A critical assessment of human-impact indices based on anthropogenic pollen indicators

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A R T I C L E  I N F O
Article history:
Received 28 January 2020
Received in revised form
24 March 2020
Accepted 24 March 2020
Available online xxx

Keywords:
Holocene
Palaeoecology
Palynology
Europe
Archaeology
Prehistory
Ancient farming
Land-use history
Past population density

A B S T R A C T
Anthropogenic pollen indicators in pollen records are an established tool for reconstructing the history of human impacts on vegetation and landscapes. They are also used to disentangle the influence of human activities and climatic variability on ecosystems. The comprehensive anthropogenic pollen-indicator approach developed by Behre (1981) has been widely used, including beyond its original geographical scope of Central and Western Europe. Uncritical adoption of this approach for other areas is risky because adventives (plants introduced with agriculture) in Central Europe can be apophytes (native plants favoured by human disturbances) in other regions. This problem can be addressed by identifying region-specific, anthropogenic-indicator pollen types and/or developing region-specific, human-impact indices from pollen assemblages. However, understanding of regional variation in the timing and intensity of human impacts is limited by the lack of standardization, validation and intercomparison of such regional approaches. Here we review the most common European anthropogenic pollen-indicator approaches to assess their performance at six sites spanning a continental gradient over the boreal, temperate and Mediterranean biomes. Specifically, we evaluate the human-indicator approaches by using independent archaeological evidence and models. We present new insights into how these methodologies can assist in the interpretation of pollen records as well as into how a careful selection of pollen types and/or indices according to the specific geographical scope of each study is key to obtain meaningful reconstructions of anthropogenic activity through time. The evaluated approaches generally perform better in the regions for which they were developed. However, we find marked differences in their capacity to identify human impact, while some approaches do not perform well even in the regions for which they were developed, others might be used, with due caution, outside their original areas or biomes. We conclude that alongside the increasing wealth of pollen datasets a need to develop novel tools may assist numeric human impact reconstructions.

1. Introduction

Palaeoecology provides valuable records of past ecological change and its drivers over centennial to millennial timescales at decadal to centennial resolution. Environmental drivers of ecosystem change (e.g. climate, human activities, natural disturbances) may operate simultaneously and thus it may be difficult to disentangle their specific role (Nelson et al., 2006). In Europe, human activities became a major driver for landscape dynamics, land-cover change, species distributions and disturbance regimes as early as ca. 9000-7000 years ago with the onset of farming at the beginning of the Neolithic. As a result, the transformation of forests into heathlands (e.g. Calluna vulgaris), shrublands (e.g. Corylus avellana, Alnus viridis), maquis, garrigue, grasslands, or meadows may have resulted from human-induced deforestation including excessive fire disturbance and/or browsing (Gobet et al., 2000; Tinner et al., 2005; Carrion et al., 2010; Rey et al., 2019). These examples illustrate the role of discrete disturbance events and
highlight the need for high-resolution reconstructions of past land use and environmental change to disentangle anthropogenic and natural forcing. The contribution of the various forcing factors may be assessed using multi-proxy palaeoecological studies providing independent lines of evidence (Birks and Birks, 2006; Colombaroli et al., 2007), where the results are ideally validated with local archaeological evidence (Hjelle et al., 2012).

Vegetation changes inferred from palynological sequences have traditionally been linked to climate change when occurring more or less synchronously over broad areas (Jalut et al., 2009), but this assumption might result in overlooking the role of broad-scale concurrent human activities (Tinner et al., 2013; Walsh et al., 2019). Previous research has also shown that climate change may exert a strong influence on land use, leading to synchronous patterns over wide areas (Gobet et al., 2003; Tinner et al., 2003; Oliver and Morecroft, 2014). For instance, widespread forest opening reconstructed from several Mediterranean pollen records for the past ca. 7000 years has been attributed to either a continental-scale decrease in moisture availability (‘aridification’ hypothesis; see Jalut et al., 2009; Sadori et al., 2011), increasing human activity, including burning (e.g. Tinner et al., 2009; Biscuit et al., 2012) or a combination of both factors (e.g. Carrion et al., 2010). This controversial Mediterranean example illustrates challenges in unambiguously inferring anthropogenic impacts.

Reconstructing human impacts on the environment using palynology has largely relied on the presence and abundance of anthropogenic pollen indicators. Pollen of adventives (i.e. plant species not native to a specific area) track intentional or unintentional (i.e. cultivated crops vs. weeds) introductions by humans and are therefore considered to be reliable indicators for past human activities (Behre, 1981, 1988; Huntley and Webb, 1988). Although with less diagnostic capacity than adventives, the pollen of apophytes (i.e. native plant species favoured by human activities) also provide information regarding anthropogenic impacts on the landscape (Behre, 1981; Lang, 1994). Offsite and onsite palaeorecords (e.g. pollen, macrofossils, megafossils, aDNA), in combination with archaeology, provide the only unambiguous evidence for determining the native ranges of cultivated plants and weeds. Such evidence has shown that depending on the region of interest, many plant species may be regarded either as adventives or apophytes (di Castri et al., 1990; Lang, 1994; Conedera et al., 2004; van Leeuwen et al., 2008; Krebs et al., 2019). In the case of palynology, data interpretation requires a strong background knowledge of the processes controlling pollen, spore and other microfossil production, dispersal and preservation (Webb and Goodenough, 2018). This condition adds further complexity to the inference of human impacts from palynological data (Behre, 1981), especially in a quantitative manner, and limits the use of pollen-inferred reconstructions of land-use history by a broader community.

Early applications of the pollen-indicator approach used pollen from plants particularly sensitive to winter frost for palaeoclimatic reconstructions (Iversen, 1944). This methodology has later been extensively applied to land-use reconstruction. Behre (1981, 1988) assembled lists of reliable anthropogenic pollen indicators for Central and Western Europe (north of the Alps). Behre’s pioneering work was later extended to other areas (e.g. the Middle East, Behre, 1990; China, Li et al., 2015; Mexico, Franco-Gaviria et al., 2018) and refined in Western Europe (Mazier et al., 2006; Brun, 2011). Moreover, Behre’s comprehensive account of anthropogenic pollen indicators has been widely used in European areas outside of its original calibration area (e.g. Novenkov et al., 2017; Cartier et al., 2018; Fredh et al., 2018; López-Sáez et al., 2018), although the chosen indicator taxa may not be necessarily suitable in these regions (apophyte vs. adventurous problem; Moore et al., 1991; Lang, 1994).

The presence and abundance of anthropogenic pollen indicators provide valuable evidence for the occurrence and intensity of past land use (Behre, 1981). The sum of the percentages of these pollen types is often plotted separately in pollen diagrams as curves of Principal and/or Secondary Indicators (‘PI’, ‘SI’; e.g. Lang, 1994). In contrast to other fields of palynology (e.g. tree-line studies), absolute values such as influx are less often used for human-impact reconstructions (Koff and Punning, 2002). To characterize and quantify past land use, pollen indices based on anthropogenic indicators were first developed to estimate the ratio of arable to pastoral farming (Steckhan, 1961; Turner, 1964; Kramm, 1978; Riezebos and Slotboom, 1978). More recently, new semi-quantitative indices of human impact are being applied, especially (see summary in Table 1): the Cultural Indicators (‘CI’) approach (Tinner et al., 2003), the Anthropogenic Pollen Indicator ‘API’ index (Mercuri et al., 2013a), the Olea-Juglans-Castanea ‘OJC’ index (Mercuri et al., 2013b) including its modification incorporating Vitis (‘OJCV’; Berger et al., 2019), and the Pollen Disturbance Index ‘PDI’ (Kouli, 2015). Complementarily, the ‘AP/NAP’ ratio between the percentages of arboreal (sum of trees and shrubs) and non-arboreal (sum of upland herbs) pollen has long been used to reconstruct changes in forest cover quantitatively, including anthropogenic clearance of forests (Aario, 1944; Berglund et al., 1991). Conventionally, the interpretation of AP/NAP is straightforward: very high (>10, corresponding to ca. 91% AP), intermediate (>4, 80% AP) and low (<1, 50% AP) values, represent very closed

| Table 1 | Main qualitative approaches to reconstruct human impacts on European landscapes based on abundances (usually in %) of anthropogenic pollen indicators. |
|---|---|
| Approach | Original Scope Area | Pollen types included |
| PI | Central Europe, North of the Alps | Cer relics: Secale cereale, Hordeum-type, Triticum-type, Avena-type, Zea. Dicotyledonous crops: Fagopyrum, Linum usitatissimum-type, Vicia faba, Cannabis-type. Adventives: Centaurea cyanus, Lychmis/ Agrostemma-type, Scleranthus annuus, Spergula arvensis-type, Polygonum convolvulus-type, Polygonum aviculare-type, Polygonum persicaria-type (Persicaria maculosa-type), Plantago lanceolata-type, Plantago major/media. Apophytes: Rumex acetosella-type, Rumex acetosa-type, Trifolium repens-type, Succisa, Jasion/Canepanula-type. Urtica, Artemisia, Melampyrum, Pteridium, Polypondium, Calluna, Juniperus-type |
| SI | Central Europe, North of the Alps | Centaurea, Cichorioideae, Plantago, Cannabis-type, Urtica, Trifolium |
| CI | North and South of the Alps | Olea, Juglans, Castanea |
| API | Mediterranean (Italy) | Olea, Juglans, Castanea, Vitis |
| OJC | Mediterranean (Italy) | Olea, Juglans, Castanea, Vitis |
| OJCV | Mediterranean (Italy) | Olea, Juglans, Castanea, Vitis |
| PDI | Mediterranean (northern Greece) | Centaurea, Cichorioideae, Plantago, Ranunculus acris-type, Polygonum aviculare-type. Sanguisorba minor-type, Urtica dioica-type and Pteridium |
| AP/NAP | Northern Europe | Olea, Juglans, Castanea, Vitis |

PI: Primary anthropogenic indicators & SI: Secondary anthropogenic indicators (Behre, 1981; Lang, 1994); CI: Cultural indicators (Tinner et al., 2003); API: Anthropogenic pollen indicators (Mercuri et al., 2013a); OJC: Olea, Juglans, Castanea (Mercuri et al., 2013b); OJCV: Olea, Juglans, Castanea, Vitis (Bevan et al., 2019; Robert et al., 2019); PDI: Pollen Disturbance Index (Kouli, 2015); AP/NAP: Arboreal pollen/non arboreal pollen ratio (Berglund et al., 1991; Favre et al., 2008).
forests, semi-closed forests and open vegetation, respectively (Mitchell, 2005; Favre et al., 2008; Zanon et al., 2018). However, detailed interpretation of intermediate values of this ratio remains unclear (Favre et al., 2008). When AP/NAP is combined with Behre’s cultural indicators, inferring the start of farming-induced forest opening in Europe is possible (e.g. Lang, 1994; Tinner et al., 2003; Rey et al., 2019).

In summary, although the potential of anthropogenic pollen indicators to reconstruct the impact of human activities on past vegetation dynamics has long been recognized and broadly used, no comparative evaluation of their performance is available yet. The emphasis of previous studies (e.g. Steckhan, 1961; Turner, 1964; Kramm, 1978; Riezebos and Slotboom, 1978; Behre, 1981; Lang, 1994; Koff and Punning, 2002; Tinner et al., 2003; Mercuri et al., 2013a;b; Kouli, 2015; Berger et al., 2019) on local to regional approaches is due to the different vegetation (e.g. biomes) and landuse (e.g. farming) conditions in space and through time. The aim of this study is to provide an overview of the existing methodologies and to understand their relative advantages and limitations. Here, we apply the most commonly used human-indicator species approaches to six study sites distributed over a wide latitudinal gradient across Europe, spanning from boreal to Mediterranean ecosystems. To evaluate their performance we compare the palynological evidence into a quantitative scale, we grouped the main archaeological and historical periods according to five stages of human impacts on the European environment: (1) very low/non detectable (corresponding to the Palaeolithic and Mesolithic), (2) low (Neolithic), (3) moderate (Bronze Age), (4) high (Iron Age, Roman Imperial Period and Early Middle Ages), and (5) very high (Middle Ages and Modern Era; Figs. 2 and 3). This classification assumes that the archaeological and historical periods correspond with economic stages and temporal transformation of technology (Kremer, 1993; Lemmen et al., 2011). The economic and technological developments alongside the assumed resulting population growth are, in turn, major determinants of human impact during the Holocene (Kremer, 1993; US Census Bureau, 2018).

To delimit the timeframe of each human-impact stage at each site, we synchronized the reference chronologies of the main, well-established archaeological and historical periods in Europe in a regional scheme (Fig. 3). While the definition of historical periods is established by events that are documented in historical sources (i.e. precisely dated), archaeological epochs are based on regionally different typo-chronological changes in material culture (i.e. classification of objects and architecture; Besserman, 1996; Shackley, 2001; Carson, 2016). When absolute dates (e.g. radiocarbon, dendrochronology) were available in the literature, we used them for the proposed chronologies (e.g. Knutsson and Knutsson, 2003; Betti Sestieri, 2013a, 2013b; Capuzzo et al., 2014; Lo Vetro and Martini, 2016; Pacciarelli et al., 2016; Stöckli, 2016; Natali and Forgia, 2018; Radi and Petrinelli Pannocchia, 2018; Alessandri, 2019). Conversely, we referred to relative dating where no absolutely dated chronologies were available. Because the limits of the different archaeological periods are not always supported by radiocarbon or dendrochronological dating, the presented supra-regional synchronization of periods is tentative, and some period boundaries

Table 2
Main features of the palynological records considered in this study.

| Site                      | Elevation (m asl) | Size (ha) | Age range (cal yr BP) | Vegetation type (Lang, 1994)                            | MAT (°C) | Reference                        |
|---------------------------|-------------------|-----------|-----------------------|--------------------------------------------------------|----------|----------------------------------|
| (a) Holtjärnen, Sweden    | 232               | 1         | 15−10500              | Boreal spruce and pine forests.                        | 4.2      | Giesecke (2005)                  |
| (b) Lake Gosciaż, Poland  | 64                | 70        | 35−12900              | Central and Eastern European mixed oak forests.        | 7.9      | Ralska-Jasiiewiczowa and van Geel (1992); Arnold et al. (1998) |
| (c) Burgășchiede, Switzerland | 465        | 21         | 59−18650              | Western, Central and Southeast European beech and beech fir forests. | 9.1      | Rey et al. (2017)                |
| (d) Lago di Origlio, Switzerland | 416        | 8          | 45−19400              | Montane and subalpine mountain coniferous forests and Krumholz bushes. | 12.0     | Tinner et al. (1999)            |
| (e) Lago dell’Accesa, Tuscany, Italy | 157   | 14         | 95−11550              | Meso-mediterranean evergreen and deciduous oak forests. | 14.0     | Colombaroli et al. (2008)        |
| (f) Gorgo Basso, Sicily, Italy | 6            | 2          | 50−10200              | Thermo-mediterranean evergreen oak forests and olive carob tree woodlands. | 17.6     | Tinner et al. (2009)            |

MAT: Mean annual temperature (Fick and Hijmans, 2017).
are uncertain. Furthermore, as Neolithisation is not a one-time event but rather a long and complex process, assigning precise dates to the boundary between the Mesolithic and the Neolithic in each region is often difficult (Dolukhanov et al., 2005; Gronenborn, 2005; Lemmen et al., 2011). Moreover, Mesolithic and Neolithic lifestyles may have coexisted simultaneously for several centuries in some regions (as e.g. proposed for Poland; Nowak, 2013). Nevertheless, the temporal resolution of our approach refers to long prehistorical and historical periods, which partially offsets possible chronological errors.

2.3. Performance of the indices

To evaluate the performance of the indices, we compared the results at the different study sites according to the technological stages (Fig. 3). To make the results comparable, we first rescaled the values of the different indices between 0 and 1 using a minimax transformation:

\[ Z_i = \left( \frac{V_i - V_{\text{min}}}{V_{\text{max}} - V_{\text{min}}} \right) \]

where \( Z_i \) is the minimax-transformed value of the index \( V \) for the \( i \)th study site.
-th sample of a given record \( (V_i) \), and \( V_{\text{max}} \) and \( V_{\text{min}} \) are the maximum and minimum values of \( V \) in the entire sequence. Secondly, we averaged the values of every index for each chronological human-impact stage and plotted boxplots to visually assess the trends in the values of the indices. We hypothesize that the magnitude of human impact on the environment will monotonically increase towards present across the stages of population and technological development of European societies during the Holocene as inferred from archaeological and historical evidence (Fig. 2). To test this hypothesis, we ran pairwise comparisons between the five considered human-impact stages on the environment (Figs. 2, 3) using the non-parametric Mann–Whitney \( U \) test (Wilcoxon rank–sum test), whose null hypothesis is that the two samples of the pairwise comparisons come from the same population.

3. Results

In northern and north-central Europe, the primary anthropogenic indicators index (PI) only increases during the last 1000–500 years at Holtjärnen (southern Sweden) and Lake Gosciaz (central Poland) (Fig. 4a and b). This striking increase during the most recent human impact stage is coupled with minimum AP/NAP values at both sites, although Lake Gosciaz records earlier openings during the Bronze Age and Iron Age. Similarly, although OJC and OJCV show null values (i.e. 0% Olea, Juglans, Castanea, and Vitis) throughout much of the Lake Gosciaz record, most of the non-zero values occur in the last 2000 years, with the exception of a peak around 6000 BC. In contrast, OJC and OJCV are zero for the entire Holtjärnen record. The secondary indicators (SI) and anthropogenic pollen indicators (API) indices have high values at the beginning of both pollen sequences (Mesolithic at Holtjärnen and Palaeolithic at Lake Gosciaz) that later decrease, to start increasing progressively from the Neolithic (Lake Gosciaz) and Bronze Age (at both sites) onwards. At Holtjärnen, CI has a discontinuous and sparse record from the Neolithic onwards and only contains continuous and remarkable values during the last millennium. At this Scandinavian site, significant values of PDI occur during the Neolithic and Iron Age.
Age but the most continuous and highest values of this index are
only present during the last millennium. In contrast, the CI record
at Lake Gosciaz starts during the Neolithic and is continuous until
the present, with conspicuous increases at the end of the Bronze
Age, and substantial increases during the Iron Age and the last
millennium. PDI mirrors the main trends of CI despite its nearly
continuous record throughout the Lake Gosciaz sequence (Fig. 4).

In Central Europe, the records of PI and CI from Burgășchisee
(Swiss Plateau) suggest that the first noticeable human impact
occurred during the Neolithic (ca. 4500 cal. BC), with remarkable
stepwise increases from the Iron Age onwards and particularly
during the past millennium (Fig. 4c). The Lago di Origlio sequence
records the presence of PI and CI on the southern Alpine forelands
as far back as ca. 7000 cal. BC, although the records are discontin-
uous until the onset of the Bronze Age (ca. 2300 cal. BC). As at
Burgășchisee, PI substantially increases at Lago di Origlio during the
last millennium, largely because Cannabis-type pollen reaches very
high shares within PI. This taxon represents 67.0 ± 20.2% at
Burgășchisee and 84.1 ± 11.3% at Lago di Origlio. At these two sites,
respectively located south and north of the Alps, API, SI and PDI
bear high values during the Younger Dryas and the onset of the
Holocene (until 9500-9000 BC, during the Palaeolithic). These three
indices contain (nearly) continuous records with noticeable in-
creases after the Neolithic and particularly from the Bronze Age
onwards. At Burgășchisee and Lago di Origlio, OJC and OJCV only
have continuous records since ca. 1900 cal BP, where their main

Fig. 4. Comparison of the anthropogenic pollen indices at different sites across Europe. Empty curves represent 10 × exaggeration. Indices used outside their geographical scope are shown in grey. Dashed lines delimit cultural periods with uncertain chronology. PI – Primary indicators, SI – Secondary indicators, CI – Cultural indicators, OJC – Olea-Juglans-
Castanea, API – Anthropic pollen indicators, PDI – Pollen Disturbance Index, AP/NAP – Arbooreal pollen/non-arbooreal pollen ratio (graphics restricted to 10 as maximum values, values of 1 and 4 are highlighted), P – Palaeolithic, M – Mesolithic, N – Neolithic, B – Bronze Age, I – Iron Age, RI – Roman Imperial Period, VA – Viking Age, EMA – Early Middle Ages, MA – Middle Ages, ME – Modern Era. Note the different scales in the X-axes. Human Impact stages range from 1 – very low to 5 – very high.
increases occur at ca. 1500 and 500 cal. BP, respectively. *Juglans* is largely dominant at Burgäschisee (48.8 ± 26.1% of OJC, 46.7 ± 25.0% of OJCV) while at Lago di Origlio, *Castanea* is the dominant taxon (89.3 ± 5.9% of OJC, 88.8 ± 5.9% of OJCV). The AP/NAP ratios show marked signs of forest opening during the Bronze Age (AP/NAP<4) at both sites and a significant enhancement of this process during the Iron Age (ca. 500 BC).

In southern Europe, SI, CI, API, and PDI are high at Lago del- l'Accesa (Tuscany, central Italy) during the early Holocene (Mesolithic; Fig. 4e). Later, their abundances decrease but their records remain continuous. PI, OJC and OJCV show discontinuous occurrences between ca. 8000 and 6000 BC, during the late Mesolithic and early Neolithic. At the Mesolithic-Neolithic transition (ca. 5800-5500 BC), an abrupt drop in the AP/NAP ratio occurs followed by increases in indices summing up weed abundances (CI, SI, PDI, API). Another remarkable decrease in the AP/NAP ratio at the beginning of the Bronze Age (ca. 2000 BC) is followed by the onset of continuous records for PI, OJC and OJCV as well as moderate increases in SI, CI, API, and PDI. The final drop in AP/NAP values dates to Early Medieval Times (ca. AD 500) and is accompanied by major increases in all the indices (i.e. PI, SI, CI, API, OJC, OJCV, and PDI). At this site, *Olea* pollen dominates the composition of the OJC (62.5 ± 47.9%) and OJCV (43.8 ± 38.3%) indices during the last millennium.

PDI, API and SI show very high values (up to 40% pollen) during the early Holocene (ca. 8000 BC) at Gorgo Basso (Sicily), whereas PI, OJC and OJCV are absent (Fig. 4f). At this site, SI, API, PDI and, to a lesser extent, CI present consistently high values (ca. 30% pollen) throughout the Mesolithic and the early Neolithic (ca. 8000-5000 BC), when the AP/NAP ratio shows very low values (<1). At the beginning of the Neolithic (ca. 5500-5000 BC), PI shows a prominent increase that is almost synchronous with a major peak in CI. Immediately after, from ca. 5000 BC, OJC and OJCV notably increase alongside the AP/NAP ratio and oscillate but maintain moderate to high values (10–20% pollen) for approximately 5000 years, until Roman Times. At Gorgo Basso in the thermo-mediterranean belt, *Olea* pollen is dominant in the composition of the OJC (98.6 ± 5.4%) and OJCV (91.2 ± 23.8%) during the fourth human-impact stage (Fig. 5), while *Juglans* is completely absent.

The behaviour of the studied cultural indicator approaches through time shows that only a few of them, particularly CI, fit our hypothesis of monotonically increasing human impact throughout

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**Fig. 5.** Boxplots comparing the distributions of the values of the different indices classified according to the different stages of human impact: 1 – No detectable/Very low, 2 – low, 3 – moderate, 4 – high, 5 – very high. Minimax transformations were calculated amongst the index values. The Y-axis of the AP/NAP plots was reversed to facilitate comparison with the other indices shown. Indices used outside their intended geographical scope are shown in grey. Different letters indicate statistically significant differences at $P < 0.05$ (nonparametric Mann–Whitney U test) among the human impact stages that according to our hypothesis, will increase its magnitude towards present.
all sites and human-impact stages (Fig. 5). PI is usually biased by the last cultural period, the Modern Era, characterised by very high abundances of cereal pollen particularly in central and northern European sites (Fig. 5a–d). Indices based on secondary indicators like SI and API often show unrealistically high values in the oldest archaeological periods, which includes the Palaeolithic and the Mesolithic. On the other hand, OJC and OJCV are absent or extremely rare in northern Europe for the entire period (Fig. 5a and b). Similar to PI, the OJC and OJCV indices are biased to the Modern Era in Central Europe and the Southern Alps (Fig. 5c and d), while farther south OJC and OJCV fit to the human impact expectations at the meso-mediterranean site (Accesa; Fig. 5e), but not at the thermo-mediterranean site (Gorgo Basso; Fig. 5f). PDI shows the expected increasing trend north of the Alps (Fig. 5a–c), while south of the Alps, the pattern is unclear (Fig. 5d–f). Finally, the pattern of AP/NAP is unrelated to any gradual increases in human impact through economic stages and archaeological and historical periods.

4. Discussion

4.1. Overall suitability of the anthropogenic indicators

In this study, we tested the suitability of widely used palynological indices based on anthropogenic pollen indicators for different European biomes. We compared the results obtained by the indices with human-impact stages, as derived from human population density growth and the related land use caused by the increasing carrying capacity of agriculture throughout different historical epochs (Kremer, 1993; Lemmen et al., 2011; US Census Bureau, 2018). The analysed indices do not always show a general increase since the Neolithic, and they also show disagreements among them on the extent and timing of land-use-related human impacts. In contrast, the human population experienced linear, exponential or logarithmic growth through the millennia with only episodic interruptions or reversed trends during environmentally caused production crises such as volcanic eruptions, mass migrations, and climatic reversals (e.g. Little Ice Age; Bentley, 2013). In this context, we identify indices as the lowest performing if they show trends that are opposite to those expected from the prehistorical and historical evidence used to model human population dynamics (Fig. 5). For instance, such dissimilarities occur in the case of high SI and API values before the Neolithic (i.e. stage 1) at several sites and in AP/NAP at all sites. Likewise, unexpected decreases in OJC and OJCV at Gorgo Basso between stages 3, 4, and 5, and in PDI, between stages 2 and 3 are seemingly inconsistent with agricultural intensification (Fig. 5). Best performance in terms of monotonic increasing trends across the human-impact stages are generally provided by indices using a few specific pollen indicators such as PI and CI. Although both PI and CI performed best among all indices at Gorgo Basso, they did not fully match population growth expectations. Similarly, SI has a good performance from the second human-impact stage onwards (except in the southern sites; Fig. 5). Changes in PI at Holtjärnen are limited to human-impact stage 5, which prevents an assessment of increasing trends (Fig. 5), but likely reflects the remoteness of the northernmost site in regard to arable farming.

In general, pollen indicator approaches perform best in the regions in which they were developed (Figs. 4 and 5). Specifically, most of the considered indicator species approaches show increasing human impacts between sequential human-impact stages outside the Mediterranean realm (e.g. PI and CI at Burgàschisee and Lago di Origlio; PI at Gosciaz), where this technique was originally developed (Behre, 1981), plant diversity is lower (Mutke et al., 2010), and wild relatives of (southwest Asian Neolithic) crops and weeds are rare (Zohary et al., 2012). Nevertheless, certain indices may perform well in regions different than the one where they were conceived. For instance, the PDI pastoral index developed in northern Greece performed reasonably well in tracking anthropogenic vegetation change in Holtjärnen (southern Sweden), particularly from the Iron Age onwards (Fig. 4). Such episodic good performances may however be coincidental. Indeed, the Holtjärnen record also provides reason for caution. An early incidence of forest opening at Holtjärnen dated around 3700 cal. BC, which caused PDI to increase, probably resulted from a shift in atmospheric circulation that naturally affected forests and not from human impacts (Hammarlund et al., 2002; Giesecke, 2005).

A given index may vary in performance among different human-impact stages when applied to the entire Holocene (e.g. Behre, 1981). In most of our cases, the AP/NAP and SI indices have a high potential in detecting deforestation at the Neolitholithic/Bronze Age transition. This transition is easy to infer because the development of more advanced farming techniques during the Bronze Age likely resulted in a permanent ecosystem shift, in contrast to earlier transient forest clearances that were followed by forest regeneration (Lang, 1994; Poska et al., 2004; Rey et al., 2019). Conversely, some indices may fail to identify human impacts at a later, higher technological stage (i.e. stages 3–4, Fig. 5), specifically at southern sites such as Accesa and Origlio. The cause might be a reduction of deforestation rates and an increased efficiency in farming practices during the Roman Imperial Period, for instance (Howatson, 2011). In addition, several centuries-long crises (e.g. migration period, Little Ice Age) are documented in archaeological and historical records (e.g. Maise, 1998) and by temporally well resolved palaeoecological records (Lottet, 1999; Tinner et al., 1999; Rey et al., 2017). These crises may not be evident in our comparisons among human-impact periods (Fig. 5), which were designed to assess the impacts of long-term trends in human population growth.

4.2. Direct indicators

The indices based on direct indicators (i.e. crops and strict adventives, CI and PI; Lang, 1994) showed an overall good performance at the temperate sites (Fig. 5a–d). In temperate environments, PI and CI were sensitive enough to detect initial stages of human impacts on the landscape when they were used in the appropriate setting, such as the early Neolithic farming (ca. 3800 BC: Cortalloid typochronological unit) at Burgàschisee (Rey et al., 2017). Similarly, CI was used to trace the major milestones in the history of human occupation around Lago di Origlio, such as Neolithisation and the establishment of permanent settlements during the Bronze Age (Tinner et al., 1999). Likewise, CI tracks the main economic changes at Lake Gosciaz since the Neolithic (Ralska-Jasiwiczowa and van Geel, 1992), whereas PI shows inconclusive evidence until the Iron Age (Fig. 4b). In boreal environments, CI performed better than PI (Holtjärnen), while PI was superior at Mediterranean sites (Lago dell’Accesa and Gorgo Basso). The reduced performance of PI in boreal environments might be connected to the prevalence of pastoral activities (Morris et al., 2014), as also revealed by the good agreement with PDI (Fig. 4). Conversely, the reduced performance of CI in the Mediterranean probably relates to the supposed natural occurrence of Plantago lanceolata-type. Indeed, Tinner et al. (2008) concluded that intense agriculture around Gorgo Basso prior to the early Neolithic (ca. 6000 BC) would be unrealistic. To overcome this issue, the authors relied on the combined evidence of crops (e.g. Cerealia-t., Ficus carica) and weeds to track the onset of Neolithitic farming (Tinner et al., 2009). Here, we cannot assess to what extent the natural...
occurrence of cereal species may affect the interpretation of Mediterranean pollen records (Roberts et al., 2011). A way to overcome this difficulty and to unambiguously identify arable farming is to associate Cerealia-type pollen with that of other crops (e.g. figs), adventives and/or apophytes (Tinner et al., 2009). Our results emphasize that the indicative power of single taxa should not be considered in absolute terms but rather within the ecological context (reflected in the pollen assemblages) in which it was growing.

Other important direct indicators according to Behre (1981) such as *Fagopyrum* and *Linum usitatissimum* were completely absent or recorded just in modern samples at our study sites and did thus in general not contribute to the index values. The only exception is a single pollen grain of *Linum usitatissimum* found at the end of the Mesolithic (ca. 3700 BC) in the Burgäschisee pollen assemblage.

An additional issue related to the use of indices based on direct pollen indicators such as the PI as quantitative proxies for human impact is the possible bias introduced by agro-industrial practices. This is the case for instance in Origlio during the stage of very high human impact (i.e. stage 5, last 1000 years) when Cannabis-type pollen became strikingly abundant in the sediment samples as a result of water-retting of hemp for fiber extraction (Bradshaw et al., 1981). These practices caused a marked rise in Cannabis-type pollen abundance (from ca. 2–40% of the terrestrial pollen sum) and an overrepresentation of this pollen type in the PI index values (up to 98.6%).

### 4.3. Indirect indicators

Our results show that the environmental context is determinant for the interpretation of indices based on secondary indicators such as SI, API and PDI. At all the study sites, but more strongly in the Mediterranean realm (i.e. Lago dell’Accesa and Gorgo Basso), these indices, particularly SI and API, suggest strong human impact during the Palaeolithic and the Mesolithic (before 9000–8000 BC; Figs. 4 and 5), which is inconsistent with archaeological evidence (Bietti Sestieri, 2013a, 2013b). The underlying reason is that several of the pollen types included in SI, API and PDI (Table 1) correspond to disturbance-tolerant plant taxa that have benefitted from anthropogenic activities. For instance, *Artemisia* was particularly abundant in the steppic communities that dominated the European landscape during the cold and dry stages of the last deglaciation (ca. 19 to 11.7 ka BP; Lang, 1994; Nolan et al., 2018). Indeed, *Artemisia* accounts for a large proportion of API index values during the first stage of human impact at Origlio and Burgäschisee. In agreement, the SI index values during the post-glacial steppic environment in Burgäschisee are almost entirely related to *Artemisia* and *Juniperus*-type pollen abundances. To account for this and also for the natural occurrence of these taxa in the local flora, Roberts et al. (2019) recommended caution when interpreting their occurrence in Mediterranean landscapes during the Holocene. Furthermore, these pollen types have sometimes been excluded from the calculations of the anthropogenic indices in dry Mediterranean settings (e.g. Cheddadi et al., 2019). As a consequence, API clearly fails to recognize low or absent human impact before the mid-Holocene, while subsequently it follows the more reliable direct indicators such as PI and CI at sites with temperate (i.e. Burgäschisee and Lago di Origlio) and meso-Mediterranean vegetation (i.e. Lago dell’Accesa, Fig. 4c–e, 5c–e). In general, SI and API show similar performances (Figs. 4 and 5). Last but not least, these indices would probably benefit from more detailed taxonomic resolution in pollen identification to enhance the value of indicator species. For instance, the API index merges several well-characterised pollen types such as *P. lanceolata*-type, *P. major*-type, *P. media*-type, *P. maritima*, *P. tenuiflora*, and *P. coronopus*-type (according to Moore et al., 1991) into the genus *Plantago*. Such coarse taxonomic resolution causes a large loss in ecological information, directly affecting human-impact reconstructions (e.g. *P. lanceolata* is likely adventive north of the meso-Mediterranean and thermo-Mediterranean vegetation types).

Other indirect indicators of human impact (Behre, 1981; Lang, 1994) displayed a very low contribution to the SI sum (e.g. *Polygonum aviculare*-type in all cases except for Höltjärnen and Accesa, where it was absent) or occurred regularly throughout the core (e.g. *Rumex acetosa*-type in all cases, with smaller percentages for Accesa and Gorgo Basso), even at stages of high human impact. These results suggest that some taxa may be used as qualitative indicators (presence—absence) more than quantitatively (i.e. with abundance values).

### 4.4. Woody crops

The performance of the indices based on woody crops, i.e. OJC and OJCV, was generally low across the selected study sites (Figs. 4 and 5), with only one exception in the meso-Mediterranean vegetation (Accesa), where these indices were originally conceived (Fig. 4f and f, 5e–f). The native status in the Mediterranean region of the constituent species (i.e. *Olea europaea*, *Juglans regia*, *Castanea sativa*), along with their relatively recent and often massive cultivation, potentially implies the coexistence of wild and domesticated trees in certain periods (Conedera et al., 2004; Pollegioni et al., 2017; Langgut et al., 2019), in addition to biased indication power (Roberts et al., 2019) when applying these methodologies. For instance, strikingly high values of OJC in thermo-Mediterranean Sicily (Fig. 4f) during the Neolithic are very likely due to abundant *Olea europaea* pollen from wild populations (*Olea europaea* var. *oleaster*, see discussion in Tinner et al., 2009). Indeed, the archaeobotanical evidence places the origins of olive tree domestication in the Mediterranean Levant during the Chalcolithic at ca. 4000 BC and tree cultivation likely arrived in Sicily at the beginning of the Bronze Age at ca. 2000 BC (Besnard et al., 2018; Langgut et al., 2019). Furthermore, an OJC drop in Sicily during Roman Times (Fig. 4f) is inconsistent with the agricultural intensification inferred from archaeological evidence during that human-impact stage. OJC values are largely driven by *Olea* pollen percentages throughout the record and primarily reflect the demise of Mediterranean mixed evergreen broadleaved woodlands related to land-use intensification (Tinner et al., 2009), rather than the collapse of olive plantations (Fig. 5f). Thus, only the later medieval increase in OJC, driven by *Olea* pollen abundance, should be attributed to broad-scale olive cultivation in the area (Fig. 4f; Tinner et al., 2009). Palaeobotanical evidence also supports the native status of *Castanea sativa* to several Mediterranean areas including the sub-Mediterranean Italian Peninsula, where it may have survived the harshest periods of the last glaciation (Krebs et al., 2004, 2019). Indeed, when the OJC index was proposed, Mercuri et al. (2013b) warned about the need for independent archaeological information and the use of other pollen indicators to support inferences based on this index. The incorporation of Vitis to the index (i.e. OJC) faces the same issues because Vitis is also native to the Mediterranean Basin (Morales and Ocete, 2015), and Vitis pollen shows regular occurrences in many Mediterranean and sub-Mediterranean palynological sequences throughout the Holocene, probably related to Vitis *vinifera* subsp. *sylvestris* (e.g. at Lago di Origlio; Tinner et al., 1995). Despite these issues, these indices may help to corroborate intensified land use where any of the included taxa constituted a relevant food source: e.g. *Juglans regia* on the Swiss Plateau, *Castanea*
sativa in the Southern Alps, and *Olea europaea* under sub-humid meso-Mediterranean conditions (Tinner et al., 1999; Colombaroli et al., 2008; Rey et al., 2017). In summary, the suitability of tree crop taxa as anthropogenic indicators is highly context-dependent (both geographical and historical), as clearly highlighted by the large dominance of single pollen types in the composition of the OJ/C/OJV depending on the site and historical period considered (see above). In this regard, similar to API and SI, OJ/C/OJV may be best interpreted as a summary of pollen types of indirect value than a human impact index *sensu strictu* (Behre, 1981).

5. Conclusions

Disentangling anthropogenic and natural drivers of vegetation change is of paramount importance in palaeoecology. The most widely used method continues to be the long-standing species indicator approach, although alternative methodologies and proxies have been developed more recently (e.g. Sugita, 2007; Fyfe et al., 2010). In particular, systematic approaches and standardized tools assisting pollen-based reconstructions of land use are still lacking. In this context, detailed and region- or site-specific assessments of the native plant range and the definition of apophytic and adventive anthropogenic pollen indicators (e.g. following a probabilistic approach as proposed by Krebs et al., 2019) is crucial to improve the performance of the existing indices to track changes in land-use intensity. Although the effects of the taxonomic resolution in the identification of human indicators has not been addressed in detail so far, enhanced taxonomic resolution allowing stricter selection of the anthropogenic pollen indicators may also play a role in improving estimates of human impact through long timescales, as the indices with low taxonomic resolution may not perform well even in their scope area. Future research on this topic should therefore aim to develop more detailed and articulated algorithms for assessing human impacts based on multi-proxy palaeoecological data. In particular, we stress the importance of developing a generalized context-dependent approach that considers the geographic area of reference and analyses the accompanying taxa in the corresponding stratigraphic levels of the pollen assemblage when assessing the indicative power. Finally, for a more precise and accurate independent validation of long-term vegetation dynamics using archaeology, it will be crucial to synthesize the available archaeological evidence (e.g. radiocarbon dates and their material culture context) to better infer major technological innovations, economic changes, land use, and population densities.

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

We are grateful to Erika Gobet, Jacqueline van Leeuwen and Christoph Schwörer for fruitful discussions, and to Natalie Kehrwald, Janet L. Slate, and the anonymous reviewers for their thoughtful comments and suggestions on the manuscript. Pollen data were extracted from the European Pollen Database and the Neotoma Palaeoecology Database; the work of the data contributors and the scientific community supporting these databases is gratefully acknowledged. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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Mara Deza-Araujo: Visualization, Investigation, Conceptualization, Formal analysis, Writing - Original Draft. César Morales-Molina: Supervision, Data curation, Conceptualization, Resources, Writing - Review & Editing. Willy Tinner: Supervision, Conceptualization, Resources, Writing - Review & Editing, Funding acquisition. Paul D. Henne: Conceptualization, Writing - Review & Editing, Funding acquisition. Caroline Heitz: Validation, Investigation. Gianni B. Pezzatti: Software, Data curation, Conceptualization. Albert Hafner: Supervision. Marco Conedera: Supervision, Conceptualization, Resources, Writing - Review & Editing, Project administration, Funding acquisition.

Funding

This work was supported by the Swiss National Science Foundation - SNSF [grant number 169371].
