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Cannabis pollen sources and dispersal in the Iberian Pyrenees during the last century: preliminary results and proposals for future studies

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Personal conflict of interest

- Sedimentary records of *Cannabis* pollen at different elevations during the last century
- Contrasting patterns for other lowland taxa (*Olea*, *Quercus*) reaching high elevations
- Discussion in terms of pollen sources (hemp/drug crops) and dispersal mechanisms
- Hypotheses and future studies are suggested to explain the *Cannabis* peculiarities

Meta-analyses of past pollen records have provided insights into the historical biogeography of *Cannabis* across the Iberian Peninsula (IP), with the southern Pyrenean flank being key to understanding cannabis cultivation and use during the Middle and Modern ages. However, studies on more recent times are rare. This paper offers a high-resolution comparison of the last century, particularly the significant *Cannabis* pollen peak observed in the mid-elevation Lake Montcortès between 1980 and 2000 CE, which was absent in the nearby highland Lake Sant Maurici. The Montcortès peak is linked to a phase of extensive hemp cultivation (1972-2006 CE) in the southeastern lowlands. The absence of a similar peak in Sant Maurici, despite the presence of other lowland pollen taxa, notably *Olea* and *Quercus*, suggests regional differences in pollen origin and dispersal likely influenced by wind patterns and rainfall. Studies on *Cannabis* pollen sources and dispersal are comparatively scarce and insufficient to provide a regional picture across the IP, similar to *Olea* or *Quercus*. However, the available data suggest that this pollen is abundant mostly locally, in the vicinity of cannabis crops. The persistent presence of *Cannabis* pollen in Montcortès after 2000 CE likely reflects ongoing illegal cultivation. The study recommends combining paleoecological and aerobiological surveys to better understand pollen dynamics in the Iberian Pyrenees, with suggestions for future research based on these findings.

***Cannabis* pollen sources and dispersal in the Iberian Pyrenees during the last century: preliminary results and proposals for future studies**

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Abstract

Meta-analyses of past pollen records have provided insights into the historical biogeography of *Cannabis* across the Iberian Peninsula (IP), with the southern Pyrenean flank being key to understanding cannabis cultivation and use during the Middle and Modern ages. However, studies on more recent times are rare. This paper offers a high-resolution comparison of the last century, particularly the significant *Cannabis* pollen peak observed in the mid-elevation Lake Montcortès between 1980 and 2000 CE, which was absent in the nearby highland Lake Sant Maurici. The Montcortès peak is linked to a phase of extensive hemp cultivation (1972–2006 CE) in the southeastern lowlands. The absence of a similar peak in Sant Maurici, despite the presence of other lowland pollen taxa, notably *Olea* and *Quercus*, suggests regional differences in pollen origin and dispersal likely influenced by wind patterns and rainfall. Studies on *Cannabis* pollen sources and dispersal are comparatively scarce and insufficient to provide a regional picture across the IP, similar to *Olea* or *Quercus*. However, the available data suggest that this pollen is abundant mostly locally, in the vicinity of cannabis crops. The persistent presence of *Cannabis* pollen in Montcortès after 2000 CE likely reflects ongoing illegal cultivation. The study recommends combining paleoecological and aerobiological surveys to better understand pollen dynamics in the Iberian Pyrenees, with suggestions for future research based on these findings.

Keywords: *Cannabis*, pollen, hemp, marihuana, dispersal, Pyrenees, Iberian Peninsula

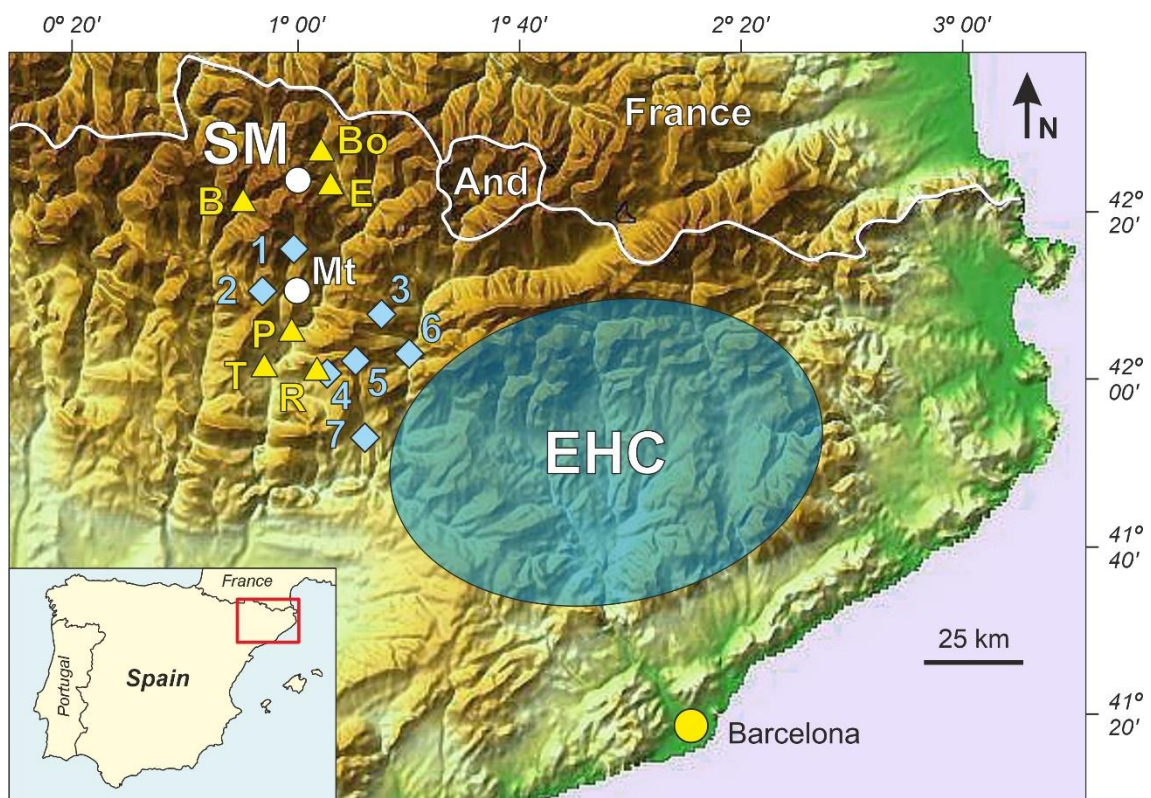
1. Introduction

The significance of *Cannabis* for human societies throughout history and the influence of humans on *Cannabis* diversification, after domestication and artificial selection, are well-known (Clarke & Merlin, 2013, 2016; McPartland, 2018; McPartland et al., 2019; Ren et al., 2021). A recent review on the origin and evolution of *Cannabis* species and varieties, along with its importance for human societies, with an emphasis on Europe, identified the Iberian Peninsula (IP) as a key region from biogeographical and cultural perspectives (Rull, 2022). Furthermore, a meta-analysis of the available *Cannabis* pollen records across the IP from the Late Pleistocene to the present revealed the changing spatiotemporal patterns of this plant during prehistoric and historical times (Rull et al., 2023). According to this study, the main

51 *Cannabis* pollen peaks occurred in the Neolithic (7-5 kyr BP) and the Middle Ages (15th century
 52 onward), whereas a maximum in hemp cultivation/retting was recorded in the Modern Ages
 53 (16th-19th centuries). This long-standing production peak was linked to the development of
 54 the Spanish Royal Navy, the main consumer for sail and rope fabrication, and the ensuing
 55 expansion of the Spanish Empire (Rull & Vegas-Vilarrúbia, 2014; Rull et al., 2022).

56
 57 A more recent peak in *Cannabis* pollen was discovered in the annually laminated (varved)
 58 sediments of the mid-elevation (1037 m) Pyrenean Lake Montcortès (Figs. 1 and 2). This peak,
 59 called 20C, occurred between 1980 and 2000 (Rull & Vegas-Vilarrúbia, 2023) and coincided
 60 with a phase of extensive hemp cultivation (hereafter EHC) for paper pulp production in
 61 central Catalonia, in the southern Pyrenean lowlands (400-900 meters), which was favored by
 62 European Union (EU) subsidies (Gorchs & Lloveras, 2003). It is currently unknown whether the
 63 20C pollen peak was a local or regional phenomenon. Given the dispersion power of
 64 anemophilous (wind-dispersed) *Cannabis* pollen, a regional pollen peak coinciding with the
 65 EHC period could be expected. If, on the contrary, the pollen peak is a local feature restricted
 66 to Lake Montcortès, other causes could be considered. Despite the cessation of extensive
 67 *Cannabis* cultivation in central Catalonia in 2006 (Gorchs et al., 2017), high levels of *Cannabis*
 68 pollen were still found in the sediments of Lake Montcortès for the years 2013-2015 (Rull et
 69 al., 2017). This suggested the possibility of illegal *Cannabis* plantations for drug production
 70 (marihuana) around Lake Montcortès (Rull & Vegas-Vilarrúbia, 2023). Unfortunately, the lack
 71 of high-resolution pollen records from the last century beyond the Montcortès watershed,
 72 along with a lack of information on illegal or domestic crops, prevented us from testing these
 73 hypotheses.

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Figure 1. Map of the study area and its situation in the Iberian Peninsula, indicating the location of lakes Sant Maurici (SM) and Montcortès (Mt). The approximate area of extensive hemp crops (EHC) during the period 1972-2006 to supply raw materials for the paper industry is indicated by a blue shadow (Gorchs & Lloveras, 2003). Blue diamonds indicate the location of illegal *Cannabis* plantations for drug production dismantled in the last years (2022 and 2023), as reported by newspapers (ACN, 2022; Manzano, 2022; EFE 2023a, b), after press notes from the Catalan autonomous police force (Mossos d'Esquadra, 2023). Yellow triangles indicate the weather stations along

83 the elevational transect. Illegal plantations: 1, Torre de Capdella; 2, Senterada; 3, Valls d'Aguiar; 4, Abella de la
84 Conca; 5, Bóxiols; 6, Coll de Nargó; 7, Baronia de Rialp. Weather stations: B, Boí; Bo, Port de la Bonaigua; E, Espot; P,
85 La Pobla de Segur; T, Tremp; R, Sant Romà d'Abella.

86
87 A high-resolution study of the last century developed on the sediments of the highland (1914
88 m elevation) Lake Sant Maurici, situated ~30 km north of Lake Montcortès (Figs. 1 and 2),
89 showed a contrasting situation, as neither the *Cannabis* pollen peak corresponding to the EHC
90 phase nor the relatively high values of the last few decades were recorded (Rull et al., 2024).
91 As hemp is typically a lowland crop, which in the Pyrenees rarely surpasses 1000 m elevation,
92 the pollen of this plant could only reach Lake Sant Maurici by upward wind dispersal, but it was
93 not the case. In contrast, the amounts of pollen from other lowland elements, notably *Olea*
94 and evergreen *Quercus*, demonstrated that upward wind transport actually occurred (Fig. 2).
95 In support to this, previous studies on modern pollen sedimentation developed in the adjacent
96 Colomers cirque, just a few km northwest of Lake Sant Maurici, documented moderate to
97 relatively high amounts of airborne *Quercus* and *Olea* pollen, but *Cannabis* was absent.
98 Similarly, *Olea* and *Quercus* pollen were commonly found between May and July during the
99 period 2013-2023 in an aerobiological station (Planes de Son) situated 8 km northeast of Lake
100 Sant Maurici at 1542 m elevation, but *Cannabis* pollen was not reported
101 (<https://aerobiologia.cat/pia/en/>).

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103 This contrasts with records from other localities of the IP, where *Cannabis* pollen is commonly
104 found during its flowering season. In these localities, dispersal modeling has allowed to
105 tentatively identify the potential sources of this pollen, with an emphasis on illegal marijuana
106 plantations, either from local or long-distance (Northern Africa) areas (Cabezudo et al., 1997;
107 Munuera et al., 2002; Cariñanos et al., 2004; Arboulaich et al., 2013; Aznar et al., 2022). During
108 recent decades, a significant increase in *Cannabis* plantations for drug production has been
109 documented in the IP, especially in Mediterranean lowlands and coasts. Spain has transformed
110 from merely being a route for exporting African hashish to becoming a significant production
111 hub (Alvarez et al., 2016; Belackova et al., 2016). On the other hand, the 1972-2006 EHC in the
112 southern Pyrenean lowlands was a short-lived and localized feature that was unparalleled in
113 other Spanish areas, except for some ephemeral initiatives between 1997 and 2001. Before
114 the 1970s, hemp was cultivated for thread, ropes, and fabric mainly in irrigated areas in the
115 eastern IP (Fig. 1). However, these practices ceased in the early 1970s when the production
116 center shifted to Catalonia, in the northeast (Gorchs & Lloveras, 2003; Gorchs et al., 2017). In
117 2006, the company that exploited hemp moved to France, and hemp cultivation also ceased in
118 Catalonia (Gorchs et al., 2006).

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120 This paper discusses the contrasting trends of *Cannabis* pollen in lakes Montcortès and Sant
121 Maurici during the last century, in terms of potential sources and dispersal mechanisms. This
122 comparison is intended as a first step toward a more regional appraisal of *Cannabis* pollen
123 sources and dispersal across the Pyrenean range. The pollen from other lowland elements,
124 such as *Olea* and *Quercus*, with better known distribution and aerobiological features across
125 the Iberian Peninsula, is used as a reference. The scarcity of similar studies on *Cannabis* pollen
126 sources and dispersal hinders the attainment of sound conclusion, but the case studies
127 discussed here may provide the basis for further investigations. The main aim of this paper is
128 to provide testable hypotheses and ideas to be evaluated with future studies, some of which
129 are specifically suggested.

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131 **2. The data**

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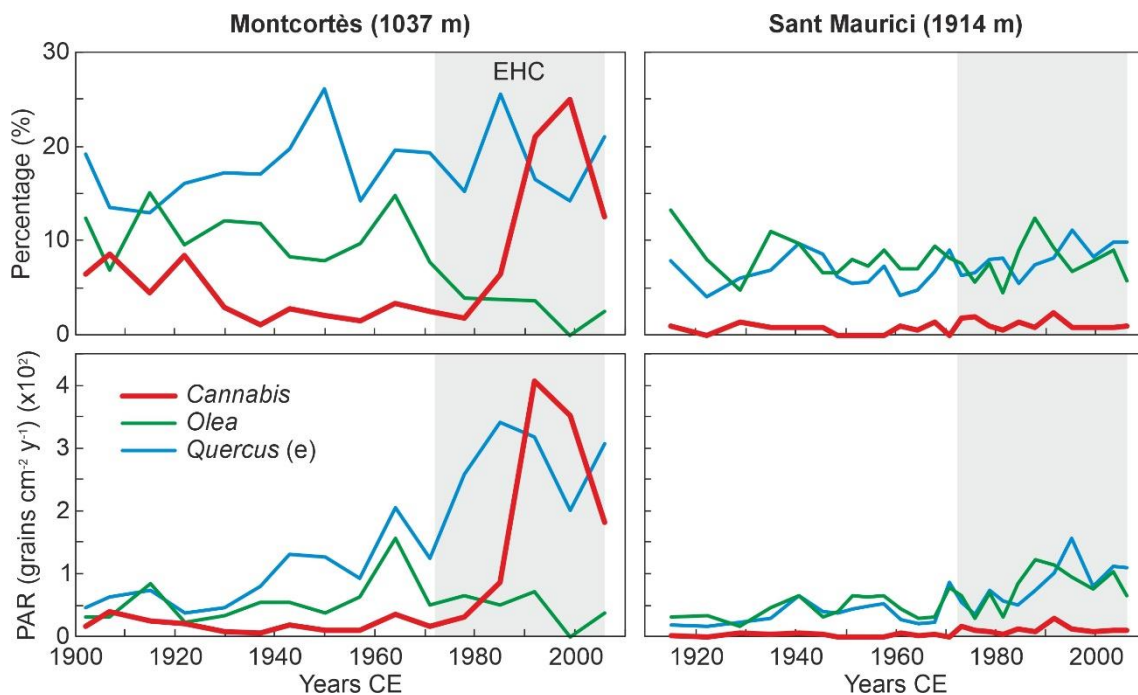
133 The raw data for Montcortès and Sant Maurici lowland pollen records are compared in Fig. 2 for
134 more clarity. The full pollen diagrams and the vegetation reconstruction are available at Rull &

135 Vegas-Vilarrúbia (2023) for Montcortès and Rull et al. (2024) for Sant Maurici. The pollen of
 136 *Cannabis* was absent or very scarce throughout the entire Sant Maurici record, rarely
 137 exceeding 1% of the reduced pollen sum (even excluding the superabundant *Pinus*). In
 138 contrast, other lowland elements from sclerophyll Mediterranean vegetation, notably
 139 evergreen oaks (*Quercus*) and olive trees (*Olea*), were present in all samples in fairly
 140 homogeneous abundances of up to 12%. This indicates that upward pollen transport from the
 141 lowlands was always possible. This is particularly puzzling when we compare this record with
 142 Montcortès, where the *Cannabis* peak is evident during the EHC period in both percentage and
 143 pollen accumulation rates (PAR).

144

145 The other lowland elements showed some quantitative differences between the two localities,
 146 but they were consistently present in significant abundances. *Quercus* was more abundant at
 147 Montcortès, both in percentage and pollen accumulation rates (PAR), likely due to its lower
 148 elevation and the prevalence of the evergreen oak *Q. rotundifolia* around the lake (Mercadé et
 149 al., 2013). While *Quercus* pollen exhibited no definitive trends in percentage, PAR values – a
 150 proxy for plant cover (Theuerkauf & Couwenberg, 2018) – showed an increasing tendency
 151 during the EHC period at both sites. *Olea* exhibited similar abundances in Montcortès and Sant
 152 Maurici, except for a significant decline in Montcortès during the EHC period, possibly due to a
 153 reduction in olive cultivation in the adjacent lowlands (Rull et al., 2021). This decline may be
 154 indicative of a shift from olive groves to hemp crops, although further evidence is needed for a
 155 thorough assessment. In summary, while there are significant differences in pollen
 156 percentages from lowland taxa, manifested in minor to moderate quantitative disparities in
 157 the case of *Quercus* and *Olea*, there are remarkable qualitative differences in *Cannabis*,
 158 especially during the EHC phase.

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162 **Figure 2.** Comparison of pollen trends from the main lowland taxa in the Montcortès and Sant Maurici records

163 plotted by time. The gray bands indicate the period of extensive hemp cultivation (EHC) in the SE lowlands.

164 Montcortès data after Rull & Vegas-Vilarrúbia (2023) and Sant Maurici data after Rull et al. (2024). PAR, pollen

165 accumulation rates.

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169 3. Potential pollen sources

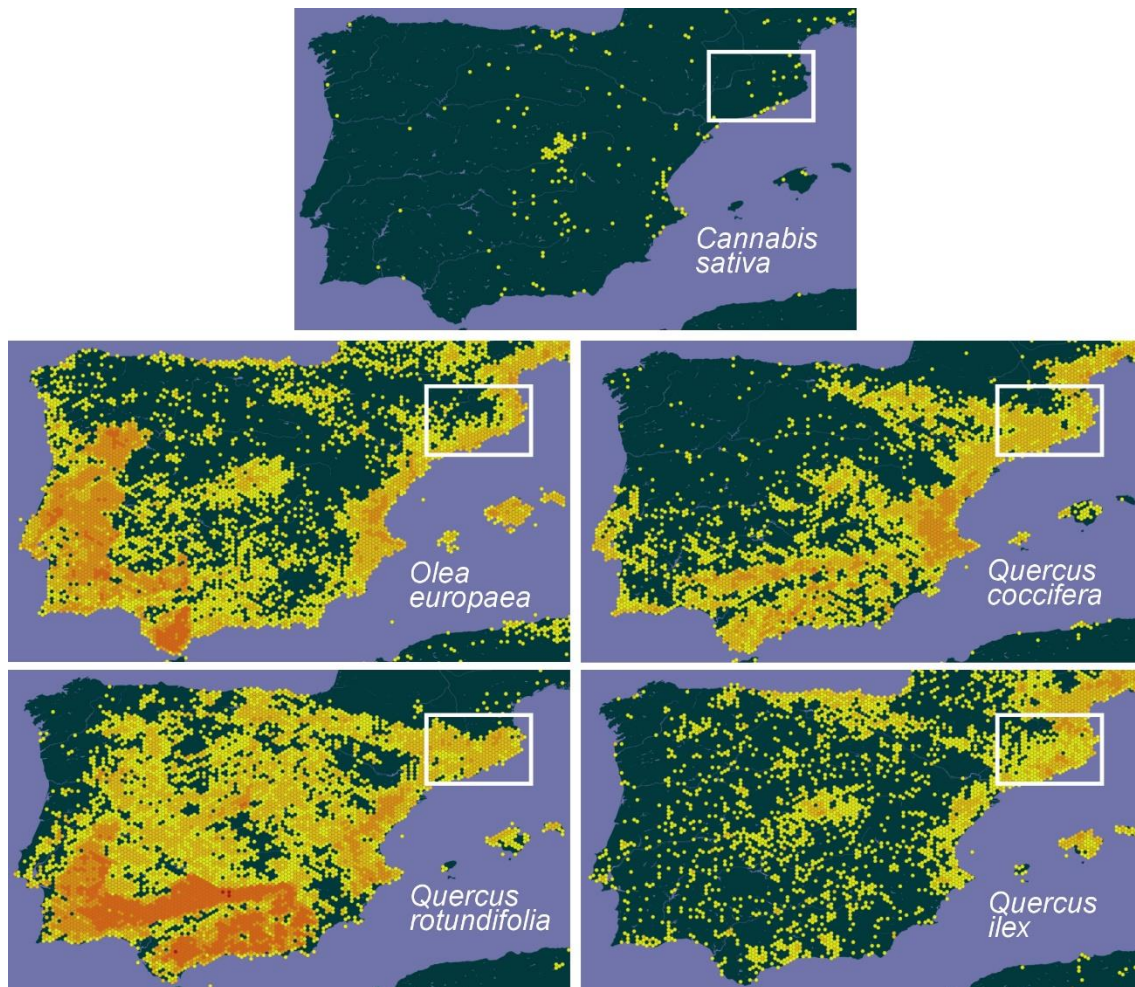
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171 The absence of the 1980-2000 *Cannabis* pollen peak in the Lake Sant Maurici record poses a
172 challenge, particularly considering its clear documentation in the sediments of Lake
173 Montcortès, located barely 30 km south on the same mountain slope. The argument based on
174 the lowland character of *Cannabis* may not hold, as pollen from other lowland elements, such
175 as *Olea* and evergreen *Quercus*, consistently appears in significant abundances in the Sant
176 Maurici record. Therefore, upward pollen dispersal from lowlands to highlands was evidently
177 active during the period of interest. Other potential factors to analyze in the search for an
178 explanation include the source of the involved pollen types and their dispersal patterns, the
179 elevational offset between the studied lakes (approximately 900 m), and the site-specific
180 meteorological conditions, particularly wind patterns.

181

182 In contrast with other regions of the world, where *Cannabis* is a common weed and its pollen
183 is a major contributor to the airborne load (e.g., Ahlawat et al., 2013), in the IP, hemp and
184 marihuana cultivation are the only sources of *Cannabis* pollen. This is evident in the
185 distribution of *Cannabis* across the peninsula, which consists of scattered and isolated
186 individual localities (Fig. 3). On the other hand, the other lowland contributors to the Pyrenean
187 airborne pollen assemblages, *Olea* and evergreen *Quercus*, are densely distributed, extensive,
188 and widespread, serving as important components of the Mediterranean vegetation (Fig. 3).
189 This implies that *Cannabis* pollen mostly originates locally from small plant stands, whereas the
190 sources for *Olea* and *Quercus* pollen are dominant, dense, and widespread vegetation types of
191 the Mediterranean biome. Therefore, it could be expected that the atmospheric pollen
192 content of *Olea/Quercus* is more extended and homogeneous across the IP, as well as more
193 consistent over time. In contrast, the *Cannabis* airborne load would be more restricted and
194 episodic, depending on the particular spatiotemporal cultivation patterns and site-specific
195 meteorological conditions. Recent aerobiological research supports these hypotheses.

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Figure 3. Distribution of *Cannabis sativa*, *Olea europaea* and the evergreen *Quercus* species from the lowland Mediterranean vegetation in the Iberian Peninsula (*Q. rotundifolia* is reported in several aerobiological studies as *Q. ilex* subsp. *ballota*, while *Q. ilex* is also reported as *Q. ilex* subsp. *ilex*). Black areas indicate no records and colors represent relative abundance from maximum (red) to minimum (yellow). White boxes highlight the study area of this paper. Black areas within these boxes correspond to highlands. Maps generated from Global Biodiversity Information Facility (GBIF) (<https://www.gbif.org/>).

4. Pollen dispersal

In the case of *Olea*, aerobiological studies conducted in central and southwestern Spain, using back-trajectory modeling, have shown that both local and regional IP pollen sources, mainly from olive groves, contribute to a similar extent to the airborne load at specific sampling points (Fernández-Rodríguez et al., 2014; Rojo & Pérez-Badia, 2015). A more recent study demonstrated that the most significant pollen sources in the southeastern IP were autochthonous vegetation (40%), whereas long-distance transport from Europe and Africa was a minority (6%). Maritime air masses, especially from the Atlantic, also contributed significantly to the regional pollen load of the IP (>50%) after crossing the peninsula and collecting *Olea* pollen originating from both wild vegetation and olive groves (Negral et al., 2021). Similar studies in other areas are unavailable, but the presence of significant amounts of airborne *Olea* pollen across the IP, especially in Mediterranean bioclimatic areas (Galán et al., 2016; Majeed et al., 2018; Alarcón et al., 2023), suggests a high degree of mixing from regional pollen sources and medium to long-distance transport (Maya-Manzano et al., 2017).

222 According to Rojo et al. (2016), the amount of *Olea* pollen at each locality depends on its
223 elevation, with sites between 300 and 1000 m receiving more pollen from local sources than
224 lower localities, where olive pollen predominantly originates from more distant sources.
225 Elevation can also affect the atmospheric *Olea* pollen load by promoting earlier flowering in
226 coastal environments than in inland uplands due to temperature gradients (Alba et al., 2006).
227 Aerobiological studies at higher elevations are scarce, but the presence of significant *Olea*
228 pollen in a station situated above 1500 m near Sant Maurici (Planes de Son;
229 <https://aerobiologia.cat/pia/en/>), as well as in modern sediments from the neighboring
230 highland (up to 2600 m) Colomers cirque (Cañellas-Boltà et al., 2009), and the 20th-century
231 San Maurici record (this paper), demonstrate a high dispersal capacity to elevations far from
232 lowland *Olea* habitats. However, comparisons between aerobiological and sedimentary
233 surveys should take into account the so-called washout effect. A significant negative
234 correlation between airborne pollen load and precipitation has been interpreted in terms of
235 rain quickly removing pollen from the atmosphere and accumulating it on the ground (Majeed
236 et al., 2018). This would have inverse effects on the air, where the pollen load strongly
237 declines, and the sediments, where the pollen content is instantaneously enriched.

238
239 Therefore, according to the reviewed literature, the mixing of airborne *Olea* pollen occurs not
240 only across space but also along elevational gradients. Some back-trajectory models suggest
241 that air masses containing *Olea* pollen can travel above 2500 m (up to 6000 m) elevation
242 (Negral et al., 2021). This may create a widespread high-elevation atmospheric pollen stock
243 (HPS) as a source for gradual and sustained pollen precipitation in the form of a relatively
244 homogeneous regional background pollen signal (BPS). Such a BPS could be added to the
245 particular airborne pollen load of each site, which varies according to its local pollen sources
246 and dispersal patterns. High-elevation atmospheric sampling and further modeling would be
247 needed to test the HPS-BPS hypothesis.

248
249 *Quercus* pollen exhibits similar aerobiological behavior and geographical distribution patterns
250 (García-Mozo et al., 2002; Fernández-Llamazares et al., 2014; Galán et al., 2016; Maya-
251 Manzano et al., 2017; Majeed et al., 2018). However, the lack of differentiation between
252 deciduous and evergreen oak pollen in aerobiological studies sometimes hinders more
253 detailed comparisons. Similar to *Olea* pollen, back-trajectory modeling suggests that medium
254 to long-distance transport of *Quercus* pollen prevails over local dispersal (Hernández-Ceballos
255 et al., 2011; Maya-Manzano et al., 2016, 2017). In this case, air masses move at atmospheric
256 elevations up to 1500 m, although this is based on a single case study from southwestern IP
257 (Maya-Manzano et al., 2016). Although the possibility of a high-elevation background signal
258 seems less clear than in *Olea*, this mechanism cannot be dismissed and should be addressed in
259 further studies.

260
261 The only available back-trajectory analysis on *Cannabis* pollen in the IP showed that local and
262 regional dispersal prevail (75%) over long-distance transport (Aznar et al., 2022). Air masses
263 transporting pollen of local origin usually travel near ground level, whereas those carrying
264 regional and long-distance pollen may reach heights of more than 3000 m. In this case, the
265 occurrence of an HPS-BPS phenomenon is less probable due to the scarcity of pollen sources
266 and the low amounts of airborne pollen compared with *Olea* and *Quercus*. Therefore, *Cannabis*
267 pollen is mostly of local origin and, as such, would be more affected by ground-level wind
268 patterns, which are strongly influenced by the local topography. In this scenario, the washout
269 effect would primarily occur on low-elevation air masses carrying *Cannabis* pollen originating
270 from local sources. The mostly local nature of airborne *Cannabis* pollen is consistent with a
271 classical study by Small & Antle (2003) demonstrating that this pollen reduced rapidly with
272 distance from the source, but much more slowly with increasing distance. These authors
273 estimated that most cannabis pollen is sedimented within 5 km distance downwind from the

274 source. However, recent studies showed that smaller but significant amounts may be recorded
 275 farther away, up to 35 km (Nimmala et al., 2024).

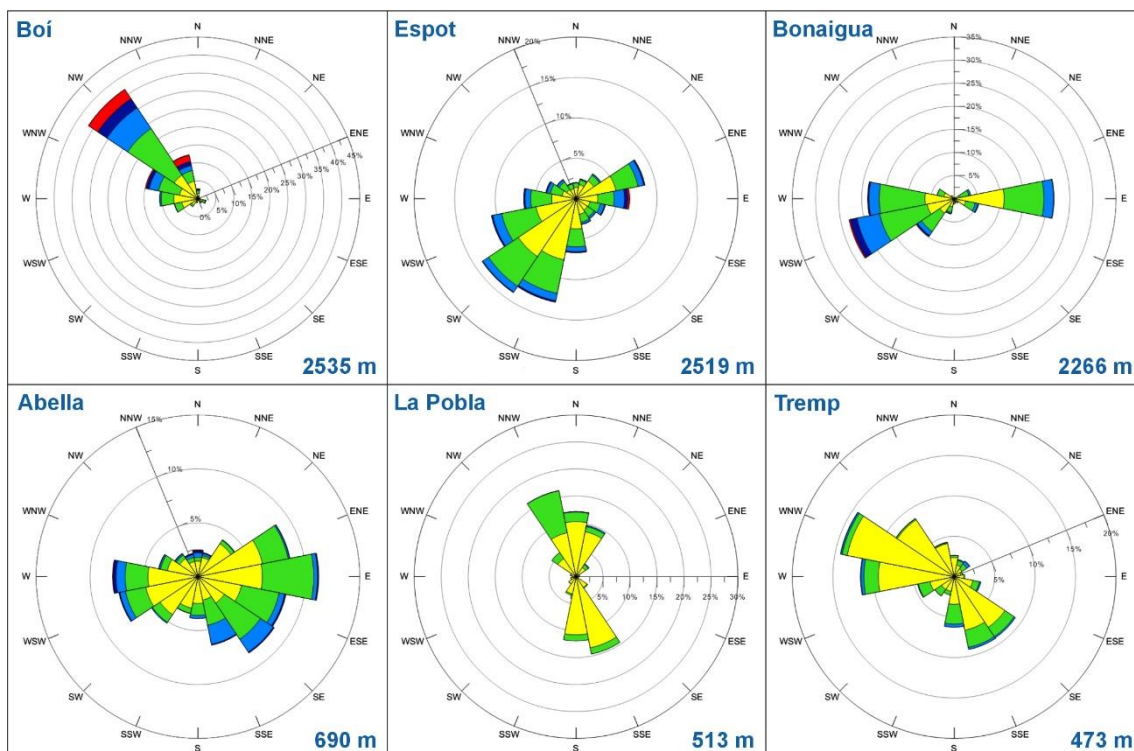
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277 5. The EHC phase

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279 According to previous studies, the only known source for the Montcortès 20C pollen peak was
 280 the EHC developed in central Catalonia between 1972 and 2006 (Rull & Vegas-Vilarrúbia,
 281 2023). This region spanned approximately 150 km in length by 50 km in width, with a total
 282 surface area of hemp cultivation of around 800 ha (Gorchs & Lloveras, 2003). The distances
 283 from this area to lakes Montcortès and Sant Maurici are approximately 40 and 60 km,
 284 respectively, in the same direction (SE) (Fig. 1). This does not represent a major difference
 285 between the two sites that could satisfactorily explain the absence of the 20C peak in Sant
 286 Maurici. If we consider the results obtained in the southeastern IP, the main transport agent
 287 would be ground-level winds. Predominant winds around Montcortès come from the east and
 288 southeast (Fig. 4), which would favor the transport of Cannabis pollen from the EHC region. In
 289 contrast, highland winds around Sant Maurici blow from other directions – especially
 290 northwest to southwest, which is opposite to the location of the EHC area – that do not favor
 291 the arrival of pollen from central Catalonia. Therefore, wind direction could explain, in part,
 292 the absence of the 20C peak in the highlands.

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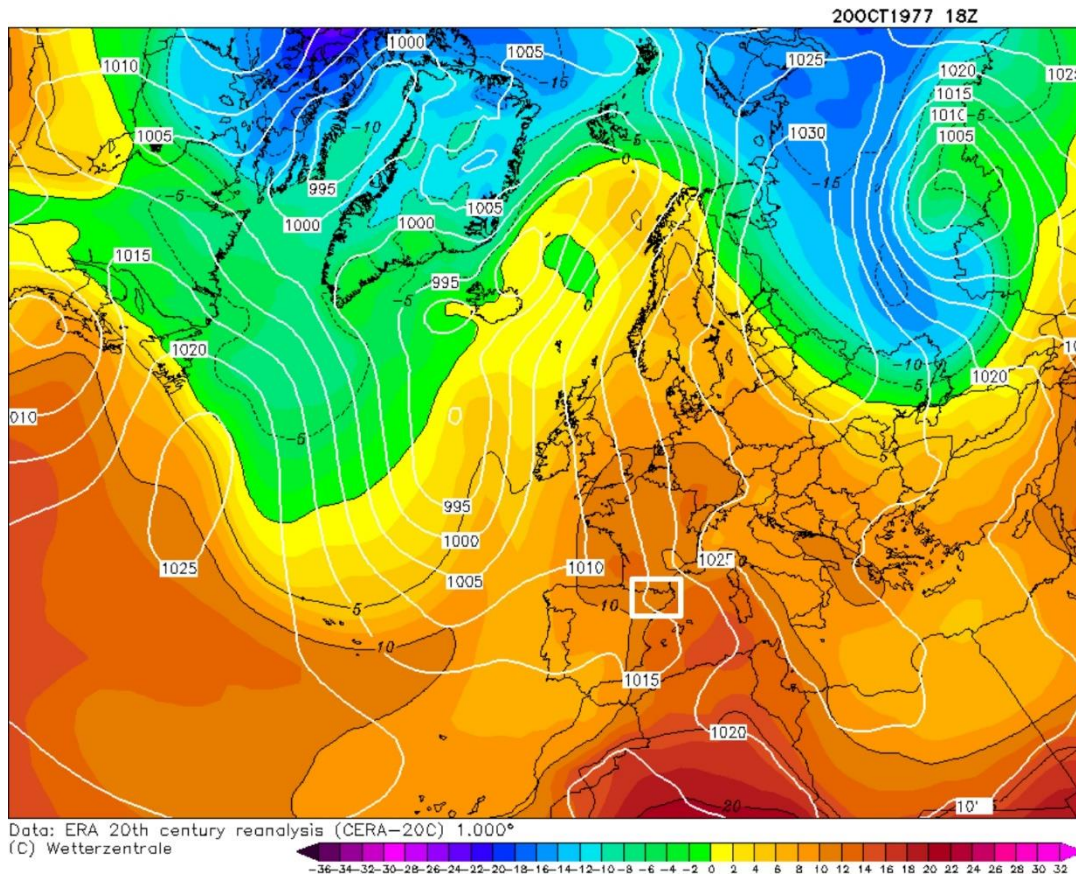
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296 **Figure 4.** Annual wind roses for the meteorological stations situated along the elevational gradient that includes
 297 lakes Montcortès and Sant Maurici for the period 2010-2023 (Fig. 1). Composed with figures downloaded from the
 298 Catalan Meteorological Service (<https://www.meteo.cat/>).

299

300 Furthermore, potential washout effects on the superficial air masses originating from the EHC
 301 region could contribute to the accumulation of pollen in Montcortès sediments, thus hindering
 302 its dispersal to higher elevations. The rainy nature of the Montcortès region (1030 mm/year)
 303 and the absence of a pronounced summer drought, characteristic of Mediterranean climates
 304 (Rull et al., 2023), would support this notion. The possibility of episodic rainfall events should
 305 also be considered. Analysis of precipitation events from August to October (1 or more

306 consecutive days) with significant rainfall (≥ 25 mm) at the nearby meteorological station of La
 307 Pobra de Segur indicates that during the EHC period, 50% of these events were associated with
 308 wind flows (South, Southeast) capable of facilitating the transport and deposition of cannabis
 309 pollen. Fig. 5 illustrates a typical synoptic situation of Southeast flows with substantial
 310 precipitation during the analyzed period. These heavy rainfall events are more frequent in
 311 autumn, coinciding with cannabis blooming and maximum pollen production (Rull et al., 2017).
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 315 **Figure 5.** Synoptic situation at 850 Hpa on 10/20/1977 with SE flows over the study area (white box), based on the
 316 ERA-20C reanalysis. The episode generated 53 mm of precipitation in La Pobra de Segur over 5 days. The colors
 317 indicate the temperature in °C. Source: wetterzentrale.de
 318

319 These hypotheses could be tested by analyzing the pollen content of 20th-century sediments
 320 along an elevational gradient of lakes and peat bogs in the southern Pyrenean slope, in
 321 combination with back-trajectory modeling using data from the Catalan aerobiological network
 322 (XAC; <https://aerobiologia.cat/pia/es/>). As mentioned above, *Cannabis* pollen is not reported
 323 on this website or in the corresponding publications (e.g., Fernández-Llamazares et al., 2014;
 324 Galán et al., 2016; Majeed et al., 2018; Alarcón et al., 2023), but whether this is due to the
 325 actual absence of this pollen type or other reasons (scarcity, lack of allergenic interest) remains
 326 unknown. Although *Cannabis* is not a classical allergen, pollinosis associated with *Cannabis*
 327 pollen exposure is increasingly reported (Stokes et al., 2000; Torre et al., 2007; Ocampo &
 328 Rans, 2015), and its permanent aerobiological monitoring would be useful.
 329

330 6. The most recent decades

331

332 As previously reported, *Cannabis* pollen in Montcortès sediments decreased after the EHC
 333 period but did not disappear and remained at values higher than before 1972 (Rull & Vegas-
 334 Vilarrúbia, 2023). Furthermore, a survey on modern pollen sedimentation during the years

2014 and 2015 reported relatively high amounts of *Cannabis* pollen, especially during the fall (Rull et al., 2017), which is the flowering season of this plant (Clarke & Merlin, 2016). This phenomenon did not occur in the highlands around Sant Maurici, neither in modern analog studies nor in aerobiological records (Cañellas-Boltà et al., 2009; <https://aerobiologia.cat/pia/en/>). This suggested the possibility of illegal marihuana plantations around Montcortès, which lies around the upper elevational limit suitable for *Cannabis* cultivation (Rull & Vegas-Vilarrúbia, 2023). This hypothesis could not be tested due to the lack of information on illegal crops, but recent news from 2022 and 2023 have confirmed the existence of such plantations around Lake Montcortès (Table 1; Fig. 1). Notably, most of these localities are situated southeast of Lake Montcortès, which is compatible with local dispersal by dominant winds, similar to the EHC period. Two localities, Torre de Capdella and Senterada, are situated north and west of the lake, respectively, but they are very close and also fall within the influence of prevailing winds (Fig. 4).

Table 1. Localities where illegal cannabis plantations have recently (2022 and 2023) been dismantled indicating their situation and distance with respect to Lake Montcortès. The data refer to the localities reported in the newspapers and the police reports (ACN, 2022; Manzano, 2022; EFE 2023a, b; Mossos d'Esquadra, 2023) and are approximate, as the exact locations of the plantations have not been provided.

Map	Locality	Elevation (m)	Distance (km)	Direction
1	Torre de Capdella	1075	10	N
2	Senterada	730	5	W
3	Valls d'Aguiar	670	29	ESE
4	Abella de la Conca	960	21	SSE
5	Bóxiols	1160	23	SE
6	Coll de Nargó	570	32	SE
7	Baronia de Rialp	750	40	SSE

No published data are available for years before 2022, but the existence of illegal crops would be a reasonable explanation for the occurrence of *Cannabis* pollen in significant amounts in 2014 and 2015. The proximity of the identified drug crops to Lake Montcortès, along with the aforementioned results of aerobiological modeling highlighting the importance of local pollen sources for *Cannabis* dispersal (Aznar et al., 2022), supports this hypothesis. Aerobiological surveys in northern Africa, one of the main producers of marihuana for European consumption, between 2008 and 2010 demonstrated that *Cannabis* pollen is especially abundant around recognized illegal plantations (Arboulaich et al., 2013). Aznar et al. (2022) attributed the increase in *Cannabis* airborne pollen recorded between 2017 and 2020 in southeastern Spain to an increase in local illegal crops. These findings highlight the potential utility of aerobiological sampling for detecting drug plantations. Our results from modern Montcortès sediments (Rull et al., 2017) suggest that these investigations may also help detect illegal crops. This would be especially useful in regions where the washing out of atmospheric pollen content by precipitation is frequent. The lack of information on illegal *Cannabis* cultivation during the EHC period prevents us from verifying whether this could have been an additional source of *Cannabis* pollen.

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372 6. Prospects for future research

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Further research is necessary to evaluate the interpretations mentioned above and also to provide a regional picture of *Cannabis* cultivation and dispersal across the southern Pyrenean flank. This includes conducting aerobiological modeling in the study area capable of simulating the dispersal of cannabis pollen and sedimentary patterns during the EHC period and recent years. Additionally, analyzing the recent sediments of a network of lakes and bogs situated at various elevations and distances around the former EHC area would be beneficial. The findings from these studies, combined with aerobiological surveys conducted in the same area, could

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381 also aid in identifying illegal drug plantations, especially in areas with high autumn
382 precipitation.

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384 As is well known, high-resolution palynological studies of the last century using lake sediments
385 are useful for reconstructing the most recent trends in vegetation and landscape dynamics,
386 and comparing them with available historical documentation. Investigations such as the one
387 presented here are able to provide additional and detailed information on the introduction,
388 cultivation, and use of characteristic plants of human interest for specific purposes.

389 In addition, these surveys can furnish information on sources and dispersal patterns for
390 particular pollen types under study, in this case *Cannabis*, well before the establishment of
391 aerobiological stations, and also in areas where these stations are lacking. This may contribute
392 not only to improving our knowledge of the atmospheric dynamics of this pollen in former
393 times but also to locating the most probable situations of illegal drug plantations.

394 Finally, these recent sedimentary studies can also complement ongoing aerobiological surveys
395 by providing information on the amount of pollen that is not recorded in aerobiological
396 stations because it settles on the ground. This is particularly useful in areas of high
397 precipitation and frequent heavy rainfall events, where the washout effect is maximized.

398 Therefore, the combination of paleoecological and aerobiological studies in areas with suitable
399 lake sediments is strongly recommended to acquire a comprehensive view of all
400 compartments where the pollen type of interest can be found after leaving its source. This
401 approach could be helpful not only in aerobiology but also in paleoecology, particularly in
402 modern analog studies aimed at linking pollen sedimentation patterns and vegetation
403 characteristics.

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406

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Declaration of interests

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