



**Late Holocene Aleppo pine (*Pinus halepensis* Miller)
woodlands in Mallorca (Balearic Islands, Western
Mediterranean): investigation of their distribution and
the role of human management based on anthracological,
dendro-anthracological and archaeopalynological data**

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Abstract:	<p>The pioneering nature of Mediterranean pines and their phytosociological role have been largely discussed in relation to different agents (e.g., edaphic, climatic or anthropogenic). In this context, Aleppo pine is one of the most widespread pine species in the Mediterranean basin, as it is especially adapted to climatic constraints, such as drought and high seasonality, and has a high tolerance for salinity and strong coastal winds. It is also well adapted to regeneration after anthropogenic landscape disturbances, highlighting its important after-fire regeneration rates. In this sense, phytosociological studies conducted in Mediterranean landscapes have found that this species' wide distribution is mostly due to its rapid regeneration after human landscape transformation, including fire, and the abandonment of agricultural lands. Aleppo pine is considered to broadly develop after human action in sclerophyllous formation, in which it would be scarce or absent without human intervention. Parallel, paleoenvironmental and archaeobotanical studies have attempted to trace these trends back to prehistoric times to investigate this species' role in Late Pleistocene and Holocene vegetation and evaluate the role of climate and human action in its diachronic dynamics. In this study, we present a compendium of anthracological, dendro-anthracological and archaeopalynological data with the objective of (i) investigating the nature and distribution of Aleppo pine on the island of Mallorca and (ii) evaluating the possibility that human action could have resulted in the spread of this pine species during the first two millennia of permanent human occupation of the island (c. 2300 cal. BCE–1st-century ACE). Investigating these archaeobotanical datasets, as well as making comparisons with anthracological and paleoenvironmental studies in neighbouring Mediterranean zones (Iberia), allowed us to attest that Aleppo pine is a natural, pre-human component of the Holocene vegetation of the island, and it is especially well-adapted to coastal environments. Moreover, we describe the trends and characteristics of the human management of pine woodlands through anthracology and dendro-anthracology, suggesting that human action did not provoke widespread growth of Aleppo pine in Mallorca at the expense of other vegetation types during prehistory. Such processes, well-documented by current phytosociological studies,</p>

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34
35 **Abstract:** The pioneering nature of Mediterranean pines and their phytosociological role have been
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42 species' wide distribution is mostly due to its rapid regeneration after human landscape
43 transformation, including fire, and the abandonment of agricultural lands. Aleppo pine is considered

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52 permanent human occupation of the island (c. 2300 cal. BCE–1st-century ACE). Investigating these
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57 characteristics of the human management of pine woodlands through anthracology and dendro-
58 anthracology, suggesting that human action did not provoke widespread growth of Aleppo pine in
59 Mallorca at the expense of other vegetation types during prehistory. Such processes, well-
60 documented by current phytosociological studies, probably began at some unknown point after the
61 Romanisation of the island.

62
63 **Keywords:** Aleppo pine (*Pinus halepensis* Miller), anthracology, anthraco-typology,
64 archaeopalynology, Mallorca (Balearic Islands).

65

66

67 1. Introduction

68 The nature and phytosociological role of Mediterranean pines have been largely discussed in the
69 botanical and paleobotanical literature. Mediterranean pines are especially adapted to post-fire
70 regeneration and are important pioneering trees in forest regeneration processes after human
71 disturbances. In the specific case of Aleppo pine, one of the most widespread Mediterranean
72 conifers, serotony and early flowering are considered adaptive traits favouring survival after crown
73 fires, even if the pine does not survive the fire itself (Tapias et al. 2004; Daskalakou and Thanos
74 1996; Thanos and Daskalakou 2000; Ne' eman et al. 2004; Ne' eman and Izhaki, 2006; Pausas et al.
75 2004). This has been a relevant element in considering Aleppo pine a pioneer and invasive tree in
76 Mediterranean environments (Pausas et al. 2002), often relating it to stages of the succession and
77 environmental degradation of broadleaved forests formations (Bellot 1978; Peinado and Rivas-
78 Martínez 1987).

79 In Mallorca, Aleppo pine woodlands represent the most widespread forest formations (IFN 2012)
80 and have experienced a major increase since the mid-twentieth century, clearly favoured by changes
81 in land use following abandoned agricultural lands and after fires (Berbiela 2015). In parallel, a
82 negative social perception of this species has been increasing among the Balearic society, where, in
83 many cases, it is considered an invasive tree brought by humans rather than via natural processes in
84 the archipelago. It is also often considered fire-promoting and responsible for many plagues
85 (Sureda-Negre et al. 2011).

86 However, recent research on Aleppo pine has noted that its adaptive and reproductive strategy, with
87 partial serotony and quick initial growth, is relevant to competing where there are frequent fires and
88 other edaphic and climatic constraints of the Mediterranean climate, especially drought (Martínez
89 del Castillo et al. 2018; Ne' eman et al. 2004). Furthermore, the paleoenvironmental literature has
90 also indicated that the post-fire regeneration and colonisation of degraded lands after human action
91 are not the only potential explanations for the presence and development of pines in Mediterranean
92 environments (Carrión et al. 2010; Carrión and Fernández 2009), at least not until more recent
93 historical times (Aranbarri et al. 2020). Pines could have constituted the climax vegetation in areas
94 where arid conditions would not have allowed the development of other types of forests (Badal,
95 2013).

96 Regarding such current discussions on the phytoecological role of Aleppo pine and the impact of
97 anthropogenic landscape management on its diachronic dynamics, in this article, we aim to (i)
98 define the use of pinewood by prehistoric societies on the island of Mallorca during the first two
99 millennia of permanent human occupation of all the biotopes of the island (c. 2300 cal. BCE–1st-
100 century ACE) and (ii) investigate the nature of Aleppo pine woodlands on the island, assessing the
101 role of anthropogenic landscape management in this species' distribution during the studied period,
102 aided by the knowledge of its actual ecological and distributional characteristics. We approach these
103 objectives using a multi-proxy strategy, combining different kinds of archaeobotanical data (i.e.,
104 anthracology, dendro-anthracology and archaeopalynology) and discussing them in relation to
105 paleoenvironmental sequences and the dynamics of Aleppo pine in neighbouring continental areas
106 (Iberia).

107

108 **2. Archaeological and environmental setting**

109 Mallorca is the largest island of the Balearic archipelago, with a total surface of 3.620 Km². The
110 geology of the island is almost exclusively calcareous, with only some non-calcareous substratum
111 (i.e., Palaeozoic and Triassic) in the northern mountain range (Rosselló et al. 2003). There are no
112 permanent watercourses on the island; its hydrographic network is composed of streams with

113 intermittent water flows, mainly during spring and autumn, when the most significant precipitation
114 occurs. There exist a number of shallow brackish lagoons along the coastline of the island that
115 allow the development of particular types of vegetation in the wetlands.

116 The vegetation of the island is typically termo- and meso-Mediterranean, characterised by an
117 important development of macchia and scrublands. Woodlands are characterised by two main
118 species: *Pinus halepensis* Miller and *Quercus ilex* L. (Llorens et al. 2007). The island is divided into
119 three hydrographic and biogeographical regions: the Tramuntana mountain range, the largest
120 mountains with some of the highest elevations of the archipelago (i.e., the maximum elevation at
121 Son Torrella is 1,445 m.a.s.l.), the Pla, the central plain, and the Llevant region along the
122 southeastern coast (Rosselló et al. 2003).

123

124 **2.1. Current distribution of *Pinus halepensis* Miller in Mallorca.**

125 Aleppo pine is a dominant species of Mallorcan tree-covered natural communities, except for oak
126 forests (*Quercus ilex* L.), riversides of freshwater streams, rocky areas, and cliffs of the highest
127 mountains. Currently, the island has 150,248.82 hectares of forested lands (IFN 2012), with Aleppo
128 pine present in more than 50% of them (Berbiela 2015). The abundance of this species is attributed
129 to its high ecological plasticity, as well as its rapid and robust regeneration in burned and unburned
130 environments, partially due to the serotinous character of its cones (Goubitz et al. 2003). Moreover,
131 human modifications of the landscape over the centuries have also been considered a key factor in
132 the current distribution of Aleppo pine woodlands in Mallorca (Bolòs 1993, Gil et al. 2003).

133 Aleppo pine occupies most of the areas suitable for the development of sclerophyllous vegetal
134 formations, where it would probably be scarce or rare, assuming that human action has favoured its
135 spread. This is why all phytosociological researchers agree on considering Aleppo pine merely an
136 accompanying species for sclerophyllous and pioneering formations. A characteristic
137 phytoecological role is only conferred to Aleppo pine in some permanent littoral habitats, where it
138 broadly develops due to its high tolerance to salinity and strong coastal winds (Bolòs 1996; Rivas-
139 Martínez et al. 1992; Llorens et al. 2007).

140 The formation and overall abundance of long-resting extensive masses of secondary pine forests are
141 interpreted as a general characteristic of Mallorcan vegetation and a direct consequence of anthropic
142 disturbance and fire regimes (Llorens et al. 2007). Aleppo pine woodlands on marginal and non-
143 cultivated areas of the island have been subject to secular exploitation. Moreover, extensive pine
144 plantations were established in different areas of Spain after the Civil War (1936-1939) and planted
145 in Mallorca primarily on sclerophyllous macchia (Gil et al. 2003). Land-use changes since the
146 second half of the 20th century, characterised by a progressive abandonment of cultivated lands due

147 to the redirection of the Balearic economy towards mass tourism and abandonment of the primary
148 sector, has resulted in a notable increase in Aleppo pine forests, which have colonised abandoned
149 cultivated lands to the point that they represent more than half of the current forested area of the
150 island (Berbiela 2015).

151

152 **2.2. Holocene vegetation dynamics in the Balearic archipelago**

153 Several paleoenvironmental studies involving radiocarbon dating have been conducted on the
154 Balearic Islands since the 1990s (e.g., Burjachs et al. 1994; Yll et al. 1997, 1999; Pérez-Obiol et al.
155 2000; Servera-Vives et al. 2018; Kaniewski et al., 2020). This research was performed on
156 sedimentary records of littoral sequences focused on the Holocene, mainly from Menorca, while
157 paleoenvironmental studies on Mallorca and Pitiusas remain scarce. At this time, there are only two
158 published palynological studies conducted on Mallorca with reliable chronological and analytical
159 resolution; both in the same wetland, s'Albufera d'Alcúdia (Burjachs et al. 1994, 1997, 2017).

160 KF14, a hemipelagic marine core, has revealed the vegetation dynamics from the upper Pleistocene
161 to the Holocene (Yll et al. 1999; Roure et al. 1995; Pérez-Obiol et al. 2000). Pollen analysis of
162 marine records allows researchers to trace regional climate and vegetation trends over time, while
163 terrestrial records are more prone to recording micro-regional variability related to human-climate-
164 environmental interactions (Mercuri et al. 2012). In this sense, the KF14 sequence has revealed pre-
165 Holocene high values of *Pinus* and steppe taxa, such as *Artemisia*, along the sequence. This
166 vegetation configuration characteristic of cold periods decreased during the
167 interglacials/interstadials, where some temperate taxa, such as *Corylus*, *Betula* and deciduous
168 *Quercus*, spread.

169 The Early Holocene implies a retreat of pine formations and the expansion of littoral communities
170 of *Juniperus* and *Ephedra* and some mesic taxa, such as *Buxus*, *Corylus* and deciduous *Quercus*
171 (Yll et al. 1997; Burjachs et al. 1994, 2017; Pérez-Obiol et al. 2000, 2001). This kind of vegetation
172 takes advantage of wetter-than-today climate conditions and the absence of reported human
173 activities until approximately the 5th-millennium cal BP. Both Mallorca and Menorca, known as the
174 Gymnesic islands, show similar trends in vegetation history. From the 6th- to 4th-millennium cal BP,
175 a deep vegetation shift occurred, implying a transition from the aforementioned mesic and littoral
176 communities to Mediterranean macchia and garrigues dominated by *Olea*, *Pistacia* and *Erica*.
177 These were prevalent plant communities during the Late Holocene, alternated with scattered open
178 areas created for agropastoral activities. Such a deep landscape transformation has been related to
179 the increasingly dry conditions in the Western Mediterranean and the possibility of agropastoral
180 practices the archaeologically-documented definitive human occupation (Burjachs et al. 2017; Yll et

al. 1999; Servera-Vives et al. 2018). Even though archaeological evidences before 2500-2800 cal BCE remain still controversial, pollen analysis carried out in Mallorca and Menorca evidence the increase of anthropogenic pollen indicators (including nitrophilous and ruderal taxa and crops), suggesting the possibility of agropastoral activities in the Balearic Islands prior to the Chalcolithic period (Carrión et al. 2010; Servera-Vives et al., 2018)

186

Despite the well-known high pollen productivity and overrepresentation of pine pollen grains in fossil and modern pollen analogue studies (Heim 1970; Ejarque et al. 2011; Miras 2009), Holocene paleoenvironmental littoral sequences from Mallorca and Menorca show low to moderate *Pinus* values, generally under 40%. This fact has been interpreted as the scarce importance of pine formations on the Gymnesic islands during the Holocene, compared to Ibiza and other eastern Iberian Peninsula sequences. Despite the overall moderate pine representation in the Balearic Holocene sequences, it is worth noting an increase in *Pinus* values (from ca. 15% to 40%) reported in s'Albufera d'Alcúdia at ca. 3000-2000 cal BCE (Burjachs et al. 1994, 2017; Kaniewski et al., 2020), suggesting a change in the spread of littoral pine formations in the area. Other palynological studies from Holocene sequences in western Mallorca also show noticeable increases of *Pinus* values, such as in Santa Ponça (Parra 1994) and Palma Nova cores (Menéndez-Amor and Florschütz 1961), but no reliable chronological data are available.

199

200 **2.3. Mallorca during prehistory and protohistory**

The process of human occupation of the Balearic Islands occurred in a relatively late chronology in comparison with other insular territories of the Mediterranean basin. Archaeological evidence for the first human occupation of the archipelago remains slippery and under debate, but there is a consensus in situating the definitive settlement of human populations at around the first half of the 3rd-millennium cal. BCE (between 2900–2500 cal. BCE [Guerrero et al. 2007; Guerrero and Calvo 2008] and 2350–2150 cal. BCE [Alcover 2008; Lull et al. 2004; Sintès 2015]). The Chalcolithic occupation of Mallorca developed between c. 2500 and 1700 cal. BCE, representing stable human occupation of the island (Calvo and Guerrero 2002; Calvo et al. 2002). Although the bioarchaeological information is scarce, it seems clear that from this period onwards, well-established agriculture and husbandry developed in the archipelago (Pérez-Jordà et al. 2018; Ramis 2018).

During the Bronze Age, the permanent occupation of all the biotopes of the island is well-evidenced, including the development of monumental vernacular architecture with cyclopean techniques. The so-called Naviform culture developed during the Bronze Age in 1700/1600–

1100/1000-850 cal. BCE (Lull et al. 1999; Micó 2006; Guerrero et al. 2007; Calvo et al. 2011; Salvà 2013). During this period, settlements consisting of groups of navetiforms, monumental boat-shaped houses built using the cyclopean technique, expanded across the island of Mallorca and elsewhere in the archipelago.

After a period of transition and transformations in the Naviform culture, the Talaiotic culture (Early Iron Age [EIA], c.850–550 cal. BCE) emerged in Mallorca and Menorca. This culture is characterised by a redefinition of monumental architecture focused on public tower-shaped buildings (i.e., so-called 'talaiots' and other types of turriforms; Calvo 2009; Gelabert-Oliver et al. 2018). A new period of transformations occurred around c.550 cal. BCE, when the Postalaiotic or Balearic culture (Late Iron Age [LIA]) developed. The Postalaiotic or Balearic culture extended until the Roman conquest of the island in 123 cal. BCE.

3. Materials and methods: archaeobotanical records of *Pinus halepensis* Miller

Tracing the history of Aleppo pine woodlands on the island of Mallorca during the Late Holocene, including its anthropogenic use and potential influence on its distribution requires different kinds of archaeobotanical materials. Accordingly, this research is based on the compilation and analysis of published and unpublished charcoal and wooden fragments and pollen analysis of prehistoric and protohistoric archaeological sites on the island of Mallorca (Figure 1) to gather information on both the landscape dynamics in the surroundings of the studied sites and on the management of woodlands by human communities. To summarise all the available datasets, we standardised and treated all the available data. The chronology of the available samples corresponds to the prehistory and protohistory of the island of Mallorca (c. 2300 cal. BCE–1st-century ADE). Samples from previous and later phases were scarce or did not meet the requirements for the data treatment proposed in this study (see below).

Figure 1: Map of Mallorca island showing the location of the archaeological sites where charcoal and pollen assemblages were studied and of the off-site paleoenvironmental sequence of s'Albufera d'Alcúdia (drawn by Alejandra Galmés, Universitat de les Illes Balears).

3.1. Archaeological wood and charcoal remains

Different wood and charcoal materials were considered in this study. Regarding charcoal assemblages, 37 samples of dispersed charcoal fragments from archaeological contexts with proper stratigraphic control and dating were analysed and considered (Table 1). As selection criteria for the samples to be analysed, we discarded those with less than 90/100 charcoal fragments. All the selected samples had been previously evaluated in terms of statistical representativeness (see

250 references in Table 1), and we took into consideration whether the samples came from demolished
251 buildings after fire episodes.

252
253 *Table 1: Description of the anthracological assemblages considered in this study.*

254
255 To standardise the taxonomical identifications of all the samples by ecological types, different
256 categories were established: xeric and sub-xeric trees, xeric and sub-xeric shrubs, and mesic taxa.
257 *Pinus* values were individualised in a separated category, and a sum of tree values was included.
258 The taxonomical identifications included in each of these categories are shown in Table 2. With the
259 37 samples, anthracological diagrams were created for the three main biogeographical regions of
260 the island: the Tramuntana mountain range in the north, the Pla (central plain), and the Llevant
261 coast. A separate diagram was created for the site of Na Galera, located in a small islet on the
262 western shores of Mallorca (Figure 1).

263
264 *Table 2: Taxa grouping according to phytosociological formations and climatic conditions in the*
265 *Balearic Islands (according to Bolós 1993; Gil et al. 2003; Llorens et al. 2007).*

266
267 Dendro-anthracological information regarding some of the *Pinus halepensis* fragments, which is
268 also available (Picornell et al. 2020), was also considered. The objective of developing dendro-
269 anthracological analysis of Aleppo pine charcoal fragments is to better define the pinewood
270 exploitation practices developed by prehistoric communities in Mallorca by differentiating branches
271 and/or trunk exploitation. The results of the dendro-anthracological analysis (charcoal-pith distance
272 combined with ring width) are organised according to anthraco-typological principles (Dufraisse et
273 al. 2018; Coubrai and Dufraisse 2019). A dendrochronological referential study of *Pinus halepensis*
274 Miller on Mallorca facilitated the establishment of four different anthraco-groups to differentiate
275 different pinewood exploitation practices (Picornell et al. 2020):

- 276 • Anthraco-group 1: A small diameter (<7cm) and slow growth (RW <1.5 mm), represent
277 branches;
- 278 • Anthraco-group 2: A small diameter (<7cm) and fast growth (RW >1.5 mm) represent the
279 internal part of mature woods from trunks;
- 280 • Anthraco-group 3: A large diameter (>7cm) and slow growth (RW <1.5 mm) represent
281 external parts of major trunks characterised by slow growth;
- 282 • Anthraco-group 4: A large diameter (>7cm) and fast growth (RW >1.5 mm) represent
283 external parts of major trunks characterised by fast growth.

284 Dendro-anthracological analysis was performed on five of the available samples from three
285 archaeological sites (Table 3). The results of the anthraco-typological analysis are represented in bar
286 diagrams representing the percentage of fragments for each category in a given charcoal
287 assemblage.

288

289 *Table 3: Description of anthracological assemblages on which dendro-anthracological and*
290 *anthraco-typological analyses were performed (Picornell et al. 2020).*

291

292 The study of archaeological objects or large fragments of wood identifiable as constructive
293 elements also included *Pinus halepensis* macro-remains. The use of this wood to manufacture
294 identifiable objects by prehistoric people has been documented in different funerary sites on the
295 island, where the use of pinewood to make coffins to bury individuals has been documented
296 (Picornell-Gelabert 2012; Calvo et al. 2020). Moreover, the use of pinewood to make different
297 architectural elements has also been documented in prehistoric and protohistoric sites on the island.
298 Both direct (i.e., burned wooden beams, posts and crosspieces) and indirect (i.e., diameter
299 estimation of *Pinus halepensis* fragments in after-fire collapsed contexts where timber was burned
300 and fragmented) evidence of timber use has been analysed in previous studies (Allué et al. 2013;
301 Picornell-Gelabert 2012; Picornell-Gelabert and Servera-Vives 2017; Piqué and Noguera 2003; Ros
302 1984; summarised in Picornell-Gelabert and Dufraisse 2018).

303

304 **3.2. Archaeopalynological materials and methods**

305 In this research, we gathered information from several archaeopalynological studies conducted on
306 Mallorca. Forty-nine archaeopalynological samples from Mallorcan archaeological sites were
307 selected for this study, ranging from the Llevant to the Tramuntana area (Table 4). To facilitate the
308 comparison of archaeopalynological and anthracological results, identifications were grouped
309 following ecological Balearic categories, while *Pinus* pollen values were assigned to a separate
310 category (Table 2). Samples were treated following different chemical procedures, including
311 standard treatments (Faegri et al. 1989) and heavy liquid separation (see Table 4). For heavy liquid
312 separation, two different methods were used in the palynological studies: (1) samples of about 2 gr.
313 of dry sediment were treated for pollen extraction according to standard procedures using tetra-Na-
314 pyrophosphate, HCl 10%, acetolysis, heavy liquid separation with sodium metatungstate hydrate,
315 HF 48% and ethanol (Florenzano et al. 2012; van der Kaars et al. 2001), and (2) samples of about
316 15 gr. of dry sediment were treated using the standard procedures described by Girard and Renault
317 Miskovsky (1969) and Goeury and de Beaulieu (1979), modified by Burjachs et al. (2003),
318 including HCl, KOH, HF and heavy liquid ZnCl₂. In all cases, final residues were mounted on

319 slides in glycerol jelly for pollen grains identification. Samples of a mean of 225 pollen grains
320 counted per slide were considered. Pollen relative values were calculated as percentages of the total
321 land pollen sum, which includes pollen from vascular plants. Pollen grains were identified and
322 counted using biological microscopes at magnifications typically ranging from 400 to 630. Pollen
323 identification was carried out using atlases and morphological keys (e.g., Punt et al. 1976-2009;
324 Moore et al. 1991; Reille, 1992, 1995; Beug, 2004). Diagrams were plotted using C2 software
325 (Juggins 2007) and refined in Illustrator.

326

327 *Table 4: Description of the archaeopalynological assemblages considered in this study.*

328

329

330

331 **4. Results.**

332 ***4.1. Archaeological wood and charcoal analysis***

333 Thirty-seven assemblages of dispersed charcoal fragments were considered in this study (Table 1):
334 25 from the Llevant coast, 10 from the central plain, 1 from the Tramuntana mountain range and 1
335 from the islet of Na Galera (Figure 2).

336

337 *Figure 2: Percentage diagrams of anthracological data for the different regions of Mallorca:*
338 *eastern coast (Llevant), central plain (Pla), Tramuntana mountain range (Tramuntana) and Na*
339 *Galera islet. The results are plotted following their chronology. Horizontal lines indicate chrono-*
340 *cultural phases: BA (Bronze Age); EIA (Early Iron Age); LIA (Late Iron Age); RT (Roman Times)*

341

342 The Llevant region has the best chronological coverage, with samples from the Early Bronze Age to
343 the 1st century ACE originating from five different archaeological sites. The different taxonomical
344 categories change over time, and the values of *Pinus* are variable, ranging from 0% to 40%. In the
345 central plain, 10 samples from 4 different sites were analysed, all of which correspond to the EIA
346 and LIA. The values are homogenous during the first part of the diagram, but changes are detected
347 in the last part of the sequence, when *Pinus* values increase significantly.

348 The only assemblage available in the Tramuntana mountain range corresponds to the LIA use of the
349 Son Ferrer hypogeum as a collective burial place. In this assemblage, *Pinus* presents significant
350 values, but the most represented taxonomical category corresponds to xeric and sub-xeric shrubs.
351 Finally, in Na Galera islet, an assemblage of charcoal fragments deposited in a dump pith over a

352 relatively long period of time during the 1st century ACE was studied. In this case, *Pinus* is the most
353 recurrent taxon identified.

354 The results of the dendro-anthracological analysis of *Pinus halepensis* charcoal fragments
355 (Picornell-Gelabert et al. 2020) allowed us to organise the results obtained (Table 5) according to
356 anthraco-typological principles, represented in Figure 3, which shows the percentage of analysed
357 fragments for each of the four anthraco-groups. The two Late Bronze Age levels analysed at
358 Building 51 of Ses Païsses showed predominance of anthraco-group 1 (representing branches),
359 especially in the habitat layer. In contrast, the LIA assemblages from Building 25 at Ses Païsses and
360 Talaiot 3 at Son Fornés were characterised by the clear predominance of anthraco-group 2 and the
361 highest values for anthraco-group 4 detected among the five assemblages. These results indicate
362 that the *Pinus* fragments originated from both trunks and branches. Finally, the assemblage from Na
363 Galera also showed a predominance of anthraco-group 1, followed by anthraco-group 2. Some of
364 these results invite reconsideration of the nature and origin of the dispersed charcoal fragments and
365 reevaluation of the context, as timber remains may have also been present (Picornell-Gelabert et al.
366 2020).

367
368 *Table 5: Results of anthraco-typological analysis (Picornell-Gelabert et al. 2020).*

369
370 *Figure 3: Bar charts showing the percentage of fragments for the four different anthraco-groups in*
371 *each assemblage.*

372
373 Regarding direct evidences of timber wood, a total of 133 architectural wooden elements were
374 identified in Bronze and Iron Age sites on Mallorca (Table 6). In all cases, the timber elements were
375 preserved after a fire event that caused the collapse of a building. The only direct evidence of timber
376 in Bronze Age sites corresponds to two *Olea* beam fragments from a Navetiform at the Hospitalet
377 Vell site. In Iron Age sites, a larger amount of architectural timber remains is present at the sites of
378 Cas Canar, Son Ferragut and Son Fornés. Most of the timber elements correspond to *Olea*
379 *europaea*, but a significant amount of *Pinus halepensis* elements were also found at all of the sites,
380 especially at Cas Canar.

381
382 *Table 6: Summary of direct evidence of timber remains identified in prehistoric and protohistoric*
383 *sites on Mallorca (after Picornell and Dufraisse 2018).*

384

385 Finally, *Pinus* wood was also used as a raw material to manufacture objects (Table 7). In all cases,
386 *Pinus* wooden objects were found in LIA funerary sites and are related to the wooden coffins
387 (Picornell-Gelabert 2012; Calvo et al. 2020).

388

389 *Table 7: Summary of Pinus halepensis wooden objects identified in prehistoric sites of Mallorca*
390 *(after Picornell-Gelabert 2012).*

391

392 **4.2. Archaeopalynology**

393 Forty-nine samples were considered in this study: 35 in Llevant, 3 in Pla, and 11 in Tramuntana
394 regions (Figure 4). Overall, the studied archaeopalynological samples showed relatively low values
395 of *Pinus* pollen (i.e., under 22%). This is consistent with the general moderate-to-low AP values
396 (generally under 40%). The chronology of the samples differed from one region to another. The
397 Llevant region presented samples from four sites with a wide time span, from the Bronze Age to
398 Roman times. These samples contained the highest values of *Pinus* pollen of all the samples
399 presented in this study, with maximal values of ca. 22%. During the Bronze Age, samples from
400 S'Hospitalet Vell and Sa Ferradura recorded the highest values of pine pollen. Later, during the
401 First Iron Age, moderate values (ca. 10-20%) of xeric and sub-xeric trees are recorded, and very
402 low values of messic (e.g., *Buxus*, *Corylus* and *Alnus*). During LIA and Roman times, an overall
403 trend toward lower *Pinus* values is highlighted in the diagram, coinciding with a noticeable increase
404 in herbaceous taxa.

405 The three archaeopalynological samples from the Pla region show almost no pine pollen, with
406 maximal values of about 1%, while AP values were always below 6%. Samples from Son Serra-
407 Muro were quite similar, even if they corresponded to different chronologies, while Cas Canar
408 samples showed relatively higher values of arboreal and shrubby taxa. Regarding the Tramuntana
409 region, the highest values of *Pinus* pollen were recorded at the site of Turó de Ses Beies (ca. 13%).
410 Additionally, during the LIA, most samples showed higher values of xeric and sub-xeric trees,
411 messic taxa, and AP but lower values of xeric and sub-xeric shrubs. TSF-56, from Tumul de Son
412 Ferrer, was the only sample with Roman chronology in the Tramuntana region and showed a
413 predominance of herbaceous taxa.

414

415 *Figure 4: Percentage diagram of archaeopalynological data for the different regions of Mallorca:*
416 *eastern coast (Llevant), central plain (Pla) and Tramuntana mountain range (Tramuntana). The*
417 *results are plotted following their chronology. Horizontal lines indicate chrono-cultural phases: BA*
418 *(Bronze Age); EIA (Early Iron Age); LIA (Late Iron Age); RT (Roman Times).*

419

420

421 **5. Discussion**

422 ***5.1 Pinewood exploitation on Mallorca during prehistory and protohistory***

423 The use of pinewood by prehistoric groups on Mallorca is well attested from the end of the
424 Chalcolithic, when the first anthracological assemblages appear (CM1, Figure 2). The presence of
425 pine charcoal fragments is ubiquitous in all regions and phases, but the percentages change from
426 one period to the other. Regarding the archaeopalynological record, percentages of pine pollen
427 grains vary from region to region and period to period. However, high percentages of pine pollen
428 are not detected in any of the assemblages, with values always under 20%, and there are samples in
429 all regions that barely register this species (Figure 4), even if pines are great pollinators (Räsänen et
430 al. 2007; Fall, 2012; Heim, 1970). Although pollen is not readily preserved in archaeopalynological
431 samples, such studies have proven their value in reconstructing human activities and landscape
432 dynamics (Florenzano et al. 2013; Mercuri et al. 2019). Moreover, *Pinus* is considered a species
433 with high preservation ability (Cao et al. 2007).

434 The archaeopalynological analyses show a mainly open landscape in the surroundings of the studied
435 sites, ranging from open to semi-open environments, with an overall predominance of herbaceous
436 taxa in all regions and chronologies. Poaceae pollen is well-detected in all samples, reaching
437 important percentages in many cases and confirming the existence of open areas near the sites.
438 Accordingly, archaeopalynological results suggest that the landscape surrounding the prehistoric
439 settlements on Mallorca were open landscapes in which crop fields and pasturelands were farmed
440 since the settlement of the Naviform villages (Mercuri et al. 2019), as also attested by carpological
441 results (Pérez-Jordà et al. 2018). The territories adjacent to human settlements would then be
442 characterised by a mosaic landscape composed of a patchy distribution of crop fields, pasturelands
443 and woody vegetal formations characterised by macchia-like scrublands. This anthropogenic
444 landscape structure appears to have been maintained over the last four millennia, as it has also been
445 suggested in off-site pollen sequences from both Mallorca and Menorca (Burjachs et al. 2017;
446 Servera-Vives et al. 2018). Accordingly, heterogeneous distributions and densities of pine forests
447 could have occurred across the island, which could explain the differences observed in the charcoal
448 record. The use of very local resources could also have increased these differences (Figure 2).

449 The area of Llevant presents the most ancient assemblages of both charcoal and pollen, as well as
450 the longest sequence in time, from the end of the 3rd Millennium cal. BCE to the 1st century ACE
451 (Figure 2, Figure 4). There are moderate percentages of pine pollen in the oldest sample from a
452 navetiform domestic unit at Hospitalet Vell and in EIA samples, but they decrease significantly

during the LIA. Moderate pine pollen values were also recorded in LBA samples from the rocky headland of Sa Ferradura. The use of pine wood shown in the anthracological record was variable during Bronze Age in this region, as some assemblages do not contain pine fragments (e.g., sample HV_N3_1) or contain minor percentages, and some have higher representations of pine. The highest values were recorded at Building 51 of the Ses Païsses site. In this case, dendro-anthracological research has shown that even if the building was abandoned after a fire episode (Table 1), what could cause the burning and subsequent fragmentation of pine timber and/or material culture, thus resulting in an overrepresentation of this taxon in the studied charcoal assemblage, the assemblages are mainly composed of pine branches (Figure 3). This is especially clear in the habitat layer (SP6), and only in the fallen roof layer (SP7) are a few fragments of trunks detected. Accordingly, it has been suggested that like the rest of the Bronze Age assemblages of the Llevant area, samples from Building 51 represent the use of pine branches as firewood, although a possible use of some timber elements made out of pinewood cannot be discarded (Picornell-Gelabert et al. 2020). Archaeopalynological samples from Building 51 of Ses Païsses show a decrease in woodland formations from the preparation levels (20B, 21) to the occupation ones (25, 26, 27), while pine pollen value remain low and do not show significative variation suggesting that pine formation or not well stablished in the area and/or that pine wood exploitation do not imply significant decrease in their extension.

Later on, during the EIA and LIA, pine charcoal percentages increase significantly, reaching values of >30%, in the two studied sites presenting assemblages from this periods, Ses Païsses and Mestre Ramon (Figure 2). The increase is significantly relevant in LIA assemblages. In this sense, the dendro-anthracological analysis shows that in Building 25 of Ses Païsses, pine branches and trunks were both used as firewood during the LIA (Figure 3), meaning that firewood procurement involved cutting down pine trees (Picornell-Gelabert et al. 2020). This is relevant considering that at Building 25, evidence of metallurgical activity was found (Aramburu 2009; Picornell-Gelabert and Carrión 2017), suggesting that increasing firewood demand may have resulted in cutting down pine trees to meet the fuel requirements of metallurgical production. This fact, together with the significant increase of pine values in the LIA anthracological assemblages in the Llevant, suggests that pinewood was a more relevant energetic resource during this period than in previous BA contexts. This is consistent with archaeopalynological data, which highlights the low representativity of pine communities in the Llevant area during the LIA.

A similar trend is shown in the central plain, where EIA and LIA charcoal assemblages at four different archaeological sites were analysed (Figure 2). During the EIA, the highest pine values were detected at the Cas Canar site. In this case, the studied assemblage collected from the interior

487 of a square talaiot (i.e., a tower-shaped public monument) rather than from a domestic space (Table
488 1). This monumental building was abandoned after a fire event, after which 101 wooden beams
489 were preserved, 22 of them corresponding to pine (Table 6). In this sense, it has been argued that
490 pine would be overrepresented in the anthracological assemblage after the burning and
491 fragmentation of timber (Picornell-Gelabert 2012; Allué et al. 2013). In any case, the 22 pine beams
492 clearly show that in this region, pine trees were cut down during EIA and their trunks used as
493 timber. This is especially relevant considering the absence of pine pollen from the EIA sample from
494 this same site and the very minor values in the other sites of this region (Figure 4), suggesting that
495 pine would not have been a recurrent species in the surroundings. Accordingly, it can be suggested
496 that pines were especially targeted for use as timber, which would have required relatively long
497 trips to reach pine populations, cut their trunks and transport them to the site.

498 In the same region, pine timber was also identified during the LIA. Direct evidence is found at Son
499 Ferragut (two beams and one crosspiece) and Cas Canar (a wooden beam) (Table 6). Moreover, the
500 dendro-anthracological analysis at Talaiot 3 of Son Fornés also showed the exploitation of pine
501 trunks (Figure 3). Considering that the LIA charcoal assemblage from this tower-shaped monument
502 was formed after a fire event (Table 1), it has been suggested that the recurrence of fragments
503 originating from pine trunks would be the result of the burning and fragmentation of pine timber
504 elements, probably beams from the roof of the talaiot (Picornell-Gelabert 2020). However, most of
505 the wooden constructive elements found in these sites are made of *Olea* trunks (Table 6). This can
506 also be explained by the fact that as archaeopalynological records indicate, pine would not be a
507 recurrent species in the area. However, during the LIA, there was a relevant increase in the use of
508 pine firewood in domestic spaces of Son Fornés (Figure 2), suggesting that this species was
509 especially appreciated as firewood during the LIA, as already proposed for the Llevant region. This
510 increase in the use of pine firewood in the central plain during the LIA would also involve the
511 organisation of trips from the villages to pine woodlands which, according to the
512 archaeopalynological results, would be distant from the settlements.

513 The other two regions present a smaller number of studied assemblages. In the case of the Serra de
514 Tramuntana, only one charcoal assemblage was studied, corresponding to the LIA funerary use of
515 the hypogeum of the Son Ferrer staggered turriform (Figure 2, Table 1). In this case, high pine
516 percentages were recorded, corresponding to the use of firewood during successive inhumations in
517 the cave (Picornell-Gelabert et al. 2018). This suggests that pinewood was also appreciated as
518 firewood in ritual and funerary contexts during the LIA. Son Ferrer is located near the coast at the
519 western end of the Tramuntana mountain range, in the same regions of the three sites presenting
520 archaeopalynological analyses (Figure 1). In this area, pine pollen is better represented in the LBA

sample, while it is rare in EIA and Roman samples (Figure 4). Nevertheless, during the LIA, pine higher pollen values were recorded in samples from the Turó de ses Beies, suggesting that pine populations were better represented in the neighbouring area of the Santa Ponça coastal lagoon.

In the case of the islet of Na Galera, the charcoal assemblage from a cistern reused as a dump pit during the 1st century ACE shows the highest pine percentages recorded among the studied samples. This assemblage corresponds to the successive deposition of charcoal debris into the dump over a relatively long period of time. The dendro-anthracological study of this assemblage (Figure 3) shows that it was mainly composed of pine branches, which indicates that the assemblage represents the deposition of firewood debris. However, some fragments corresponding to trunks are detected, which could also represent firewood debris or the cleaning of pine timber elements from a neighbouring building that burned down at the time (Picornell-Gelabert et al. 2020). Accordingly, the assemblage suggests that pine provided most of the firewood used during the 1st century ACE. Since it is a secondary deposition of firewood debris, it is difficult to assess the original use of fire. In the small islet where the archaeological site is located, both ceremonial and metallurgical activities were documented. Moreover, the small size and the lack of soils in the islet suggest that firewood would have been transported from Mallorca, probably after the exploitation of coastal vegetation. Hence, as it is documented at Son Ferrer and other LIA sites from the other regions, pine branches appear to be a relevant fuel resource.

539

Altogether, the charcoal and pollen results both show that Aleppo pine had been present in the vegetal landscape of Mallorca island since the beginning of the permanent occupation of all the biotopes by sedentary human groups practising long-lasting agricultural and pastoral activities. Pinewood was exploited in all regions and periods to fulfil different social demands, such as firewood and timber. However, both the distribution of pine woodlands and their exploitation appear to have changed over time. During the Bronze Age, the exploitation of pinewood as fuel is well attested in the Llevant region, but its use is irregular among the studied sites and, when present, presents minor values. In any case, it is relevant the presence of domestic contexts with no charcoal fragments from this species. Moreover, the use of pinewood as timber is not well documented, as only a few charcoal fragments resulting from trunks (anthraco-group 4) were included in the dendro-anthracological analysis of the fallen roof layer of Building 51 at Ses Païsses.

This situation changes during later phases. During the EIA, pine percentages increase in the anthracological record in the two regions where assemblages were studied, the Llevant and the central plain. At this time, clear exploitation of pine trunks as constructive timber is well-documented at the Cas Canar site. Subsequently, pine percentages increase significantly in LIA

anthracological assemblages in all the studied regions, showing a clear preference for using this species as firewood in both domestic and ritual contexts. In Building 25 of Ses Païsses, this clear increase in the use of pine firewood is also related to the cutting down of pine trees to fulfil the energetic demand of metallurgical activities, a case that is also possible at the Na Galera site. Moreover, the use of pine trunks as constructive timber is also well-documented with both direct (burnt beams) and indirect (dendro-anthracological analyses in burnt contexts) evidence (Picornell-Gelabert and Durfaisse 2018; Picornell-Gelabert 2020). In this same period, the use of pinewood as raw material is documented for wooden object manufacturing (Table 7). Pinewood was frequently used to manufacture different elements of wooden coffins, including the coffin itself, as well as covers and mortise-and-tenon joinery elements (Picornell-Gelabert 2012). The size of these elements, especially coffins and covers, shows that only trunks would be large enough to create the cavities that hosted the body of the deceased. Hence, again, the cutting of pines to use their trunks is also attested in these LIA contexts.

When comparing anthracological and archaeopalynological results, it seems clear that it was during the LIA when human groups targeted the exploitation of pines. This is especially relevant in the case of the central plain, where a clear increase in the use of pine firewood and pine trunks as constructive timber occurs in a region where pine pollen percentages are significantly low (or even absent), suggesting a cultural choice that involved transportation of pine wood from distant areas to the sites. Aleppo pine trees produce a relevant amount of deadwood, representing >70% of the deadwood in current Balearic forests (IFN 2012). Even if Aleppo pine is not a self-pruning tree (Ne'eman et al. 2004), the production of deadwood in the lower parts of the trunk would have created a reservoir of easily reachable dry wood to be used as firewood. As it has been pointed out, this fuel resource was exploited during all the studied periods, but it is particularly appreciated during LIA in domestic, metallurgical and ritual contexts. In this period, the practise of cutting down pine trees for use as fuel for metallurgical activities, timber procurement and objects manufacturing is well documented.

581

582 **5.2. Late Holocene Aleppo pine woodlands in Mallorca**

Aleppo pine has been considered by many authors to be a species linked to the stages of early succession and degradation of other forest formations, such as *Quercus* and other broadleaved trees (Bellot 1978; Peinado and Rivas-Martínez 1987). In many palaeobotanical sequences, an expansion of this species is documented from the introduction of farming, without ruling out that it was also favoured by its adaptability to temperature and aridity increase (Martínez del Castillo et al. 2018). The ecological role of Mediterranean pines has been largely discussed, including whether its

589 expansion is a consequence of major human landscape disturbances or it is driven by its particular
590 adaptation to certain climatic and edaphic tough conditions (e.g., Barbero et al. 1998; Quézel and
591 Barbero 1992; Ne'eman and Trabaud 2000). Serotony and early flowering of Aleppo pine are
592 considered favourable traits to survive crown fires (Tapias et al. 2004; Daskalakou and Thanos
593 1996; Thanos and Daskalakou 2000; Ne'eman et al. 2004; Ne'eman and Izhaki 2006; Pausas et al.
594 2004). Accordingly, it is considered to be a pioneer and an invasive tree in Mediterranean
595 environments (Pausas et al. 2002). However, even if the adaptive and reproductive strategies of this
596 tree have generally been explained after its adaptation to post-fire regeneration and colonisation,
597 recent research agrees in highlighting other relevant constraints to which pines are especially
598 adapted, such as drought and unstable edaphic conditions, which would also explain its regeneration
599 and expansion (Ne'eman et al. 2004).

600 Archaeobotanical and paleoenvironmental literature on the Western Mediterranean has often
601 discussed this subject. In Mediterranean Iberia, Aleppo pine is one of the most extended trees in
602 thermo- and meso-Mediterranean formations (Rivas-Martínez 1987). As in the Balearics,
603 phytosociology has discussed the 'naturalness' of Aleppo pine populations in Iberia and their current
604 distribution, which remains a matter of debate (Aranbarri et al. 2020). The adaptation of this tree to
605 especially unstable edaphic conditions, as well as its post-fire regenerative capacity and subsequent
606 pioneering role, have been considered the explanation for the development of Aleppo pine
607 woodlands after human disturbances (Costa 1987; Braun-Blanquet and Bolós 1987; Quézel and
608 Barbero 1990). However, paleoenvironmental research has often found this specific explanation,
609 based on current vegetation observations, to be problematic in explaining the trends and dynamics
610 of Holocene vegetation (Carrión et al. 2010; Carrión and Fernández 2009).

611 The Holocene dynamics of Aleppo pine woodlands in the Ebro basin were recently reviewed by
612 Aranbarri et al. (2020), who concluded that the current distribution of this species is explained by
613 anthropogenic environmental degradation and as a consequence of other factors, such as long-term
614 responses to climate changes and edaphic conditions. The expansion of Aleppo pine woodlands
615 appears to have been well-documented since the Mesolithic period (Aranbarri et al. 2020; Badal
616 2013). Accordingly, its distribution before the onset of human landscape transformations during the
617 Neolithic period is considered the result of natural vegetation dynamics and the adaptation of this
618 species to the climatic and edaphic conditions of the region. In fact, they consider that Neolithic
619 Aleppo pine's decreased presence in anthracological and palynological records is the result of the
620 development of more mesic environmental conditions. They also refer to climatic instability

621 detected during the Bronze and Iron Ages, which favoured the spread of macchia and pine
622 formations at the expense of broadleaved forests (Aranbarri et al. 2020).

623 In northeastern Iberia, the Holocene development of Aleppo pine woodlands is well-documented
624 along the coast, especially south of the Llobregat river and has been attributed to a north-south
625 gradient of increasing aridity and seasonality (Allué et al. 2017; Burjachs et al. 2000; Carrión 2003;
626 Grau and Duque 2007). Such climatic trends would explain the spread of not only pine formations
627 but also macchia-like scrublands in the region during the Mid and Late Holocene periods.
628 Accordingly, these vegetation dynamics on the Mediterranean coast of Iberia have been interpreted
629 as a differentiated trend in relation to central European dynamics, according to which aridity and
630 seasonality rather than a human disturbance of broadleaved formations would explain the
631 prehistoric development of both pine woodlands and macchia (Allué et al. 2017; Carrión et al.
632 2010; Carrión et al. 2011). In the context of discussing the prehistoric anthropogenic impacts
633 causing vegetation changes in the northeastern Mediterranean region, the well-documented
634 prehistoric anthracological records of the Garraf area do not reflect a decrease in broadleaved
635 forests and a subsequent development of Aleppo pine woodlands after anthropogenic landscape
636 impacts. Neither Neolithic nor Bronze or Iron Age human activities in the landscape, which would
637 include bushfires and timber and firewood procurement, seem to have induced a significant
638 decrease in broadleaved forests (*Quercus*) and a parallel spread of pine species. The
639 increase/decrease of Aleppo pine in the anthracological record is parallel to the representation of
640 xeric and thermophilic shrubs. This is why its development is considered a climate-related dynamic,
641 due to aridity and seasonality increases, rather than human-induced processes after major landscape
642 degradation (Allué et al. 2017).

643 Further south, Aleppo pine is also a key element in the Holocene woodlands of eastern and
644 southeastern Iberia. Paleobotanical data have allowed documenting the presence of the Aleppo pine
645 during the Last Glacial Maximum and the Late Glacial period in some areas of southern and eastern
646 Iberia (Badal 1998; Aura et al. 2005). Radiocarbon dates on Aleppo pine macro-remains show the
647 presence of this species at the end of the 7th-millennium cal. BCE in Mesolithic contexts (García
648 Puchol and Aura Tortosa 2006; Badal 2013), although there is a lack of direct dating for previous
649 chronologies. In general, during the early Holocene, the remains of Aleppo pine are minor in
650 relation to broadleaved species, among which *Quercus* plays a key role.

651 In Neolithic sequences from this area, an important presence of xeric and thermophilic species,
652 among them Aleppo pine and the wild olive tree, is documented, especially at coastal sites, and has
653 a somewhat minor presence in inland and mountain areas. From the 5th to 4th-millennium cal.

654 BCE, *Quercus* forests seem to have reduced gradually as the formations of Aleppo pine, olive trees,
655 strawberry trees, and scrubs increased in different studied sites, as a result of the settlement of
656 Neolithic communities and the systematic use of fire (Badal and Roiron 1995; Badal 1990; Badal et
657 al. 1994; Vernet et al. 1987). These dynamics intensified from 3000 cal. BCE onwards, with the
658 expansion of pine forests, along with Fabaceae, *Erica*, *Rosmarinus officinalis* and *Cistus* understory
659 (Badal 1990; Carrión Marco 2003; Soler et al. 1999). In contrast, in some Neolithic II open air sites,
660 the persistence of *Quercus* forests, showing a dynamic similar to that proposed above for
661 northeastern Iberia, might be the result of a different exploitation of the land

662

663 Finally, the recurrent use of Aleppo pine in the construction of Bronze and Iron Age villages in
664 eastern Iberia shows the great availability and abundance of this species in the region (Mata and
665 Bonet 1983; Grau Almero 1990; Bonet and Mata 2002; Carrión Marco and Grau Almero 2015).
666 Hence, Aleppo pine must have survived in some enclaves during the Pleistocene and the early
667 Holocene in eastern and southeastern Iberia, as it happened in the Ebro basin, from where it would
668 have expanded afterwards. In coastal Neolithic sequences, its presence is observed earlier, while it
669 expands later in sites located in meso-Mediterranean areas, suggesting a better adaptation to
670 Mediterranean coastal environments. In this sense, against the general view of Aleppo pine as a
671 mere intrusive component of a successional community, the native character of this species is
672 claimed based on paleobotanical data for some southern or arid areas of Mediterranean Iberia
673 (Badal 1998).

674 Based on the anthracological and paleoenvironmental data from neighbouring Iberia, it seems clear
675 that Aleppo pine is a native tree and has been present in the regions since the Pleistocene.
676 Furthermore, it presented an important development during Mesolithic, prior to the occurrence of
677 potentially relevant anthropogenic landscape disturbances during the Neolithic, Bronze and Iron
678 Ages. The parallel trends of Aleppo pine and other xeric and thermophyllous shrubby taxa also
679 suggest that the spread of these species during prehistoric times would have been the result of
680 climatic instability and increasing aridity and seasonality, and, in some regions, no clear evidence of
681 broadleaved forest substitutions after anthropogenic disturbances has been found. However, in
682 others sites (those with long-term occupations) the use of fire and human activity seem to be
683 responsible for the rapid expansion of pine forests and the associated understory. These specific
684 trends in Mediterranean Iberia, therefore, appear to be differentiated dynamics in relation to other
685 continental regions in temperate Europe, where such kind of vegetation substitutions seem to be
686 documented in paleoenvironmental records (Carrión et al. 2010). Hence, the development of

687 Aleppo pine seems to be parallel to a process of the increasing shrubby character of the vegetation
688 during the Holocene, linked to a north-south gradient of increasing climate aridity and seasonality,
689 especially relevant in the coastal areas (Burjachs et al. 2000; Carrión et al. 2010).

690

691 In this context, the archaeobotanical and paleoenvironmental data from the island of Mallorca allow
692 for a discussion of the role of Aleppo pine in this insular ecosystem. The KF14 marine sequence
693 shows the continuous presence of pine pollen since the Upper Pleistocene and during all of the
694 Holocene (Yll et al. 1999; Roure et al. 1995; Pérez-Obiol et al. 2000). In the Holocene coastal
695 paleoenvironmental records in all the Balearic Islands, pine is also present throughout the sequence.
696 In Mallorca and Menorca, an Early Holocene decrease in pine is detected in favour of the
697 development of messic taxa (e.g., *Buxus*, *Corylus* and deciduous *Quercus*) and coastal formations of
698 *Juniperus* and *Ephedra* (Yll et al. 1997; Burjachs et al. 1994, 2017; Pérez-Obiol et al. 2000, 2001;
699 Servervá-Vives et al. 2018). This has been interpreted as a result of wetter-than-today conditions in
700 a context where human action was absent or scarce until at least the 5th or 4th-millennium cal BP,
701 when major vegetation changes occurred. Macchia-like vegetation, such as *Olea*, *Pistacia* and
702 *Erica*, broadly developed in detriment to the messic taxa, forming the typical thermo- and meso-
703 Mediterranean vegetation that has characterised the insular vegetation since then (Burjachs et al.
704 2017; Yll et al. 1999; Servervá-Vives et al. 2018). The establishment of this new vegetal landscape
705 across the archipelago has been interpreted as the result of the development of drier and more
706 seasonal climatic conditions and a resilient human-climate-environmental relationship during the
707 first centuries of prehistoric human occupation of the archipelago (Burjachs et al. 2017; Servervá-
708 Vives et al. 2018).

709 Archaeopalynological data from Mallorca show how the territories surrounding Bronze and Iron
710 Age human settlements were characterised by an open landscape with a mosaic structure containing
711 macchia-like forests, crop fields, and pasturelands (Mercuri et al. 2019; Servervá-Vives and
712 Picornell-Gelabert 2018). Significant values of pine are not detected in any case, and this tree is
713 even absent in some of the archaeological samples (Figure 4). Pine pollen values are low or
714 moderate (<40% in almost all cases) in coastal paleoenvironmental sequences in Mallorca and
715 Menorca, with an increase in pine communities between ca. 3000-2000 cal. BC, as reported in the
716 s'Albufera d'Alcúdia sequence (Burjachs et al. 2017, Kaniewski et al., 2020), also coinciding with
717 drier climate conditions. Therefore, considering the high pollen productivity of pines (e.g., Heim
718 1970), the relatively low values in many archaeological samples, and its low to moderate values in
719 littoral sequences, it can be suggested that the regional presence of pine is well attested by both
720 palynological and archaeopalynological data, although they not seem to be as extensive as they are

721 in the current landscape of the island. Otherwise, better development of pine woodlands seems to be
722 attested in the southern Pitiüses islands (Eivissa and Formentera) as it happened on the southeastern
723 coast of Iberia, proposing that such species would have increased development towards the southern
724 territories (Burjachs et al. 2017).

725 Pine pollen values present a moderate increase at c. 3000 cal BCE in s'Albufera d'Alcúdia, with
726 values between c.15% and 40% (Burjachs et al. 1994, 2017; Kaniewski et al., 2020), coinciding
727 with the Chalcolithic-Bronze Age transition. This slight increase in pine pollen is parallel to the
728 increase of other xeric and thermophilic trees, such as wild *Olea* and *Quercus*. This fact probably
729 reflects an increase in the tree cover on this part of the coast, related to a retreat of microregional
730 human activities, as attested by the decline of ruderal taxa. While pine pollen expansion probably
731 reflects the substitution of the former littoral juniper formations by pine communities, the evergreen
732 *Quercus*' expansion probably reflects the regional expansion of these taxa in the Serra de
733 Tramuntana mountains. It is around this time that the first archaeopalynological data are available
734 for the Bronze Age sites of the Llevant region (Figura 4). Pine pollen values are again significantly
735 minor in archaeological samples than in the coastal sequence of s'Albufera d'Alcúdia, and more
736 significant values are detected at sites closer to the coast (e.g., Mestre Ramon and Ferradura, Figure
737 1). In the central plain, pine pollen values are especially low during the Iron Age, with contexts
738 where pine pollen is absent (Cas Canar). Higher values are detected in the western coastal sites of
739 the Tramuntana region during this same period, thus reinforcing the idea that at the beginning of the
740 Late Holocene, pines were relevant only in coastal areas.

741 The increased archaeopalynological values of pine appear to be parallel to that of xeric and sub-
742 xeric shrubs. This is especially relevant in the Llevant and Tramuntana regions, where pine values
743 are more significant (Figure 4). Such xeric shrubs constitute the undergrowth of pine woodlands in
744 Mallorca (Llorens et al. 2007). Accordingly, the parallel trends of pine and xeric shrubs suggests
745 that their increase would represent an increase in forests around the sites, well adapted to both
746 human and climatic agents. This parallel development of pine and xeric shrubs is also visible in the
747 anthracological assemblages, especially in the Llevant and Tramuntana regions (Figure 2). In
748 neighbouring continental areas (Iberia), the development of pine and xeric shrub formations, to the
749 detriment of broadleaved forests, has also been detected at the beginning of the Late Holocene,
750 which, as commented before, has been attributed to an increase in climatic instability (i.e., aridity
751 and seasonality; Allué et al. 2017; Aranbarri et al. 2020; Carrión et al. 2010). Moreover, in the Ebro
752 basin and along the eastern and southeastern coast, it has also been highlighted that both timber and
753 firewood demands related not only domestic energy consumption but also pottery and metal
754 production would have represented an increase in wood exploitation during the Bronze and Iron

755 Ages. In this context, pine would have been an especially targeted wood resource, so human activity
756 is suggested to be more of a constraint than a promoter of pine tree development (Aranbarri et al.
757 2020).

758 In this line, pinewood exploitation has been proved to be irregular during prehistory in Mallorca. As
759 discussed previously, pine is not generally considered to have been a relevant firewood resource
760 during the BA. However, its use as firewood, timber and raw material increased significantly during
761 the IA, especially in the LIA. This is notably relevant in the central plain, where the important use
762 of pine firewood and timber is parallel to low, and even absent, pine pollen values, indicating that
763 this tree would be a resource located far from the sites. The cutting down of pine trees is also
764 documented in the central plain and in the Llevant. In this second region, it is relevant to detecting
765 the cutting of pine trees to provide firewood for metallurgical activities at Ses Païsses (Picornell-
766 Gelabert et al. 2020). Altogether, the anthracological and dendro-anthracological data suggest that
767 Aleppo pine became a resource targeted by IA settlers of Mallorca.

768 Accordingly, the available archaeobotanical and palaeoenvironmental records in Mallorca seem to
769 clearly reflect that Aleppo pine represents a local, natural species throughout the Holocene. The
770 development of pine woodlands does not appear to be relevant during the first two millennia of
771 permanent human occupation of the island according to Late Holocene palynological and
772 anthracological evidence. The development of pine woodlands seems to be rather limited, probably
773 only in coastal areas. This development of pine is parallel to the development of other xeric and
774 sub-xeric taxa, indicating that these taxa were better adapted to Late Holocene climatic conditions
775 of increasing instability, aridity and seasonality. In fact, the relevant shift on the vegetation
776 landscape of the archipelago appears to have occurred prior or parallel to the first human occupation
777 of the islands, when macchia formations broadly developed at the expense of an abrupt decrease in
778 messic taxa (Burjachs et al. 2017; Servera-Vives et al. 2018).

779 Altogether, then, the development of pine woodlands between c.2300 cal. BCE and the 1st century
780 ACE does not appear to have been the result of the substitution of other vegetation formations after
781 anthropogenic landscape transformation. Aleppo pine is especially adapted to the main constraints
782 of Mediterranean environments, such as climatic instability and seasonality, drought, and
783 disadvantageous edaphic conditions. This seems to be the reason its development was especially
784 focused in coastal areas during this period. In this sense, anthracological studies have not shown an
785 over-exploitation of *Juniperus* and *Ephedra* coastal formations, reported to have been important in
786 previous, more humid climatic conditions according to paleoenvironmental records (Burjachs et al.

2017), resulting in the spread of pines in these areas. Hence, this substitution seems to be explained by climatic and ecological agents rather than anthropogenic action.

Therefore, a relevant development of Aleppo pine woodlands on the island after human landscape transformation during prehistory and protohistory does not seem to have been detected. Such anthropogenic landscape transformation processes resulting in the spread of pine species would develop in later periods, sometime after the Romanisation of the islands or during historical times. However, the lack of archaeobotanical data for historical periods makes it impossible to further define the nature and chronology of such processes, while it has been possible for neighbouring regions (Aranbarri et al. 2020). The well-dated palynological sequence of s'Albufera des Grau (Burjachs et al. 2017) records the expansion of pine formations after the Christian conquest of Menorca in the 13th century. In the case of Mallorca, the sequence of Santa Ponça (Parra, 1994) also shows the expansion of pinewoods in the upper part of the diagram, with no reliable chronology ascribed. However, high-resolution paleoenvironmental and archaeobotanical studies are still needed to precisely trace pine species in the Balearics over the past 2000 years.

As stated previously, pinewood formations in Mallorca increased dramatically during the latter half of the previous century due to dramatic changes in land use. Indeed, according to the phytosociological idea of unfixed floristics of pinewood communities in Mallorca, they occupy a quite broad range of ecological conditions. The prospect of future increases in aridity and seasonality due to climate change would be a limitation for most of the broadleaves species to spread throughout the archipelago. Considering the broad versatility of *Pinus halepensis* to phytoclimatic characteristics and edaphic conditions, increased aridity would severely affect this species only in the extremes of its area of suitability (Camara 2001), but there are some indications of severe impacts and decay due to heavy drought episodes (Esteve et al. 2007). In Balearic vegetation, such climatic changes should favour the maintenance of paraclimatic communities, as macchia or garrigues of xeric shrubs cover a broad area of the island, both coastal and inland, where *Pinus halepensis* could play a dominant role.

6. Conclusions

Aleppo pine is a dominant species in all current tree-covered vegetation formations on the island of Mallorca, with the only exception being oak forests (*Quercus ilex* L.) and riparian forests. Pine-dominated woodlands represent the most widespread forest formations in the Balearic archipelago (IFN 2012). Ecological and reproductive studies suggest that this is because of its ecological plasticity and rapid post-fire regeneration due to serotony (Goubitz et al. 2003), a characteristic that also improves its adaptation to climatic (especially drought) and edaphic constraints in

821 Mediterranean environments (Ne'eman et al. 2004). These traits could explain the pioneering role
822 and spread of Aleppo pine woodlands after major anthropogenic landscape transformations,
823 especially in areas suitable for the development of sclerophyllous vegetal formations in which it
824 would have been rare or scarce (Bolòs 1993; Gil et al. 2003). This Aleppo pine expansion has been
825 especially relevant since the mid-20th century, when the massive abandonment of former
826 agricultural and pastoral lands led to a crucial process of landscape transformation in the Balearics,
827 as well as in many other parts of the Mediterranean basin (Grove and Rackham 2003).

828 The study of the role of Aleppo pine woodlands at the beginning of the Late Holocene becomes a
829 relevant subject when evaluating the nature of the presence of this tree in the Balearics and the role
830 of human action regarding its distribution during the first two millennia of permanent human
831 occupation of the island. As in many Mediterranean environments, the use of archaeobotanical data
832 becomes a relevant proxy for paleobotanical studies, as inland lakes, peat bogs and other reliable
833 paleoenvironmental records are not available. In this sense, anthracological, dendro-anthracological
834 and archaeopalynological data from the Chalcolithic, Bronze and Iron Age, along with available
835 off-site paleoenvironmental sequences, allow us to evaluate the spread of Aleppo pine woodlands
836 on the island and the role of human action in relation to it.

837 It seems clear that Aleppo pine constitutes a natural species of the Holocene vegetation of Mallorca,
838 as is the case for other islands of the archipelago. However, according to the archaeobotanical data,
839 it seems clear that the spread of pine woodlands would be more constrained than it is today and
840 better developed in coastal areas. There is no evidence of the spread of pine-dominated woodlands
841 on Mallorca during prehistory and protohistory as a consequence of the substitution of other forest
842 formations due to human action. It should be taken into account that during these periods, there was
843 an increase or decrease in parallel with pine of other xeric, sclerophyllous and thermophilic taxa,
844 especially shrubs, which would be especially favoured by Late Holocene climatic conditions on the
845 island.

846 The use of pine as firewood and timber appears to have been minor during the Bronze Age.
847 However, its use increased during the IA, especially the LIA, when pines were especially targeted
848 to fuel domestic, ritual and metallurgical fires, as well as used as construction timber. In these last
849 moments of prehistory, the increasing exploitation of pines could be explained by the fact that in a
850 context of increasing fuel demands, this would be a common and available tree of a relevant height,
851 along with wild olive trees. Although pines are not self-pruning trees (Ne'eman et al. 2004), they
852 produce an important amount of deadwood (IFN 2012), which could also be related to its increasing
853 use as firewood. Moreover, wild olive is the most used tree for construction timber, followed by

854 pine (Picornell-Gelabert and Dufraisse 2018), thus indicating selective exploitation of the woody
855 vegetation according to specific demands. Hence, when timber and firewood demand increased
856 during the EIA and, especially during the LIA, cutting down pines by human groups occurred, as
857 shown by dendro-anthracological data. However, the archaeobotanical records do not suggest that
858 this increasing forest resource exploitation resulted in a human-induced spread of Aleppo pine on
859 the island. Such processes, which are well attested in the current vegetation landscape of Mallorca,
860 would have begun sometime after the Romanisation of the island.

861

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872

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Figure 1

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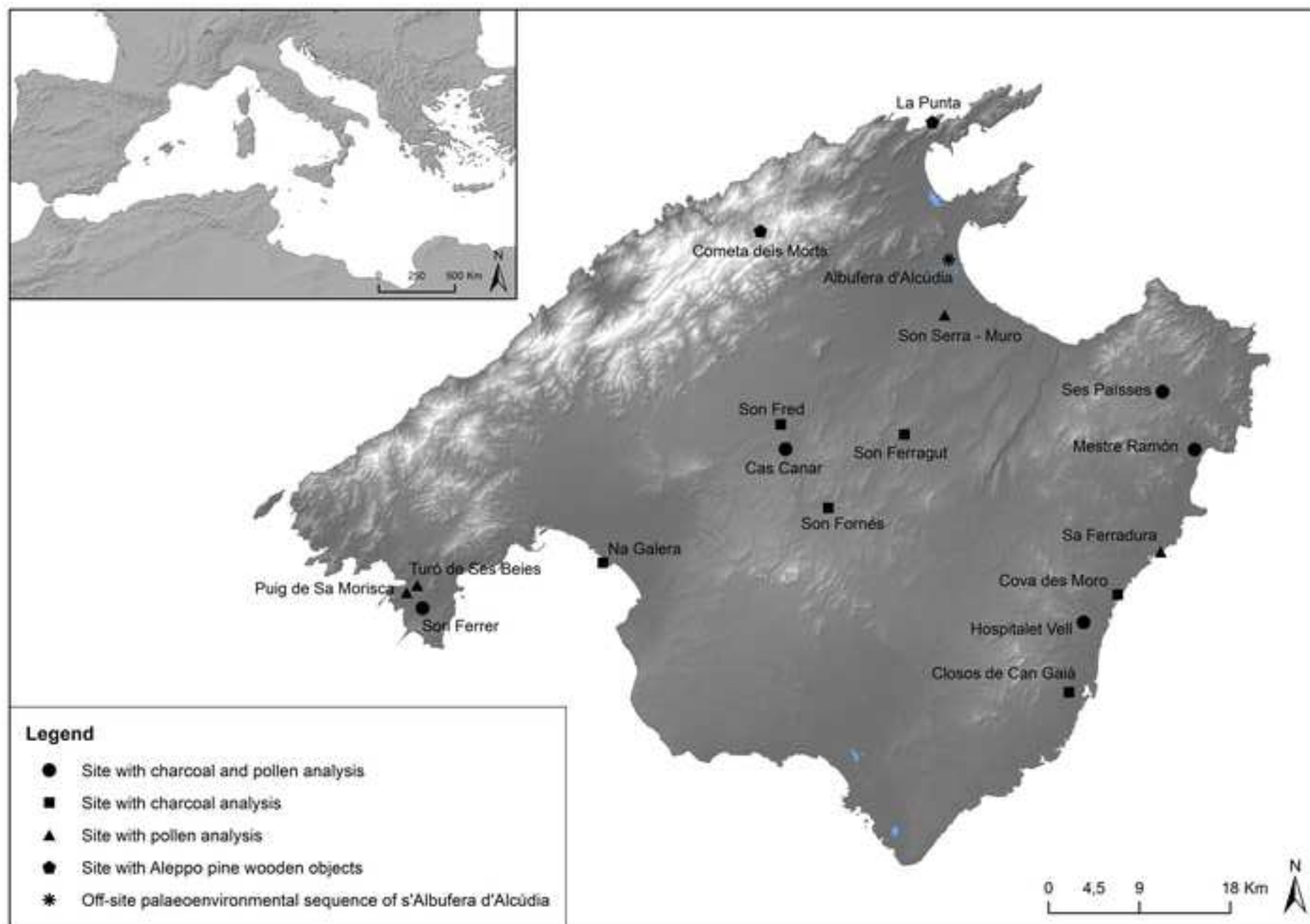


Figure 2

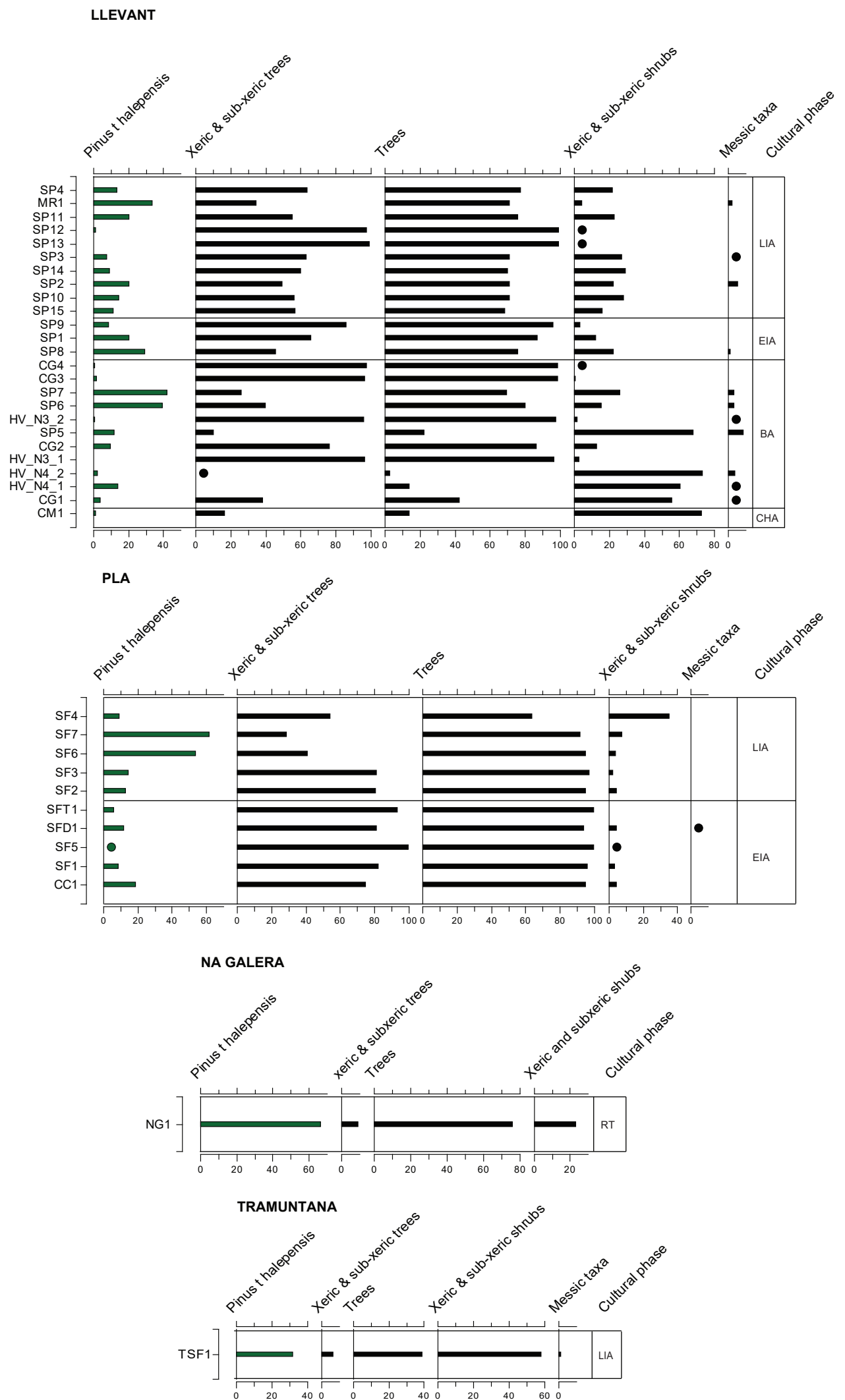


Figure 3

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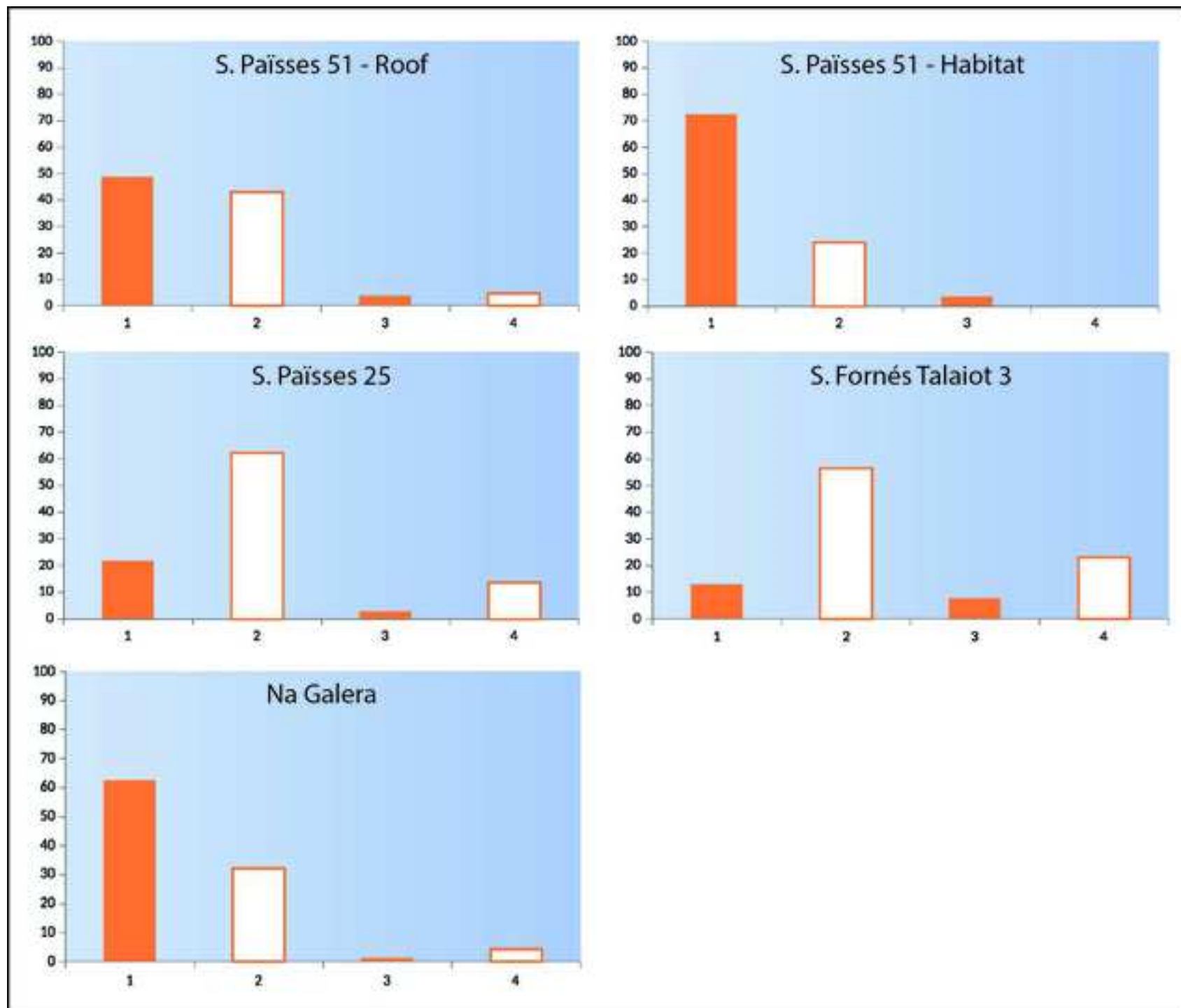
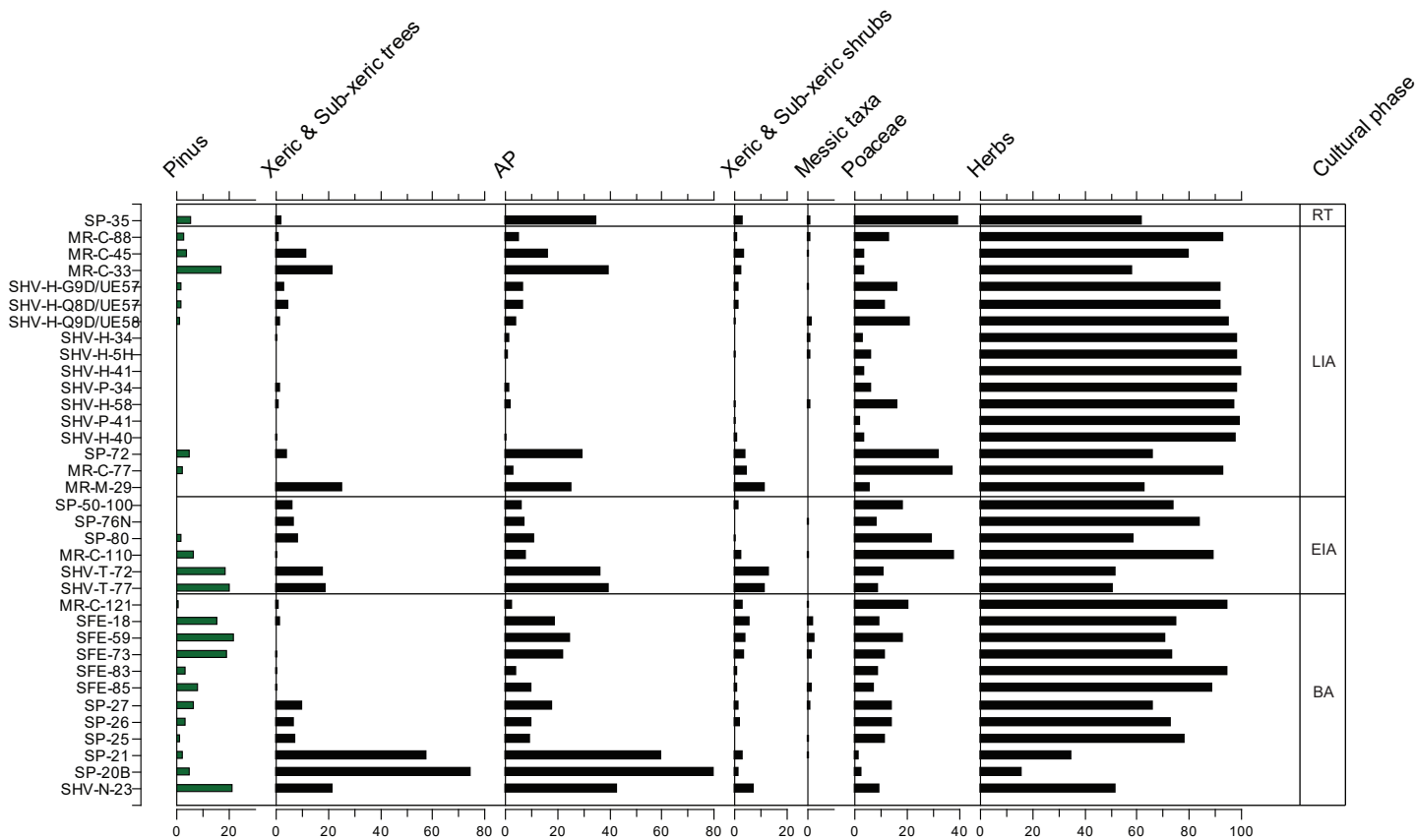
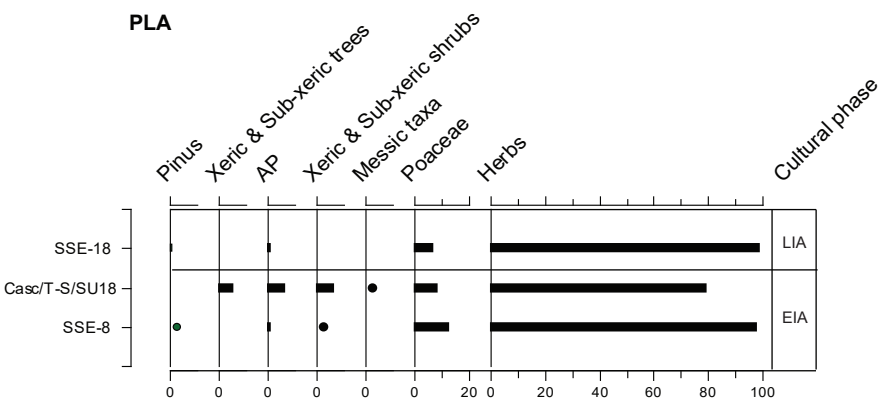


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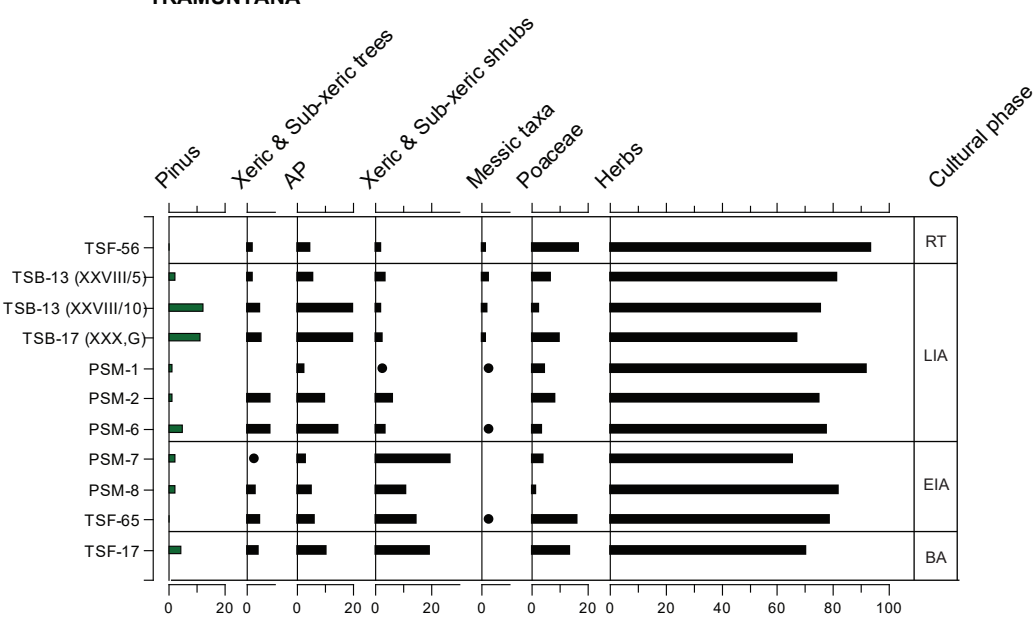
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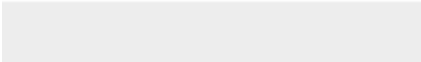




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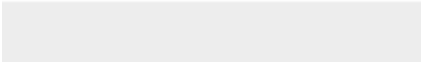




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☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Quaternary International

We the authors declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Sincerely,

On behalf of all authors



Llorenç Picornell-Gelabert (corresponding author on behalf of all the co-authors)

University of the Balearic Islands