 2003, 2005
	8. Lengi Egga	46.396840, 7.980020	2557	2.89	10–12,600	−0.6	Tinner and Theurillat, 2003
	9. Gouillé Rion	46.157222, 7.362778	2343	0.16	−50–11,950	1.0	Tinner et al., 1996
Submediterranean	10. Lago di Origlio	46.060435, 8.942306	416	8	−50–18,900	10.6	Tinner et al., 1999
	11. Lago di Muzzano	45.996621, 8.928177	337	22	−50–15,150	11.5	Tinner et al., 1999; Gobet et al., 2000
	12. Lago Piccolo di Avigliana	45.05000, 7.383334	356	60	320–19,350	11.8	Finsinger et al., 2006; Finsinger and Tinner, 2006; Vescovi et al., 2007
	13. Pavullo nel Frignano	44.318335, 10.837500	675	ca. 20	100–16,300	12.6	Vescovi et al., 2010a
	14. Lago del Greppo	44.119722, 10.683055	1442	0.018	−50–14,950	6.7	Vescovi et al., 2010b
Mesomediterranean	15. Lago di Massaciuccoli	43.83784, 10.3308	0	700	0–7000	15	Colombaroli et al., 2007
	16. Lago dell'Accesa	43.059388, 10.898260	157	16	50–11,600	14.2	Colombaroli et al., 2008, 2009; Vannière et al., 2008
Thermomediterranean	17. Lago di Baratz	40.68089, 8.22551	27	60	−20-8000	15.8	Pedrotta et al., 2021
	18. Sa Curcurica	40.45547, 9.78752	0	38	−50-8100	17.3	Beffa et al., 2016
	19. Gorgo Basso	37.609174, 12.654939	6	3	−50– 10,200	18.1	Tinner et al., 2009
	20. Biviere di Gela	37.01879, 14.34455	7	120	−50– 7350	18.5	Noti et al., 2009

the abundances of taxa with a high AIV. By doing so, we assume that pollen samples featuring more pollen types of cultural indicator taxa with higher AIV are more likely to express agricultural land use, as quantified by the LUP value.

To implement the LUP we use a set of twenty palynological sequences from lakes located along a large environmental gradient spanning from the treeless alpine belt of the Swiss Alps to the subtropical thermomediterranean belt in coastal Sicily (southern Italy). The lakes are comparable in terms of size (small to medium), and their sediment records mostly consist of autochthonous organic sediment (i.e., gyttja and silty gyttja). We pay attention to general bioindication criteria (Diekmann, 2003; Gerhardt, 2002) like the achieved taxonomic resolution (Deza-Araujo et al., 2022) and the historical biogeography of the taxa (e.g., adventive vs. apophyte; Deza-Araujo et al., 2020; Fig. S1). We perform two external validations, using on the one hand an independent set of pollen sequences and on the other hand a set of archaeological radiocarbon dates as an independent proxy for human activity. We finally suggest possible implications of the LUP index as a proxy for human impact quantification.

2. Material and methods

2.1. Study sites and pollen data

For the assemblage and calibration of the LUP index, we selected 20 well-dated lake pollen records in a latitudinal transect encompassing Switzerland and Italy (Figs. 1a, 2; Table 1). We selected these sites because (i) they were analysed in the same laboratory (Institute of Plant Sciences, University of Bern, Switzerland) and the pollen taxonomic resolution is therefore comparable, and (ii) they are located along an environmental gradient which covers all major vegetation types of Europe. The study sites are located in five vegetation belts (Lang, 1994): 1) the cold subalpine/alpine belt with treeless meadows and scrubland above the tree line, conifer-dominated forests (mostly evergreen but sometimes deciduous or mixed when *Larix decidua* is present) and the transitional tree line ecotone (high elevation areas in the Alps). 2) The cool-temperate colline/montane belt with mostly broadleaved deciduous forests of the northern Alpine forelands (e.g. *Quercus robur, Quercus petraea* or *Fagus sylvatica*). 3) The warm-temperate and rather humid submediterranean belt in the low and mid elevation sites of the southern Alps and the northern Apennines with mixed broadleaved deciduous forests characteristic for southern Europe (e.g., *Castanea sativa*, *Ostrya carpinifolia*, *Quercus pubescens*, *Quercus cerris*, *Fraxinus ornus*). 4) The warm and summer-dry mesomediterranean belt with evergreen and deciduous oak forests in lowland central Italy (e.g. with *Quercus ilex* and *Quercus pubescens*). 5) The very warm and summer-dry thermomediterranean belt with evergreen forests, woodlands and maquis in coastal areas of Sardinia and Sicily (e.g. *Q. ilex, Quercus coccifera, Olea europaea, Chamaerops humilis*, *Ceratonia siliqua*; Figs. 1a, 2). These vegetation belts correspond to different climatic conditions, and these are relevant to farming activities (e.g., crop selection for securing and maximising harvest success).

The pollen datasets were retrieved from the Alpine Palaeoecological Database (ALPADABA) via Neotoma (Williams et al., 2018). The chronologies in ALPADABA correspond to those produced by the authors in the original publications (see Table 1). For each study site, we calculated the percentages of the most frequently used cultural indicator pollen types according to Behre (1981, 1990), Mercuri et al. (2013a) and Deza-Araujo et al. (2022). Pollen percentages were calculated with respect to the terrestrial pollen sum (trees, shrubs and upland herbs), excluding *Cannabis*-t., which is often overrepresented in lake sediments due to retting. We plotted every potential cultural indicator using '*tidyverse*'

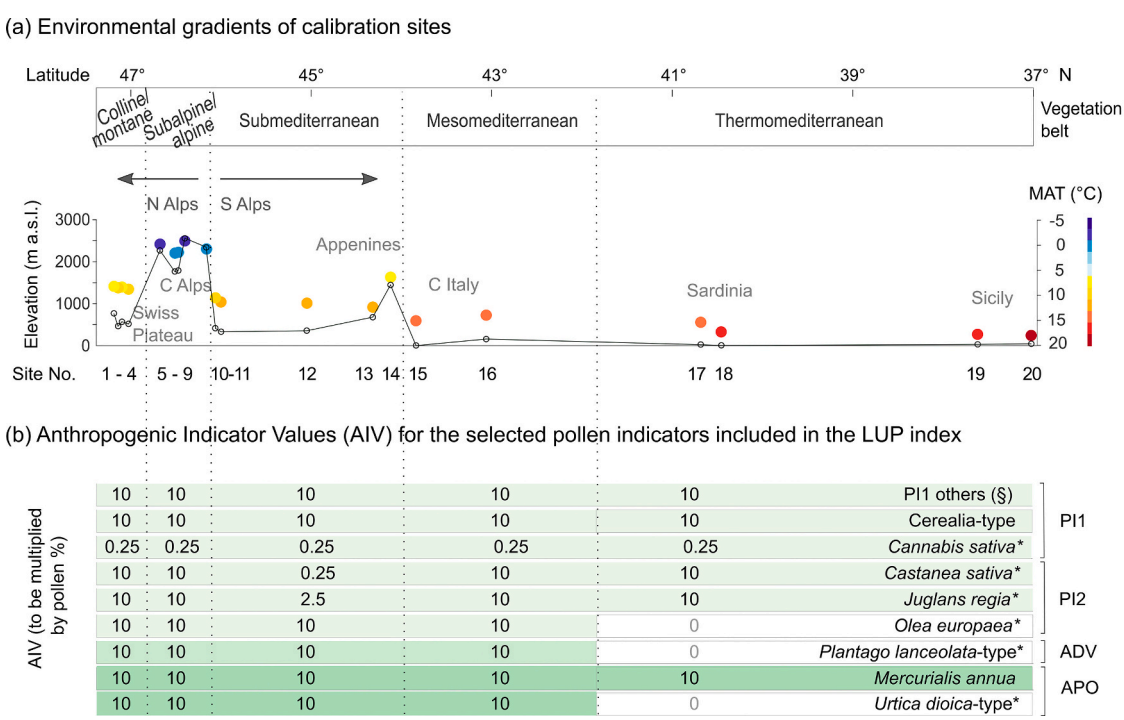

Fig. 1. (a) Environmental gradients of the pollen sites considered in this study: Elevation (m a.s.l.), mean annual temperature (MAT; °C), latitude (°N), geographical region and vegetation belts. (b) Selected pollen indicators and their corresponding anthropogenic indicator values (AIV) in the land use probability (LUP) index. PI1 others (§): *Avena*-t., *Hordeum*-t., *Triticum*-t., *Secale*-t., *Zea mays*, *Pisum sativum*, *Vicia faba*-t., *Fagopyrum*, *Linum usitatissimum*-t. * denotes pollen indicators with reduced or not AIV in at least one vegetation belt. The LUP index does not consider the use of *Olea europaea*, *Plantago lanceolata*-t. and *Urtica dioica*-t. in the thermomediterranean vegetation belts. *Juglans regia* is seldom recorded in the thermomediterranean study sites. Site No.: 1 = Egelsee (Menzingen), 2 = Burgäschisee, 3 = Soppensee, 4 = Moossee, 5 = Bachalpsee; 6 = Lej da San Murezzan, 7 = Lej da Champfèr, 8 = Lengi Egga, 9 = Gouillé Rion, 10 = Lago di Origlio, 11 = Lago di Muzzano, 12 = Lago Piccolo di Avigliana, 13 = Pavullo nel Frignano, 14 = Lago del Greppo, 15 = Lago di Massaciuccoli, 16 = Lago dell'Accesa, 17 = Lago di Baratz, 18 = Sa Curcurica, 19 = Gorgo Basso, 20 = Biviere di Gela.

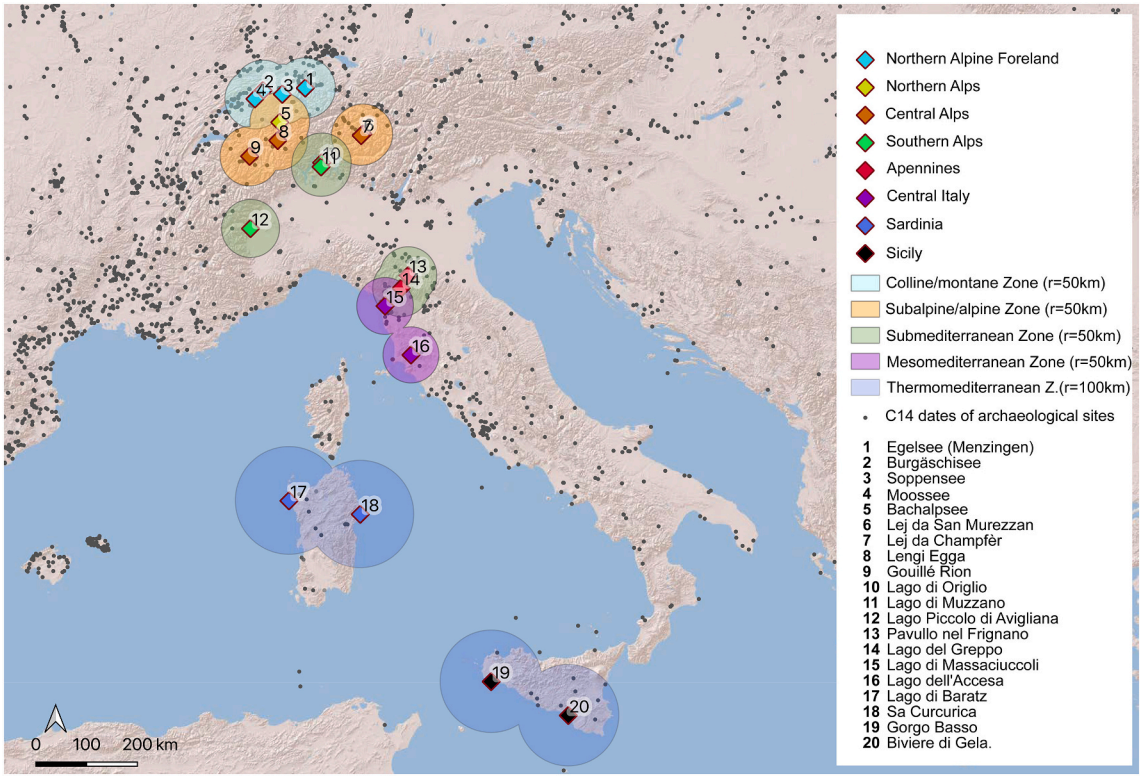

Fig. 2. Calibration sites and buffer areas used to select the radiocarbon data as proxy for human activity. The radius around the sites is 50 km for all sites with exception of the thermomediterranean areas (100 km) in Sardinia and Sicily, due to the reduced number of available radiocarbon dates resulting from coastal location (as the area under the radius includes sea).

version 1.3.0 (Wickham et al., 2019) running in the R environment (R Core Team, 2020).

2.2. Selection of cultural indicator pollen types

We identified five criteria out of the full list considered by the bio-indicator approach as the most relevant to pollen analysis after Gerhardt (2002). The criteria used to select and rank the considered pollen types on a four-point scale (i.e., excellent, good, fair and poor) according to their cultural indicative capacity (Tables 2, S1) are as follows:

i. *'Adventive/apophyte status'* (Lang, 1994; Deza-Araujo et al., 2020). Pollen from adventive plants (non-native, introduced with agriculture) has higher indicative value than those from apophytes (native, favoured by human disturbances) because their introduction resulted from human agency and their habitats are mostly restricted to places disturbed by farming activities. The most reliable human indicators will be adventive primary agricultural indicators (i.e., crops non-native to the study area).

ii. *'Taxonomic resolution'* (Deza-Araujo et al., 2022). Precise pollen identification is key to the interpretation of pollen data in terms of agricultural land use. The closer the taxonomic correspondence between pollen types and their potential source plants, the more accurate the reconstruction of the anthropogenic environments around the study site. In this regard, easiness of the determination of the pollen grains to high taxonomic resolution fosters the indicative power of cultural indicator pollen types. Complete ecological knowledge of the indicator plant species is a needed prerequisite.

iii. *'Pollen production/dispersal/robustness'*. Anemophilous taxa are better represented in pollen spectra than zoophilous species (Regal, 1982). For this reason, certain indicators such as the autogamous cereals (e.g., *Hordeum vulgare*), which are dispersed shorter distances than wind-pollinated species such as *Secale cereale* (Josefsson et al., 2014), are considered less consistent cultural indicators. Likewise, pollen of plants usually grown in extensive monocultures will be better represented in pollen assemblages and will therefore be more consistent cultural indicators than taxa only found in small amounts in family gardens or orchards. Thus, 'ubiquity' and abundance in pollen records is a desirable feature that reinforces indicative power. Additionally, selecting pollen types not particularly prone to degradation is important to avoid differential preservation issues that might bias land-use reconstructions based on pollen data. For example, the great indicative capacity of Cerealia-t. as an indicator of agricultural activities is somewhat hampered because its large pollen grains (>37 μm; Beug, 2004) may be more prone to chemical and mechanical damage, resulting in broken or crumpled grains (Delcourt and Delcourt, 1980) that do not allow more precise identification.

iv. *'Exponential increase in the pollen diagram'*. This feature is assumed to reflect the sensitivity and responsivity of the plant taxon to human-induced disturbance or its deliberate cultivation. Although exponential growth of plant populations can also occur independently of human action (Magri, 1989), here we consider only the exponential growth of taxa unambiguously related to human activities (Deza-Araujo et al., 2020).

v. *'Representation in pollen assemblages'*. Good correspondence between plant and pollen abundances is important. Cultural indicator pollen types should increase monotonically alongside the rising dominance of the corresponding crop or weed.

We assessed each cultural indicator in our calibration datasets by conducting a literature review on their pollen characteristics and visually inspecting the pollen curves to identify the temporal distribution of their relative abundances and to ascertain whether their curves behaved

Table 2
Pollen indicators included in the land use probability (LUP) index and results of the four-point scale analysis to measure empirical relationships between various aspects of the indicators and their importance to record land use in pollen diagrams (Bradshaw et al., 1981; Broström et al., 2005; Deza-Araujo et al., 2020, 2022; Lang, 1994; Molina et al., 1996; Prentice and Webb, 1986). See also Table S1 for a complete list of the cultural indicator pollen types considered in the analysis but eventually not included in LUP. *Cerealia-t. refers to the same Cerealia taxa indicated in PI1, but at lower taxonomic resolution.

Human Pollen indicators	Overall indicative capacity	Adventive-ness	Taxonomic resolution	Pollen production/ deposition	Exponential increase in the pollen diagram	Overrepresentation in the pollen diagram
		Adventive = Excellent	High= Excellent	High= Excellent	Always = Excellent	Almost Never True = Excellent
		Apophyte = Poor	Low = Poor	Low = Poor	Rarely = Poor	Almost Always True = Poor
Included in the LUP index						
PI1						
Avena-type	●●●●	●●●●	●●●●	●●●●	●●●○	●●●●
Fagopyrum	●●●●	●●●●	●●●●	●●●●	●●●○	●●●●
Hordeum-type	●●●●	●●●●	●●●●	●●●●	●●●○	●●●●
Triticum-type	●●●●	●●●●	●●●●	●●●●	●●●○	●●●●
Zea mays	●●●●	●●●●	●●●●	●●●●	●●●○	●●●●
Pisum sativum	●●●●	●●●●	●●●●	●●●●	●●●○	●●●●
Secale cereale	●●●●	●●●●	●●●●	●●●●	●●●○	●●●●
Vicia faba-type	●●●●	●●●●	●●●●	●●●●	●●●○	●●●●
Linum usitatissimum-type	●●●●	●●●●	●●●●	●●●●	●●●○	●●●●
PI1 - other						
Cannabis sativa-type	●●●●	●●●●	●●●●	●○○○	●●●●	●○○○
Cerealia-type*	●●●●	●●●●	●●●○	●●●●	●●●●	●●●●
PI2						
Castanea sativa§	●●●●	●●○○	●●●●	●●●○	●●●●	●●●●
Juglans regia§	●●●●	●●○○	●●●●	●●●○	●●●●	●●●●
Olea europaea§	●●●●	●●○○	●●●●	●○○○	●●●●	●○○○
ADV						
Plantago lanceolata-type	●●●●	●●●●	●●●●	●●●○	●●●●	●●●●
APO						
Mercurialis annua	●●●●	●●○○	●●●●	●●●○	●●●●	●●●●
Urtica dioica-type	●●●●	●●○○	●●●●	●●●○	●●●●	●●●●

Excellent indicator	Good indicator	Fair indicator	Poor indicator
●●●●	●●●○	●●○○	●○○○

PI1 = primary indicators (crops) non-native to Europe; PI2 = primary indicators native to Europe. SI = secondary indicators (weeds): ADV = adventives (non-native); APO = apophytes (native). (§) adventive in the colline/montane and subalpine vegetation belts.

as expected (overall exponential increase in the pollen diagram). To keep the LUP index as parsimonious as possible, only taxa with the highest overall indicative capacity were retained (Fig. 1b), irrespective of their presence in all calibration pollen datasets (Table S2).

2.3. Assemblage and calibration of the LUP index

The LUP index of a given pollen assemblage is calculated as follows:

$$LUP_i = \sum_{j=1}^{n} x_{ji}\, AIV_j$$

where LUP_i is the value of the LUP index for the pollen sample i; x_{ji} is the relative abundance of the pollen type j (one of the n selected cultural indicator pollen types present in the pollen sequence) in the pollen sample i, expressed as a percentage of the terrestrial pollen sum; and AIV_j is the anthropogenic indicator value assigned to the pollen type j at the study site, according to the vegetation belt where this is located because this is relevant to the adventive/apophyte status and the agricultural systems used (Figs. 1, 2). Thus, the AIVs modulate the LUP index to account for the adventive/apophyte status of the selected cultural indicators in the different vegetation belts.

Selected pollen indicators differ in their relative abundances in the calibration pollen datasets. To standardise their percentages around similar values and thus correct over- and underrepresentation in pollen diagrams, we used AIVs as weighting coefficients. AIVs for a given pollen type can differ among vegetation belts, which allows accounting for different crops and historical biogeographical aspects specific to each location. As a result, AIV values for the selected cultural indicators vary among pollen types and the five vegetation belts considered.

We assigned an AIV of 10 to most cultural indicator pollen types in all vegetation belts (Fig. 1b) with the following aims: (i) to increase the weights of cultural indicator pollen types because these are often rare or underrepresented, particularly during the initial stages of farming development, and (ii) to enhance visualisation. In contrast, we down-weighted and assigned lower AIVs to pollen types which tend to be overrepresented or to account for the native status of the plants producing such pollen types (Fig. 1b). This correction was sometimes applied to specific vegetation belts (Fig. 1b). For example, *Cannabis sativa* received an AIV of 0.25 to counterbalance its large overrepresentation in lake pollen assemblages due to retting. Likewise, fruit trees with moderate to large pollen production and good dispersal such as *O. europaea*, *Castanea sativa* and *Juglans regia* received AIVs lower than 10 in areas where they have been widely cultivated and/or are considered native (i.e., in submediterranean and thermomediterranean settings; Fig. 1b).

The LUP index values were then plotted for the 20 pollen records of the training dataset to check if the LUP curves showed long-term increasing trends as expected from the archaeologically and historically inferred developments in population density and technology (Deza-Araujo et al., 2020 and references therein). AIVs <10 were assigned to apophytes and overrepresented taxa following an iterative process

aimed at meeting the two following requirements: (i) LUP maximum values on a given pollen diagram are close to 100 to allow comparisons among sites and vegetation belts, and (ii) LUP curves follow a monotonically increasing trend towards present (with generally rising human impact; Fig. S1). We grouped the results of the LUP index by archaeologically inferred levels of human impact intensity, from very low to very high (Palaeolithic to Modern Era; Deza-Araujo et al., 2020), and plotted them as boxplots to assess whether the LUP values followed the desirable monotonic increasing trend across the gradient in land-use intensity (Fig. 3).

2.4. Validation of the LUP index

The validation of the LUP index was two-fold. First, we evaluated the performance of the LUP index in predicting agricultural land use by applying it to an independent dataset consisting of eleven lake pollen records from the five investigated vegetation belts (Table 3), and checking if the trends of LUP were comparable to those observed at the sites used for its development. These pollen records were obtained from ALPADABA and the European Pollen Database (EPD), and we used the chronologies produced by the authors for the ALPADABA records and

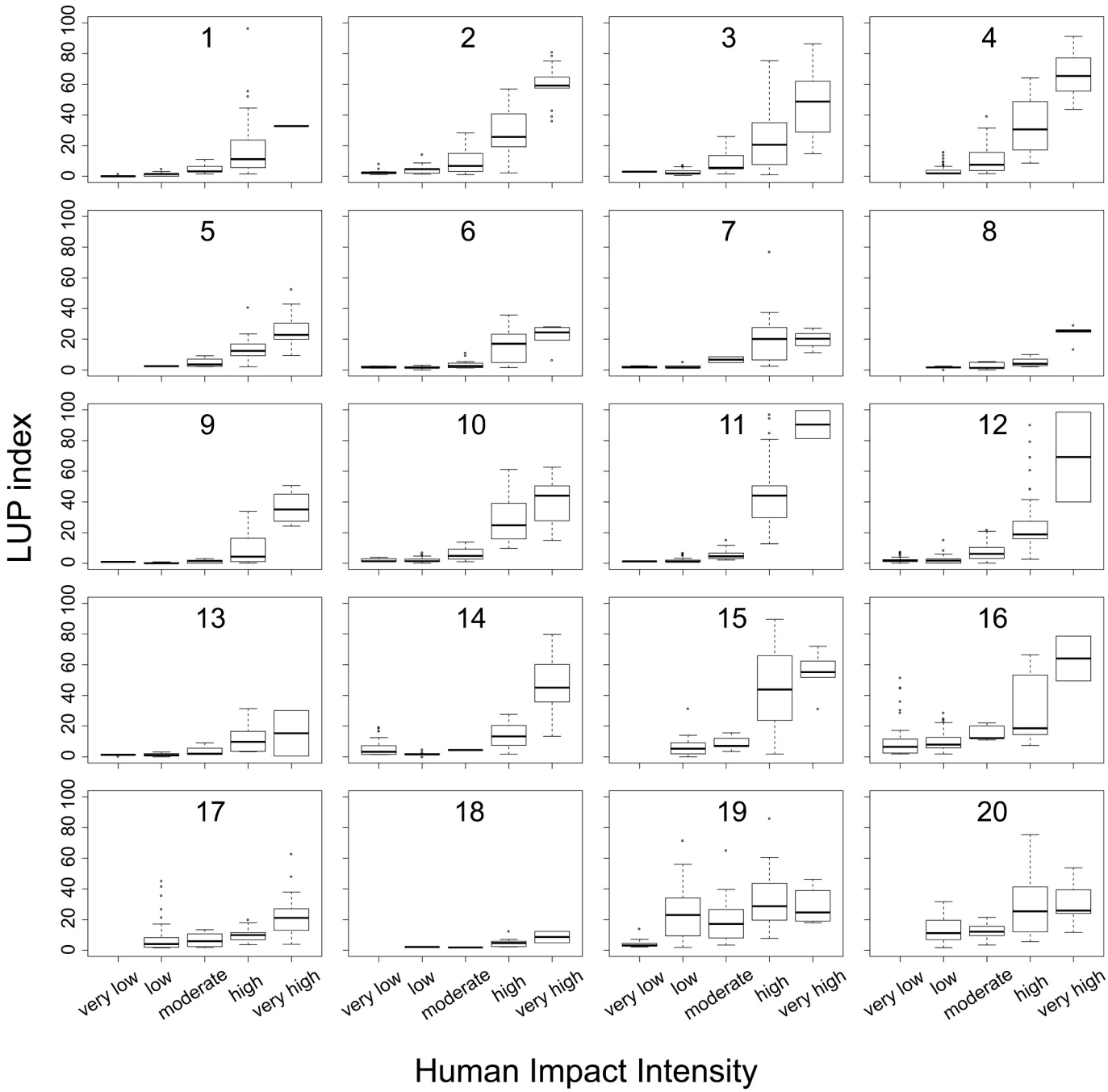

Fig. 3. Boxplots of the land use probability (LUP) index response to degrees of human impact intensity (Deza-Araujo et al., 2020) in the calibration sites: 1 = Egelsee (Menzingen), 2 = Burgäschisee, 3 = Soppensee, 4 = Moossee, 5 = Bachalpsee; 6 = Lej da San Murezzan, 7 = Lej da Champfèr, 8 = Lengi Egga, 9 = Gouillé Rion, 10 = Lago di Origlio, 11 = Lago di Muzzano, 12 = Lago Piccolo di Avigliana, 13 = Pavullo nel Frignano, 14 = Lago del Greppo, 15 = Lago di Massaciuccoli, 16 = Lago dell'Accesa, 17 = Lago di Baratz, 18 = Sa Curcurica, 19 = Gorgo Basso, 20 = Biviere di Gela. The degrees of Human Impact Intensity correspond with the following archaeological and historical periods: very low = Palaeolithic and Mesolithic; low = Neolithic; moderate = Bronze Age; high = Iron Age, Roman Imperial Period, Early Middle Ages; and very high = High Middle Ages, Modern Era.

Table 3
Main features of the palynological records considered in the external validation of the land use probability (LUP) index.

Vegetation belt	Site	Lat (°N), Long (°E)	Elevation (m a.s.l.)	Area (ha)	Age range (cal. yr BP)	MAT (°C)	Reference
Colline/ montane	A) Etang de la Gruère	47.240556, 7.050000	1005	22.5	800–11,900	5.5	Roos-Barraclough et al., 2004
	B) Launensee	46.39684, 7.331430	1381	8.78	−50–14,200	4.9	Rey et al., 2013
Subalpine/ alpine	C) Iffigsee	46.38679, 7.405890	2065	10	−50–11,250	6.5	Schwörer et al., 2014, 2015
	D) Hopschensee	46.25250, 8.023056	2026	1	100–13,600	7	Curdy et al., 2020
Submediterranean	E) Lago del Segrino	45.82802, 9.26482	374	38	−50–14,350	12	Gobet et al., 2000
	F) Lago Verdarolo	44.359222, 10.123111	1390	1	−50–14,450	6	Morales-Molino et al., 2021
	G) Limni Zazari	40.625277, 21.547222	606	200	−50–22,300	12.3	Gassner et al., 2020
Mesomediterranean	H) Lago di Martignano	42.11227, 12.31566	204	244	0–11,700	17	Kelly and Huntley, 1991
	I) Ojos de Villaverde	38.79895, −2.36032	870	0	−50–9700	13–14	Carrión et al., 2001
Thermomediterranean	J) Stagno di Chia	38.896512, 8.874978	0	16	−50–7850	19	Unpublished data
	K) San Rafael	36.773611, −2.601389	0	ex-marsh	0–20,580	19.5	Pantaléon-Cano et al., 2003

the MADCAP ones for the EPD sites (Giesecke et al., 2014). Then, LUP values of both the 20 calibration and 11 validation datasets were compared to the density of archaeological radiocarbon dates around the sites (Rykiel, 1996; Figs. 2, 5, 6). This comparison is intended as an independent validation. We assume that the more sites per time interval and area are recorded using radiocarbon dates, the higher the archaeological site density known for that time, and therefore the larger the overall past human activity and/or population density (Shennan et al., 2013). This approach is one of the few archaeological options to develop continuous records of human activity (Hinz, 2020) that can be used for comparison with the selected pollen datasets. We used the radiocarbon dates available within a 50-km radius around most palynological sites. However, for thermomediterranean sites this radius was increased to 100 km because these sites are located on the coast where there is less adjacent land area and in turn lower amounts of radiometric data. The dates for the cumulative radiocarbon proxy curves come primarily from the database XRONOS, but the set was enlarged using data from Laabs (2019) for Switzerland, Martínez-Grau et al. (2021) for Switzerland and

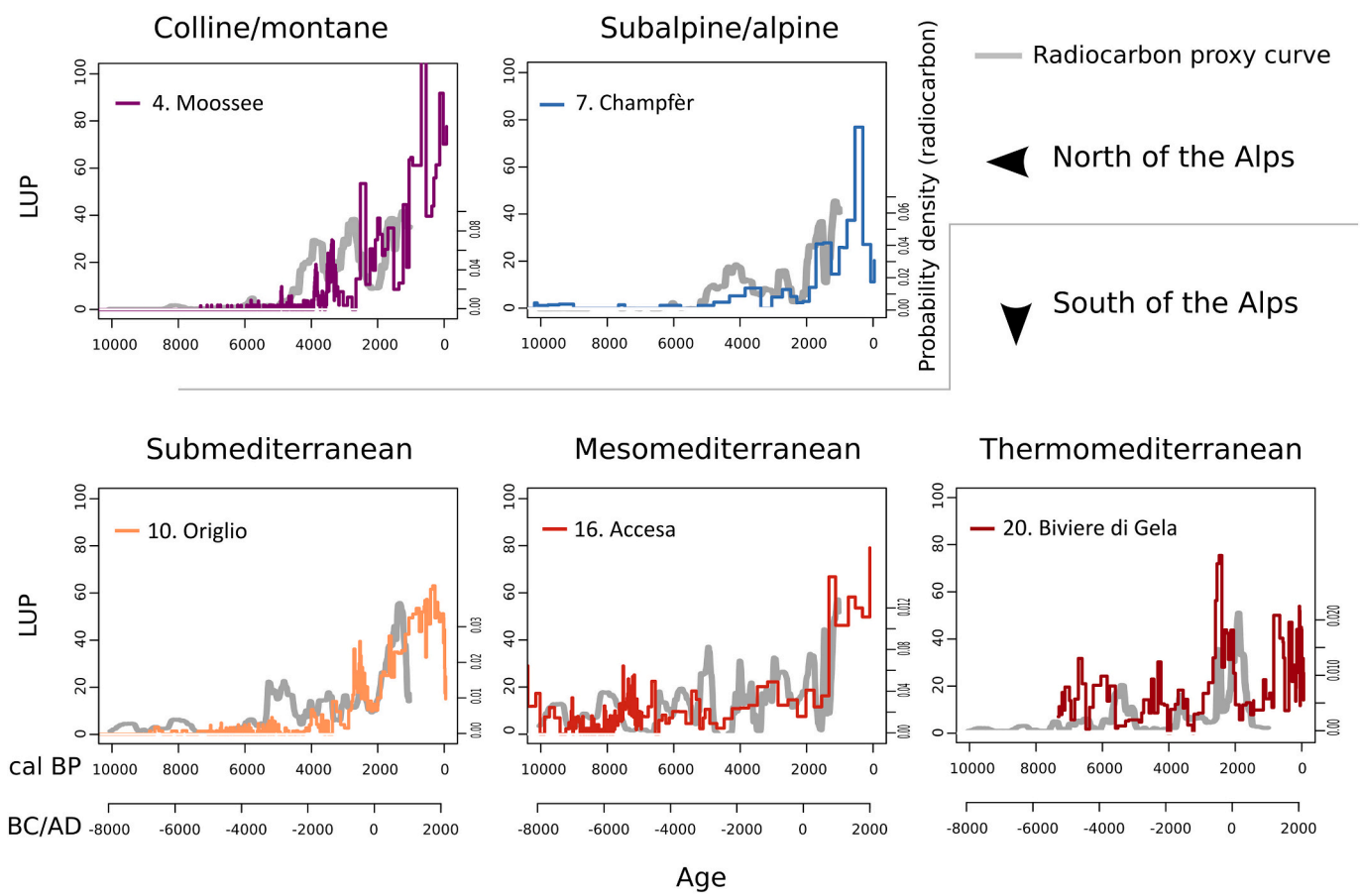

Fig. 4. Land use probability (LUP) index at some of the sites included in the calibration dataset. Only one site per vegetation belt is shown (see Fig. S2 for the curves of all the sites of the calibration dataset). Y-axis "LUP" is limited to a maximum of 100. In gray, the curve of radiocarbon proxy calculated from sites within a 50-km radius buffers around the sites combined into one curve per vegetation type (subalpine/alpine to thermomediterranean, see Fig. 2) used for archaeological validation, except at the thermomediterranean sites, where the buffers had 100-km radius.

northern Italy, Palmisano et al. (2018) for Italy, and Lugliè (2018) for Corsica and Sardinia (a complete list of the archaeological dates can be found in Table S3). The summed probability distributions (SPD) were calculated using the R package 'Rcarbon' (Crema and Bevan, 2021). We used the unnormalised approach and binned the dates according to site. No temporal binning was accomplished to avoid artificial separation of connected land-use phases. The cumulative radiocarbon proxy curves were then grouped into the five vegetation belts considered in this study (Figs. 4, 5, S2). Because of this grouping (method category 1 in Crema et al., 2017), our approach is not spatially explicit, and corrections for potential spatial-temporal autocorrelation of the sites are therefore not necessary. We used a smoothing window of 50 years.

3. Results and interpretation

3.1. Cultural indicator pollen types included in AIV

3.1.1. Non-native primary indicators (PI1)

We selected the following pollen types that can be unambiguously identified at the highest taxonomic resolution attainable and are directly associated with agriculture (food and fibre crops): *Avena*-t., *Fagopyrum*, *Hordeum*-t., *Linum usitatissimum*-t., *Pisum sativum*, *S. cereale*, *Triticum*-t., *Vicia faba*-t. and *Zea mays* (Figs. 1b, 3). *Hordeum*-t. may include pollen of some wild grasses in certain sites (Beug, 2004), which could be corrected readily by reducing its AIV. These taxa are mostly self- and insect-pollinated, resulting in low pollen production and relatively poor pollen dispersal, except for wind-pollinated *S. cereale* (Trondman et al., 2015). These crop species are non-native to Europe and are therefore almost unequivocal indicators of farming, particularly north of the Alps (Behre, 1981; Zohary et al., 2012). Although some close relatives of these crops (sometimes within the same genus) are native to Europe, we assume that the contribution of such native taxa to these pollen types is very low (Beug, 2004). These pollen types were included in the LUP index for all vegetation belts. However, at some sites several pollen types are grouped as Cerealia-t., which includes *Avena*-t., *Hordeum*-t. and *Triticum*-t., but not *Z. mays* or *S. cereale*. Furthermore, pollen of non-cultivated Mediterranean grasses, such as *Bromus*-t. may be classified as Cerealia-t. (Tweddle et al., 2005). Cereal pollen is usually very rare in fossil pollen assemblages (Lechterbeck et al., 2014) and regular occurrences of Cerealia-t. pollen are mostly recorded in close proximity to cultivated fields (Niebieszczański et al., 2018). Further, pollen deposition of autogamous cereals (e.g., *Triticum*, *Hordeum*) increases notably during harvesting and threshing and cereal pollen is consequently rather abundant in pollen sites near Neolithic lakeshore dwellings (Behre, 1981). Consequently, Cerealia-t. pollen is an overall very good indicator of agricultural land use.

Another pollen indicator with high cultural value is *Cannabis*-t. (Figs. 1b, 3). The exponential growth of the *Cannabis*-t. curve at most sites largely coincides with the intensification of human activities during the last centuries. Prominent peaks of this indicator in the Middle Ages and Modern Era, particularly in temperate settings such as the colline/montane and submediterranean belts (e.g., Egelsee, Burgäschisee, Soppensee, Origlio, Muzzano, and Avigliana; Fig. 1a), are related to water retting for fibre extraction (Bradshaw et al., 1981), which justifies a

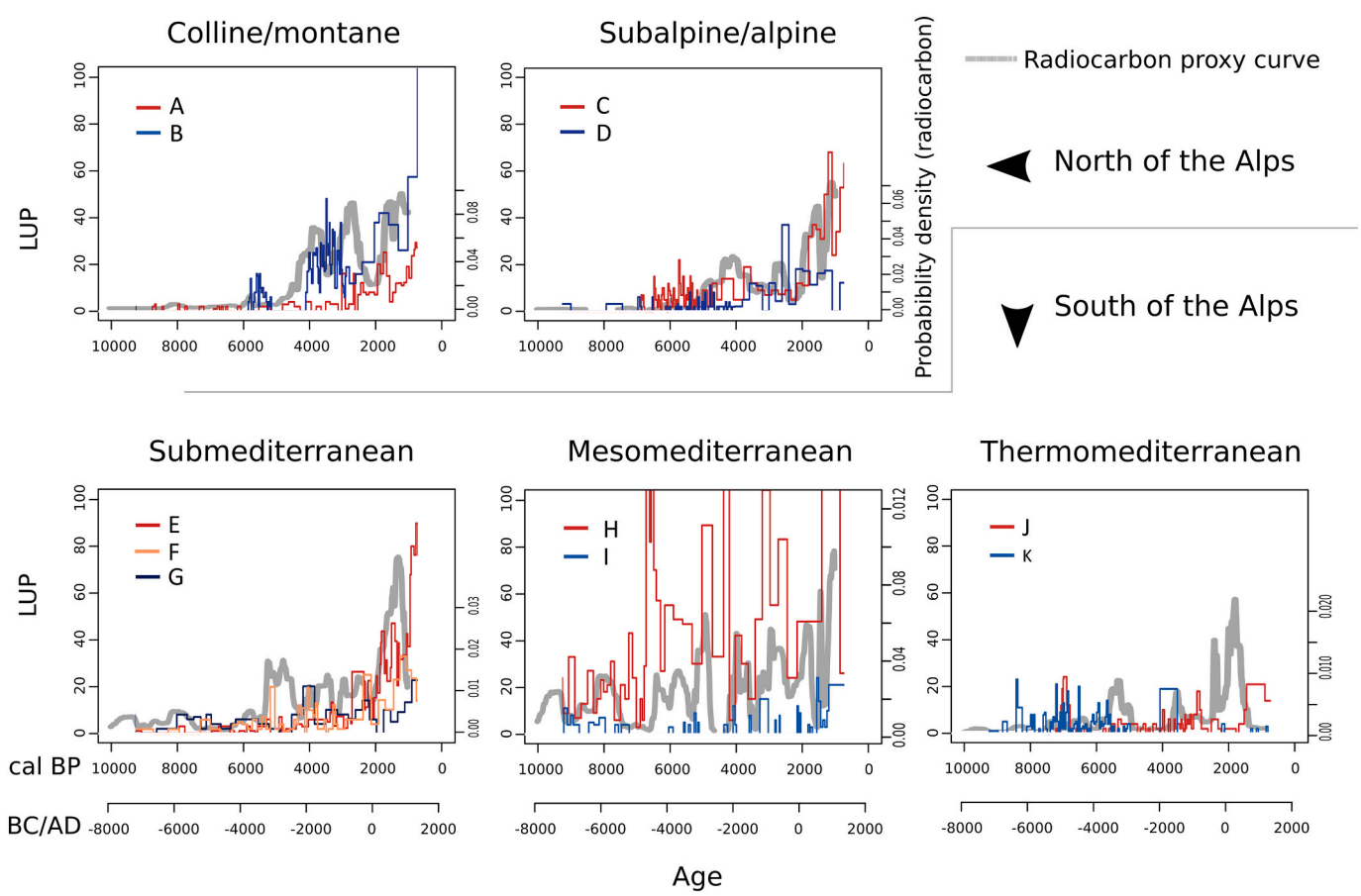

Fig. 5. Validation of the land use probability (LUP) index with independent sites: A = Etang de la Gruère, B = Launensee, C = Iffigsee, D = Hopschensee, E = Lago del Segrino, F = Lago Verdarolo, G = Limni Zazari, H = Lago di Martignano, I = Ojos de Villaverde, J = Stagno di Chia, K=San Rafael.
Y-axis "LUP" is limited to a maximum of 100. In gray, the curve of radiocarbon proxy calculated from sites within a 50-km radius buffers around the sites combined into one curve per vegetation type (subalpine/alpine to thermomediterranean, see Fig. 2) used for archaeological validation, except at the thermomediterranean sites, where the buffers had 100-km radius. For the individual site plots, see Fig. S3.

lower AIV of 0.25 (Fig. 1b). Until ca. 100–200 years ago, *Cannabis sativa*, which is not native to Europe (McPartland et al., 2019), was widely planted for medicinal, food and fibre uses (Plants for a future, 2018; Russo, 2007).

3.1.2. Native primary indicators (PI2)

Although several more fruit trees and vines of cultural importance are native to Europe (e.g., *Corylus avellana*, *Vitis*, *Pistacia*), we selected *Castanea sativa, O. europaea* and *J. regia* for the LUP index because these trees are usually rare in the natural forests or woodlands. *Castanea sativa* is currently dominant in submediterranean woodlands and forests but palaeoecological evidence has proven that humans extended its range and increased its abundances through Roman Times and the Middle Ages until the Modern Period (e.g., Morales-Molino et al., 2015). This is the underlying reason why we have included *Castanea sativa* in the LUP formula assigning to it a lower AIV in this environmental context (Fig. 1b). Similarly, *O. europaea* is a relevant component of thermomediterranean woodlands, but its importance declines sharply outside of this southern vegetation type. For instance, in the mesomediterranean vegetation type, other species like *Q. ilex* are more competitive under natural conditions (Costa et al., 2005). The abundance of *O. europaea* pollen in thermomediterranean records under natural conditions (e.g., Gorgo Basso; Tinner et al., 2009) led us to remove it from this vegetation belt. *Castanea sativa*, *O. europaea* and *J. regia* are routinely found in Holocene pollen assemblages from Europe because they are (partly) anemophilous. However, *Juglans* and *Castanea* pollen percentages are sometimes low, even in the presence of crops, except when they are very close to the pollen site (Di Pasquale et al., 2010) or dominating in the forest vegetation (Tinner et al., 1999). Therefore, occasionally the finding of few pollen grains might be considered indicative of their cultivation (Russo Ermolli et al., 2018).

3.1.3. Non-native and native secondary indicators

P. lanceolata-t. pollen has been conventionally regarded as an excellent cultural indicator (Iversen, 1941) because in temperate and boreal Europe it is considered to mostly derive from *P. lanceolata,* which is an adventive species that is favoured by farming practices. The pollen type is absent or only very rarely found in non-Mediterranean pollen assemblages before the onset of agricultural activities. *P. lanceolata* features a remarkable adaptation capacity to environmental variation (Bischoff et al., 2006), plays a significant role in the recolonisation of abandoned cultivated land (Behre, 1981), and is a ruderal and trampling indicator. However, *P. lanceolata*-t. pollen is quite abundant in thermomediterranean pollen sequences during the early Holocene (e.g., Gorgo Basso; Tinner et al., 2009), perhaps because of the presence of other *Plantago* species producing the same pollen type, so we excluded it as a cultural indicator in that setting.

Urtica dioica-t. pollen is mostly produced by the homonymous plant species (Lang, 1994), which is an apophyte in Europe, typical of ruderal communities. In pollen diagrams, it usually presents a regular, increasing curve, particularly marked in the subalpine vegetation belt (e.g., Bachalpsee, Gouillé Rion). *U. dioica* has long been consumed as food (leaves and oil) and has medicinal properties (Plants for a future, 2018). It is among the commonest food plant found in Neolithic Linear Pottery culture (LPC) sites (Colledge and Conolly, 2014). Additionally, its fibres were used for fabric weaving as early as the Bronze Age, representing a valuable resource traded over long distances in Europe (Bergfjord et al., 2012). *Urtica membranacea*, which has less specific ecological requirements, is often combined with *U. dioica* as *Urtica*-t. in thermomediterranean settings. Therefore, we did not include *Urtica*-t. as a cultural indicator in the thermomediterranean belt.

Finally, *Mercurialis annua* consists of a complex of closely related wind-pollinated annual plant taxa native to central and western Europe, the Mediterranean region and western Asia that grow mainly in ruderal places (e.g., fallow land, vineyards, or vegetable gardens) and roadsides on nutrient-rich, loamy and relatively dry to moderately moist soils (Güemes, 1997; Pignatti et al., 2005; Lauber et al., 2018). Because of these ecological requirements, *M. annua* has been used as an indicator of early human habitation in the Mediterranean (e.g., Bottema and Sarpaki, 2003). This pollen type was not found in all the training sites, although it had a good representation at the thermomediterranean sites. Due to its often-low taxonomic identification as *Mercurialis*-t., we could not use *M. annua* at every site, as the related pollen type, *Mercurialis perennis*, grows in woodlands.

3.2. Evaluation and validation of the LUP index

The LUP index values show a general exponential growth throughout the Holocene, with first non-zero values occurring in the study area around the early Neolithic (8000–6000 cal. BP) and remarkable increases usually during the early Bronze Age at ca. 4200 cal. BP or at the latest at the onset of the Iron Age at ca. 2800 cal. BP (Figs. 3, 4). Whereas this general trend is observed in all vegetation types (Figs. 3, 4) increases in LUP are punctuated by several transient troughs corresponding to times of land abandonment and population decline such as the "Late Bronze Age collapse" at ca. 3200 cal. BP (Figs. 4, S2). The boxplots show a significant variability in LUP values for the 'high' and 'very high' categories of human impact intensity, which correspond to the Iron Age to Early Middle Ages and High Middle Ages to present respectively, as shown by the large interquartile ranges (Fig. 3).

Maximum LUP values are reached at the colline/montane and submediterranean sites where high peaks of *Cannabis*-t. occur (Figs. 3, 4). In contrast, LUP values from the cold subalpine/alpine vegetation belt are rather low (Figs. 3, 4). Similarly, LUP values are generally low in the four thermomediterranean sites where LUP curves do not show marked oscillations (Figs. 3, 4).

The application of the LUP index to the eleven independent palynological records (Table 3) produced land-use patterns similar to those observed in the pollen datasets used for the LUP development (Figs. 4, 5, S2). Although the mesomediterrnean validation site of Lago di Martignano shows similar patterns, the range of LUP values is notably wider than in the calibration datasets and the rest of validation sites due to the high pollen percentages of *O. europaea*. Taken together, LUP patterns suggest that agricultural land use increased towards the present but fluctuated considerably, likely in association with episodes of '*landnám*' and land abandonment (Figs. 4, 5, S2). Lower LUP values in the cold subalpine/alpine vegetation belt may reflect less intensive agricultural land use due to the harsh environmental conditions. In contrast, lower LUP in the thermomediterranean (Fig. 5) are most likely a calculation artefact due to the exclusion of major food sources such as *Olea*, if compared to the other vegetation types. Finally, the archaeological radiocarbon proxy (Figs. 4, 5, S2) for anthropogenic activity resembles the overall increasing trends observed in the LUP curves, some of their wiggles, as well as events of rapid decline of human population (dependent and independent data) for the prehistorical periods. This finding suggests that the LUP index generally produces realistic agricultural land use trends (Figs. 4, 5, S2). Discrepancies between the two proxies might derive from uncertainties inherent to both approaches.

4. Discussion

4.1. What is new in the LUP approach?

In this study, we used bioindication criteria to select the best suited cultural indicator pollen types for reconstructing past agrarian land use. Compared to Behre's (1981) list of 38 cultural indicator pollen types, in this study we have considered 17 cultural indicators, a figure that can be reduced depending on the vegetation and climate setting (Fig. 1). Such a procedure allows the identification and straightforward interpretation of a limited number of pollen indicators for land-use reconstruction purposes in very different ecosystems, from the alpine/subalpine belt to the thermomediterranean vegetation types (i.e., most major land-use

conditions in Europe). We acknowledge that focusing on a limited number of pollen types may mean a loss of information. Earlier studies aimed at land-use reconstruction also focused on a reduced number of cultural indicator pollen types to stay as parsimonious as possible, often considering just two to four diagnostic pollen types out of several hundred (e.g., Tinner et al., 2003; Mercuri et al., 2013a, 2013b). In comparison, our new approach is more integrative because it considers up to 17 cultural indicators. Moreover, to some extent, the LUP index overcomes misleading interpretations of anthropogenic impact related to the imprecise assignment of pollen types to the crop and adventive categories (Deza-Araujo et al., 2022).

Further, the geographical scope of the LUP index may be expanded to other regions because most of the selected cultural indicators correspond to plants widely distributed, in contrast to other previously proposed methodologies for land-use reconstruction in Europe (Mercuri et al., 2013b; Kouli, 2015). Additionally, the LUP index has the capacity to detect human impact coming from various land-use systems, as it considers cultural indicator pollen types specifically used as proxies for agricultural (Cerealia-t., *P. lanceolata*-t.), pastoral (*U. dioica*-t.), and agroforestry or arboriculture systems (*O. europaea, Castanea sativa, J. regia*). These cultural indicator pollen types have been widely used separately as part of indices previously proposed for local human-impact reconstructions (Tinner et al., 2003; Mercuri et al., 2013b; Kouli, 2015).

The LUP-based quantification of human impact was possible thanks to the use of region-specific weighting coefficients (AIV) to adjust the relative abundances of cultural indicators. These region-specific AIVs aim to boost the relative abundances of often scarce but very important primary pollen indicators. This adjustment also downweights spikes deriving from overrepresented indicators such as *Cannabis sativa*-type that may inflate the estimation of human impacts. As a result, the abundances of all the selected indicators should be comparable. The use of AIV also allows accounting for the native status of a given taxon to certain geographic areas, thus disentangling the land-use impact from the possible natural occurrence of the indicator (e.g., *O. europaea* at thermomediterranean sites). Considering these factors, i.e., pollen representation and nativeness, AIVs could be assigned to the selected cultural indicators in other geographical settings, enabling the use of the LUP index. One of the most important criteria when selecting the pollen indicators used in the LUP index was that their relative pollen abundances in the calibration datasets showed steady increases in response to changes in land-use intensity (Behre, 1981). AIVs are intended to be a first step to refine such approximation, but there is room for further developments of the weighting procedure.

4.2. Overall performance of the LUP index

At the sites used to develop the LUP index, the curves follow the expected increasing trend in human impact intensity during the Holocene (Fig. 3; Deza-Araujo et al., 2020; Mottl et al., 2021), with major rises usually occurring in periods when European civilizations became more complex (i.e., Iron Age, Roman Times, Middle Ages and Modern Period; Moore and Armada, 2012). The overall good match between the curve of the LUP index and the radiocarbon proxy for anthropogenic activity suggests a good performance of the LUP index in quantifying Holocene human impact (Fig. 4). We acknowledge that both, LUP and the radiocarbon time series, have their own data-inherent limitations as proxies of past human impact (see e.g. discussion in Freeman et al., 2018), however given the good match in the general trends across many sites, we assume that both proxies are primarily related to the intensity of past anthropogenic activities, e.g. via number of dated remains of material culture (radiocarbon proxy) or number of flowering crops and weeds (LUP). Often, changes in some cultural indicators like Cerealia-t. can be closely related to demographic trends because they directly determine the carrying capacity (Izdebski et al., 2016; Tinner et al., 2003). This relationship is not always straightforward but may be particularly explicit during early agriculture phases, when worn-out fields were abandoned as fallow land, and later subjected to colonization by native pioneer vegetation. This was often the case between the Neolithic and the Early Bronze Age (Montgomery, 2007), as observable in the pollen records of Lago di Origlio and Lago Piccolo di Avigliana (Fig. SI). During these prehistoric periods, human population dynamics and land-cover change appear intimately linked, as shown by the overall close correspondence between cultural indicator pollen types and archaeological radiocarbon date density (Lechterbeck et al., 2014). This relationship is also marked during times of rapid land abandonment at the end of the farming cycles of the Neolithic, Bronze Age, Iron Age and Roman societies, and the Medieval and Modern periods (Montgomery, 2007). Such oscillations may correspond to major breaks like the "Neolithic decline" in northern and western Europe (~3000 BCE, ~4950 cal. BP; Kristiansen, 2015), the probable "Late Bronze Age collapse" in the Mediterranean (~1200 BCE, ~3150 cal. BP; Knapp and Manning, 2016), the fall of the Western Roman Empire at 476 CE (1474 cal. BP), the 1315–1317 CE European famine (635–633 cal. BP), or the 1348 CE (602 cal. BP) Black Death (Fig. 4). Moreover, high-resolution studies on varved sediments in Central Europe with an extremely high chronological precision suggest several synchronous agrarian land-use oscillations over the Neolithic, probably in response to changing environmental conditions (Rey et al., 2019a, 2019b). However, synchronous long-term oscillations of agrarian land-use activities over wide areas were reconstructed for the Bronze Age and the subsequent periods, including the Little Ice Age (Maise, 1998; Tinner et al., 2003, 2009).

High LUP values may be associated to environments with a high degree of vulnerability to human impact, as in the colline/montane and submediterranean belts. For instance, the Neolithic agriculture expansion from the valley bottoms up to treeline and higher up (Hafner and Schwörer, 2018) may have increased erosion on formerly forested steep slopes (Montgomery, 2007). Human transformation of forest into arable fields may have triggered soil degradation and/or eutrophication and favoured the extensive spread of taxa such as *P. lanceolata* and *U. dioica* (higher LUP values at the submediterranean and colline/montane sites, Figs. 4, 5, S2). Moreover, evergreen mediterranean woodlands are among the most sensitive ecosystems to human activities such as grazing or agriculture, because they are subjected to soil-water deficit during summer and usually grow on steep and unstable slopes (Burri et al., 1999).

In the LUP formula, we combine woody and herbaceous taxa to accomplish a more nuanced understanding of changing impacts, as we acknowledge the relevance of using short-living taxa such as Cerealia-t. together with other non-native primary indicators and adventive herbs. This combination is because wind-pollinated fruit trees are better represented in pollen records and thus among the most widely used cultural indicator pollen types (Mercuri et al., 2013b) compared to herbaceous plants with annual or biannual life cycles and low pollen taxonomic resolution (Deza-Araujo et al., 2022). However, fruit trees such as *Castanea* and *Olea,* may persist longer during land abandonment phases (Morales-Molino et al., 2015) and are therefore unsuitable to track decadal-scale events.

4.3. Evolution of LUP values in the different vegetation types of the study region

The sites located in the cool-temperate colline/montane vegetation belt north of the Alps (Fig. 1) do not show continuous signs of human impact before ca. 6000 cal. BP (Figs. 4, S2). In the original pollen diagrams, these sites include late Mesolithic occurrences (after ca. 8700 cal. BP) of Cerealia-t. and *P. lanceolata*-t. pollen (Lotter, 1999). Later, more detailed palynological analyses showed that among them are more diagnostic cereal taxa such as *Triticum*-t. and *Avena*-t. (Tinner et al., 2007), which suggests that agricultural activities may have initiated long before signs of human impact became continuous (i.e., 6750 vs. 4050 BCE, 8700 vs. 6000 cal BP). During the Neolithic (ca. 5500–2200 BCE, 7450–4150 cal. BP), pollen of cereals and weeds such as

P. lanceolata occurs regularly and this translates into very low (⟨20) but continuous LUP curves. In prehistoric times, the introduction or expansion of cultivated plants (Cerealia-t.) and weeds (*P. lanceolata*-t.) is linked directly with phases of increased human impact in the form of forest clearances at ca. 3700, 2700, 1900, 1550 BCE (5650, 4650, 3850, 3500 cal. BP) and after 650 BCE (2600 cal. BP; Rey et al., 2019a). Similarly, from the Bronze Age to the Middle Ages, episodes of forest clearance in the study region were connected to agricultural land use intensification at ca. 2100–1900 BCE (4050–3850 cal. BP), 1750–1650 BCE (3700–3600 cal. BP), 1450–1250 BCE (3400–3200 cal. BP), 800 BCE (2750 cal. BP), 650–450 BCE (2600–2400 cal. BP), 50 BCE-100 CE (2000–1850 cal. BP) and ca. 700 CE (1250 cal. BP; Tinner et al., 2003). Concerning the general long-term trends, pollen of crops and weeds increased during the Bronze Age, suggesting an expansion of permanent settlements and agricultural activities, including intensified transhumance (Wehrli et al., 2007). Human impact increased further during the Iron Age and the Roman period (ca. 2800–1600 cal. BP), as indicated by the appearance of new crops such as *J. regia* and *Castanea sativa* (e.g., Rey et al., 2020). Some dominant species such as beech were able to recover even after the periods of greatest anthropogenic impact and forest clearance (e.g., Iron Age, Roman Period) as soon as agricultural land use decreased (e.g., Migration Period at ca. 1600–1400 cal. BP; Rey et al., 2020). Agricultural land use increased during the Early Middle Ages and later, causing widespread forest opening (Rey et al., 2017). Whereas major episodes of forest clearance and establishment of permanent fields and pastures occurred during the Iron Age near environmentally favoured population centres, they occurred only during the late Middle Ages in cool and/or humid marginal areas (Lotter, 1999; Tinner et al., 2005). The widespread cultivation of *Cannabis sativa* during the Middle Ages is reflected in pollen values of up to 70% during the past millennium (Rey et al., 2017; Wehrli et al., 2007). After low LUP values related to the European famine of 1315–17 CE (~ 635 cal. BP) and the Black Death of 1348 CE (~ 602 cal. BP, Figs. 4, S2), LUP reaches particularly high values during the past ca. 600 years. This period experienced a marked vegetational change with the expansion of *P. lanceolata*-t., Poaceae and other herbaceous pollen types and the decline of tree taxa such as *Abies alba* and *F. sylvatica* (e.g., Wehrli et al., 2007).

At the cold subalpine/alpine sites in the Alps (Fig. 1), LUP and archaeological radiocarbon density curves show similar trends to those at the cool-temperate colline/montane sites north of the Alps (Figs. 4, S2). However, the magnitude of LUP is lower at the subalpine/alpine sites, which suggests lower land-use activities at the cold sites. Here, the archaeological radiocarbon density curves may overestimate human activities, given that the large radius (50 km) considered may include warmer and more fertile valley bottoms and lowlands, which are more attractive for human settlers. The catchments of the subalpine/alpine sites have been used as summer pasturelands at the latest since the Bronze Age (Gobet et al., 2003; Hafner and Schwörer, 2018). From 3000 cal. BP onwards, human-induced deforestation was the main driver of timberline lowering, which reached its most intense pulses since the Middle Ages (Gobet et al., 2003). The agricultural intensification phases recorded regionally during the Bronze Age, the Iron Age and the Roman period at the colline/montane sites (Tinner et al., 2003) are also documented in the subalpine sites (4050–3850, 3700–3600, 3400–3200, and 2000–1850 cal. BP; 2100–1900 BCE, 1750–1650 BCE, 1450–1250 BCE, 50 BCE–100 CE; Gobet et al., 2003, 2005; Tinner et al., 1996). The palynological results suggest for this vegetation belt continuous human influence and the absence of trees near the lakes up to the present (e.g., Lotter et al., 2006), with progressively lower human impact in the last 200 years (Figs. 4, S2).

At the submediterranean sites south of the Alps (Fig. 1), the LUP values become continuous at ca. 6000–5000 BCE (7950–6950 cal. BP, Figs. 4, S2), which corresponds to the onset of the Neolithic in this region. This pattern is mirrored in the archaeological radiocarbon density curve (Figs. 4, S2). Marked vegetation changes occurred during the late Neolithic and Bronze Age, when archaeological findings suggest increased human impact and pollen shows clearly marked land-use phases (Finsinger and Tinner, 2006; Vescovi et al., 2010b). Both the LUP index and the archaeological radiocarbon density curve feature very low values at the submediterranean sites simultaneously at ca. 1200 BCE (3150 cal. BP, "Late Bronze Age collapse"; Knapp and Manning, 2016; Andrea, 2009). During the Middle Bronze Age (1650–1350 BCE, 3600–3300 cal. BP), human activities increased steadily, as indicated by the significant rise of *P. lanceolata*-t. pollen around 1550 BCE (3500 cal. BP) at Pavullo nel Frignano (Vescovi et al., 2010b). Forest clearance further peaked during the Iron Age at ca. 650–450 BCE (2600–2400 cal BP, Tinner et al., 2003; Finsinger and Tinner, 2006). Subsequently, trees associated with Roman agricultural activities such as *Olea, Castanea* and *Juglans* were commoner in Insubria in the southern Pre-Alps than in the Northern Apennines (Watson, 1996; Morales-Molino et al., 2021). LUP suggests that human activities were not substantially more intense during Roman and early Middle Ages than during the Iron Age, but this may relate to *Castanea* pollen being downgraded in the LUP formula, and not to a stagnancy in agriculture (Figs. 4, 5, S2). Agricultural intensification continued towards the present, suggesting that agricultural land use further intensified during the past millennium (Finsinger et al., 2006; Finsinger and Tinner, 2006; Vescovi et al., 2007, 2010a).

In the mesomediterranean sites of central Italy (Fig. 1), LUP values become continuous at the beginning of the Neolithic (ca. 6000 BCE, 7950 cal. BP) at most sites (Figs. 4, S2). For instance, the decline of *Q. ilex* around 6000–5700 BCE (7950–7650 cal. BP) at Lago dell'Accesa was associated with an increase of deciduous oak and plants indicating disturbance and/or human activities (e.g, *Pteridium*, Poaceae, *P. lanceolata*-t. at 7900–7700 cal. BP, see Colombaroli et al., 2008). In contrast to other European regions where the "Neolithic decline" was quite conspicuous, the archaeological radiocarbon density curve denotes population growth during the late Neolithic around the Italian mediterranean sites, as also found in previous studies (Palmisano et al., 2017). In general, the LUP values for the Bronze Age at the mesomediterranean sites are comparable to those of the submediterranean sites south of the Alps and to those of the colline/montane sites north of the Alps. This suggests increasing agricultural activities during the Bronze age, in agreement with estimates of human population growth during the Bronze Age in the Mediterranean region (Vannière et al., 2008). However, after having remained rather stable during the Iron Age, the LUP index shows further increases ca. 2000 years ago at the mesomediterranean sites likely related to the Roman Empire. The match with the strongly oscillating archaeological radiocarbon density curve (and with fewer dates) is generally poor for this vegetation belt, but increases towards the end of the Roman Times, after a very acute depopulation period at the fall of the Western Roman Empire (around 476 CE, Figs. 4, S2). Prehistoric and historical agricultural land use dramatically changed the vegetation structure and composition at the mesomediterranean sites (Colombaroli et al., 2007, 2008; Drescher-Schneider et al., 2007). For instance, land use gradually converted natural mixed *Q. ilex-A. alba* forests into coastal maquis and garrigue (evergreen scrub communities that replace lowland Mediterranean woodlands following disturbances) during the middle and late Holocene (Colombaroli et al., 2007). The vegetational degradation to maquis and garrigue increased during the past 700 years and was strongly related to an intensification of agriculture (Colombaroli et al., 2007).

At the thermomediterranean sites in Sardinia and Sicily (Italy), the Neolithic land use dynamics is well documented by the LUP values (Figs. 4, S2). Neolithic farming started at ca. 6000 BCE (7950 cal BP) in Sicily, where the first unambiguous pollen imprint has been dated to around 5500 BCE (7450 cal BP) at Gorgo Basso as indicated by Cerealia-t. increases, together with *Ficus* (Tinner et al., 2009). Similarly, in Sardinia, the first archaeological evidence of Neolithic farming dates to 6000–5700 BCE (7950–7650 cal. BP, Pedrotta et al., 2021), although pollen (e.g., Cerealia-t., *P. lanceolata*-t.) and macrofossil evidence

suggests only marginal farming activities until 5300 BCE (7250 cal. BP), when a first prominent peak of arable farming occurred (Pedrotta et al., 2021). Increases in pastoral farming indicators such as *Urtica*, *Rumex acetosa*-t., *Rumex acetosella*-t. and Poaceae suggest an intensification of agricultural land use at 6500–6100 cal. BP (Pedrotta et al., 2021). Interestingly and in agreement with very low radiocarbon date density, LUP values seem to document the "Neolithic decline" around 3000 BCE (4950 cal. BP) in the thermomediterranean belt of Sicily and Sardinia around 3000 BCE (4950 cal. BP; Figs. 4, S2). During this period, a gradual but marked vegetation shift from evergreen oak woodland to maquis occurred at Biviere di Gela in Sicily in association with increased fire activity (Noti et al., 2009), while forests remained dense at Gorgo Basso, the other Sicilian coastal site (Tinner et al., 2009). In Sardinia, evergreen oak forests expanded massively into *Erica* woodlands (Beffa et al., 2016; Pedrotta et al., 2021) at ca. 3000 BCE (4950 cal BP), when farming activities were low. Pollen evidence from Sicily and Sardinia points to an intensification of agricultural activities during the Bronze Age at ca. 2000–1000 BCE (3950–2950 cal BP), which continued until 800 BCE (2750 cal. BP, Noti et al., 2009; Tinner et al., 2009; Beffa et al., 2016), when agricultural activities peaked at most thermomediterranean sites during the Iron Age (with the exception of San Rafael in southeastern Spain; Figs. 4, 5, S2). At 450–1750 CE (1500–200 cal. BP), a further pronounced intensification of land use resulted in the current (mostly) open landscape of coastal Sicily and Sardinia (Noti et al., 2009; Tinner et al., 2009; Beffa et al., 2016; Pedrotta et al., 2021). As in other vegetation belts, depopulation following the Great European Famine of 1315–17 CE (~ 635 cal. BP) and the Black Death of 1347 CE (~ 603 cal. BP), also occurred in the thermomediterranean area (Figs. 4, S2). Sa Curcurica and to a lesser extend Gorgo Basso might be an exception for the Great European Famine, as it is not reflected in LUP data (sites 18 and 19 in Figs. 4, S2). This finding is in agreement with historical evidence pointing to southern Italy as one of the regions that exported food during the climatically-driven Great European Famine (Baek et al., 2020).

5. Conclusions

In this study, we developed and tested a new agricultural land use probability (LUP) index based on selected and weighted anthropogenic indicator values (AIV). Because the AIV values account for regional differences in plant distributions, abundances, and agricultural practices, the new LUP index is in its nature probabilistic and region-specific. The LUP index represents a general procedure with a high indicative power for most major biomes of Europe that, with due caution, is easy to apply for pollen-inferred land-use reconstructions. When the boundary conditions and premises for its applicability are met (e.g., sufficient taxonomic resolution), our index faithfully reflects the trajectory of human impacts as inferred from the original pollen profiles. The LUP index is parsimonious and makes comparisons across sites within similar vegetation types possible (e.g., subalpine/alpine, colline/montane, submediterranean, mesomediterranean and thermomediterranean). The crops and weeds native to the Mediterranean deserve special attention and are in our case probably leading to an underestimation of human activity in the warmest thermomediterranean belt.

The determination of the most useful quantitative pollen indicators for a given area needs a thorough validation with independent evidence, for instance from archaeology and archaeobotany. So far, numerical archaeological evidence readily comparable to stratigraphic land-use evidence like that coming from palynology is very scarce. Our tentative validation with independent pollen sequences and compiled radiocarbon dates from archaeological contexts suggests that the LUP index procedure may be applied outside the regions used for its development, as long as new cultural indicator pollen types can be incorporated to adjust the AIVs. Further developments in this field include the use of new technologies (e.g., sedimentary ancient DNA, molecular biomarkers) for refining the taxonomic resolution of the pollen indicators and biogeography evidence that attributes categories of adventive or apophyte, according to geographic location.

Declaration of Competing Interest

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

Acknowledgements

This research was funded by the Swiss National Science Foundation (QuantHum project; SNSF Grant No. 169371). We are grateful to our colleagues of the Palaeoecology group at the University of Bern, especially Christoph Schwörer and Erika Gobet, for fruitful discussions. Pollen data were obtained from the Alpine Palaeoecological. Database (ALPADABA) and the European Pollen Database (EPD) via the Neotoma Paleoecology Database, and the work of the data contributors and the scientific community supporting these databases is gratefully acknowledged. We thank Dr. Susann Stolze, Natalie Latysh and two anonymous reviewers for their comments and suggestions on a previous version of the manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2022.111051.

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