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## Modelling dendro-anthracological parameters with dendrochronological reference datasets: interrogating the applicability of anthraco-typology to assess Aleppo pine (*Pinus halepensis* Miller) wood management from archaeological charcoal fragments --Manuscript Draft--

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<b>Abstract:</b>	<p>Aleppo pine (<i>Pinus halepensis</i> Miller) is present in the palaeoenvironmental records of Mallorca (Balearic Islands, Western Mediterranean) since the Early Holocene. It is also documented in the archaeological charcoal analysis (aka anthracology) of early prehistoric sites, but it was especially exploited at certain sites during the Late Iron Age. However, different woodland exploitation strategies cannot be deciphered purely through the taxonomical identification of charcoal fragments, so it is difficult to assess if the presence of Aleppo pine in archaeological assemblages is due to specific social management strategies (branches and/or trunks exploitation). Anthraco-typological methods, based on the measurement of charcoal-pith distance (allowing original wood diameters to be inferred) and ring width, have already been proposed for temperate species (<i>Quercus petraea/robur</i>) as a methodology to define the woodland exploitation of past societies and human impact on forest formations. However, such an approach yet to be set up for conifers growing in Mediterranean environments. In this study we have adapted the anthraco-typological methodology to conifer wood anatomy and evaluated its applicability on the archaeological charcoal assemblages of Aleppo pine, through complete dendrological analysis of the referential material. Our research is based on the systematic measurement of two different dendro-anthracological parameters on archaeological charcoal fragments: charcoal-pith distance and ring width. The results have been compared with the information on ring width and the growing conditions of modern trees in three different forest formations in Mallorca, representing the entire environmental variability of the Aleppo pine forests on the island. Trunk cores and wood discs of different diameter were measured in order to establish criteria to distinguish between both tree organs from the archaeological charcoal fragments. Analysis of this dataset has proved that anthraco-typological methods are applicable to Mediterranean conifers and to further interrogate pinewood exploitation in prehistoric Mallorca. Additionally, we have been able to question the formation of archaeological charcoal assemblages, identify various woodland management strategies and the human impact on woodlands during prehistory.</p>

## Highlights

Dendro-anthracological and anthraco-typological methods are tested for *Pinus halepensis*.

A dendrochronological reference dataset has been created and analysed.

Anthraco-typological methods are proved to be applicable to Mediterranean conifers.

Archaeological charcoal fragments of *Pinus halepensis* has been studied.

Anthraco-typology allowed for the interrogation of pinewood exploitation practices.

1

2 **Modelling dendro-anthracological parameters with dendrochronological reference datasets:**  
3 **interrogating the applicability of anthraco-typology to assess Aleppo pine (*Pinus halepensis***  
4 **Miller) wood management from archaeological charcoal fragments.**

5

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22

23 **Abstract:** Aleppo pine (*Pinus halepensis* Miller) is present in the palaeoenvironmental records of  
24 Mallorca (Balearic Islands, Western Mediterranean) since the Early Holocene. It is also documented  
25 in the archaeological charcoal analysis (aka anthracology) of early prehistoric sites, but it was  
26 especially exploited at certain sites during the Late Iron Age. However, different woodland  
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4 ring width. The results have been compared with the information on ring width and the growing  
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6 environmental variability of the Aleppo pine forests on the island. Trunk cores and wood discs of  
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13

14 **Keywords:** dendro-anthracology, anthraco-typology, charcoal-pith distance, diameter estimation,  
15 radial growth, *Pinus halepensis* Miller, firewood/timber exploitation.

16

17

## 18 **1. Introduction**

19 The study of archaeological charcoal assemblages (anthracology) has been developed, to a relevant  
20 extent, on the prehistoric sites of the Balearic Islands (Western Mediterranean). This research has  
21 allowed the advancement of palaeoenvironmental approaches to past vegetation dynamics and  
22 enabled the analyses of the role of wood and firewood in past socio-environmental relations (i.e.  
23 Picornell-Gelabert 2012; Picornell-Gelabert and Servera-Vives 2017; Picornell-Gelabert and  
24 Carrión 2017; Picornell-Gelabert and Dufraisse 2018; Piqué and Noguera 2002). In this context,  
25 Aleppo pine appears to be an important tree in Balearic Holocene vegetation (Burjachs et al. 2017;  
26 Servera-Vives et al. 2018) as its presence in the anthracological record of Mallorca is well attested.  
27 However, percentages of pine in anthracological assemblages appear to fluctuate between different  
28 sites and chronologies. Aleppo pine is a lowland Mediterranean species with a high ecological  
29 plasticity and regeneration rate – especially after heavy or episodic fires, which are common in its  
30 natural habitat (Goubitz et al. 2003, Ne'eman et al. 2004) – and is a dominant tree species within the  
31 current forest cover of the Balearic archipelago (Gil et al. 2003). The development of extensive  
32 masses of secondary pine forests in Mallorca is seen, at least in part, as a consequence of anthropic  
33 disturbance (Llorens et al. 2007) and centuries of human landscape management (Gil et al. 2003).  
34 Evaluating the role of human landscape management in the development of Aleppo pine forests in  
35 the past and interpreting the variability of its representation in the anthracological record is difficult

1 to assess using only taxonomical identification. This study, therefore, offers relevant information  
2 beyond taxonomical identification, in order to better interrogate diverse pinewood management  
3 practices and, subsequently, the impact of human exploitation of this tree species during prehistory.  
4 Taxonomic identification is the basic information provided by all bioarchaeological disciplines. In  
5 anthracology, taxonomic identification has been the cornerstone for palaeoecological and landscape  
6 dynamic reconstructions and for the interrogation of past woodland management practices (e.g.  
7 Asouti and Austin 2005; Chabal et al. 1999; Théry-Parisot et al. 2010). However, both ethnographic  
8 (Picornell-Gelabert 2009; 2017; Picornell-Gelabert et al. 2011, Dufraisse et al. 2007) and  
9 archaeological works (Dufraisse 2008) dealing with trees and forest resource management have  
10 stated that there are other important variables beyond taxa which need to be taken into account if  
11 the social management of woodlands is to be fully explained. Among these factors, the diameter of  
12 exploited wood constitutes one of the key elements to understand wood exploitation practices  
13 (Dufraisse 2012).

14 Determining the diameter of the wood exploited in the past remains a difficult task. Charcoal  
15 fragments preserve the original wood anatomy, allowing their taxonomical identification, but when  
16 the wood is burnt mass loss and fragmentation occurs. As a result, a direct estimation of the original  
17 wood diameter is not possible after observing the wood anatomy of a single charcoal fragment.  
18 Equally, diameter does not allow us to determinate the tree organ (trunk or branch) from which the  
19 charcoal fragments originate.

20 In order to evaluate the exploited wood diameters of a taxon present in an archaeological charcoal  
21 assemblage, two steps are necessary: the first consists of evaluating the charcoal-pith distance in  
22 each charcoal fragment; the second is to recompose the exploited wood diameters from the  
23 measured charcoal-pith distances (Dufraisse and Garcia 2011).

24 However, fragments of small diameter can correspond to both the branches and/or the inner parts of  
25 bigger trunks. In order to distinguish between small fragments deriving from branches and trunks,  
26 radial growth (ring width) is also measured. This combination of dendro-anthracological parameters  
27 was initially tested on ring-porous angiosperm species growing in temperate forests in Western  
28 Europe (*Quercus petraea/robur*) (Dufraisse et al. 2018a). In this case, the distinction between  
29 heartwood and sapwood was added to tree-ring width and charcoal-pith distance, by means of the  
30 tylosis count in earlywood vessels (Dufraisse et al. 2018b). The combination of these three  
31 parameters led to an anthraco-typological approach, whose interpretations are based on the  
32 establishment of a modern dendrochronological reference dataset. Anthraco-typology for *Quercus*  
33 f.c. is based on eight different anthraco-groups that, when applied to archaeological charcoal, allows  
34 the exploitation of trunk, branches and/or entire trees in a given assemblage to be discriminated  
35 (Dufraisse and Coubray 2018, Coubray and Dufraisse, 2019). We suggest that it also allows the

1 appropriate charcoal fragments (i.e. eliminating branches) to be selected, enabling further specific  
2 questions on the evolution of tree-ring widths through time and the impact of human exploitation  
3 and climate on forests to be evaluated (Marguerie and Hunot 2007).

4 The anthraco-typological approach defined for *Quercus* f.c. is not directly applicable to  
5 gymnosperms when considering their wood anatomy, as the heartwood–sapwood discrimination  
6 tool is not suitable because of the absence of vessels and, subsequently, of tylosis. In order to  
7 discriminate trunks from branches in gymnosperms, the combination of ring widths and charcoal-  
8 pith distance is considered as a potentially discriminant factor, as has been shown for *Quercus* f.c.  
9 (Dufraisse et al. 2018a).

10 In this sense, the objectives of this study are:

11 i) To test and validate the applicability of an anthraco-typological approach based on the  
12 combination of charcoal-pith distance and tree-ring widths according to gymnosperms wood  
13 anatomy growing in Mediterranean environments (Aleppo pine, *Pinus halepensis* Miller);

14 ii) To build up a referential model of the radial growth (tree-ring width) depending on  
15 diameters and tree organs of Aleppo pine in Mallorca, according to different ecological conditions,  
16 in order to allow specific interpretation of the anthraco-typological approach;

17 iii) To test the application of the anthraco-typology approach on Aleppo pine charcoal  
18 fragments in order to further interrogate pinewood uses and exploitation strategies on archaeological  
19 sites from Mediterranean environments. In this sense, the referential dendrochronological dataset  
20 turned out to be imperative, as the radial growth on trunks and branches from the same individuals  
21 had not been approached before.

22 This research was conducted on the island of Mallorca (Figure 1). Different pine populations from  
23 diverse biogeographic zones were studied in order to characterise the radial growth of both tree  
24 organs: trunk and branches. The results were then analysed in order to validate the applicability of  
25 anthraco-typology principles. Finally, the model established after the referential study was applied  
26 to different archaeological charcoal assemblages from prehistoric and protohistoric sites on the  
27 island.

28

29 *Figure 1: Map of the island of Mallorca showing the location of the forest stations sampled for the*  
30 *reference dendrochronological dataset and the archaeological sites studied*

31

## 32 **2. Materials and methods**

33 The methodology used consists of the measurement of two dendro-anthracological parameters  
34 (diameter and ring width) from both archaeological wood charcoal fragments and modern Aleppo  
35 pine samples, and in the interrogation of the results using anthraco-typological principles (Figure 2).

1 Accordingly, two different kinds of dataset were produced: i) a dendrochronological study of  
2 current Aleppo pine populations in Mallorca, measuring tree-ring width in trunks and branches  
3 according to diameter; and ii) the application of different dendro-anthracological parameters to  
4 Aleppo pine archaeological charcoal fragments, comprising measurements of the missing radius  
5 (charcoal-pith distance), modelling diameter (ADmodel) and tree-ring width. This allowed for the  
6 application of the anthraco-typological principles to the obtained dendro-anthracological datasets  
7 according to the results of the dendrochronological referential.

8

9 *Figure 2: Synthesis of the developed methodological approach, combining the study of modern*  
10 *dendrochronological reference datasets and dendro-anthracological analysis of Aleppo pine*  
11 *archaeological charcoal fragments.*

12

### 13 **2.1. Referential study of the radial growth of Aleppo pine in Mallorca**

14 In order to obtain a dendrochronological referential dataset of Aleppo pine, 53 trees from 4 different  
15 populations of this species were studied (Table 1). The sampling stations were distributed along the  
16 different biogeographic regions of the island representing diverse altitudes and annual precipitation  
17 rates (Table 1; Figure 1). At each site, dominant and codominant trees with no visible damage were  
18 selected and cored twice at breast height (1.3 m), perpendicular to the slope direction so as to avoid  
19 tension wood anomalies when using Pressler increment borers. In addition, two wood discs from  
20 branches were obtained from each tree using a hand saw. In the laboratory, the cores and wood discs  
21 were air-dried and sanded with progressively finer grades of sandpaper (80, 180, 300, 500 grit) until  
22 the tree-ring structure was clearly visible under the stereo microscope. Later, the cores were  
23 scanned and cross-dated using CooRecorder v8.0 (Larsson, 2013) and verified by COFECHA  
24 software (Holmes, 1994). Finally, the tree-ring width measurements were done to the nearest 0.01  
25 mm using TSAP-Win™ and LINTAB™ (Rinntech, Heidelberg, Germany).

26

27 *Table 1: Description of the forest stations sampled for the referential dendrochronological study*

28

29 The main objectives of this referential study were: i) to characterise the growth trends of Aleppo  
30 pine in Mallorca, and ii) to characterise the growth rate in trunks and branches. Growth trends are  
31 characterised in dendroecology by combining ring width and cambial age. However, although  
32 cambial age is not measurable on archaeological charcoal fragments, the charcoal-pith distance can  
33 be calculated using a trigonometric tool, and the growth ring patterns in segments of cambial age  
34 are suitable to approach forest dynamics and development (Haneca et al. 2005). In this study, we  
35 considered the combination of ring width and diameter classes as a relevant proxy to characterise

1 and interrogate the dendro-anthracological results. Accordingly, the average ring width of the  
2 different trees sampled was calculated for each cambial age and also for each diameter class,  
3 obtaining a dendrochronological referential comparable to the dendro-anthracological results.  
4 To characterise the trunk growth trends of Aleppo pine, the average ring width was calculated for  
5 both the cambial age and diameter classes on 38 trees from 3 different stations (Table 1). To  
6 characterise the growth rate of trunk and branches, three stations and five trees from each one were  
7 additionally sampled (Table 1). In this case, a trunk core and three to four wood slides from  
8 branches of different diameters were sampled and measured. The average ring width of both organs  
9 (trunk and branches) was calculated in relation to cambial age and diameter classes. The results  
10 were compared to attempt to discriminate trunk and branches radial growth on archaeological  
11 charcoal fragments when combined with charcoal-pith distance (see section 3.1).

12

## 13 **2.2. Archaeological charcoal assemblages analysed**

14 The anthraco-typological approach was applied to five different assemblages of dispersed charcoal  
15 fragments from three sites in Mallorca, dating from the Late Bronze Age to the Late Iron Age/Early  
16 Roman period (Figure 1). The main characteristics of the assemblages are summarised in Table 2.

17

18 *Table 2: Description of the archaeological charcoal assemblages analysed*

19

20 Three of the assemblages originate from a fire, in which it is assumed that the timber burnt down  
21 and fragmented. As a consequence, the pine fragments may potentially represent both firewood  
22 and/or timber remains and be subsequently overrepresented in the anthracological spectra. This is  
23 the case of the two assemblages from Building 51 in Ses Païsses – one corresponding to the habitat  
24 level and one to the roof collapse – and the assemblage of the Talaiot 3 in Son Fornés, a tower-  
25 shaped public monument inside the village.

26 The other two assemblages originate from archaeological deposits formed after a deliberate  
27 abandonment. The assemblage from the interior of Building 25 in Ses Païsses corresponds to  
28 dispersed charcoal fragments linked to metallurgical activity: firewood residues covering a  
29 relatively long time span.

30 Finally, the assemblage from the Na Galera site, located in a small islet near the Mallorca shore, is  
31 the result of residue deposits from a cistern reused as a dump. In this case, the assemblage showed  
32 an abundance of big charcoal fragments, most of which were pine. As the associated building  
33 presents several collapsed and rebuilding phases, the original excavators hypothesised that this  
34 charcoal assemblage represents timber remains.

35

## 1 **2.3 Dendro-anthracological tools**

### 2 *2.3.1. Measurement of the charcoal-pith distance*

3 Different methodologies have been proposed to calculate the distance between the charcoal  
4 fragment and the pith of the trunk/branch from where it originated (radius) and to infer a minimum  
5 diameter for the original wood (radius x2) (see a detailed analysis in Dufraisse et al. 2019). Among  
6 these, estimating the missing radius based on the trigonometric tool of a right-angled triangle  
7 provided reliable measurements and estimations of the original diameters of charcoal fragments.  
8 This technique and the correction factors were tested on seven taxa (including *Pinus halepensis*)  
9 providing relevant results and systematising the use of the pith-location tool for wood diameter  
10 estimation (Dufraisse et al. 2019).

11 The pith-location tool is based on the measurement of the angle and the distance between two  
12 ligneous rays at its intersection with the ring boundary.

13 All measurements were taken using a Nikon AZ100 macroscope with magnifications from x5 to  
14 x400, associated with a Nikon camera. The measurements of the distance and the angle between  
15 two ligneous rays were obtained using a semi-automatic system based on four landmarks integrated  
16 into the Nikon NIS Elements software. The calculation of the charcoal-pith distance, based on the  
17 trigonometry of an isosceles triangle, was automatically done by the software (Figure 2).

18 The measurements were obtained on the last preserved tree ring of every fragment. For each  
19 fragment, five separate measurements using different rays crossing at the same ring boundary were  
20 obtained. The two extreme values obtained for the charcoal-pith distance (the largest and the  
21 shortest) were discarded and a mean value of the remaining three measurements was calculated.  
22 The projected diameter (charcoal-pith distance x2) was then established for every fragment. Diverse  
23 experimental studies on fresh and carbonised wood, especially on *Pinus halepensis* Miller  
24 (Dufraisse et al. 2020, García and Dufraisse 2011), allowed us to establish exclusive criteria to  
25 reduce the margins of error and improve the archaeological application of the pith-location tool, and  
26 to establish correction factors linked to the tool (i.e. under and overestimation) (Dufraisse and  
27 Garcia 2011; Garcia and Dufraisse 2011). Accordingly, the exclusive criteria used in this study  
28 were:

- 29 i) Measurements of distance between the two rays <2mm were excluded;
- 30 ii) Angle between the two rays <2° were excluded;

31 and the correction factors applied were:

- 32 iii) A correction factor linked to the trigonometric tool was applied due to the underestimation  
33 by 20% of the missing radius on projected diameter classes between 5 cm and 10 cm;
- 34 iv) No reliable measurements of charcoal-pith distance >12.5 cm were considered;
- 35 v) A correction factor taking into account wood shrinkage during carbonisation (20%) was

1 applied to the measurement of the charcoal-pith distance.

2 The final value was classified according to different (projected) diameter classes established by the  
3 standard dendrometrical plans used by foresters (Gaudin 1996; Deleuze et al. 2014). In such  
4 models, conventional wood cuts are 4 cm, 7 cm, 20 cm, etc. For gymnosperms, Deleuze et al.  
5 (2014) propose to include additional cuts of 14 cm. According to the experimental studies,  
6 especially wood shrinkage (García and Dufraisse 2011) and the precision of the archaeological  
7 questions, we also added cuts of 2 cm and 10 cm, resulting in the following projected diameter  
8 classes: [0–2] cm; [2–4] cm; [4–7] cm; [7–10] cm; [10–14] cm; [14–20] cm and [>20] cm.

### 10 2.3.2. Diameter analysis tool (*ADmodel*)

11 During carbonisation wood experiences both mass loss and fragmentation, so the measured  
12 charcoal-pith distance (and the projected diameter) on charcoal fragments does not represent the  
13 unburnt wood diameter. In order to correct this bias, the Analysis Diameter tool (*ADmodel*) was  
14 established, based on the fact that every trunk is biologically considered to be a stack of cones. This  
15 model assists in interpreting the distribution of the charcoal-pith distances from a charcoal  
16 assemblage of theoretical unburnt wood diameters (Dufraisse 2006). The *ADmodel*, developed by  
17 the DENDRAC project, is available (for both gymnosperms and angiosperms) as an open access  
18 Excel macro on the project's website (<https://dendrac.mnhn.fr/spip.php?article237>).

### 20 2.3.3 Radial growth (*tree-rings width and growth rate*)

21 Ring width was measured for the preserved tree rings visible in each charcoal fragment using the  
22 Nikon AZ100 microscope, the Nikon camera and NIS Elements software. A correction factor (20%)  
23 was applied to all the measures obtained due to wood shrinkage during carbonisation (Dufraisse et  
24 al. 2018a). An average ring-width value was calculated for each fragment and considered in relation  
25 to the projected diameter class calculated for the same fragment. An average value for the ring  
26 width of all the fragments for every projected diameter class in each assemblage was also  
27 calculated. This data was analysed according to the results of the referential study on the radial  
28 growth of Aleppo pine trees in Mallorca (see section 3.1).

## 30 2.4 Anthraco-typology: theoretical principles and referential model

31 In order to easily compare the dendro-anthracological data between the archaeological charcoal  
32 fragments and the referential model, the principles of anthraco-typology (i.e. the combination of the  
33 dendro-anthracological parameters) were applied (Dufraisse et al. 2018a; Dufraisse and Coubray  
34 2018). Considering the wood anatomy of gymnosperms and the combination of two dendro-  
35 anthracological parameters (charcoal-pith distance and growth rate), a total of four anthraco-groups

1 were defined based on two different variables of the charcoal fragments: projected diameter classes  
2 and average ring width (Figure 3).  
3 According to the standard dendrometrical parameters used by foresters, a threshold between  
4 trunk/branches was established at 7 cm of the diameter (Gaudin 1996; Deleuze et al. 2014).  
5 Moreover, the dendrochronological referential of the Aleppo pine in Mallorca allows the  
6 interrogation of different growth rates for both organs, trunks and branches, discriminating between  
7 fast and slow growth (see section 3.1). Accordingly, by combining these two parameters, measured  
8 both on the referential and on the archaeological materials, four anthraco-groups were considered as  
9 discriminating between small and large diameters (</> 7 cmn) and fast and slow growth (</>  
10 threshold established after the dendrochronological referential) (Figure 3).

11  
12 *Figure 3: Synthesis of the anthraco-groups defined by the anthraco-typology principles adapted to*  
13 *gymnosperms' wood anatomy.*

14  
15  
16 **3. Results**

17 **3.1 Dendrochronological results of the referential study**

18 3.1.1 Growth trends of Aleppo pine populations in Mallorca

19 The trunk cores of the three stations presented similar growth trends, characterised by fast or very  
20 fast growth in juvenile trees that is progressively reduced due to the age effect (Figure 4a). This  
21 growth trend is coherent with other Aleppo pine populations studied along the Mediterranean Basin  
22 (de Luís et al. 2013) and is maintained when ring width is plotted against diameter classes, as with  
23 anthracology (Figure 4b).

24 These three Mallorcan pine populations showed similar responses to climate and a parallel  
25 evolution between the three different stations (Figure 4a). However, although the annual trend of the  
26 three stations described parallel curves, they presented different ring-width values. The stations  
27 presenting the highest ring widths (Binissalem and Caimari) recorded the highest average annual  
28 precipitation, and the station with the lowest ring widths (Ses Salines) documented the lowest  
29 average annual precipitation (see Figure 4a and Table 1). This suggests that one of the most relevant  
30 factors conditioning the growth of Aleppo pine in Mallorca is precipitation, a trend that is coherent  
31 with the available dendroecological studies for this species across its present distribution (de Luis et  
32 al. 2013).

33  
34 *Figure 4: Results of the dendrochronological measurements of trunk cores from referential stations:*  
35 *a) ring width vs. cambial age; b) ring width vs. diameter classes.*

1

### 2 3.1.2 Growth rate of trunk and branches

3 Radial growth measurements were compared in trunk and branches with the same cambial age in 15  
4 different trees from 3 stations (Table 1). Ring width is significantly different for the trunk and  
5 branches of the same cambial age in all the stations, but is remarkably smaller for branches (Figure  
6 5a). Again, this growth trend is maintained when replacing cambial age by diameter classes (Figure  
7 5b).

8

9 *Figure 5: Results of the dendrochronological measurements of trunk cores and branches from*  
10 *referential stations: a) ring width vs. cambial age; b) ring width vs. diameter classes.*

11

12 Considering all the ring widths measured for trunks and branches from the 15 trees in the 3 different  
13 stations, mean values between trunks and branches were different in every station according to  
14 different climatic conditions (precipitation) (Figure 6a). Also, when considering each station  
15 independently and then all the stations together, the average ring width was always  $> 1.5$  mm for  
16 trunks and  $< 1.5$  mm for branches.

17 When the ring width of all the sampled trees was calculated for each diameter class (considering  
18 both trunks and branches together), this 1.5 mm value divided the diameter classes above and under  
19 7 cm (Figure 6b). Considering these results, ring width was also plotted on samples above and  
20 under 7 cm of diameter for both trunks and branches (Figure 6c). In this case, it is clearly visible  
21 that both groups are divided at 1.5 mm of ring width:  $> 1.5$  mm in the trunk samples and  $< 1.5$  mm  
22 in the branch samples.

23

24 *Figure 6: A boxplot and a mean and whisker plot of the ring width measurements for the trunk and*  
25 *branches from referential stations: a) ring width for trunks and branches by each station and*  
26 *altogether; b) ring width by diameter classes for trunks and branches from all the stations; c) ring*  
27 *width by  $<$  and  $>$  7cm of diameter on trunk and branches from all the stations.*

28

29 These results allowed us to establish two thresholds differentiating trunks and branches according to  
30 diameter and ring width, applicable to the archaeological charcoal fragments. Both values enable  
31 the application of the anthraco-typological principles as follow:

32 i) Diameters above and under 7 cm can be considered as the distinction between trunks ( $>$   
33 7cm) and branches ( $<$  7 cm); this referential study confirms the standard ranking used by foresters  
34 for Aleppo pine;

35 ii) There is a quantitative difference in the radial growth of trunks and branches for Aleppo

1 pine that clearly defines differentiated growth rates for both organs of the tree:  $< 1.5$  mm for  
2 branches and  $> 1.5$  mm for trunks.

3

### 4 **3.2. Anthraco-typology: establishment of the anthraco-groups according to the** 5 **dendrochronological reference dataset.**

6 According to the results obtained from the referential study, the established thresholds for diameter  
7 and growth trends for trunks and branches can be used to discriminate between these two tree  
8 organs, after the dendro-anthracological measurements of archaeological charcoal fragments  
9 according to diameter classes ( $< 7$  m vs.  $> 7$  cm) and ring width ( $< 1.5$  m vs.  $> 1.5$  mm). Both  
10 parameters were therefore used to organise the dendro-anthracological data, according to the  
11 anthraco-typological principles adapted to gymnosperms wood anatomy (see section 2.3), and  
12 characterise the four different anthraco-groups established (Figure 3):

- 13 i) Small diameter ( $< 7$ cm) and slow growth (RW  $< 1.5$  mm) represents branches;
- 14 ii) Small diameter ( $< 7$ cm) and fast growth (RW  $> 1.5$  mm) represents internal part of mature  
15 woods;
- 16 iii) Large diameter ( $> 7$ cm) and slow growth (RW  $< 1.5$  mm) represents external parts of major  
17 trunks characterised by slow growth;
- 18 iv) Large diameter ( $> 7$ cm) and fast growth (RW  $> 1.5$  mm) represents external parts of major  
19 trunks characterised by fast growth.

20

### 21 **3.3 Dendro-anthracological and anthraco-typological results on archaeological charcoal** 22 **assemblages**

#### 23 *3.3.1. Minimum diameter estimation results (charcoal-pith distance and ADmodel)*

24 The results obtained after measuring the charcoal-pith distances are shown in Table 3. The  
25 percentage of fragments corresponding to each diameter class are expressed both before and after  
26 the application of the ADmodel. It is significant to remark that the trends shown by both values did  
27 not present significant variances (Figure 7a). The only remarkable variation between both values is  
28 found in the case of the Talaiot 3 in Son Fornés.

29

30 *Table 3: Results of the charcoal-pith distance measurements expressed by diameter classes and*  
31 *modelled according to the ADmodel.*

32

33 *Figure 7: Results of the dendro-anthracological measurements on archaeological charcoal*  
34 *fragments of Aleppo pine: a) charcoal-pith distance and ADmodel; b) average ring width by*  
35 *diameter classes.*

1

2 The two Late Bronze Age levels of Building 51 (Ses Païsses) show projected diameters generally  
3 smaller than 7 cm (Figure 7a). The wood collection is oriented towards the same diameter classes in  
4 both the fallen roof and the occupation level. We observed, however, a slight difference in the fallen  
5 roof level in relation to the occurrence of bigger diameters, though its appearance is noticeably  
6 reduced. The Iron Age assemblages of Building 25 (Ses Païsses) and Talaiot 3 (Son Fornés) also  
7 show the exploitation of small woods, although the projected diameters are oriented towards larger  
8 values, between 4 and 7 cm. Moreover, the occurrence of bigger diameters, up to 20 cm, is clearly  
9 represented. Finally, the results of Na Galera show a clear predominance of small diameters,  
10 specifically fragments under 4 cm.

11

### 12 *3.3.2. Radial growth results (ring width and diameter classes)*

13 The results obtained by measuring the average ring width of the fragments of every diameter class  
14 were variable for each assemblage (Figure 7b). In Building 51 (Ses Païsses) both assemblages  
15 (occupation layer and fallen roof) show remarkably narrow ring widths, mostly under 1 mm or less,  
16 in all diameters classes. In the Iron Age assemblages from Building 25 (Ses Païsses) and Talaiot 3  
17 (Son Fornés), ring width is remarkably higher (more than double) than in Building 51 and clearly  
18 above the established 1.5 mm threshold. Finally, the ring width measured at Na Galera is variable  
19 along the different diameter classes: it is low and predominantly under the 1.5 mm threshold for  
20 diameter classes smaller than 7 cm; only a few fragments with diameters above a 7 cm ring width  
21 clearly exceed this value.

22

### 23 *3.3.3. Anthraco-typology*

24 The results of the charcoal-pith distance and the ring width measurements were sorted, according to  
25 the anthraco-typological principles and the definition of the anthraco-groups, and reviewed against  
26 the results obtained from the referential study (results expressed in Table 4 and Figure 8). The two  
27 levels of Building 51 (Ses Païsses) were characterised by a clear predominance of anthraco-group 1.  
28 However, both levels were differentiated by a higher presence of anthraco-group 2 in the roof  
29 collapse layer than in the habitat layer. In contrast, the Iron Age assemblages from Building 25 (Ses  
30 Païsses) and Talaiot 3 (Son Fornés) were characterised by a predominance of anthraco-groups 2 and  
31 4. Finally, the results from Na Galera again showed a clear predominance of anthraco-group 1,  
32 followed by anthraco-group 2.

33

34 *Table 4: Results of the dendro-anthracological parameters measured on Aleppo pine archaeological*  
35 *charcoal assemblages (projected diameter classes and average ring width) according to anthraco-*

1 *typology principles.*

2

3 *Figure 8: Anthraco-typology diagrams for each archaeological assemblage (values expressed as %*  
4 *of fragments for each of the anthraco-groups).*

5

6

## 7 **4. Discussion**

### 8 **4.1. Dendrochronological reference dataset: modelling of the dendro-anthracological** 9 **parameters for Aleppo pine**

10 Two different referential datasets were created from the pine populations in Mallorca – one  
11 reflecting radial growth in pine trunks, the other comparing the radial growth of trunk and branches  
12 in the same individuals. These enabled us to test the applicability of dendro-anthracological  
13 parameters and tools, and the reliability of an anthraco-typological approach to Aleppo pine  
14 charcoal fragments.

15 The radial growth of trunks is characterised by fast growth in juvenile trees and a subsequent  
16 decrease of the growth rate due to the age effect (Figure 4a). This pattern also evidences the  
17 replacing of cambial age by diameter classes (Figure 4b), an aspect that can be measured on  
18 archaeological charcoal fragments (charcoal-pith distance). The average ring width in trunks was  
19 variable from one station to another (Figure 4a). As the three different stations used cover a range of  
20 climatic variance, especially in relation to average annual precipitation (Table 1), it can be  
21 suggested that this growth variation is linked to climatic variables, coherent with other Aleppo pine  
22 populations studied (de Luís et al. 2013). Differences in radial growth for both the trunk and  
23 branches of the same individual trees are shown for both tree organs. Again, the growth rate of  
24 trunks was variable among the three stations (Figure 5a) according to the average annual  
25 precipitation (Table 1). In all cases, the radial growth of branches was significantly lower than that  
26 of trunks for the same cambial age, a pattern that is also clear when replacing the cambial age for  
27 the diameter classes (Figure 5b). Moreover, even if branches may be sensitive to climatic events  
28 (possible registration of extreme years in the dendrochronological curves of branches), no  
29 overlapping with the radial growth of trunks and branches with the same cambial age (Figure 5a)  
30 and/or diameter class (Figure 5b) was detected. Both curves presented distinctively different growth  
31 rates, significantly lower in branches, independently of the different climatic conditions recorded in  
32 the three pine populations studied. The average measured ring width values for individual trees at  
33 the three stations also show a clear differentiation between trunks and branches. The results, both in  
34 every station and combined, highlight a distinction between the growth rate of both tree organs  
35 (Figure 6a). If we consider the measured ring width from all the stations in relation to the diameter

1 classes, the values obtained clearly indicate a parallel increase of diameter and ring width (Figure  
2 6b), confirming the 1.5 mm threshold discrimination between diameters  $>$  and  $<$  7 cm (Figure 6c).  
3 The results obtained in this referential study also show that the accumulated branch radius did not  
4 exceed 3.5 cm, that is 7 cm of the diameter (Figure 5b), confirming the 7 cm threshold used by  
5 foresters to distinguish between trunk and branches for Aleppo pine (Gaudin 1996; Deleuze et al.  
6 2014). This, together with the clearly distinguished growth rate of both organs ( $<$  and  $>$  1.5 mm),  
7 attests that the different radial growth trends of Aleppo pine are linked to the different organs of the  
8 tree (trunk and branches), regardless of the ecological growing conditions in Mallorca. The  
9 combination of both parameters (ring width and diameter classes) allows for the discrimination  
10 between trunks and branches after the dendro-anthracological analysis of archaeological charcoal  
11 fragments.

12

## 13 **4.2. The reliability of the anthraco-typological approach to Aleppo pine archaeological** 14 **charcoal fragments.**

### 15 *4.2.1. The applicability of anthraco-typology to Aleppo pine archaeological charcoal fragments*

16 Considering the results of the referential dendrochronological model, we can see that the  
17 applicability of the dendro-anthracological parameters and tools and the anthraco-typology  
18 principles offer a relevant opportunity to better interrogate the Aleppo pine archaeological charcoal  
19 fragments to identify past uses of this tree.

20 The charcoal-pith distance measurements and results, expressed as the occurrence of different  
21 diameters classes, provides a general picture of wood diameters exploited in the past for a given  
22 charcoal assemblage. The occurrence of big diameter classes indicates the presence of medium/big  
23 wood logs, while the ADmodel helps identify the possible underrepresentation of small diameter  
24 classes (section 3.3, Figure 7a). In any case, as the original provenance of small diameter classes  
25 cannot be established solely using the charcoal-pith distance, as they can represent both branches  
26 and/or the internal part of bigger trunks, it needs to be considered alongside other proxies.

27 Radial growth, which can be modelled using modern dendrochronological datasets, has therefore  
28 been established as a parallel proxy to distinguish between trunk and branch exploitation. As  
29 previously mentioned (section 4.1), the growth trends of trunks and branches differs significantly,  
30 with a clear threshold emerging from the referential dataset, showing that branch growth is  $<$ 1.5  
31 mm and trunk growth is  $>$ 1.5 mm (Figure 6).

32 This differential radial growth in trunk and branches, together with the distinction between both tree  
33 organs of 7 cm diameter (Figure 5b), allows the application of anthraco-typological principles to  
34 Aleppo pine charcoal fragments. Combining both proxies and considering the referential model, the  
35 results of the dendro-anthracological measurements of charcoal fragments can be organised into

1 four anthraco-groups for each assemblage (section 3.2, Figure 8). Accordingly, the measurement of  
2 dendro-anthracological parameters (charcoal-pith distance and ring width) and their subsequent  
3 organisation into anthraco-typological groups allows us to distinguish past pinewood exploitation  
4 models.

5

#### 6 *4.2.2. Anthraco-typology applied to archaeological charcoal assemblages: characterisation of* 7 *pinewood exploitation in prehistoric and protohistoric sites in Mallorca*

8 Dendro-anthracological parameters (charcoal-pith distance and ring width) were measured in  
9 Aleppo pine charcoal fragments from five prehistoric and protohistoric sites in Mallorca (Table 2).  
10 The results, according to the different anthraco-groups, allowed the management practices of  
11 Aleppo pine to be proposed for specific archaeological contexts. In Building 51 (Ses Païsses),  
12 anthraco-group 1 (corresponding to a small diameter <7 cm and slow growth <1.5 mm, representing  
13 branches) was predominant in both assemblages, corresponding to the habitat layer and the fallen  
14 roof after the fire event (Figure 8). Accordingly, pine branches constitute a relevant part of the  
15 charcoal assemblage in these contexts and would have been used as firewood to provide light and  
16 calorific energy to the activities carried out there. Anthraco-groups 3 (large diameter >7 cm and  
17 slow growth <1.5 mm, representing the external part of mature trunks) and 4 (large diameter >7 cm  
18 and fast growth >1.5 mm, also representing the external part of mature trunks) presented minor  
19 values in both assemblages. However, anthraco-group 2 (small diameter <7 cm and fast growth  
20 >1.5 mm, representing both branches and/or the internal part of mature trunks) presented important  
21 values in the fallen roof level (being also present, but with inferior values, in the habitat layer). In  
22 order to distinguish if these fragments of anthraco-group 2 corresponded to internal parts of bigger  
23 trunks and/or to small branches, ring width was analysed.

24 The mean ring width of the charcoal fragments measured for anthraco-groups 2 and 4 in these two  
25 assemblages was well above the 1.5 mm threshold (around 2.5 mm, Figure 9). This fact, together  
26 with the documentation of some fragments of anthraco-group 4 in the roof layer, suggests that  
27 trunks could have been used as firewood or as constructive timber. The fact that anthraco-group 4 is  
28 only present in the roof layer and that the values of anthraco-group 2 are higher here, suggests that  
29 trunks would have been used as construction timber, burnt after the fire event that destroyed the  
30 building, rather than as fuel (which, in the case of pine, would focus on branches).

31

32 *Figure 9: Mean and whisker plot of the ring widths measured on the charcoal fragments for each*  
33 *anthraco-group: a) Building 51 in Ses Païsses (left: fallen roof level; right:habitat layer); b) Na*  
34 *Galera.*

35

1 The anthracological assemblages of Building 25 (Ses Païsses) and Talaiot 3 (Son Fornés) present  
2 different anthraco-typological results (Figure 8). Both assemblages are characterised by the  
3 predominance of anthraco-groups 2 and 4. Anthraco-group 1 is also documented in both  
4 assemblages, especially in Building 25. This result suggests the exploitation of both small woods  
5 and larger trunks (especially with fast growth), indicating the use of all tree organs. This could  
6 represent the cutting down of pines, but it is not possible to confirm that both organs came from the  
7 same trees.

8 In the case of Building 25, where no fire event was detected, the anthracological assemblage  
9 represents fuel consumption debris, probably linked to metallurgical activities (Aramburu 2009;  
10 Picornell-Gelabert and Carrión 2017). These results suggest that Late Iron Age groups in Mallorca  
11 were cutting down pines to fulfil the significant fuel demands of industrial activities, such as  
12 metallurgy.

13 In the case of Talaiot 3, the presence of charcoal fragments derived from the burning of trunks also  
14 represents the use of this tree as construction timber. The assemblage was generated after a fire  
15 event that ended with the collapse of this monumental tower-shaped building, in which wooden  
16 beams burnt down and fragmented into charcoal pieces. This indicates that during the Late Iron Age  
17 pine populations on the island would have also been affected by the cutting down of individual trees  
18 to provide timber.

19 Finally, the anthraco-typology of Na Galera shows a clear predominance of small diameter and slow  
20 growth fragments (anthraco-group 1, Figure 8), originating from branches. The occurrence of  
21 fragments with diameters larger than 7 cm and fast growth (anthraco-group 4) is minor and does not  
22 suggest relevant presence of trunks in the assemblage. However, anthraco-group 2 presents  
23 important values and could represent both branches and/or the internal part of trunks. In this case,  
24 the average ring width of the charcoal fragments from anthraco-group 2 were just slightly above 2  
25 mm (Figure 9), so do not indicate the recurrent presence of fragments from the internal part of  
26 mature trunks, as detected in the roof layer of Building 51 in Ses Païsses (Figure 9). Accordingly, it  
27 can be suggested that most of the fragments anthraco-group 2, as well as those of the predominant  
28 anthraco-group 1, represent the use of branches. These branches would have been used to fulfil the  
29 fuel demands of the diverse activities carried out in this Late Iron Age ceremonial building. This  
30 fuel debris was then deposited in the cistern, which had been repurposed as a dump during 1<sup>st</sup>  
31 century AD.

32 However, some of the fragments from anthraco-group 2 and a few from anthraco-group 4 may  
33 represent pieces of larger trunks. Considering that the assemblage originates from the use of a dump  
34 over a relatively long period of time (secondary position), it is difficult to assess the origin of the  
35 charcoal fragments. During the excavation of the dump, the discovery of large charcoal fragments,

1 with a similar chronology to those of the ceremonial building, suggest that this assemblage  
2 represents the debris of burnt timber removed during cleaning. Therefore, even if some of the  
3 fragments derive from large trunks, they probably represent the timber elements of the building  
4 destroyed by the fire (Arqueover 2016). The debris from the destruction of the main building could  
5 therefore also have been discarded in the same dump. However, the fact that big articulated charcoal  
6 fragments were detected during the excavation of the pit, together with the clear predominance of  
7 branch exploitation attested by anthraco-typology, suggests that fuel debris was cleaned on a  
8 frequent basis and that once deposited in the pit charcoal suffered little mechanical disturbance.  
9 Moreover, the fact that most of the wood used is so uniform, does not allow us to rule out the use of  
10 branches for the construction of specific structures (e.g. trusses, palisades, roofs). These results,  
11 however, undoubtedly lead us to review the context and the initial association with timber attributed  
12 to this charcoal assemblage. The evidence of metallurgical activity carried out on the Na Galera  
13 islet during the Punic period (thanks to the discovery of iron slag and a foundry mold), may also  
14 explain the need for fuel of a specific caliber (Guerrero 1981, 2003); but, there is no a clear  
15 association with these metallurgical activities and the studied materials from the dump.

16

## 17 **5. Conclusions**

18 This study shows that the anthraco-typology approach created for temperate angiosperms with ring-  
19 porous wood anatomy (*Quercus petraea/robur*, Dufraisse et al. 2018a) is applicable to  
20 Mediterranean gymnosperms (*Pinus halepensis*), provided that an appropriate dendrochronological  
21 referential is built. The combination of diverse dendro-anthracological parameters (diameter and  
22 growth) measurable with dendro-anthracological tools and the adjustment of the anthraco-typology  
23 principles to gymnosperms wood anatomy (due to the heartwood–sapwood distinction tool not  
24 being applicable) allowed us to interrogate the anthracological assemblages beyond taxonomical  
25 identification and to characterise diverse pinewood exploitation strategies.

26 The model is based in the fact that charcoal-pith distance cannot single-handedly distinguish  
27 between the charcoal fragments derived from trunks or branches. Large diameter classes correspond  
28 to mature woods or trunks, but fragments with small diameter classes can stem from both branches  
29 and trunks. Radial growth has therefore been proposed as a complementary proxy to distinguish  
30 between them for the smaller diameter classes measured in an archaeological charcoal assemblage.  
31 The modern dendrochronological dataset has allowed us to i) identify differential radial growth  
32 rates for both organs of the same tree with the same cambial age; ii) prove that this is also  
33 applicable when replacing cambial age for diameter classes; iii) establish a threshold dividing slow  
34 (<1.5 mm) from fast (>1.5 mm) radial growth; and to iv) model differential growth rates for both  
35 branches (< 7 cm diameter) and trunks (>7 cm diameter).

1 The combination of both parameters, according to the anthraco-typological principles, allowed us to  
2 establish four different anthraco-groups, characterising the exploitation of trunks and branches after  
3 the dendro-anthracological analysis of Aleppo pine archaeological charcoal fragments. This study,  
4 therefore, confirms that the development of dendrochronological referential datasets for different  
5 species and regions is needed to adapt the anthraco-typological principles to every tree species.

6 Accordingly, the application of the anthraco-groups, defined after the referential dataset, to five  
7 different archaeological assemblages in which dendro-anthracological parameters were measured,  
8 has allowed the different pinewood management practices in prehistoric and protohistoric sites of  
9 Mallorca to be defined. In Building 51 (Ses Païsses), the dendro-anthracological analysis has  
10 confirmed that, even if the assemblage was formed after a fire event that affected the entire  
11 building, most of the charcoal fragments from the occupation layer correspond to branches that  
12 would have been used as fuel. However, the results obtained from the roof layer highlight the  
13 presence of trunk fragments that may represent the use of pine as constructive timber (burnt and  
14 fragmented after the fire event). In this sense, the dendro-anthracological study suggests a possible  
15 diverse origin of the pine charcoal fragments from the two different layers: one corresponding to the  
16 occupation and the other to the fallen roof after the fire. This information complements the  
17 interpretation of the formation of the deposit made by the excavators (differentiation in the sub-  
18 layers, fallen roof and occupation layer).

19 The use of pine trunks as constructive timber seems clear during the Late Iron Age phase of Talaiot  
20 3 in Son Fornés. Even though during the excavation of the fire destruction layers no pine beams  
21 and/or other wooden architectural elements were detected, dendro-anthracological analysis of the  
22 charcoal assemblage of this layer shows a clear predominance of fragments derived from the  
23 burning of pine trunks.

24 A similar anthraco-typological diagram was detected in Building 25 (Ses Païsses), where evidence  
25 of metallurgical production was identified. In this case, the charcoal fragments must have originated  
26 from the use of wood as fuel, as no evidence of a fire event was detected during excavation. In this  
27 sense, the identification of charcoal fragments deriving from pine trunks suggests that the Late Iron  
28 Age populations of Mallorca cut down trees to fulfil specific energetic demands for various  
29 activities, such as metallurgical production.

30 Finally, dendro-anthracological analysis of the charcoal assemblage from the Na Galera dump  
31 allowed us to discriminate the different origins of the charcoal fragments deposited here during a  
32 relatively long period of time in the the 1<sup>st</sup> century AD. Most of the assemblage is composed of  
33 fragments deriving from small branches, used as firewood, the debris of which would have been  
34 cleaned up and deposited in the dump. However, part of the assemblage could derive from larger  
35 trunks, suggesting that another kind of charcoal debris was deposited in the same place.

1

2 The measurement of these dendro-anthracological parameters and the treatment of the results  
3 according to anthraco-typological principles, allowed us to analyse the archaeological charcoal  
4 fragments beyond their taxonomical identification. The anthraco-typological characterisation of the  
5 charcoal fragments of Aleppo pine enabled us to obtain valuable information to better interpret both  
6 the formation of the anthracological assemblages and past human behaviour (pinewood  
7 management practices). Anthraco-typology, therefore, constitutes a relevant tool to ascertain the  
8 origin, homogeneous or diverse, of charcoal fragments forming an anthracological assemblage after  
9 a destructive fire, where the potential burning and fragmentation of timber may occur (distinguished  
10 by the presence/absence of timber and/or firewood in an assemblage), as seen in Building 51 (Ses  
11 Païsses). In this case, the possibility to characterise the presence/absence of firewood and/or timber  
12 remains allows us to explain the formation of the archaeological layers and identify different wood  
13 uses for the same species. A similar case was described at Talaiot 3 (Son Fornés), where the  
14 anthraco-typological analysis shows that timber elements were burnt down and fragmented during  
15 the fire that destroyed the building.

16 Moreover, in secondary deposits, it is difficult to assess the original use (or uses) of the wood that  
17 generated the charcoal fragments. In the case of the dump at Na Galera, anthraco-typology suggests  
18 two potentially different origins for the pine charcoal fragment assemblage: firewood debris  
19 deposited after the cleaning of the hearth, and charcoal fragments derived from the burnt and  
20 fragmented timber from a neighbouring building destroyed by fire.

21 Finally, the anthraco-typological analysis has also allowed us to identify relevant forest  
22 management practices in relation to the energetic demands of prehistoric societies, which are not  
23 possible to identify solely after the taxonomical identification of charcoal fragments. In Building 25  
24 (Ses Païsses), where evidence of metallurgical activity was detected, a recurrent use of pine trunks  
25 as firewood was identified. This suggests that, during the Late Iron Age, the specific fuel demand  
26 generated by industrial activities, such as metalworking, would often lead to the cutting down of  
27 pine trees to provide firewood. Identifying the forest management practices of prehistoric societies  
28 enlarges the scope of the charcoal record regarding socio-environmental practices, natural resources  
29 management and human impact on forest ecosystems.

30 Finally, it is important to note that after dendrochronological reference datasets and the testing of  
31 applicability of anthraco-typology, further studies look to improve the interrogation of the  
32 anthracological record. The development of dendro-anthracological datasets will allow us to  
33 interrogate the impact of wood exploitation on past woodlands and offer new insights to identify  
34 more suitable fragments for anthraco-climatic analyses (or select the most reliable charcoal  
35 fragments for isotopic analysis) contributing to the future development of archaeological wood

1 charcoal analysis.

2

3

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23

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Site	Location			Altitude m.a.s.l.	Slope and orientation	Bioclimatology	Average annual precipitation (ml)	Forest formation	Trees sampled			Average diameter (with standard deviation)		
	Quadrant	X	Y						Average annual precipitation (ml)	Trunks only	Trunks + branches	Period represented	Average tree's age	Trunks: Average diameter at breast height (DBH)
Caimari	31S	490764	4404219	324-370	Flat	Messomediterranean subhumid	696	Aleppo pine and holm oak ( <i>Quercus ilex</i> ) forest colonizing ancient olive terraces	13	5	1888-2017	84,7	37,9 (12,9) cm	Small: 1,6 (0,7) cm / Medium: 2,9 (0,9) cm / Large: 6,0 (1,6) cm
Binissalem	31S	487856	4392904	120-147	Flat	Thermomediterranean dry	440	Aleppo pine plantation	13	0	1914-2011	88,2	38,0 (7,0) cm	No branches sampled
Cap Salines	31S	504662	4346360	8-12	Flat	Thermomediterranean semiarid	236	Coastal macchia with pine and Phoenician juniper ( <i>Juniperus phoenicea</i> )	12	5	1890-2017	106,6	24,3 (5,3) cm	Small: 1,3 (0,2) cm / Medium: 2,9 (0,8) cm / Large: 5,6 (0,9) cm
Comuna Lloret	31S	496626	4385222	139-142	Flat	Thermomediterranean dry	487	Macchia with Aleppo pine	0	5	1972-2017	40,6	30,7 (6,9) cm	Small: 1,1 (0,3) cm / Medium: 2,8 (0,7) cm / Large: 5,6 (0,8) cm

Table 1: Description of the forest stations sampled for the referential dendrological study

Sample name	Site	Type of site	Building	Chronology	Type of building	Type of assemblage	Archaeological context	Abandonment after a fire event	Total n° of fragments identified	N° of <i>Pinus halepensis</i> fragments identified	N° of fragments measured	N° of rings measured	References
Ses Païsses 51 – Roof	Ses Païsses	Village	51, Phase 2	1000-850 cal. BC	Small building attached to the central turriform of the site	Dispersed charcoal fragments	Layer corresponding to the fallen roof of the building after a fire event	Yes	568	221 (corresponding to the 38,91% of the total assemblage)	109	373	Picornell-Gelabert 2012; Picornell-Gelabert and Carrión Marco 2017
Ses Païsses 51 – Roof	Ses Païsses	Village	51, Phase 2	1000-850 cal. BC	Small building attached to the central turriform of the site	Dispersed charcoal fragments	Layer corresponding to the occupation of the building during this phase	Yes	243	85 (corresponding to the 34,98% of the total assemblage)	61	313	
Ses Païsses 25	Ses Païsses	Village	25, Phase 2	350-200 cal. BC	Domestic building with evidences of metalworking	Dispersed charcoal fragments	Layer corresponding to the occupation of the building during this phase	No	1202	216 (corresponding to the 17,97% of the total assemblage)	74	135	
Son Fornés Talaiot 3	Son Fornés	Village	Talaiot 3	IV-III century BC	Megalithic tower-shaped building of ceremonial public use	Dispersed charcoal fragments	Layer corresponding to the last use and collapse of the building	Yes	1579	201 (corresponding to the 12,73% of the total assemblage)	78	274	Picornell-Gelabert 2012; Picornell-Gelabert and Dufraisse 2018
Na Galera	Na Galera	Ceremonial complex in an small isled in front of the seachore of Mallorca	Cistem (EU160)	1 <sup>st</sup> Century AD	Cistem attached to a ceremonial building	Secondary deposition of charcoal fragments	Cistem reused as dump pith	No	329	119 (corresponding to the 36,17% of the total assemblage)	93	504	This study

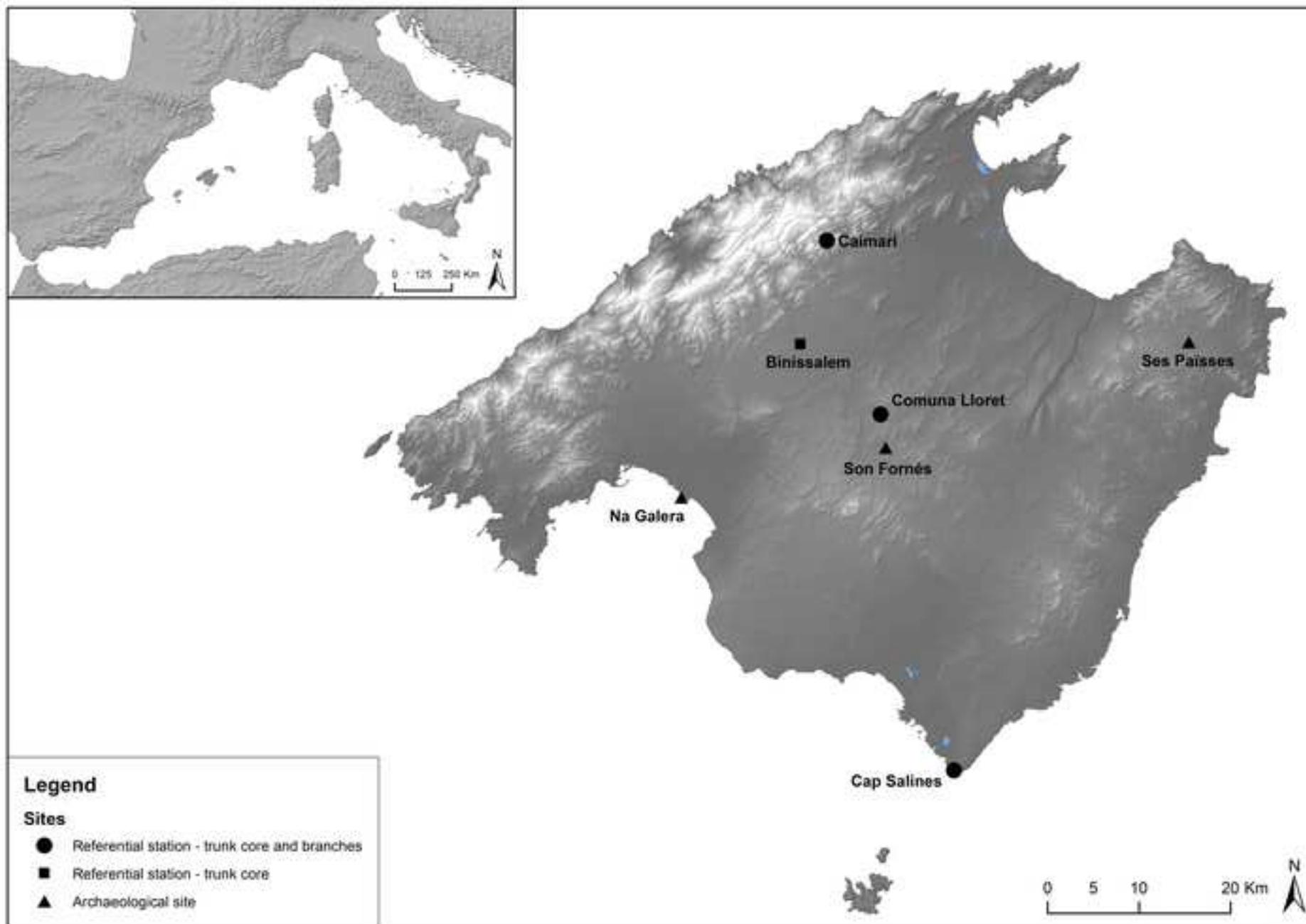
Table 2: Description of the archaeological charcoal assemblages analysed

<i>PITH- LOCATION TOOL</i>	Galera			Ses Païsses									S. Fornés		
	SU160			51-Roof			51-Habitat			Ed. 25			Talaiot 3		
<b>Dalculated diameter classes</b>	<b>n</b>	<b>%</b>	<b>% Admodel</b>	<b>n</b>	<b>%</b>	<b>% Admodel</b>	<b>n</b>	<b>%</b>	<b>% Admodel</b>	<b>n</b>	<b>%</b>	<b>% Admodel</b>	<b>n</b>	<b>%</b>	<b>% Admodel</b>
1_]0-2]cm	36.00	38.71	23.88	34.00	31.19	17.17	13.00	21.31	3.57	11.00	14.86	3.74	7.00	8.97	0.00
2_]2-4]cm	41.00	44.09	52.74	46.00	42.20	47.47	32.00	52.46	59.69	25.00	33.78	29.95	22.00	28.21	24.04
3_]4-7] cm	11.00	11.83	14.43	20.00	18.35	22.73	14.00	22.95	33.16	26.00	35.14	47.59	25.00	32.05	33.33
4_]7-10] cm	3.00	3.23	4.98	5.00	4.59	7.07	1.00	1.64	1.53	6.00	8.11	10.70	14.00	17.95	29.51
5_]10-14] cm	1.00	1.08	1.99	2.00	1.83	2.02	1.00	1.64	2.04	4.00	5.41	2.14	6.00	7.69	2.19
6_]14-20] cm	1.00	1.08	1.99	2.00	1.83	3.54	0.00	0.00	0.00	2.00	2.70	5.88	4.00	5.13	10.93
7_]>20 cm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>93.00</b>	<b>100.00</b>	<b>100.00</b>	<b>109.00</b>	<b>100.00</b>	<b>100.00</b>	<b>61.00</b>	<b>100.00</b>	<b>100.00</b>	<b>74.00</b>	<b>100.00</b>	<b>100.00</b>	<b>78.00</b>	<b>100.00</b>	<b>100.00</b>

Table 3: Results of the charcoal-pith distance measurements expressed by diameter classes and modelled according to the ADmodel.

<b>Anthraco- group</b>	<b>Galera</b>		<b>Ses Païsses</b>						<b>Son Fornés</b>		
	<b>SU160</b>		<b>51-Roof</b>		<b>51-Habitat</b>		<b>Ed. 25</b>		<b>Talaiot 3</b>		
	<b>n</b>	<b>%</b>	<b>n</b>	<b>%</b>	<b>n</b>	<b>%</b>	<b>n</b>	<b>%</b>	<b>n</b>	<b>%</b>	
<b>1</b>	58	62.37	53	48.62	44	72.13	16	21.62	10	12.82	
<b>2</b>	30	32.26	47	43.12	15	24.59	46	62.16	44	56.41	
<b>3</b>	1	1.08	4	3.67	2	3.28	2	2.70	6	7.69	
<b>4</b>	4	4.30	5	4.59			0	10	13.51	18	23.08
<b>Total frags.</b>	<b>93</b>	<b>100</b>	<b>109</b>	<b>100</b>	<b>61</b>	<b>100</b>	<b>74</b>	<b>100</b>	<b>78</b>	<b>100</b>	

Table 4: Results of the dendro-anthracological parameters measured on Aleppo pine archaeological charcoal assemblages (projected diameter classes and average ring width) according to anthraco-typology principles.



# DENDRO-ANTHRACOLOGICAL PARAMETERS AND TOOLS

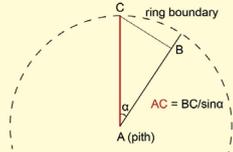
## Dendro-anthracological parameters

Charcoal-pith distance



## Morpho-anatomical criteria

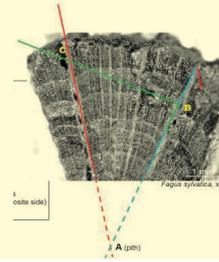
Distance and angle between ligneous rays



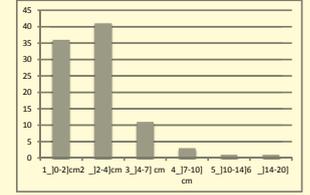
$\alpha$  : angle between 2 ligneous rays  
 BC : distance between 2 ligneous rays  
 AC : pith-charcoal distance

## Tool

Image analysis Macroscope



## Numerical and graphic expression



Radial growth



Tree-ring width

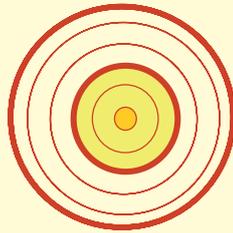
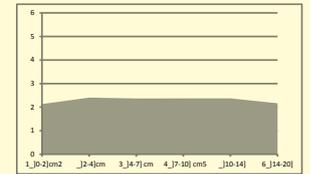


Image analysis Macroscope

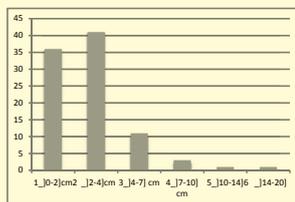


# COMBINED ANALYSIS OF DENDRO-ANTHRACOLOGICAL PARAMETERS

## ANTHRACO-TYOLOGY

### Dendro-anthracological parameters and criteria

Charcoal-pith distance  
 Diameter estimation

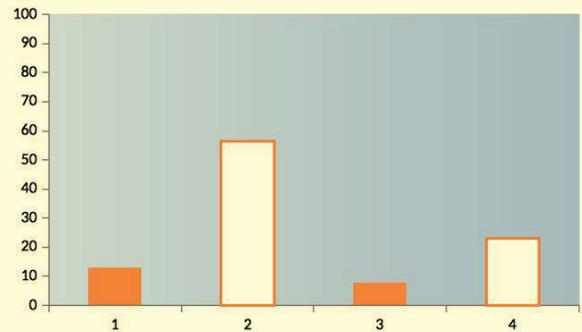


### Data organization and interpretation

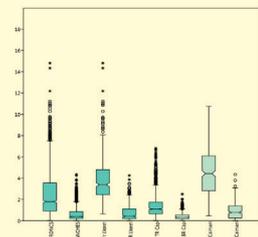
Diameter classes  
 Based on foresters systematisation

### Combination of parametrs Graphic expression

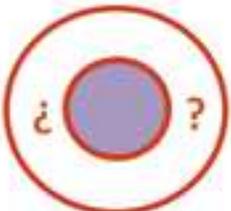
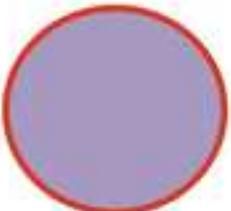
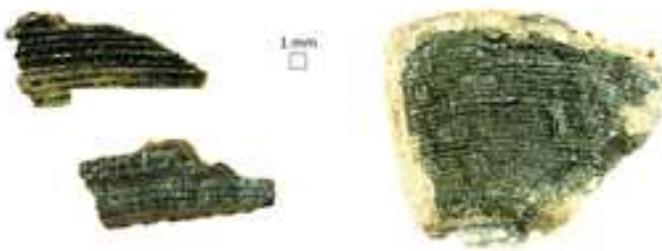
Anthraco-groups  
 Diameter and ring width



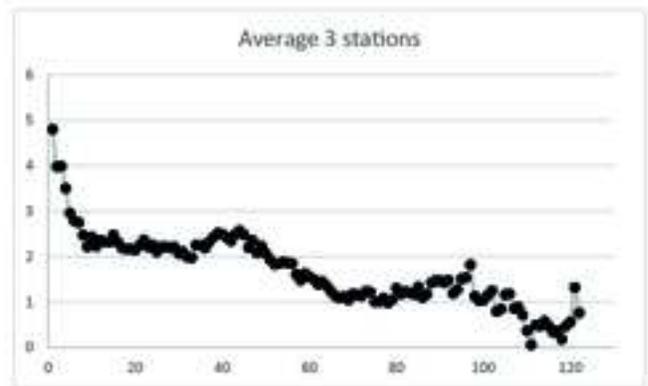
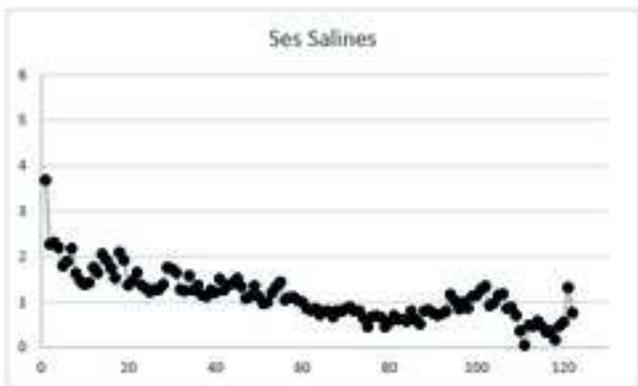
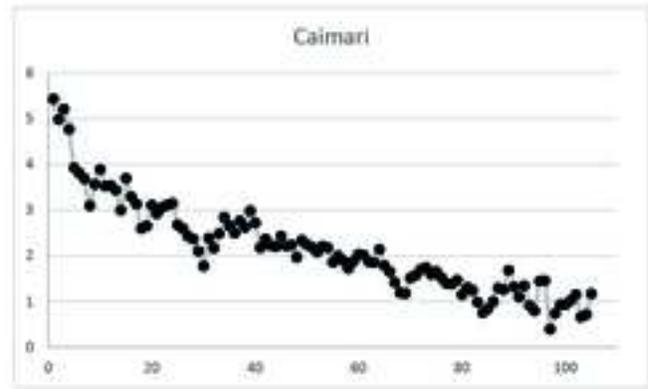
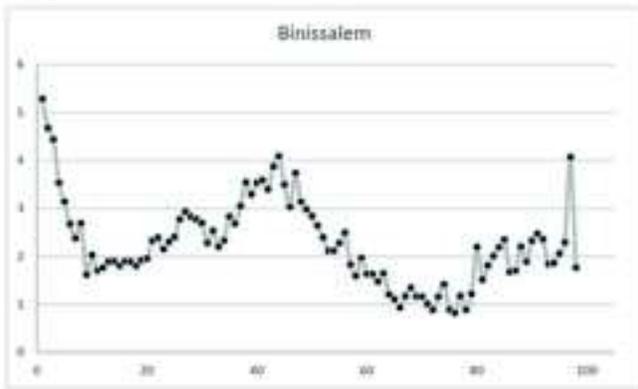
Radial growth  
 Tree-ring width



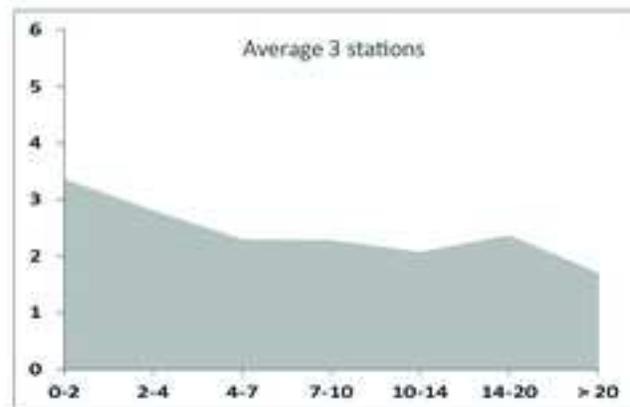
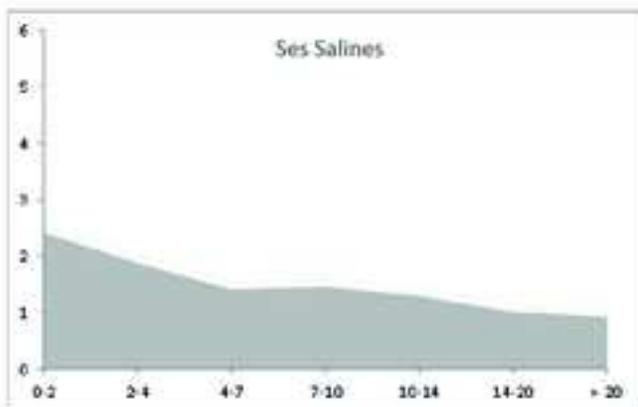
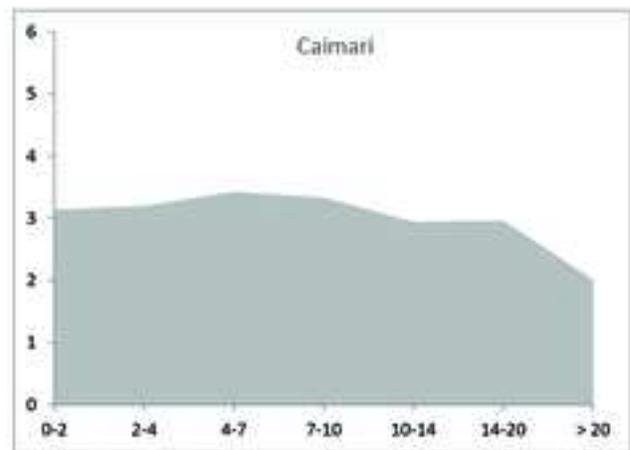
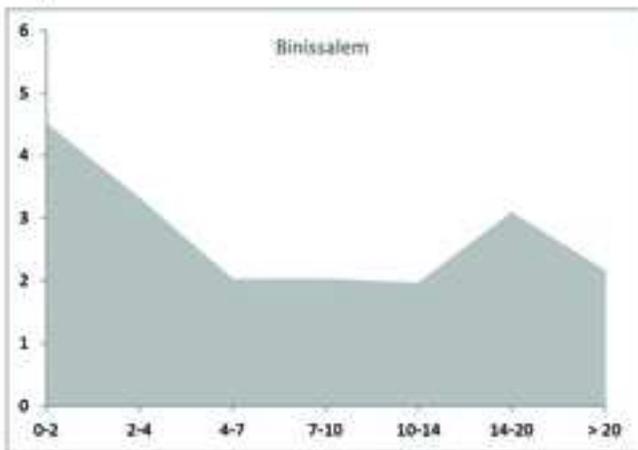
Fast and slow growth  
 Based on referential model

Charcoal-pith distance	Tree-ring width	Anthraco - groups	Charcoal fragments
Diameter < 7 	Narrow rings < 1,5 mm  (slow growth)	1 	
	Large rings > 1,5 mm  (fast growth)	2 	
Diameter < 7 	Narrow rings < 1,5 mm  (slow growth)	3 	
	Large rings > 1,5 mm  (fast growth)	4 	

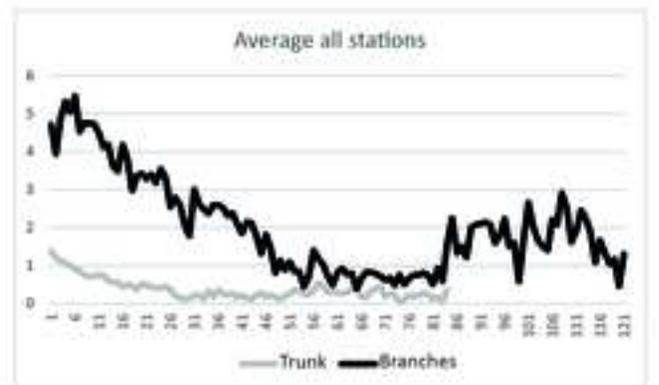
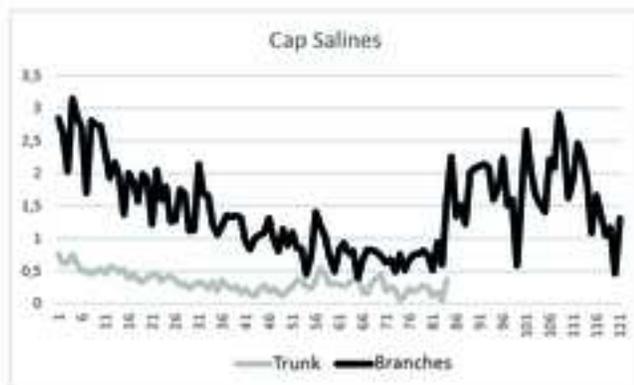
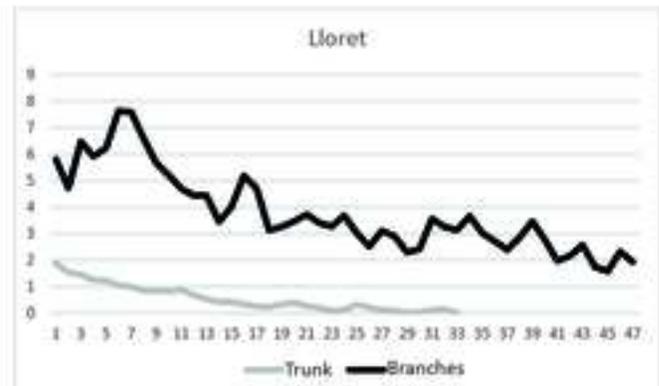
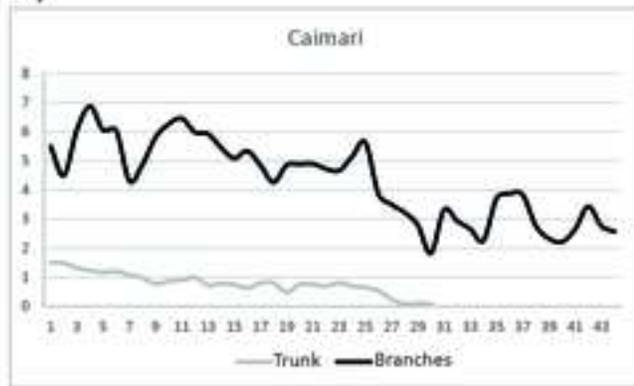
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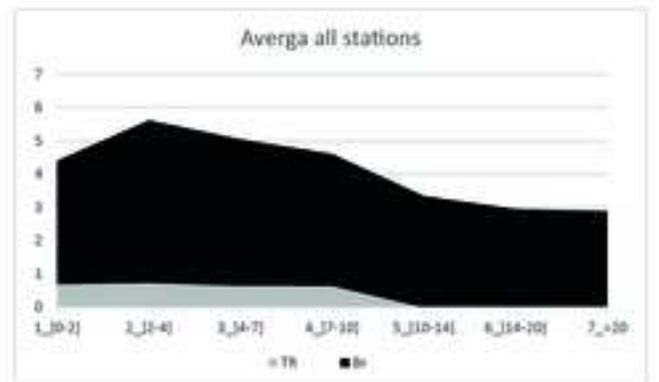
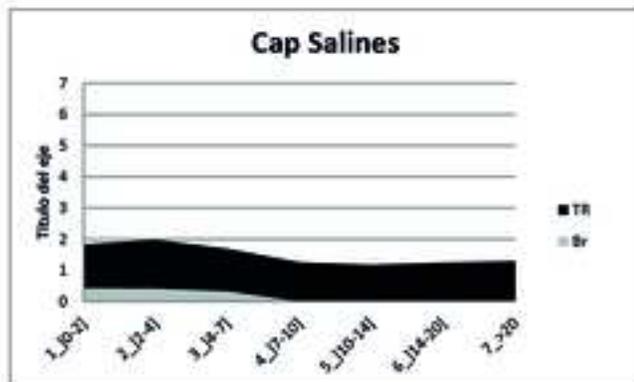
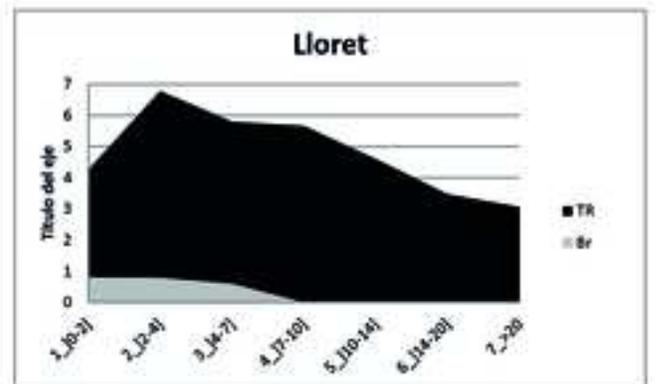
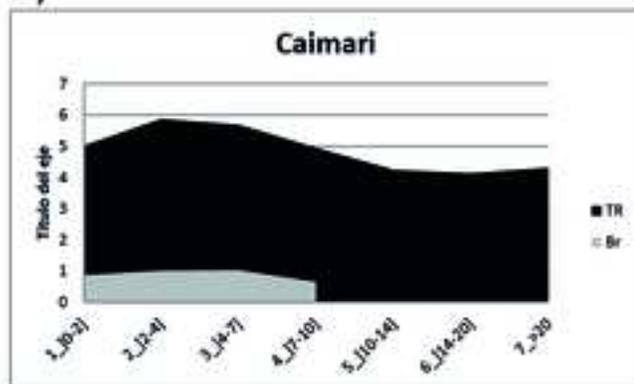
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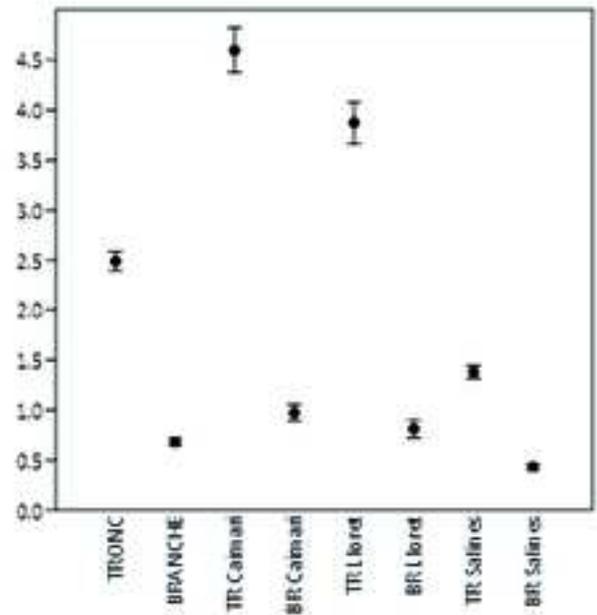
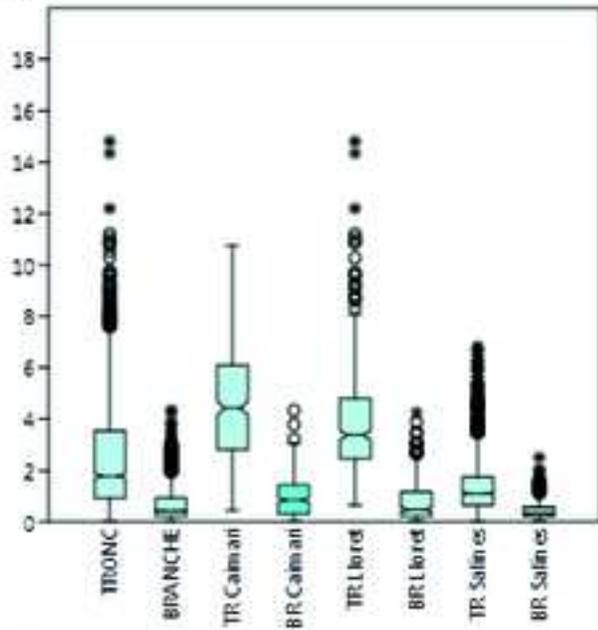
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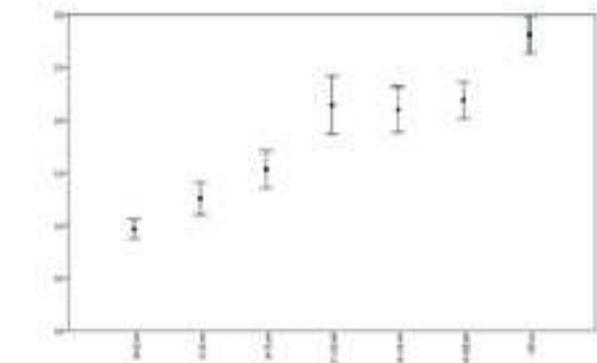
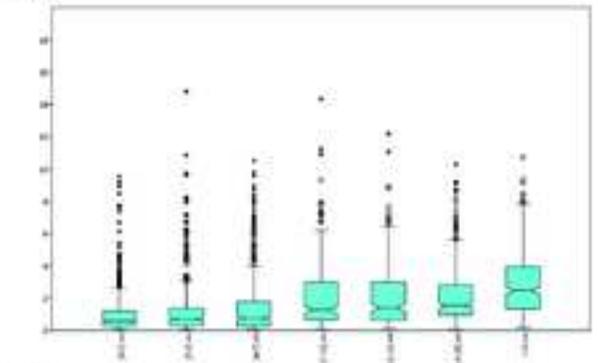
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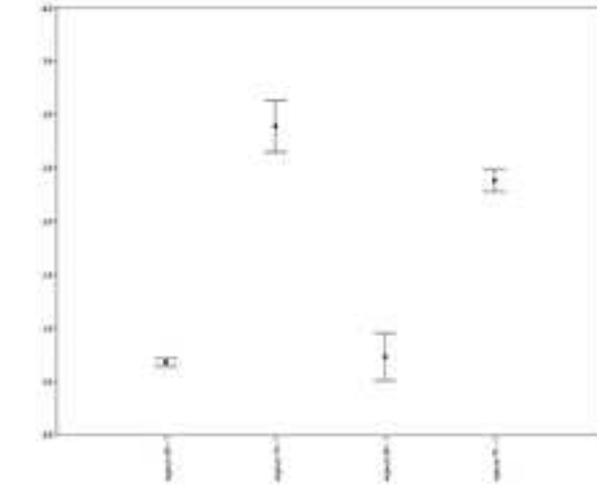
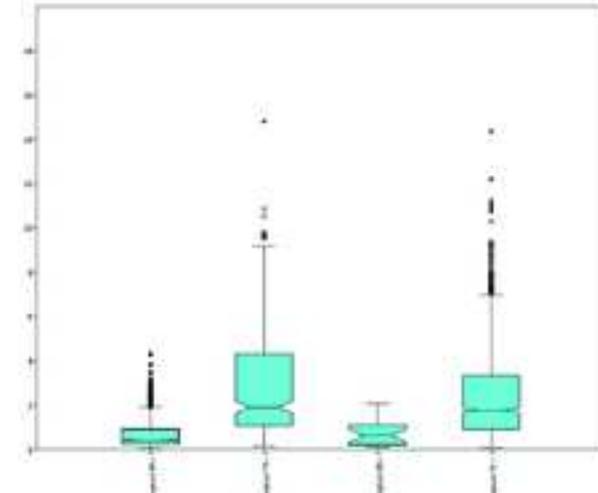
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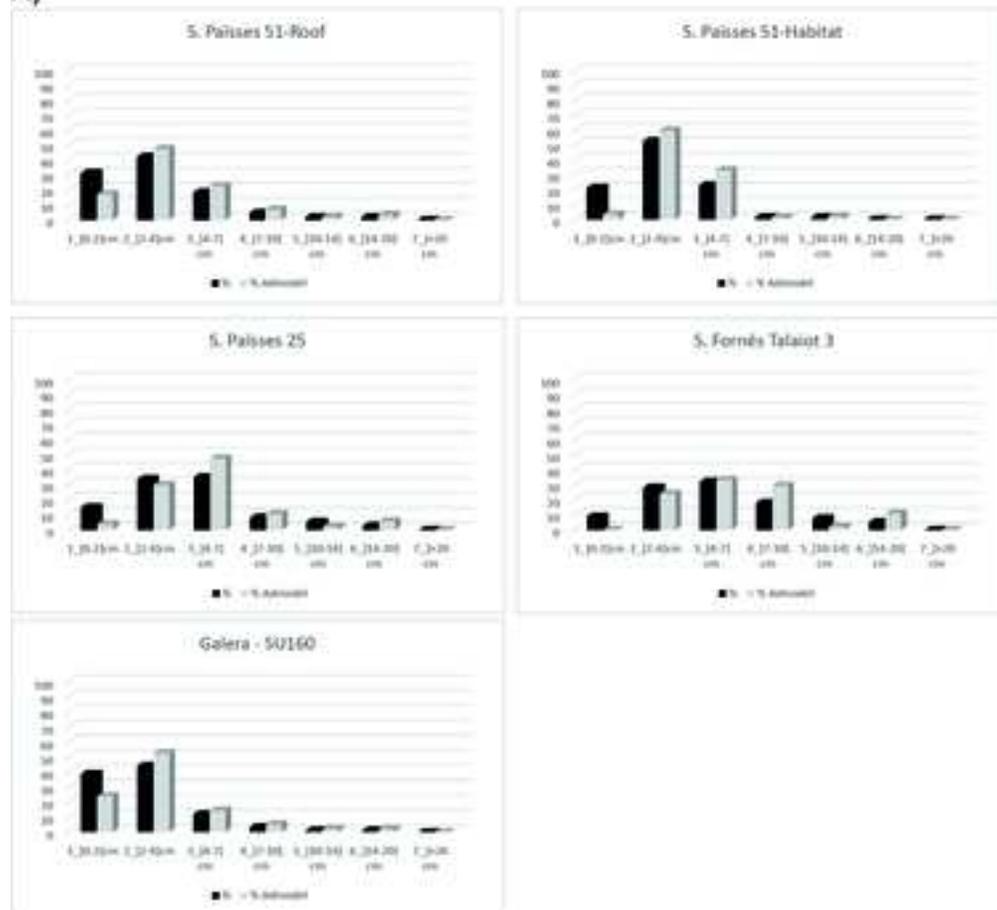
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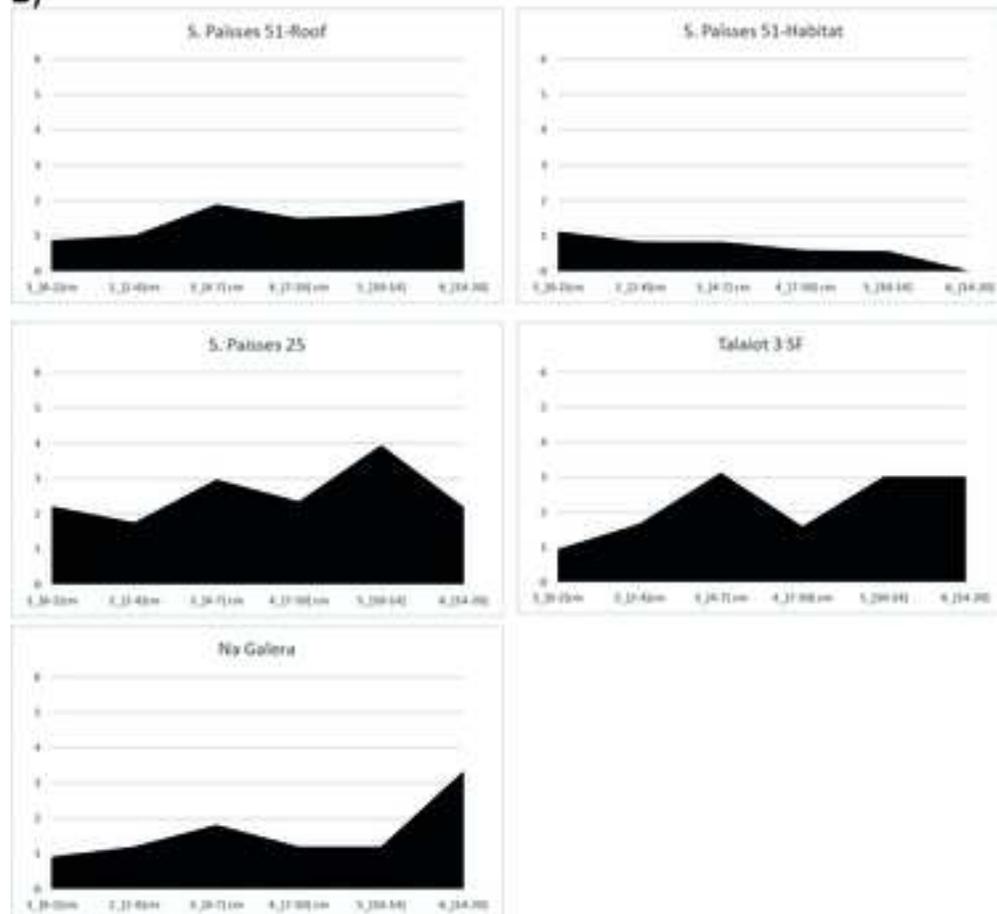
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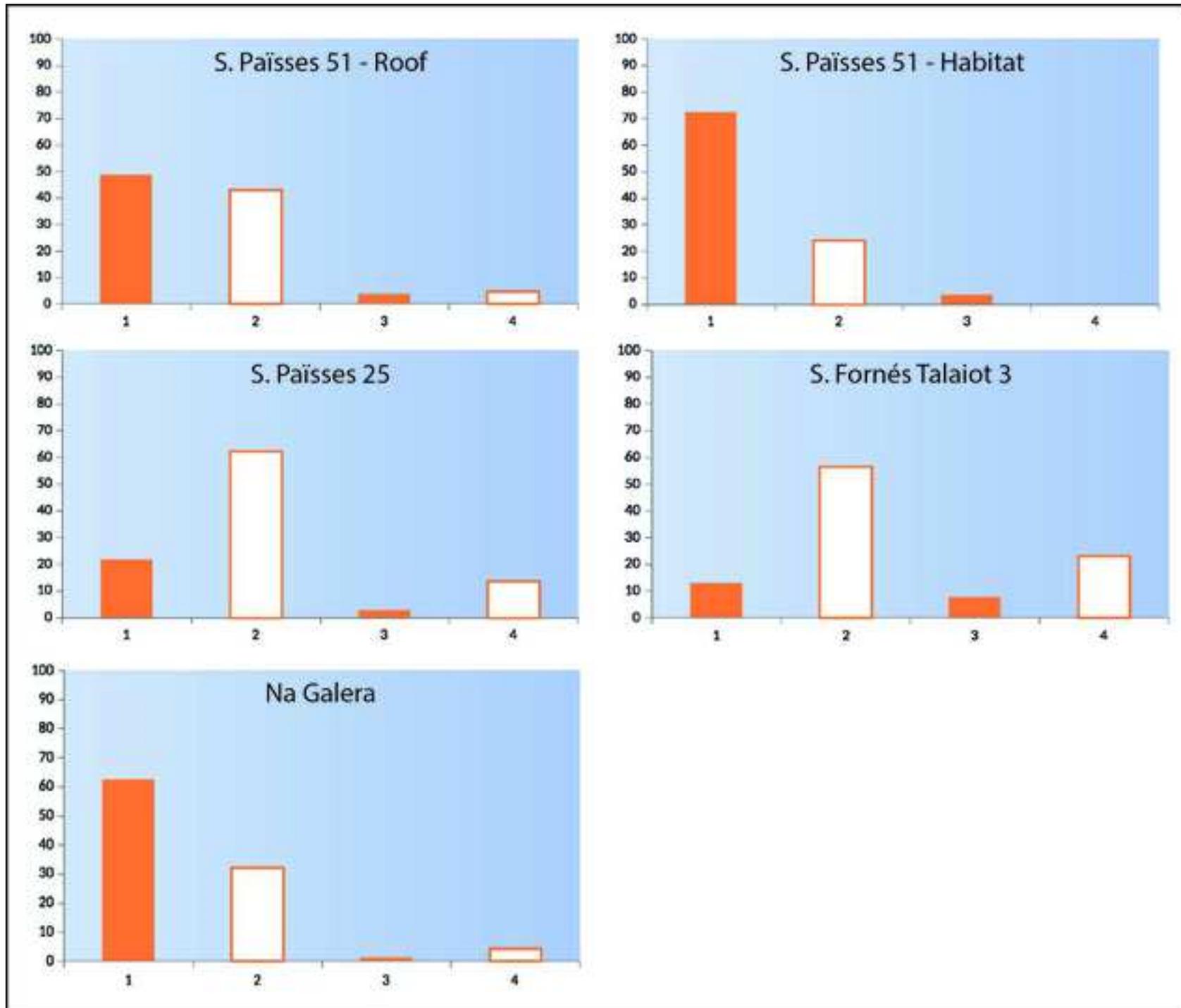


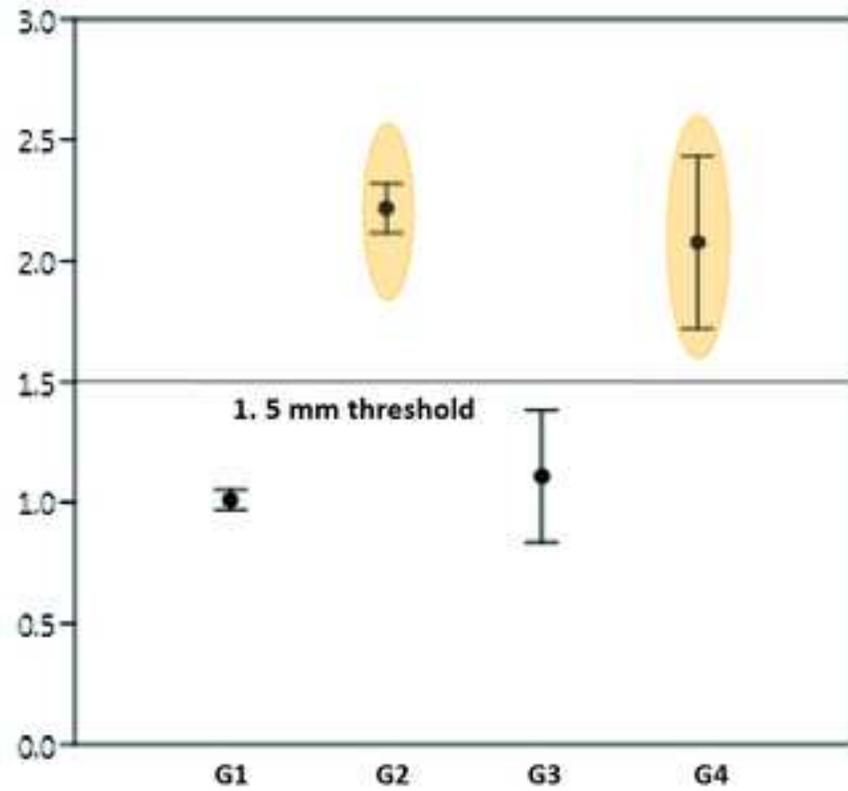
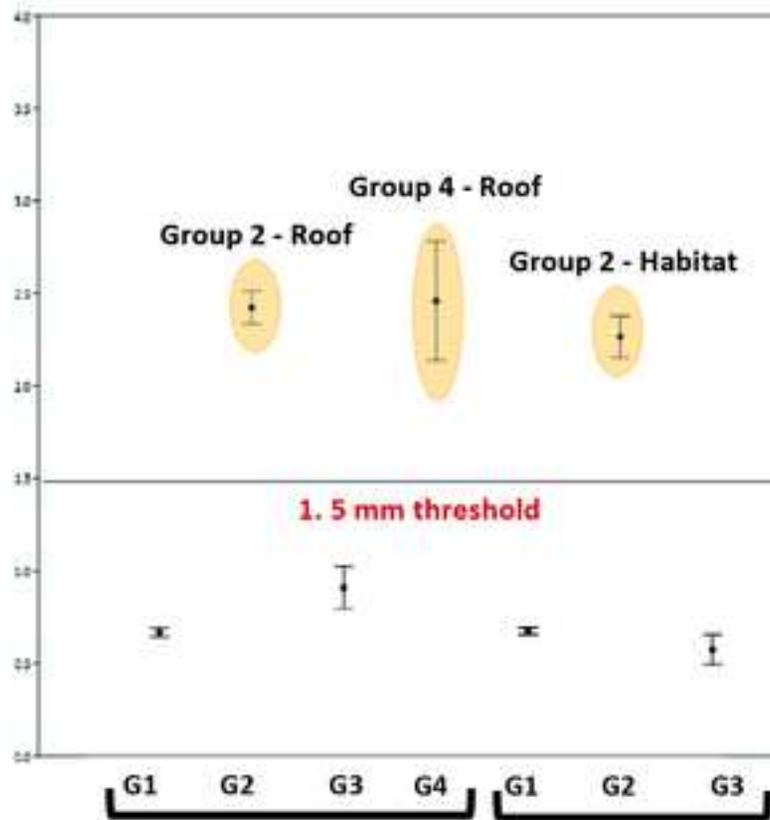
A)



B)







Palma, Balearic Islands, Spain

17<sup>th</sup> June 2020

**Declarations of interest: none.**

Dear editors,

We declare that there's no financial nor personal interest or belief that could affect the objectivity of our paper.

A handwritten signature in blue ink, appearing to be 'Llorenç Picornell-Gelabert', written over a horizontal line.

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

University of the Balearic Islands