



**Modelling date-palm ancient areas (*Phoenix* spp.,
Arecaceae): Bayesian analysis of biological and cultural
evidence**

Journal:	<i>Botanical Journal of the Linnean Society</i>
Manuscript ID	Draft
Manuscript Type:	Original Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Rivera, Diego; Universidad de Murcia, Biología Vegetal Abellan, Francisco-Javier; Universidad de Murcia, Física Palazon, Jose-Antonio; Universidad de Murcia, Ecología e Hidrología Obón, Concepción; Universidad Miguel Hernández, Biología Aplicada Alcaraz, Francisco; Universidad de Murcia, Biología Vegetal Carreño, Encarna; Universidad de Murcia, Biología Vegetal Laguna, Emilio; Generalitat Valenciana, CIEF ; Generalitat Valenciana, Service of Biodiversity Ruiz, Alberto; Universidad de Murcia, Departamento de Informática y Sistemas Johnson, Dennis
Keywords:	Africa < Geography, Europe < Geography, Asia < Geography, fossil evidence < Geology, seed morphology < Morphology, palaeogeographical distribution < Palaobotany, Phytogeography, Arecaceae < Taxa, Coryphoideae < Taxa, computer modelling < Techniques

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Modelling date-palm ancient areas (*Phoenix* spp., Arecaceae): Bayesian analysis of biological and cultural evidence

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Acknowledgements: Supported by INIA-MINECO projects RF2007-00010-C03, RF2010-00006-C02 and RFP2013-00004-00-00 (European Regional Development Fund 2007-2020); RFP2017-00004-00-00. We are grateful to Samson Katsipis of the Museum of Minerals & Fossils of the Cultural Society of Thira for his help with the study of Fira Paleosol fossils.

Author Contributions: D.R. designed the sampling and coordinated data analysis. F.A. performed cartography. C.O. performed data streaming. J.P., A.R. and J.A. contributed to the development of Bayesian models and wrote programs in R and Python. C.O., D.J., E.C. and E.L. contributed to the discussion and revised different versions of the text.

Authors Information: No competing financial interests. Correspondence and requests for materials should be addressed to rivera@um.es.

Short running title: Modelling *Phoenix* palm ancient areas

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Abstract

The date palm (*Phoenix dactylifera* L.) yields food, medicines, and materials which are useful for building and handicrafts. Other *Phoenix* species present similar uses. Our aim is to build a model of *Phoenix* expansion that can be linked to domestication processes. Paleontological and archaeobotanical evidence concerning date palm is extremely diversified around the Mediterranean Basin and in West Asia, mainly consisting of date fruit remains, but also leaf fragments and other plant remains. This biological evidence is further compared with cultural evidence (coinages, pottery, ancient texts) and the present distribution of *Phoenix* spp. in the area.

Bayesian methods working with likelihood and conditional probabilities are successfully applied to generate a model for displaying in maps the ancient distribution of palm groves in terms of probabilities.

The model suggests the domestication of *Phoenix dactylifera* occurred mainly to the east of 30° E Long., and most likely in the Jordan Valley area, starting before 7 ka and, in a millenary westward shift, it was gradually superposed onto pre-existing local western populations of the same genus, especially in the Nile valley. It seems that this mainly affected the *Phoenix dactylifera* western cluster (*P. excelsior*, *P. atlantica*, *P. iberica*). However other persisted as independent species (*P. theophrasti*, *P. canariensis*).

Keywords: Archaeobotany; Bayes' theorem; Conditional probabilities; Date palm; Paleogeography; Paleontology; *Phoenix canariensis*; *Phoenix dactylifera*; *Phoenix theophrasti*.

INTRODUCTION

Phoenix is the single one genus within tribe Phoeniceae, subfamily Coryphoideae of Arecaceae (Baker & Dransfield, 2016; Dransfield *et al.*, 2005), and comprises between 13 and 20 species depending on the authors (Barrow, 1998; Beccari, 1890; Rivera *et al.*, 2014). *Phoenix* stands out among the most cold-tolerant palm genera being able to extend into temperate climates (Reichgelt *et al.*, 2018). Date palm (*Phoenix dactylifera* L.) yields food, medicines, and materials for buildings and crafts (Middle East, the Mediterranean and North Africa), it can grow in very hot and dry climates, and is relatively tolerant of salty and alkaline soils but requires abundant underground water near the surface or irrigation (Chao & Krueger, 2007; Rivera *et al.*, 2012). Areas climatically suitable for date palm cultivation may become over centuries unsuitable and vice versa according to different climate scenarios which can be modelled (Shabani *et al.*, 2012).

Regarding where and when *P. dactylifera* was domesticated, molecular, morphological and archaeological evidences show at least two main geographical groups (western and eastern) (Arabnezhad *et al.*, 2012; Chaluvadi *et al.*, 2018; Fuller, 2018; Hazzouri *et al.*, 2015; Mathew *et al.*, 2015; Pintaud *et al.*, 2013; Rivera *et al.*, 2014; Zehdi-Azouzi *et al.*, 2015). However there was detected a certain amount of mixture within these groups (Moussouni *et al.*, 2017; Zehdi-Azouzi *et al.*, 2015).

It would be highly useful to have a methodology for combining different types of evidence in order to assess the geography and chronology of this domestication event, considering the presence in part of the area of other *Phoenix* species.

In the beginning of crop geography Alphonse De Candolle (1885) determined the origin of cultivated plants and how their culture spread in different directions at successive epochs in terms of probabilities. With this purpose in mind De Candolle (1885) considered biological and cultural (historical, philological) evidence and stressed the necessity for combining the different methods, which are of unequal value. He gave major relevance to the recovery of biological remains in archaeological contexts and to the spontaneous presence in modern times of a species in a given country. Vavilov (1927) determined the centers of “type-formation” of cultivated species by exhaustively analyzing the distribution of diversity within each species and superposing this evidence. Using the same method superposing the evidence for numerous species Vavilov (1992) obtained a model for the universal centers of cultivated plants. Harlan (1971), followed a similar approach, but, using a broader range of evidence (historical, archaeological,

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3 genetic, etc.), strongly criticized the theory of “centers” and concluded that “crops did not necessarily
4 originate in centers (in any conventional concept of the term), nor did agriculture necessarily develop in a
5 geographical center”.

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10 *Phoenix* palms, not only *P. dactylifera*, but also *P. theophrasti* and other species, left cultural traces in
11 different places and cultures (anthropic environments) in the form of biological remains or images and
12 texts. Biological remains consist mainly in phytoliths, inflorescences, pollen, seeds and fruits, and stems
13 and leaves more or less transformed. These can be recovered from paleontological and archaeobotanical
14 contexts. Also palms and palm trees appear cited in texts and represented in pottery, coinages, scarabs,
15 medals, paintings, frescoes, bas reliefs, mosaics, and cylinder seals of antiquity during the early Middle
16 Ages, for instance in Egypt, Assyria, Persia, Greece, Rome and Carthage (Baumann, 2005; Bircher, 1990,
17 1995; Danthine, 1937; Ferrer, 1999; Michel & Caubet, 2013; Mundell, 2002; Mahe, 2014).

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20 For the purpose of the present study “*Phoenix* date palm” is not a single species. It is mainly represented
21 by (Carreño, 2017; Rivera *et al.*, 2014; Rivera *et al.*, 2019) (Fig. 1 and Fig. 2):

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23 • *P. theophrasti* Greuter in Crete, surrounding islands and continental areas of Asia and Europe
24 (Fig. 1. E).
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26 • *P. reclinata* Jacq. in Africa south of parallel 15°N (Fig. 1. H).
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28 • *P. canariensis* H.Wildpret in the Canary Islands (Fig. 1. B). This species became widespread in
29 cultivation since 1850 as an ornamental palm (Rivera *et al.*, 2013; Zona, 2008).
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31 • *P. dactylifera* L. western cluster in the W Mediterranean and NW Africa (including *P. iberica*
32 D.Rivera *et al.* (Fig. 1. C) and *P. excelsior* Cav. (Fig. 1. D), in the Iberian Peninsula, and *P.*
33 *atlantica* Cheval., in Cape Verde Islands (Fig. 1. A)).
- 34
35 • *P. arabica* Burret (Fig. 1. H) and *P. caespitosa* Chiov. in Somalia and Southern Arabian
36 Peninsula.
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38 • *P. dactylifera* eastern cluster in NE Africa and W Asia (Fig. 1. G).

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53 Bayesian data analyses include practical methods for making inferences from data using probability
54 models for quantities observed and for quantities about which we wish to learn. Bayesian methods
55 explicitly use the probability to quantify the uncertainty in inferences based on the analysis of statistical
56 data (Gelman *et al.* 2009). Bayesian methods are widely used in archaeological and paleontological
57 sciences for varied purposes, such as: calibration of radiocarbon information (Ramsey, 2009), combining
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3 radiocarbon dating and archaeological information (Buck *et al.*, 1991, 1992, 2006; Ramsey, 1995);
4 relative archaeological chronology building (Buck and Sahu, 2000); date of species extinction (Buck &
5 Bard, 2007); automatic assembly of pots from fragments (Copper *et al.*, 2002); classification of objects
6 found in excavations such as ceramic sherds, artefacts, etc. (Moustaki & Papageorgiou, 2005); deposition
7 models for chronological records (Ramsey, 2008); mapping the movement of species decline (Lee, 2012;
8 Ramsey & Lee, 2013) and the possible occurrence of archaeological sites (Finke *et al.*, 2008).

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11 The purpose of this paper is to determine, within a probabilistic framework, the localization of the
12 different areas where date palm and related species were likely growing wild or cultivated up to the mid
13 second millennium AD around the Mediterranean Basin, West Asia and Africa, based on the available
14 evidence. With this purpose in mind we use the different types of evidence as tests to determine
15 probabilities of presence and absence using the Bayes theorem (Bayes, 1763).

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18 As basic hypotheses, we assume first that the probability of date palm groves (natural and/or anthropic)
19 occurring within a determined cell and period is directly proportional to the number of coinciding positive
20 types of evidence (biological or strictly cultural), which for each cell range from 0 to 13. Second, for the
21 purpose of calibration of the different types of evidence we assume as a reference test the presence within
22 the cell of modern palm groves (wild or cultivated) (Fig. 2). Hence, we analyze the sensitivity and
23 specificity of the thirteen different types of evidence available (six biological and seven strictly cultural)
24 for determining the areas where date palm was grown or occurred spontaneously and calculate for each
25 one of the 1978 cells of $2^{\circ} \times 2^{\circ}$, conditional probabilities. The odds in favor of the presence of the date
26 palm during the period considered are the ratio of the probability it occurred to the probability that it did
27 not. Further, we try to determine the pattern of dissemination of *Phoenix* through times and the milestones
28 of this process.

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31 This research aims to produce a systematic framework for comparison with molecular and morphological
32 evidence to shed light on the complex phylogeny and taxonomy of *Phoenix* genus. This investigation
33 generates a tool which can be incorporated in the study of domestication processes and rates of evolution
34 of other fruit crops like olive, grapevine or fig, but also myrtle or rosemary.

METHODS

TYPES OF EVIDENCE, CHRONOLOGY, GEOGRAPHICAL LIMITS AND SCALE

Thirteen types of evidence, six different types of biological (mainly archaeobotanical but also fossils) (Table 1) and seven of strictly cultural evidence (Table 2) related to *Phoenix*, were analyzed and georeferenced which offered information relevant to determine the localization of date palm within the period covered here.

The earliest unequivocal fossil palm material probably dates from the early to mid-Late Cretaceous (Harley, 2006). A series of form genera could represent *Phoenix* ancestors since the early Tertiary, such as *Monocolpopollenites* Pflug & Thompson in Thompson & Pflug 1953 (pollen), *Phoenicites* Brongn. 1828 (leaves, inflorescences, fruits), *Palaeophoenix* Sap. 1882, *Palmoxylon* Schenk 1882 (stipe), *Palmocaulon* Menon 1964 (pseudopetioles and rachises), *Palaeospatha* Unger 1855 (spathae), and *Rhizopalmoxylon* Felix 1883 (stipe and roots) (Harley, 2006). However only fossil seeds can with high likelihood be linked with *Phoenix* L. (Rivera *et al.*, 2014). *Phoenix* seeds have been recorded from the Tertiary of eastern Texas as *Phoenicites occidentalis* Berry; from the middle Eocene of Germany (Geiseltal) as *Phoenix hercynica* Mai and *Serenoa carbonaria* Mai and from the lower Miocene of Central Europe as *Phoenix bohémica* Buzek (Berry, 194; Buzek, 1977; Harley, 2006; Mai, 1976). Other *Phoenix*-like fossil seeds were recovered from the Ypresian (lower Eocene) levels of the London Clay Flora under the names of *Palmospermum ornatum* and *P. ovale* (Chandler, 1961).

Stipe fragments, leaves, pollen and phytoliths from deposits of the Pleistocene and later, in areas where other genera of related Arecaceae are currently infrequent or absent, are attributed by authors to *Phoenix* species (Barboni *et al.*, 2010). This is most evident in dynastic period Egyptian archaeology (Täckholm & Drar, 1950).

In order to develop an exhaustive search of available evidence the study was limited to an area from 26° W to 75° E longitude and 35° S to 56° N latitude and divided in an array of 2° x 2° equaling 1978 cells. Modern *Phoenix* populations were also surveyed over 26° W to 72° E longitude and 35° S to 56° N (Fig. 2). A database was built containing the different types of evidence with the coordinates and elevation for each independent record. Over 750 squares or cells exclusively covered water areas (oceans and seas).

Table 1. Types of archaeobotanical and paleontological evidence and the existence of *Phoenix* palm formations.

	Identification and sources	Geographical information	References
<i>Date remains</i> (Fig. 3. A)	Commercial dates susceptible of preservation belong especially to the dry type of <i>P. dactylifera</i> (eastern cluster). Dates from other species and types of <i>P. dactylifera</i> are consumed fresh or given to livestock. Identification of seeds is successful to the level of genus, and often species, and can be successfully employed with fossil material. Carbonized seeds require the use of conversion factors.	Dates and seeds can be recovered far away from their place of origin (thousands of km) in areas where actually palms did not exist due to commercial activities.	Rivera <i>et al.</i> , 2014
<i>Inflorescences</i> (Fig. 3. E)	Male inflorescences are used to artificially fecundate female palms, these are removed from the palm tree and stored during short periods. Female inflorescences are rarely removed from the palm tree, although in Hawara and El Faiyum (Egypt) there were recovered necklaces made with female inflorescences. Eocene fossils of male flowers were identified as <i>Phoenix windmillis</i> although other genera cannot be discarded.	Although male inflorescences are transported their presence is associated to palm groves. There is no evidence of long-distance female inflorescence transport.	Allen, 2015; Täckholm & Drar, 1950
<i>Leaves</i> (Fig. 3. D)	Leaf pinnate, pinnae (leaflets) induplicate (v-shaped) on adaxial surface; those lowermost on the rachis spine-like (Read & Hickey, 1972). Date palm leaves were used in basketry and ropes, shoemaking, roofs and fences in the gardens, but also in religious festivals. Leaves of, at least, <i>P. dactylifera</i> , <i>P. canariensis</i> and <i>P. theophrasti</i> are used.	Present uses in Christian and Jewish festivities require transportation far away from the palm groves. Other uses in agriculture and building are more local.	El Hadidi & Hamdy, 2011
<i>Stems and charcoal</i> (Fig. 3. C)	Surface processes and microscopy allow to determine palm stems. The number of wide metaxylem elements per fibrovascular bundle is 2, like in <i>Hyphaene</i> , <i>Livingstonia</i> , and <i>Nypa</i> (these are 1 in <i>Borassus</i> , 3-4 or more in <i>Chamaerops</i>). Phytoliths are present all around the fibrous part. It is an attribute of the ground parenchyma sustained growth pattern (phytoliths are not developed in stems with centrifugal differentiation). Species identity cannot be established on the sole stem anatomy. In areas where other palm genera exist care must be taken in order to distinguish between these and <i>Phoenix</i> whether possible, otherwise these must be excluded.	In areas where date palms are abundant, their stems are used in buildings. There is textual evidence of long distance transport of date palm stems for luxury buildings, but local uses are more frequent.	Nesbitt, 1993 a; Tengberg, 2012; Thomas & Boura, 2015; Thomas & De Franceschi, 2013

	Identification and sources	Geographical information	References
Pollen (Fig. 3. B)	<i>Phoenix</i> pollen grains are typically symmetric ellipsoid, monosulcate (sulcus length as long axis, usually with pointed apices or shorter than long axis, then usually with rounded apices), reticulate (24-30 x 10-19 µm) and differ from those of <i>Chamaerops</i> (disulcate), <i>Borassus</i> (gemmate, 46-51 x 36-41 µm) and <i>Hyphaene</i> (gemmate, 32-38 x 27-37 µm)	The medicinal use of <i>Phoenix</i> pollen grains may involve transport away from the palm groves. Wind transport of pollen is at relatively short distance	Ferguson <i>et al.</i> , 1987; Gosling <i>et al.</i> , 2013; Harley & Baker, 2001; Wodehouse, 1935
Phytoliths (Fig. 3. G)	Globular phytoliths are found in stems, leaves and epicarp of Arecaceae, those of <i>Phoenix</i> are 6-13 µm in diameter and present 12-25 spines or tubercles	<i>Phoenix</i> phytoliths are reported from sediments and also from human dental calculi.	Benvenuto <i>et al.</i> , 2015; Miller, 2003

Table 2. Types of cultural evidence and the existence of *Phoenix* palm formations.

	Identification and sources	Geographical information	References
Texts	Descriptions of palm groves, uses and cultivation details are found in different texts from Mesopotamian tablets, through Egyptian papyri to medieval manuscripts. Most may refer to <i>P. dactylifera</i> but some Greek texts clearly refer to <i>P. theophrasti</i> .	Often is difficult to determine with precision the place of a locality mentioned in ancient documents	Smith & Crane, 2001
Coinages (Fig. 3. I)	Images of complete palm trees, young or adult, fertile or sterile, more or less realistic are identifiable. These can easily be recognized as <i>Phoenix</i> but specific identity cannot be established.	Most mints localities fall within the area of modern <i>Phoenix</i> palms groves. Coins are a fertile source of information for ancient history and geography	Howgego, 1995; Rivera <i>et al.</i> , 2018
Pottery (Fig. 3. M)	Id.	Does the object represent local or imported ware? To what extent this is related to neighboring palm groves?	Price & Burton, 2011
Wood paintings, papyri and scrolls	Id.	Id.	Watrous, 1991
Jewelry, gold cups and seals (Fig. 3. L)	Id.	Id.	Pernicka, 2014; Tissot <i>et al.</i> , 2015

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Identification and sources	Id.	Geographical information	References
<i>Rock and Wall painting and mosaic</i> (Fig. 3. F, H, K)	Id.	Does the figured palm represent local groves or foreign landscapes?	Warren, 1979
<i>Sculpture (stone, bronze and wood)</i> (Fig. 3. J)	Id.	Was it locally sculpted or elsewhere? Does the figured palm represent local groves or foreign landscapes?	Margolis, 1989

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3 Analysis of archaeobotanical and paleontological evidence began with an exhaustive review of the
4 literature and of materials deposited in museums. The collections of the Oriental Institute (Chicago),
5 British Museum (London), *Museo delle Antichità Egizie di Torino* (Turin), *Aegyptisches Museum und*
6 *Papyrussammlung* (Berlin), Museum of Minerals and Fossils of the Cultural Society of Thira, *Museo*
7 *Canario* (Las Palmas) and Royal Botanic Gardens Kew (Economic Botany Collections) were studied.
8
9 Information on archaeobotanical evidence was recorded and treated independently according to the type
10 of materials. Consequently, it was organized in six types: phytoliths, pollen, inflorescences, date fruits
11 and seeds, leaves and stems, often more or less transformed in the form of different artefacts. The
12 commercial relevance (past and present) of especially dry types of date fruits, associated with their ritual
13 uses, presumably led to a wider distribution through commercial routes. On the other hand, there is no
14 evidence of a mainstream commerce of palm inflorescences and leaves. Although palm leaves were, and
15 still are, a material of international commerce for use in religious festivals of, mostly, Christians and
16 Jews, but also in ancient Rome, their presence in archaeological reports is scarce (excepting ancient Egypt
17 and aboriginal Canary Islands sites) and there is no evidence of long-distance commerce. Although the
18 analysis was exhaustive, lack of evidence for a determined cell must be taken as “no data” and not as
19 “negative occurrences” in the sense of Finke *et al.* (2008), since there are numerous factors determining
20 the lack of archaeological date palm remains such as fruits or leaf fragments (intensity of exploration,
21 criteria of researchers concerning recovery of plant remains, post-depositional factors, etc.).
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Classical texts were analyzed to record localities and areas of date palm cultivation for the period under consideration. Main cultivation areas were recorded together with incidental cultivation associated with ornamental purposes or religious practices. Here we had to deal with the uncertain geographical place of numerous localities and areas cited by ancient geographers and naturalists. Although these are not numerous, clay tablets from different sources and periods (particularly the first millennium BC) of Mesopotamia offered information related to places of trade and cultivation activities concerning date palm (Geller, 2005; Rivera *et al.*, 2012; Spar and Jursa, 2014; Spar & Von Dassow, 2001). We analyzed information on date palm distribution available in classical Greco-Roman texts: *Homer* (c. 750–650 BC) (Butcher & Lang, 1909; Cowper, 1920; Foster, 1936; Pope & Buckley, 1899); *Herodotus* (c. 484 – 425 BC) (Beloe, 1830; Foster, 1942); *Euripides* (c. 480 – 406 BC) (Coleridge, 1938); *Xenophon* (c. 430 – 354 BC) (CAIS, 2014; Mather & Hewitt, 1962); *Theophrastus* (c. 371 – c. 287 BC) (Hort, 1916); *Titus Livius* (64 or 59 BC – 17 AD) (Roberts, 1912); *Strabo* (64/63 BC – c. 24 AD) (Jones H, 1930, 1967); *Pliny* (23 –

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3 79 AD) (Jones W, 1961, 1963, 1966; Rackham, 1960, 1961a,b); *Dioscorides* (c. 40 – 90 AD)
4 (Osbaldeston, 2000); *Flavius Josephus* (37 – c. 100 AD) (Whiston, 1895); *Plutarch* (c. 46 – 120 AD)
5 (Cole, 1936; Goodwin, 1874) and *Suetonius* (c. 69 – after 122 AD) (Kellum, 1994; Rolfe, 1914).
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10 Medieval texts by *Al Idrissi* (c. 1150 AD) (Dozy & De Goeje, 1866); *Ibn-Khordadbeh* (c. 900 AD)
11 (Barbier, 1865); *Ibn Serapion* (c. 900 AD) (Le Strange, 1895) and *Al Bakri* (c. 1050 AD) (Guckin, 1869)
12 contain information on palm groves and date production areas. The Saharan localities were identified
13 following Lange & Berthoud (1977). Here the analysis was exhaustive enough for Greek and Roman
14 authors, to consider “lack of evidence” for a determined cell as “negative occurrences” in the sense of
15 Finke *et al.* (2008); however, previous and later texts were not so exhaustively examined, therefore
16 overall, lack of evidence is here “no data.”
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24 Images representing date palm trees were systematically investigated consulting catalogues of museums,
25 especially The British Museum, The Metropolitan Museum, The Danish National Museum, forums, on-
26 line search engines and auction catalogues. Materials exhibited at the *Stattliche Museen zu Berlin und*
27 *Altes Museum (Münzkabinett Berlin)*, *Staatliches Museum Ägyptischer Kunst* (Munich), Leiden Museum,
28 *Museo Nazionale Romano - Palazzo Massimo (Collezione Numismatica and others, Rome)*, *Museo*
29 *Nazionale d'Arte Orientale "Giuseppe Tucci"* (Rome), *Museo d'Arte Orientale di Torino*, *Museo Egizio di*
30 *Torino*, *Museo archeologico Nazionale di Napoli*, *Museo archeologico Bosco Reale*, *Fondazione*
31 *Giuseppe Whitaker (Isola di Mozia)*, *Museo Mandralisca* (Cefalu), *Museo archeologico regionale*
32 *“Antonio Salinas”* (Palermo), *Museo Archeologico “Baglio Anselmi”* (Marsala), *Museo Arqueológico*
33 *Nacional* (Madrid), *Museo de la Alcudia* (Elche), *Museo de Albacete*, *Musee du Louvre* (Paris), Oriental
34 Institute University of Chicago, Archaeological Museum of Thesaloniki, Archaeological Museum of
35 Thera, Athens National Archaeological Museum, Heraklion Museum, Mycenae Museum, Numismatic
36 Museum (Athens), National Museum of Beirut and the Museum of Fine Arts (Boston), were also studied.
37 For pottery, bas-reliefs, paintings, sculpture and jewels the materials were georeferenced according to the
38 site where these were originally recovered, according to the records of the museums or original
39 publications. Concerning coins we linked the information to the mint where, according to previous
40 numismatic research, each coinage was issued, not the place where different coin hoards were recovered
41 (Rivera *et al.*, 2018). Here the analysis was exhaustive enough to consider lack of evidence for a
42 determined cell as “negative occurrences” in the sense of Finke *et al.* (2008), since numismatic evidence
43 concerning mints issuing coinages with date palm images is relatively complete and precise at the scale of
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3 the present research. Other types of cultural evidence although exhaustively analyzed are considered less
4 complete.
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7 The present palm groves and palm areas were exhaustively studied using different sources, notably
8 Google Earth (2018) and Phoenix-Spain (2018), but also GBIF (2017a and b) and local floras. These were
9 georeferenced in terms of degrees, minutes and seconds of latitude and longitude. Here the analysis was
10 also exhaustive enough to consider lack of evidence for a determined cell as “negative occurrences” in the
11 sense of Finke *et al.* (2008), although a probability exists of having overlooked the existence of palm
12 groves in a determined cell.
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20 **HANDLING OF CRUDE DATA**

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22 The use of a grid of 2° x 2°, with 1978 cells, is the result of a search for an optimum in combining data
23 with different degrees of precision in terms of geographical reference, while having a relatively high level
24 of resolution. We implemented different combinations of formulas and functions in Excel to determine
25 with respect to presence/absence, the links of each one among the thirteen different types of evidence
26 considered with each one of the 1978 cells.
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32 **ANALYSIS OF RECORDS**

33 **NON-BAYESIAN MODELS**

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39 These were generated in two ways: first by totalizing the evidence available for each cell (number of
40 records) and second by calculating the entropy.
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44 Totalized data were calculated by totalizing the ensemble [1].
45

46 [1]
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$$48 T = \sum_{i=1}^n n_i$$

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54 Where n_i is the number of records of one particular type of evidence. This approach furnishes maps which
55 are informative, but extremely dependent of the intensity and quality of exploration for each area and type
56 of evidence.
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Another approach is to calculate the entropy of the set of data for each individual cell [2] (Shannon, 1948):

[2]

$$H = -K \sum_{i=1}^n p_i \log p_i$$

Where p_i is the proportion (n_i/N) of records of one particular type of evidence (n_i), divided by the total number of records of the different types of evidence (N). This is a measure of information, choice and uncertainty. For a given n , H is maximum and equal to $\log n$ when all the p_i are equal. This is also intuitively the most uncertain situation, in terms of interpreting strings of text but in the case of biological systems it is an index of diversity and, within our research, of balanced evidence. However, this approach is computable only when $p_i > 0$ and for $p_i = 0$ requires manually to assign $p_i \log p_i = 0$. This focuses on the uniformity of records for the different types of evidence as opposed to those with one single type of evidence overrepresented. We, first calculated the entropy for two separate sets: the strictly biological and the cultural evidence, and then for the ensemble of thirteen tests.

THE BAYES THEOREM

The Bayes theorem (Laplace, 1774; Jeffreys, 1939; Von der Linden *et al.*, 2014) tells us that [3]:

[3]

$$p(A | B) \propto p(B | A)p(A)$$

Where A is the hypothesis (or a parameter, or a set of parameters) and B the data (observations or measurements made). Thus $p(A)$ is the *prior* based on the information about A we have apart from the measurements. Then $p(B | A)$ is the *likelihood* for the measurements B given a set of parameters or hypothesis A and $p(A | B)$ is the *posterior* probability, or the probability of a particular parameter set or hypothesis A occurring given the measurements and the *prior*. In a Bayesian analysis, we have to express the information we have in these terms (Bronk, 2009).

In the case of the ancient *Phoenix* areal [4] for the 2° x 2° cells with positive data, evidence recorded (PD)

[4]

$$p(H | PD) = (p(H) p(PD | H)) / p(PD)$$

Where $p(H)$ is the probability of existing ancient palm groves within the $2^\circ \times 2^\circ$ cell and $p(+)$ is the probability of positive data (PD). Thus [5]

[5]

$$p(PD) = p(H) p(PD | H) + p(no H) p(PD | no H)$$

Where $p(no H)$ is the probability of not existing ancient palm groves within the $2^\circ \times 2^\circ$ cell.

As a starting point, we do not know whether ancient date palm groves existed or not within the entire area or in a determined cell of the 1978 in which this is divided. However numerous sources of evidence converge to lead us to assume that a probability of existing at least one cell of the 1978 where an ancient palm grove existed is equal to 1, being therefore an event certain. Thus our purpose is to further determine the probability for each one of the 1978 individual cells, which theoretically vary from 0 to 1 (certain). In the present analysis we assigned equal prior probability for presence of ancient palm groves and for absence, thus 0.5, for each one of the 1978 cells. The final probability will be determined by the successive application of different tests.

TESTS BASED IN THE TYPES OF EVIDENCE: SENSITIVITY AND SPECIFICITY

We systematized the thirteen types of archaeobotanical and cultural evidence in thirteen individual arrays using an Excel spreadsheet, which were taken as tests for the localization of ancient *Phoenix* palm as follows.

Given a test T_i for $i=1$ to 13 [6].

[6]

$$p(H | +_i) = \frac{p(H, +_i)}{p(+_i)} = \frac{p(H) p(+_i | H)}{p(+_i)} = \frac{p(H) p(+_i | H)}{p(H) p(+_i | H) + p(no H) p(+_i | no H)}$$

Where $p(H | +_i)$ is the probability of having existed ancient date palm groves in a determined cell if the test i is positive for this determined cell, $p(H)$ is the probability of ancient palm groves in the ensemble of the area (prevalence or relative abundance), $p(no H)$ is $1 - p(H)$, $p(+_i | H)$ is the probability of a positive

test if palm groves existed, it is a likelihood, $p(+_i | no H)$ is the probability of a positive test if palm groves did not exist, $p(+_i)$ is the overall probability of a positive i test.

Accordingly, the probability of ancient palm groves having existed in a determined cell of the grid if the test i is negative is not negligible and it is given a test T_i for $i=1$ to 13 [7].

[7]

$$p(H | -_i) = \frac{p(H) p(-_i | H)}{p(-_i)}$$

Considering that [8,9]

[8]

$$p(-_i | H) + p(+_i | H) = 1, \text{ and}$$

[9]

$$p(-_i) + p(+_i) = 1, \text{ thus [10]}$$

[10]

$$p(H | -_i) = \frac{p(H) (1 - p(+_i | H))}{1 - p(+_i)}$$

This approach of conditional probability is frequently used in medicine and veterinary to determine the probability for a given individual who has received a positive result in a screening test for a disease of actually suffering from the disease. In this case $p(H)$ is the prevalence of the disease in the population (epidemiological data), i.e. the percentage of the population which actually suffers this disease, which is calculated with other resources and techniques, for instance reference tests (gold standard) (Dendukuri and Joseph, 2001; Schlichting *et al.*, 2015). Further previous information for such a test are [11, 12]:

[11]

Sensitivity $\equiv p(+ | H)$, the probability of a positive test given that the individual has the disease, and

[12]

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2
3 Specificity $\equiv p(- | no H)$, the probability of a negative test given that the individual is well. These are
4
5 given and constitute the prior and the likelihood of a Bayesian formula.
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8 The key question here is how to determine $p(H)$, $p(+ | H)$ and $p(- | H)$ for ancient date palm groves.
9

10 For this purpose, we need to “calibrate” each i test, by setting a hypothetic array of cells, positive and
11
12 negative, against which to compare the results of the individual test. This array is generated by using a
13
14 Gold Standard (a test considered to be accurate with probability equal to 1). In the absence of a gold
15
16 standard several models based on multiple diagnostic testing are available (Branscum *et al.*, 2005; Enϕe
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18 *et al.*, 2000; Jones *et al.*, 2010; Joseph *et al.*, 1995). These models require independence of tests, several
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20 populations sampled, and barely intuitive calculation. An alternative is to refer to modern *Phoenix*
21
22 distribution area as a prior. Modern areas were determined considering field records, Google Earth survey
23
24 (Google Earth, 2018), and GBIF (2017 a & b) database and herbarium specimens.
25

26
27 When building the standard for calibration we paid special attention to records of consolidated date palm
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29 groves and palm areas, although extensive novel plantations were also recorded (Fig. 2). The area of date
30
31 production in the Arabian Peninsula and the Middle East has increased dramatically during recent
32
33 decades and is expected to increase in the future as a result of the continuously increasing demand (Chao
34
35 and Krueger, 2007). In Israel, date plantations now exceed the ancient areas, extending south along the
36
37 Arava Valley (21% of Israeli plantations), and to the north (Lake Kinneret area (29%) and Bet She’an
38
39 Valley (31%). Thus traditional areas house only a 19% of plantations of the country (Blumberg, 2008).
40
41 However this is compatible with the persistence of traditional palm groves and cultivation practices
42
43 (Johnson *et al.*, 2013). Therefore, the distribution of present-day date palm gardens is far from
44
45 synonymous with the past distribution. Indeed, new industrial date palm plantations have appeared during
46
47 the last half century in previously non cultivated regions thanks to intensive irrigation from underground
48
49 aquifers, for example in the Persian Gulf states and in Saudi Arabia.
50

51 Presently, *Phoenix* genus is represented in this area by at least five different taxa (Fig 2), viz. *P.*
52
53 *theophrasti* Greuter, *P. canariensis* H.Wildpret, *P. reclinata* Jacq., *P. arabica* – *P. caespitosa* complex,
54
55 and the *P. dactylifera* L. complex (Table 3). *P. dactylifera* is divided in two geographical groups; western
56
57 and eastern (Hazzouri *et al.*, 2015). *P. dactylifera* western cluster includes palm groves of NW Africa and
58
59 the Iberian Peninsula. Molecular data connect with this last group both *P. atlantica* Chev. from Cabo
60
Verde Islands, and *P. iberica* D.Rivera *et al.* from SE Spain (Carreño, 2017). *Phoenix arabica* and *P.*

caespitosa, which were considered synonyms by Barrow (1998), are taxa morphologically intermediate between *P. dactylifera* and *P. reclinata*, presently under study (Carreño, 2017).

Table 3. Number of localities where modern *Phoenix* populations were recorded

Taxa	Zone N	Zone S
	latitude 10° to 50° N	latitude 35° S to 10° N
<i>P. dactylifera</i> (eastern and western clusters)	814	18
<i>P. canariensis</i>	131	0
<i>P. theophrasti</i>	24	0
<i>P. reclinata</i>	23	342
<i>P. iberica</i>	40	0
<i>P. atlantica</i>	6	0
<i>P. arabica</i>	3	0
<i>P. caespitosa</i>	2	4

Although the true status of ancient *Phoenix* areas cannot be determined, the distribution of modern *Phoenix* palm offers an approximate Gold Standard. Thus, within an individual 2° x 2° cell ancient date palm presence is “*a priori*” assumed where modern palm groves (wild or cultivated) exist, being otherwise negative. This is applied to validate each Test T_i for $i=1$ to 13 (Table 4) for the ensemble of 1978 cells (n).

Table 4. Basic structure of information necessary for the calibration of tests.

Test _{<i>i</i>} results	Ancient palm exists (Y)	Ancient palm does not exists (N)	Total
Positive (+)	a =True Positive= $n(Y,+)/n=p(Y,+)$	b =False Positive = $n(N,+)/n=p(N,+)$	$a+b=n(+)/n=p(+)$
Negative (-)	c =False Negative= $n(Y,-)/n=p(Y,-)$	d =True Negative= $n(N,-)/n=p(N,-)$	$c+d=n(-)/n=p(-)$
Total	$a+c=n(Y)/n=p(Y)$	$b+d=n(N)/n=p(N)$	$a+b+c+d = n/n = 1$

And, therefore [13, 14]

[13]

Sensitivity $\equiv p(+ | Y) = a/(a+c) = p(Y,+)/p(Y)$, and

[14]

Specificity $\equiv p(- | N) = d/(b+d) = p(N,-)/p(N)$.

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3 A negative result is reliable in a high sensitivity test (values near 1), because the low proportion of false
4 negatives. However, a negative result in a low sensitivity test is not useful for ruling out the hypothesis. A
5 positive result in a test with high specificity (values near 1) is useful for accepting the hypothesis, because
6 the low proportion of false positives. The test rarely gives positive results in areas where $p(Y)$ is 0 or near
7 0. However a negative result in a test with high specificity is not useful for ruling out the hypothesis.
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13 CALCULATING THE BAYES FACTOR FOR ANCIENT PALM GROVES PRESENCE

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15
16 The odds in favor of an event are the ratio of the probability it will occur to the probability that it will not.
17 If we have two hypotheses, A and B , the ratio of posterior probabilities, given D data, is [15]
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19
20

21 [15]

$$22 \frac{p(A | D)}{p(B | D)} = \frac{p(A)p(D | A)}{p(B)p(D | B)}$$

23
24
25
26
27
28 If A and B are mutually exclusive and collectively exhaustive ($p(B) = 1 - p(A)$), the ratio of the prior and
29 the ratio of the posteriors can be written as odds. The posterior odds are the prior odds times the
30 likelihood ratio (Bayes factor) (Kass & Raftery, 1995) [16-18].
31
32
33

34 [16]

$$35 o(A | D) = o(A) \frac{p(D | A)}{p(D | B)} \text{ (and, for our hypothesis) } o(Y | +) = o(Y) \frac{p(+ | Y)}{p(- | N)}$$

36
37
38
39
40
41 [17]

$$42 \text{ (For cells +) } o(Y | +) = o(Y) \frac{p(+ | Y)}{p(+ | N)} = \frac{\text{Sensitivity}}{1 - \text{Specificity}}$$

43
44
45
46
47
48 [18]

$$49 \text{ (For cells D) } o(Y | -) = o(Y) \frac{p(- | Y)}{p(- | N)} = \frac{1 - \text{Sensitivity}}{\text{Specificity}}$$

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54 This form is most convenient for representing the information obtained from the application of the test
55 addressed to determining the localization of ancient date palm groves and the extension of *Phoenix* in the
56 period under consideration.
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CALCULATING PROBABILITIES USING THE ENSEMBLE OF TESTS

The probability can be calculated for each single cell applying one single test or a combination of tests.

For the purpose of the first step of calculation we assign the uniform probability of 0.5 to all cells (prior or $p(H_0)$), because this is the less informative option before data and thus maximizes entropy. The thirteen tests are combined as follows [19]:

[19]

$$o\left(\prod_{i=1}^X Y_i \mid DI_i\right) = \prod_{i=1}^n o(Y_i) \frac{p(+_i \mid Y_i)}{p(+_i \mid N_i)} \prod_{i=1}^o o(Y_i) \frac{p(-_i \mid Y_i)}{p(-_i \mid N_i)}$$

Where DI is the ensemble of data for a particular cell after applying the ensemble of tests, X is number of combined biological and cultural tests, n is the number of tests where result is positive, and o is the number of tests where result is negative.

CALCULATING PROBABILITIES UNDER DIFFERENT CHRONOLOGICAL SCENARIOS

The Bayesian model was applied under different possible chronological scenarios, based on the datation of the archaeological evidence and texts examined. For this purpose each one of the records was chronologically referenced to an approximate calendar date based on the evidence furnished by the sources consulted (along the text we use dates before present, million years are abbreviated Myr and millennia ka). The precision of dates assigned to different events under each one of the thirteen tests is unequal, ranging from years to centuries.

Starting from the oldest, the ensemble of records was analyzed until a determined upper chronological limit was reached, using the ensemble of thirteen tests. Our maps are the result of a rudimentary geographic information system and similar in aspect to those generated by the program *Oxcal* (Lee, 2012; Ramsey & Lee, 2013). Further information can be obtained considering the formula [20]

[20]

$$C = \sum_{c=1}^n \text{Log}_{10} \left(o\left(\prod_{i=1}^X Y_i \mid DI_i\right) \right)$$

1
2
3 Where C is an index of the number of cells where the estimate of Bayes factor is >1 for the ensemble of
4 the region, and c is each single cell. The temporal variation of this index combined with the variation of
5 geographical pattern is useful to determine key periods and zones.
6
7

8
9 For representing these processes a first approach was to generate a model based on the accumulated
10 evidence in form of the sum of the \log_{10} of Bayes factor of cells where the Bayes factor is >0 and the sum
11 of entropy (Shannon index), from the beginning to that date.
12
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15 16 **PYTHON AND R PACKAGE**

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18
19 The above routines were summarized in a series of Excel macros. In order to facilitate the use of this
20 novel methodology by other researchers we compiled an R package (R, 2019) and Python application
21 (Python Software Foundation, 2019) which are accessible at Phoenix-Spain (2018).
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23
24

25 26 **MAPS AND GRAPHICS**

27

28 29 **DRAWING MAPS**

30

31
32 Base maps (Fig. 2, 4, and 6) in Mercator projection were drawn using Quantum Gis (2014) for digitizing
33 polygons and GMT (2014) to generate the final maps. In Fig. 5 we used an equirectangular projection
34 map which maps meridians to vertical straight lines of constant spacing and circles of latitude to
35 horizontal straight lines of constant spacing. This projection introduces distortions but establish a
36 particularly simple relationship between the position of an image pixel and its corresponding geographic
37 location on Earth (Wikipedia, 2019). The map was created in R (2019) using the package Maps (2019). In
38 Fig. 4, 5 and 6, over the base maps we superimposed graphics, generated in Excel, using Power Point. For
39 Figs. 4 and 6 positions are referenced in distances (km) from the Equator and Greenwich meridian, fig. 5
40 uses geographical coordinates. The bubbles of Fig. 5 present surface proportional to the \log_{10} of odds of
41 palm groves presence vs. absence (as an estimate of Bayes factor), scaled at 50%.
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51 52 **COMPUTING BARYCENTER**

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55 Each single type of evidence follows a peculiar geographical pattern which was summarized calculating
56 the barycenter of the x and y coordinates for the distribution of each one of the thirteen types of evidence
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based on their respective ensembles of records. The barycenter for the accumulated assemblage of data within a determined period was also calculated.

The calculation of the barycenter is based on determining the values of the average of the latitude and longitude of the cells that meet a certain requirement. Initially it was calculated considering the values in degrees, but since the length in kilometers of an arc of a parallel depends on its latitude, the distances in kilometers to the Greenwich meridian (longitude) [21] and to the equator (latitude) were calculated for each cell and used to compute the barycenter.

[21]

$$Longitude_{km} = 111.32 (\cos Latitude_{radians}) = 111.32 (\cos (Latitude_{degrees}\pi/180))$$

The use of degrees or kilometers little influenced the resulting graphics. However it is relevant to recall here that the surface in square kilometers of a 2° x 2° cell is 49 568 km² at the equator but it is only 32 462 km² at 49° of latitude. This supposes a reduction of 35% of the surface of the cell. Since most of our data are comprised between 19 and 40 degrees of latitude N the range of variation is of c. 17%

RESULTS

OVERALL RESULTS AND TEST CALIBRATION

When calculated for the different T_i tests, overall the sensitivity is low but specificity is acceptable or excellent (Table 5), assuming that modern *Phoenix* areas are our reference. The low sensitivity is due to the relatively low representation of the thirteen types of evidence in the 1978 cells of the grid and especially in cells where modern *Phoenix* palm populations exist. This is particularly lower south of 10° N in Africa (Table 6). On the contrary high specificity values are reached because in cells where tests give a positive result modern *Phoenix* populations are found.

Table 5. Results of the calibration of the thirteen tests.

Biological	Sensitivity	Specificity
Test T _{1a} Date remains	0.20	0.97
Test T _{2a} Inflorescences	0.005	c. 1
Test T _{3a} Leaves	0.07	0.99
Test T _{4a} Stems and charcoal	0.045	0.99

Test T _{5a} Pollen	0.03	0.99
Test T _{6a} Phytoliths	0.015	c. 1
Cultural	Sensitivity	Specificity
Test T _{1c} Coinages	0.13	0.99
Test T _{2c} Texts	0.42	0.99
Test T _{3c} Pottery	0.08	c. 1
Test T _{4c} Wood paintings, papyri and scrolls	0.025	c. 1
Test T _{5c} Jewelry, gold cups and seals	0.09	0.99
Test T _{6c} Rock and Wall painting and mosaic	0.09	c. 1
Test T _{7c} Sculpture (stone, bronze and wood)	0.04	c. 1

NON-BAYESIAN MODELS

The number of records and cells in which biological and cultural evidence was recorded is summarized in Table 6. North of parallel 10° N fruit and leaf remains are the most widely represented biological evidences, whereas to the south it is pollen, this last is due to the low proportion of archaeobotanical studies in this southern area and the relative abundance of paleobotanical analyses. Each single type of evidence follows a peculiar geographical pattern which was summarized calculating the barycenter of the x and y coordinates for the distribution of each one of the thirteen types of evidence based on their respective ensembles of records (Fig. 4; Table 6).

Table 6. Number of available records of Phoenix and number of cells of the grid for which evidence is positive.

Codes: **Z**, Zones; S, latitude 35° S to 10° N; N, latitude 10° to 50° N. Cells, number of 2° x 2° cells of the grid.

Biological		Z							Reference
		Date remains	Inflorescence	Leaves	Stems and charcoal	Pollen	Phytoliths	Modern palm groves	
Records	N	231	4	64	36	23	12	997	
Cells	N	75	1	24	20	8	5	197	
Records	S	1	0	0	0	14	3	325	
Cells	S	1	0	0	0	5	1	88	
Cultural		Z							

		Coinages	Texts	Pottery	Wood paintings, papyri and scrolls	Jewelry, gold cups and seals	Rock and Wall painting and mosaic	Sculpture (stone, bronze and wood)
Records	N	203	524	57	13	128	44	37
Cells	N	39	98	18	7	27	20	14
Records	S	0	0	0	0	0	3	0
Cells	S	0	0	0	0	0	1	0

Totalized evidence available for each cell (number of records), where the biological and cultural types of evidence were considered both/either separately or together, produced maps which are informative, but extremely dependent of the intensity and quality of exploration for each area and type of evidence.

Entropy of the data set for each individual cell (Shannon, 1948) is proportional to the uniformity of records for the different types of evidence and produces values near 0 as a result for cells where one single type of evidence is extremely overrepresented. Here we analyzed the number of records for each pair cell-test. The highest values mark areas where the ensemble of evidence is best balanced. The Lower Nile Valley areas in Egypt and Mesopotamia are notably balanced in terms of biological and the ensemble of evidence. Cultural evidence appears shifted northwards around the Mediterranean.

BAYESIAN MODELS BASED ON THE ENSEMBLE TESTS

First we proceeded using both categories of types of evidence (biological and cultural) separately as a singular test for each one of the 1978 cells of the study area. Here again the systematized information responds to the peculiarities of the type of research behind each particular test. Comparison of the assemblages of biological and cultural tests shows a distinct bias towards the North in the cultural evidence when compared with biological evidence. This suggests focus on areas relevant for further specialized archaeological research.

The different models point to a few cells with higher likelihood of ancient date palm groves or ancient cultivation. The model represents the superposed data from the earliest to the latest giving a summary for the *Phoenix* areas during the considered period until 1 500 AD but this is not useful for reconstructing how and when these areas evolved.

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3 Given the exhaustive analysis of available evidence, we modelled how evidence was accumulating, and
4 evolving, through time for date palms in Europe, Africa and West Asia (Fig. 5).
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8 9 **DISCUSSION**

10 11 12 **BIOLOGICAL AND CULTURAL EVIDENCE FOR *PHOENIX* CULTIVATION AND**

13 14 15 **DOMESTICATION**

16 17 18 **DATE FRUITS AND SEEDS**

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21 Archaeobotanical evidence for date fruit and seed storage in the area is represented by subfossil
22 desiccated fruits and/or seeds from, among others, Tayma Oasis (Saudi Arabia), Susa (Iran), Mahmudiya
23 (Iraq), Failaka (Kuwait), Karanis (Egypt) and Masada and Abi'or Cave (Israel), and carbonized seeds and
24 dates from Qal'at al-Bahrain (Bahrain), Pompeii (Italy) and Lattara (Lattes, France). In particular, Karanis
25 (c. 120 AD) presented a wide range of seed morphologies corresponding to different date palm cultivars
26 (Rivera *et al.*, 2014).
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34 Most date palm cultivation areas around the Mediterranean produced (2.4-1.8 ka) exclusively fresh dates
35 suitable only for local consumption and not for storage and commerce (Cyprus, Spain, Alexandria in
36 Egypt, Africa) as it was attested by Pliny (Rackham 1961c). This has implications concerning
37 archaeobotanical materials, because these dates or their seeds are unlikely to be recovered from storage or
38 burial contexts. On the contrary ready-to-export dry types of dates from the Jordan Valley were widely
39 traded along the southern Mediterranean Coast (Rackham 1961c), which is consistent with the
40 distribution of dry-dates versus fresh-dates related markers in *P. dactylifera* eastern and western clusters
41 (Matthew *et al.*, 2015).
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51 The pattern of archaeobotanical findings of date fruits and seeds closely fits the model for ancient date
52 palm groves, and is even more accurate when considering totalized records. However some areas, situated
53 southwards, below 20° N Lat., and westwards in the periphery of the model, are underrepresented in terms
54 of archaeobotanical remains and, according to the model, are promising for further archaeobotanical
55 investigation and systematic recovery of plant remains during archaeological excavations. On the
56 contrary, the numerous findings of date seeds and fruits in Roman sites of northern France, northern Italy,
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3 Great Britain, The Netherlands, Belgium, and Bulgaria, above 40° N Lat., are placed by the model clearly
4 outside the main area for date palm growing activities and confirm the interpretation given to the remains
5 by different archaeologists in their reports in the sense of imported goods consumed or offered within
6 certain ritual contexts (Livarda, 2013). Although most of the evidence south of 43° N seems to refer to
7 dates locally produced, the dates of *Lattara* (France) and *Pompeii* (Italy) could indicate long-distance
8 trade of dried dates (Rivera *et al.*, 2014).
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15 At Carthage (6th – 2nd cent. BC), notwithstanding the relevance of palms and the high diversity of date
16 palm tree types on coins, there is not yet archaeobotanical evidence of dates or date palms. However, it is
17 likely that not only fresh dates were consumed and dry types could have been imported to Carthage from
18 palm groves oases in the North African desert (Van Zeist *et al.*, 2001). Therefore, further excavations
19 could furnish the missing evidence.
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25 Fuller (2018) suggests that large datasets of simple metrics from date seeds, but also other fruit crops, are
26 useful to estimate rates of evolution under domestication. Fuller (2018) reports a major trend in date stone
27 length increase taking place from 5 to 2 ka, although larger seeds preexisted, at least, since c. 7.3 ka
28 (Table 7).
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34 OTHER DATE PALM REMAINS

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37 The richness of other types of date palm tree remains (wood, leaves, pollen and phytoliths) is poor and
38 extremely uneven. Overall these types of evidence were recorded with preference in the SE quadrant (Fig.
39 4) which is shown by the displacement of their barycenter.
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41
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44 Date remains, stems and charcoal, inflorescence and leaves present their respective barycenter above 27°
45 N, whereas those of phytoliths and pollen are below 25° N. *Phoenix* pollen is mainly reported from lake
46 sediments of Africa.
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50 It is apparent that the high specificity of these tests is supportive for placing areas of ancient date palm
51 between 17° and 37° N Lat. Overall this category of evidence is linked to the presence, within a radius of
52 a few kilometers, of date palms and groves since the commercial dispersal of leaves and palm culms over
53 a long distance is infrequent. Vegetative date palm remains from the Canary Islands are attributed, in the
54 literature analyzed, to *Phoenix canariensis* and those from Crete and the Aegean to *P. theophrasti*,
55 exclusively on biogeographical grounds. Those archaeological artefacts conserved in museums, including
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3 baskets and caps, are systematically attributed in Western Mediterranean region to *Chamaerops humilis*
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5 but they merit to be further analyzed in order to precisely determine their botanical origin.
6
7

8 IMAGES OF PALMS

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10 Usually images on coins, mosaics and other artefacts represent symbols relevant for their issuers or
11
12 creators, hence the presence of palm tree images provides information of the local relevance of date palms
13
14 and groves. Wood paintings, papyri and scrolls and coinages present barycenter above 37° N and
15
16 westwards of 20° E, thus central Mediterranean (Fig. 4). Those of jewelry, gold cups and seals, and
17
18 sculpture (stone, bronze and wood) are near 34° N and 34° E (eastern Mediterranean). Pottery and rock
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20 and wall painting and mosaic present their barycenter in NE Africa (31-33° N – 18-30° E) (Fig. 4).
21
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23 The localities of mints issuing coins with palm images coincide, between 30° and 38° N Lat., within cells
24
25 with a high likelihood for ancient palm groves, except in the northern Aegean area of modern Greece and
26
27 Turkey, where date palm seems to have been merely a symbol for Apollonian sanctuaries and due to
28
29 climatic factors it was not actually grown or it was only incidentally grown (Rivera *et al.*, 2018). We
30
31 cannot neglect the hypothesis that most of these palms were in fact *P. theophrasti* instead of *P.*
32
33 *dactylifera*. Below 30° N Lat. and, also, to the east of 40° E Long., numerous cells with a high likelihood
34
35 of ancient date palm presence do not coincide with mints issuing coins with date palm images. This is
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37 related to the lower density of mints below 30° N Lat. in the former case, and the concentration of mints
38
39 in the eastern quadrants in areas not suitable for date palm cultivation in the later.
40

41 TEXTS

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44 Texts from the fifth century BC until 1200 AD report numerous localities where date palms were actually
45
46 grown and produced fruits for local consumption or suitable for exportation. Overall, the localities are
47
48 given in the texts with enough precision to allow a localization of the sites and their archaeological
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50 remains or ruins. These localities extend from 10° to 41° N Lat. and along almost the whole range from
51
52 13° W to 57° E Long., with a barycenter at N Libya (Fig. 6). Some of the localities are shown to coincide
53
54 with current date palm groves by the Google Earth® images.
55

56 Texts constitute a very rich source of information because they furnish not only data on the
57
58 presence/absence, but, also, on the characteristics of the date palms species, varieties and palm groves,
59
60 their management and uses, as well as their cultural and economic relevance. For instance, according to

the texts, Phoenicians seem to have been irrelevant concerning successful date-palm cultivation, which in the eastern Mediterranean area was restricted to the drier valleys of Judaea and the Sinai, notably Jericho, *Archelais*, *Livias* and *Phaselis* (Jordan River area), and the Dead Sea area; but they traded dates from these palm groves (Goor, 1967).

CHRONOLOGY OF PRE-DOMESTICATION *PHOENIX* AREAS EXPANSION

AMERICA

The existence of different *Phoenix* fossils in North America was reported. Sexual dimorphism in the genus *Phoenix* has been dated back to the Eocene period (Blue Rim flora of the Bridger formation, c. 49.5 Myr) on the basis of fossil records of *Phoenix windmillis* S.E. Allen male flowers (Allen, 2015; Cherif *et al.*, 2012). *Phoenix* has diverged from a hermaphroditic ancestor which is also shared with *Trachycarpeae* before speciation (Cherif *et al.*, 2016; Torres *et al.*, 2018).

However this evidence is controversial, since the specimen of *Phoenicites occidentalis* seed from Texas is lost and no re-examination is possible, being only available the original drawing which depicts one seed largest (Table 7) than those of all modern *Phoenix* species, including *P. dactylifera* (Berry, 1914 & 1924; Rivera *et al.*, 2014). *Phoenix windmillis* is exclusively based on male flowers and pollen (Allen, 2015). further evidence is required to substantiate the presence of *Phoenix* ancestors in America.

Table 7. Chronological and taxonomic variation of *Phoenix* seeds dimensions

Note: The arithmetic mean is the value represented, data from Rivera *et al.*, 2014 and the original database updated. Seeds: number of seeds analyzed. * Pleistocene seeds correspond to *P. theophrasti* or *P. reclinata* depending on the localities, thus present average smaller dimensions. ** Archaeological samples from the *** There is molecular evidence for the presence in Gökölü of hybrids *P. dactylifera* x *P. theophrasti*. **Abbreviations:** L. Length. B. Breadth. D. Depth. VP. Volume of the prism. F: Frequency of the type (0-1)

Working taxa or Period	L (mm)	B (mm)	D (mm)	VP (mm ³)	Dominant Shape (F)	Seeds
FOSSILS						
Eocene (<i>Phoenicites occidentalis</i>)	40.0	15.0	16.9	10134.0	Elliptic oblong (1)	1
Eocene (Geiseltal)	20.0	6.0	8.0	960.0	Cylindrical (1)	1
Eocene	8.9	5.6	4.9	257.6	Ovoid (0.5)	8
Miocene	16.1	9.8	8.9	1425.6	Ellipsoidal (1)	11
Pleistocene*	14.6	8.2	7.5	955.6	Ovoid (0.7)	10
ARCHAEOLOGICAL						
Neolithic	18.6	7.9	7.0	1080.9	Ovoid (0.5)	8
Chalcolithic	13.4	6.1	5.6	522.4	Elliptic oblong (0.7)	14
Bronze Age	14.0	6.3	5.9	536.0	Cylindrical (0.7)	75
Iron Age	17.0	7.5	6.2	827.7	Cylindrical (0.5)	29
Garamantian	17.5	7.0	6.5	796.3	Elliptic oblong (1)	1
Roman	23.2	8.5	7.4	1557.8	Elliptic oblong (0.5)	35

Working taxa or Period	L (mm)	B (mm)	D (mm)	VP (mm ³)	Dominant Shape (F)	Seeds
Middle Ages	21.0	8.0	7.0	1278.5	Elliptic oblong (0.5), Cylindrical (0.5)	6
Middle Ages Canaries**	12.1	7.4	6.7	621.7	Ellipsoidal (0.7)	61
MODERN						
<i>Phoenix dactylifera</i> s.l.						
<i>P. dactylifera</i> Eastern cluster	22.5	8.1	7.0	1314.4	Elliptic oblong (0.4), Cylindrical (0.4)	644
<i>P. dactylifera</i> Intermediate	26.2	8.3	7.4	1618.0	Cylindrical (0.6)	271
<i>P. dactylifera</i> Western cluster	23.0	9.1	7.7	1658.7	Elliptic oblong (0.5)	2449
<i>P. dactylifera</i> x <i>P. sylvestris</i>	22.2	10.7	9.8	2357.9	Elliptic oblong (0.8)	22
<i>P. atlantica</i>	20.2	9.4	8.2	1613.6	Elliptic oblong (0.5)	119
<i>P. iberica</i>	17.2	9.0	7.9	1229.3	Ellipsoidal (0.5)	241
<i>P. dactylifera</i> x <i>P. reclinata</i>	16.3	7.9	7.2	997.1	Elliptic oblong (0.9)	34
<i>Phoenix sylvestris</i>						
<i>P. sylvestris</i>	17.2	9.6	8.7	1455.6	Elliptic oblong (0.6)	188
<i>Phoenix canariensis</i> s.l.						
<i>P. canariensis canariensis</i>	14.3	8.8	8.0	1041.2	Ellipsoidal (0.9)	2883
<i>P. canariensis porphyrococca</i>	15.6	8.8	8.0	1143.7	Elliptic oblong (0.6)	165
<i>P. canariensis macrocarpa</i>	16.0	9.6	8.7	1394.9	Ellipsoidal (0.8)	1032
<i>P. dactylifera</i> x <i>P. canariensis</i>	17.0	8.8	8.0	1248.9	Elliptic oblong (0.7)	207
<i>P. canariensis</i> x <i>P. reclinata</i>	12.6	8.1	7.4	857.2	Ellipsoidal (0.8)	57
<i>Phoenix theophrasti</i> s.l.						
<i>P. theophrasti</i>	13.9	7.6	7.0	752.0	Ovoid (0.7)	207
<i>P. theophrasti</i> Datça	14.2	7.2	6.5	681.4	Ovoid (0.5)	35
<i>P. theophrasti</i> Gölköy***	16.7	8.1	7.1	954.0	Ovoid (0.5)	15
<i>Phoenix</i> others of the area						
<i>P. reclinata</i>	11.5	6.4	5.6	440.1	Ellipsoidal (0.5)	161
<i>P. abyssinica</i>	11.7	6.4	5.6	423.1	Ellipsoidal (1)	15
<i>P. arabica</i>	11.8	6.8	6.0	490.4	Ellipsoidal (1)	44
<i>P. caespitosa</i>	10.7	7.2	6.5	510.8	Ellipsoidal (0.5)	30

EUROPE AND THE MEDITERRANEAN

Faurby *et al.* (2016) placed the root age calibration for Coryphoideae at the Late Cretaceous (Campanian) (c. 75.8 Myr). The earliest divergence among extant lineages of Trachycarpeae and Phoeniceae (*Phoenix*) (both within Coryphoideae) is estimated to have occurred in Eurasia along the Eocene, according to the results of molecular dating and ancestral area reconstruction methods, with a stem node estimated age of 48.57 Myr (incertitude range of 65–37 Myr) (Dransfield *et al.*, 2005). *Phoenix* expanded subsequently into Africa, the Indian Ocean and India (Baker & Couvreur, 2013).

Read and Hickey (1972) explicitly mention typical leaves of genus *Phoenix* from the Eocene of Puy-en-Velay (France). Different *Palmosperrum* *Phoenix*-like seed types were recovered from Ypresian (Lower Eocene, c. 56–49 Myr) levels of London (Great Britain) (Chandler, 1961) which show morphology similar to modern *Phoenix* seeds (cf. *P. paludosa*). Other fossil seeds from Upper Eocene levels of Tagebau Neumark-Süd (Geiseltal, Germany) presented typical *Phoenix dactylifera* eastern cluster seed morphology, and those of Miocene of Bohemia (Czech Republic), are similar to those of *P. iberica*, *P. sylvestris* and *P. canariensis* var. *macrocarpa* (Table 7) (Rivera *et al.*, 2014).

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2
3 Oligocene *Phoenix* type pollen was recovered from the Caucasus (Georgia) (Shatilova *et al.*, 2011). The
4 coastal facies of Late Oligocene floras from central Europe yielded various palms, including *Phoenix*,
5
6 *Sabal*, *Trachycarpus*, and *Calamus* (Sytchevskaya & Popov, 2005).
7
8

9
10 Main diversification within Laurasian Trachycarpeae occurred associated to dispersal events and islands
11 radiation along the Miocene (22–10 Myr) (Bacon *et al.*, 2012) a parallel could be expected within
12
13 Phoeniceae. *Phoenix* type pollen was recovered from Miocene sites around the Mediterranean: Bés-
14 Konak and others in Anatolia (Turkey) (Biltekin *et al.*, 2006; Paicheler & Blanc, 1981), Arroyo del
15 Culebro (Spain) (Cuevas, 2005). Pollen of Areaceae was recovered in Early Pliocene floras, from
16
17 Barcelona to south of the Ebro Delta (Spain) (Suc *et al.*, 2018). This is consistent with other evidence
18
19 here analyzed (Fig. 5) and supports the existence of *Phoenix* populations in the southern part of the
20
21 Mediterranean during the Miocene. This widespread presence of *Phoenix* could be associated to the onset
22
23 of a differentiation process which persisted during the Pliocene and is the more likely period for the
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25 hybridization event reported by Flowers *et al.* (2019) between *Phoenix theophrasti* and *P. dactylifera*
26
27 long before domestication occurred.
28
29

30
31 Migliore *et al.* (2018) modelling past areas of suitability for *Myrtus communis* identified a few relatively
32
33 small long-term refuge, suggesting that it survived in temporary refuges during glacial periods. For
34
35 instance during the Last Glacial Maximum (26–19 ka), using the MIROC-ESM climate model, these areas
36
37 extended along the coasts of Sicily, Cyclades Islands and Crete, the Levant, Cyprus, southern Spain and
38
39 parts of the Maghreb, and the Canary Islands and the Atlantic coasts of Africa in front of these. However
40
41 the long-term persistence areas inferred as continuously suitable areas over the Last Inter-Glacial period,
42
43 the Last Glacial Maximum and Mid-Holocene are much thinner and, depending on the combined models,
44
45 the Canary Islands and southern Spain disappear (Migliore *et al.*, 2018). *Myrtus communis* is
46
47 characterized by a higher genetic diversity and distinctiveness in the southern part of its range, where it
48
49 was less impacted by glaciations. *Myrtus* is representative of a Tertiary cold-sensitive lineage (as it does
50
51 *Phoenix*) and the severe effects of Pleistocene glaciations were faced despite a relatively small role of
52
53 long-term refuges. *Myrtus communis* seems to have survived the Quaternary glaciations by successive
54
55 regional range shifts towards temporary refuges (migrations) (Migliore *et al.*, 2012, 2018), some western
56
57 cultivars with peculiar morphology like the Nasrid Matle of the Alhambra could have been introduced
58
59 later since these present differences with the neighboring wild populations (De la Herrán *et al.*, 2016).
60

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2
3 The present distribution of *Phoenix* populations seems to have been influenced by its ancient area in
4 continental Eurasia, by plate tectonic movements over long periods of geological time (Eocene to
5 Pliocene), and by reduction and shifting of populations during the colder Quaternary, similarly to what
6 occurred with *Chamaerops* (García-Castaño *et al.*, 2014). Quaternary glaciations strongly determined the
7 present distribution of animal and plant species around the Mediterranean, and parts of the Iberian, Italian
8 and Balkan peninsulas played a role as refuge areas during the last glacial maximum (Mateu-Andrés *et*
9 *al.*, 2013) which could explain the present distribution of endemics such as *Phoenix theophrasti* (eastern
10 Mediterranean), *P. dactylifera* western cluster (Ibero-North African) (Fig. 2). The existence of glacial
11 refugia in the Balkans and western Europe has been confirmed by the integration of phylogeography and
12 population genetics data for other genera (*Olea*, *Myrtus*, *Vitis*) (Table 8) and *Juglans regia* (Pollegioni *et*
13 *al.*, 2017).

24 25 AFRICA

26
27
28 The Phoeniceae expansion into Africa seems to have occurred early since a pollen record of *Phoenix*
29 *reclinata*-type was identified in samples from lacunar environment occupying the Lokichar Basin during
30 Oligocene–early Miocene in northern Kenya (Vincens *et al.*, 2006). It documents what seems to be the
31 earliest African record of *Phoenix* (Pan *et al.* 2006). Middle Miocene palm fossils from the Rusinga
32 Island, on the Kenya shore of Lake Victoria, include a likely *Phoenix* seed (Collinson *et al.* 2009; Pan *et*
33 *al.*, 2006). *Phoenix* pollen is represented, in high proportions, 3.7-9%, of Upper Pliocene layers of Kurkur
34 oasis (Egypt) (Maley 1980). *Phoenix reclinata* seeds were recovered from Pleistocene levels of Sibudu
35 (Kwazulu-Natal, South Africa) (Hall *et al.*, 2014; Wadley, 2004).

36
37
38 Maley (1980) refers to Early Pliocene the colonization of present Sahara by northern and southern floras
39 with different bioclimatic profiles. The dating of lacustrine sediments show that the “green Sahara” also
40 existed during the last interglacial (c.125 ka) and provided green corridors that could have formed
41 dispersal routes. During the early Holocene humid period (c. 1-8.7 ka) and, likely, the Mid-Holocene
42 (7.2-4.5 ka) the region contained a series of linked lakes, rivers, and inland deltas comprising a large
43 interlinked waterway into and across the Sahara, thus facilitating dispersals (Drake *et al.*, 2011; Hoag &
44 Svenning, 2017; Sereno *et al.*, 2008).

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46
47 No evidence was found pointing specifically for *Phoenix arabica* or *P. caespitosa* but this can be due to
48 the low intensity of archaeological investigation in their areas.
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ASIA

Phoenicicaulon mahabalei was described by Bonde *et al.* (2000), as a sheathing leaf base of *Phoenix* from the Deccan Intertrappean beds of India (Upper Cretaceous). A supposed Phoeniceae fossil seed was found in a sauropod coprolite from the Upper Cretaceous at Lameta Formation of Pisdura, Maharashtra (India) (Ambwani and Dutta, 2005), however the section shown (embryo shape and lack of ventral furrow) does not correspond with a *Phoenix* seed. Recently Arecaceae pollen type was identified from this formation at Nand-Dongargaon Basin (Sonkusare *et al.*, 2017). However no evidence of *Phoenix* fossil seeds has been found (Bonde, 2008).

The presence in Shanidar III (Zagros, Iraq) of *Phoenix* phytoliths c. 45 ka (Henry *et al.* 2011) stands as the earliest evidence for *Phoenix* in southwest Asia. Shanidar III *Phoenix* phytoliths are also the earliest evidence of date consumption by humans, in this case Neanderthals.

Table 8. Milestones in the Chrono-geography of *Phoenix* compared with other genera.

Codes: DS, Domestication Syndrome with larger fruits and seeds.

Period	Age	<i>Phoenix</i>	<i>Olea</i>	<i>Myrtus</i>	<i>Vitis</i>	Paleoclimate and geography
Eocene	50-30 Myr	The earliest divergence among extant lineages of Trachycarpeae and Phoeniceae (<i>Phoenix</i>) occurred in Eurasia. Fossil seeds (London and Geiseltal) and leaves (Puy-en-Velay, France)			<i>Vitis</i> originates in the New World and migrates to Eurasia	Onset of the Antarctic ice-sheets. First isolation of the Mediterranean sea (33.9 Myr)
Oligocene	30 Myr	<i>Phoenix</i> type pollen from Georgia (South Caucasus)	Macrofossils (Aix en Provence, France)	Putative <i>Myrtus</i> macrofossils in deposits from central Europe	Bohemian Massif <i>Vitis</i> macrofossils (leaves and seeds). <i>Vitis</i> diversification	
Miocene	23-11 Myr	Fossil seeds of the <i>P. dactylifera</i> type, Tucharice (Czech Republic). Pollen in Lokichar basin (Kenia). First migration episode to Africa (ancestry of <i>P. reclinata</i> ?)		Macrofossils (France), pollen (Spain). <i>Rhodomyrtus</i> – <i>Rhodamia</i> – <i>Myrtus</i> divergence (c. 22 Myr)	Divergence of Eurasian and North American <i>Vitis</i> c. 11 Myr	
Miocene	8-4 Myr	Widespread around the Mediterranean. Onset of an east (<i>Phoenix theophrasti</i>)-west (<i>P. dactylifera</i> western cluster) structure?	Widespread around the Mediterranean, common ancestry, divergence through isolation	Origin of extant lineages of <i>Myrtus</i> (c. 6.7 Myr). Macrofossil fossil at Cornelianio d'Alba (Lago-Mare formation, 5.4 Myr)	Bohemian Massif <i>Vitis</i> macrofossils (leaves and seeds). Divergence of European and Asian species	Mediterranean “salinity crisis” 7.25-5.96 Myr. Mediterranean Sea desiccation (5.9-5.3 Myr)
Pliocene	5-2.8 Myr	Extinction in the center of origin in Central Europe? <i>Phoenix</i> pollen in the Oasis of Kurkur (Egypt) (3.6-2.7 Myr)		Onset of an east-west structure c. 4 Myr. Widespread distribution.		Warm interval 4.1-3.7 Myr. Cooling drier periods 3.7, 3.5 and-3.2 Myr. Mediterranean climate onset c. 3.2 Myr with a warmth event c. 3.2-3 Myr
Pleistocene	2.5-0.2 Myr	Migration to Asia and colonization of the Canary Islands	Widespread around the Mediterranean, divergence through isolation. <i>Olea</i> pollen in Peninj (Tanzania)	Distinct migration events from western Mediterranean to Macaronesia. Fossils in Sao Jorge leaf bed (Madeira Island, Portugal).	Wood resembling that of <i>Vitis vinifera</i> and seeds of <i>V. sylvestris</i> in Tegelen (The Netherlands)	Warmth periods: MIS 9 (0.34-0.32 Myr), MIS 7 (0.25-0.19 Myr),

Period	Age	<i>Phoenix</i>	<i>Olea</i>	<i>Myrtus</i>	<i>Vitis</i>	Paleoclimate and geography
Pleistocene	150-40 ka	Increment of evidence from Africa and west Asia. Migration events from Mediterranean to the Sahara? <i>P. reclinata</i> fossil seeds from Sibudu Cave (KwaZulu-Natal)	Three plastid lineages divergence (c. 130-74 ka)	Divergence of western Mediterranean populations At least two migration events from Mediterranean to the Sahara. The Strait of Gibraltar does not constitute a barrier to gene flow for <i>Myrtus communis</i>		Green Sahara and Mediterranean major forested period during the last interglacial period MIS 5 (126-90 ka). The Strait of Gibraltar acted as a bridge for terrestrial fauna and flora from 90 ka onwards. Onset of Last Glacial Period.
Pleistocene	38-12 ka	Refuge areas in the southern Mediterranean. Seeds of <i>P. reclinata</i> type in Kharga (Egypt). Impression of a <i>Phoenix</i> fruit from Fira Paleosol at Santorini (c. 37 ka). Two episodes of increasing biological evidence occur (based on fossil records from SE Mediterranean)	<i>Olea</i> persisted in glacial refugia (the Near East including Cyprus, The Aegean area and the Strait of Gibraltar)	<i>Myrtus</i> persisted in glacial refugia. Reached the Lake Chad area	Pre-domestication divergence between <i>sylvestris</i> and <i>vinifera</i> populations. The <i>vinifera</i> lineage experienced a steady decline in population size thereafter	Several intense cooling events 38-34, 23.8 (H2), 16 (H1) ka. Last Glacial Maximum (23-19 ka). Relatively milder Bolling-Allerod ((15-13 ka). An extremely arid and cold period in Younger Dryas (12.7-11.5 ka)
Holocene	11.7-7 ka	Repeated presence of <i>Phoenix</i> pollen in Takarkori rock shelter in central Sahara. Earliest cultural evidence (<i>Phoenix</i> palm image in rock paintings of East Africa). First occurrence of <i>Phoenix</i> in the Arabian Peninsula (phytoliths from Awafi c. 8 ka)	Recolonization of the Mediterranean from glacial refugia	<i>Myrtus</i> wood remains in el-Wad Cave (Israel)	Mild domestication bottleneck. Seeds of domesticated types in Southern Caucasus and West Asia. DS (doubtful datation). Earliest biomolecular evidence for grape wine in the South Caucasus (8-7.8 ka) and the Near East (7.4-5 ka)	Glacial retraction. Early Holocene humid period, the wettest phase of the last 25 000 years (9.5-8 ka). A sudden cooling and decrease in precipitation (c. 8.2 ka). Abrupt desertification in Africa (8-4.5 ka)
Holocene	6.5-5 ka	Spread throughout SW Asia, cultivation and domestication of <i>P. dactylifera</i> eastern cluster. Seed remains in the Teshuinat Valley (Libya). Beginning of a sigmoidal pattern due to the increase of cultural evidence (Fig. 7)	Eastern Mediterranean olive oil trade. DS. Olive seeds from Neolithic site Mora Cavorso (Italy) identified with DNA barcode		Spread of grapevine cultivation to Egypt and Lower Mesopotamia. Earlier <i>Vitis</i> pollen records in northern Iran	A wetter period gradually evolving to drier conditions (6-5.4 ka)
Holocene	4.7-4 ka	Beginning of date palm cultivation in the Nile Valley (Egypt). <i>Phoenix</i> pollen in Gobero cemetery (Niger) (c. 4.7 ka)	Western Mediterranean olive exploitation. DS			Fully developed aridity in the Mediterranean but attenuated in the eastern part (4.5-4 ka)

Period	Age	<i>Phoenix</i>	<i>Olea</i>	<i>Myrtus</i>	<i>Vitis</i>	Paleoclimate and geography
Holocene	4-1.35 ka	Continuous increase of seed dimensions. DS. (c. 5-1.3 ka)		Spread of eastern cultivars in western Mediterranean	Spread of grapevine cultivation to western Europe. Divergence between wine and table grapes	More pronounced arid conditions occurred in West Asia c. 3 ka
Holocene	2-1.5 ka	Spread in the Mediterranean and North Africa of <i>P. dactylifera</i> western cluster cultivation. Wide commercial diffusion of <i>P. dactylifera</i> eastern cluster	Eastern morphotypes appear in the western part. DS	Widely used in West Asia and the Mediterranean in medicine and magic		Periods of increased moisture at times e.g. 1.6-1.2 ka
References		Baker & Couvreur, 2013; Cremaschi <i>et al.</i> , 2014; Flowers <i>et al.</i> , 2019; Fuller, 2018; Maley, 1980; Mercuri, 2008; Parker <i>et al.</i> , 2004; Rivera <i>et al.</i> , 2014; Sereno <i>et al.</i> , 2008; Tengberg, 2012; Wadley, 2004. Fig. 6; Fig. 7	Besnard <i>et al.</i> , 2013, 2018; Dominguez <i>et al.</i> , 2001; Fuller, 2018; Gismondi <i>et al.</i> , 2012; Kassa <i>et al.</i> , 2019	De la Herrán <i>et al.</i> , 2016; Góis <i>et al.</i> , 2018; Kovar <i>et al.</i> , 2006; Migliore <i>et al.</i> , 2012; Rivera <i>et al.</i> , 2012	Burgh, 1974; Kvaček & Teodoridis, 2007; Liu <i>et al.</i> , 2016; McGovern <i>et al.</i> , 2017; Naqinezhad <i>et al.</i> , 2018; This <i>et al.</i> , 2006; Wan <i>et al.</i> , 2013; Zhou <i>et al.</i> , 2017	Abrantes <i>et al.</i> , 2012; Drake <i>et al.</i> , 2011; Finné <i>et al.</i> , 2011; Hoag & Svenning, 2017; Robinson <i>et al.</i> , 2006; Sereno <i>et al.</i> , 2008; Soria <i>et al.</i> , 2017

PRE-DOMESTICATION GENERAL VIEW

Our model (Fig. 7) shows an almost parallel evolution of Bayes factor and Shannon index values. Accumulated evidence shows a progress with several milestones: First, c. 32 ka and, second, 18 ka, two episodes of increasing biological evidence occur (due to fossil records). Presumably with scarce to null human influence. The increase of biological evidence after 16 ka concentrates in the SE Mediterranean and Egypt (Fig. 5. B), and, it is mainly related to species like *P. theophrasti* or *P. reclinata* c. 10 ka.

The above milestones coincide with shifts of the barycenter (Fig. 6). From 50 Myr until 11 ka the barycenter moved southwards 25 degrees. This is seemingly due to the steady southwards spread of *Phoenix* genus from its Eurasian center of origin into Africa, the Indian Ocean and India followed by local extinction in northern Eurasian areas during coldest episodes of glaciations. According to the paleontological evidence (Table 7, Rivera *et al.*, 2014) *Phoenix* palms with seeds similar to those of modern *P. dactylifera* Eastern cluster, *P. iberica*, *P. theophrasti*, *P. canariensis* and *P. reclinata* existed during the Tertiary in Europe and around the Mediterranean. The possibility of superposing areas and hybridization events between these, like those reported by Flowers *et al.* (2019), was possible and therefore could have occurred long before the onset of domestication.

PHOENIX (ARECACEAE) CENTERS AND NONCENTERS

GEOGRAPHICAL LIMITS AND BARYCENTER

For historical reasons our database is overloaded with details on modern date palm groves in Spain (Iberian Peninsula and the Canary Islands) which is evident in Fig. 2. However Bayesian (Fig. 5) and entropy analyses overcome this bias and are a relatively good marker for ancient cultivation, particularly above 17° N. Lat. The low values below this parallel merit study and can be read as a result of a relatively low intensity in the investigation from an archaeological view point to the south of 17° N Lat. Thus, likely novel discoveries referring to *Phoenix* palm, wild and cultivated, can be expected from this area.

Latitude determines clear limits for *Phoenix* populations, wild and cultivated. These limits vary according to different climate scenarios. Under the current conditions, in Europe and West Asia, the northern limit is, with a maximum likelihood, situated along parallel 37° (36° to 38 N°) from the Aegean shores to the southern Iberian Peninsula. Some exceptional northern isolates are situated in Menton (France) and the

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3 Italian Riviera (Sasso Valley at Bordighera). Fluctuations of this northern limit determined shifts of the
4 barycenter for the accumulated assemblage of data within a determined period (Fig 6). The barycenter
5 started far north because the *Phoenix* fossils seeds were recovered from the Tertiary of Central Europe,
6 which seems to be the center of origin for the genus *Phoenix* (Rivera *et al.*, 2014). Major driving factors
7 were the variation of average and extreme temperatures. The Earth's climate became cooler through the
8 Tertiary (65 Myr) with frequent oscillations that increased in amplitude and lead to the series of major ice
9 ages of the Quaternary (2.4 Myr to the advent of a warmer climate since 12 ka) (Hewitt, 2000; Hughes *et*
10 *al.*, 2006). Southern limits are clearly defined in Africa, India and Sri Lanka and less defined in SE Asia.
11 *P. reclinata* extends south to the Cape Region in Africa and biological evidence is available for this
12 species near the equator in East Africa before 0.15 Myr (Fig. 5 A), however evidence (biological and
13 cultural) is scarce within the area of this species. Evidence is absolutely missing for the area of *P.*
14 *caespitosa* and *P. arabica*, presumably due to the lack of detailed archaeological and paleontological
15 studies.
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29 The western limit is defined by the barrier that constitutes the Atlantic Ocean. However, *Phoenix* reached
30 in different periods Atlantic archipelagos like the Canary Islands, Madeira, Azores and Cabo Verde. The
31 Indus Valley marks the eastern limit for the ensemble of species here analyzed. However this is an
32 artificial limit, here adopted, based on the easternmost areas of *P. dactylifera*, since other *Phoenix* species
33 extend into East Asia (Barrow, 1998; Beccari, 1890; Rivera *et al.*, 2014). Genus *Phoenix* extends east to
34 the islands of Taiwan and of Batanes in the Philippines where other species occur (Barrow 1998; Rivera
35 *et al.*, 2014). The barycenter for the ensemble of data moved eastwards since 15 Myr to 3.7 ka (Fig. 6)
36 due to the increasing evidence recovered from West Asia and East Africa (Fig. 5). Since 3.7 ka the
37 barycenter shifted westwards associated to the increase of *Phoenix dactylifera* cultivation in North Africa
38 and the Mediterranean (Fig. 6).
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49 Consider that the small points in Fig. 5 appearing in central and northern Europe since 7 ka onwards, are
50 due to the resilience of our accumulative model with respect to fossil evidence and to the presence of
51 imported date fruits.
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CENTERS OF ORIGIN FOR DOMESTICATED *PHOENIX DACTYLIFERA*

The image shown in Fig. 2 for date palm species modern distribution is closest to Harlan's view of diffuse centers or, in his term, "noncenters." However, as we will see later, Bayesian models offer a more accurate picture.

The Bayesian model for the assemblage of tests shows a radial pattern of lines (in red in Fig 5.C-E) connecting areas with higher likelihood, some extending along thousands of kilometers:

- a. From the Mediterranean shores and Jordan Valley to Iran and the Indus Valley (Fig. 5. C), a line connect sites where it was documented *Phoenix dactylifera*, but also existed *P. theophrasti* in the western end and *P. sylvestris* in the eastern. The presence of 27 palm phytoliths interpreted as date palm (*P. dactylifera*) in the Pottery Neolithic site of Tell Wadi Feinan (8.3 ka) is one of the earliest records of this species in Jordan, an intrusion of these phytoliths from later deposits is a possibility but unlikely (Jenkins *et al.*, 2011). An earlier record comes from Ghwayr 1 (c. 10 ka) in form of a seed (Simmons & Najjar, 2006). The presence of Arecaceae phytoliths, likely of *Phoenix*, is detected in the Arabian Peninsula since 8 ka, however pollen is missing (Parker *et al.*, 2004). Evidence exists for the presence of *Phoenix* in the Indus valley since c. 8 ka (Fig. 5), which could be related to *P. sylvestris* or to *P. dactylifera* eastern cluster. An important zone confirmed by the assemblage of tests is eastern Mediterranean (the Levant), which coincides with the area of *P. theophrasti* (Fig. 2) but also, at least in its southern part, of *P. dactylifera*. Analysis of cytoplasmic DNA (Chaluvadi *et al.*, 2018; Flowers *et al.*, 2019) and whole genome sequencing (Flowers *et al.*, 2019) are at odds on the origin of the *Phoenix dactylifera* western cluster, the later proposes *Phoenix theophrasti* as male donor for nuclear genome. Thus, at least, part of the *P. dactylifera* western cluster would be a result of hybridization of Cretan palm (*P. theophrasti*) with palms of the *Phoenix dactylifera* eastern cluster. This hypothesis could be further tested by analyzing DNA from "Methuselah" (Sallon *et al.*, 2008), as well as other plants obtained through induced germination of archaeological seeds (2000 years old) from Masada (Israel). Further studies of *Phoenix theophrasti* populations would be advisable, since *Phoenix dactylifera* is known to be widely cultivated in Crete and continental Greece in Orthodox monasteries and churches for food and religious purposes, thus, it may mask the direction of hybridization (Obón *et al.*, 2018). However we could not dismiss the possibility of hybridization

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3 events occurring long before cultivation and domestication occurred, when ancestors of modern
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5 *Phoenix* species cohabited around the Mediterranean (Table 7).
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- 7 b. A line which requires further confirmation, but is older than 7 ka, connects central Sahara with
8
9 northern Sahel (Fig. 5. C-D). Here apparently existed *P. dactylifera* to the north and *P. reclinata*
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11 to the south. Notably late Pleistocene and early Holocene palaeohydrology of the Sahara (Drake
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13 *et al.*, 2011) could explain this line.
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- 15 c. The line linking upper Mesopotamia with north-eastern Oman through the shores of the Persian
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17 Gulf and the Gulf of Oman c. 5 ka-0.5 ka (Fig. 5. D-F). This line seems associated to the
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19 cultivation of typical *Phoenix dactylifera* eastern cluster. Note that for this zone the pre-
20
21 domestication evidence is missing (Fig. 5. B). The lack of fossils before the Holocene in the
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23 western shores of the Persian Gulf and the whole Arabian Peninsula (Fig. 5. B & C) supposes a
24
25 relatively late introduction of *Phoenix dactylifera* eastern cluster individuals in the area, likely
26
27 imported from the Jordan Valley zone. These palms seemingly produced fruits with shorter and
28
29 thinner seeds than those of the western cluster and similar to those of modern cultivars of the
30
31 eastern cluster (Table 7). Notably Tepe Gaz Tavila (Iran) (7.4 ka) and Dalma Island (UAE) (c. 7
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33 ka) seeds present this morphology (Rivera *et al.*, 2014). Mehrgarh (Indus Valley, Pakistan) (c.
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35 7.5 ka) seeds are similar but somewhat longer (c. 20 mm long) than the former. A recent study
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37 proposes palms from Oman as remains of wild date palm populations and poses them at the
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39 origin of the *Phoenix dactylifera* eastern cluster (Gros-Balthazar *et al.*, 2017; Wales &
40
41 Blackman, 2017). In Dhofar (Oman) *Phoenix* occurs sporadically in the *khawrs* (small estuaries
42
43 without mangroves) but its pollen is only, and rarely, found in the more recent layers of the
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45 palynological assemblage, 2.7-0 ka, investigated by Hoorn & Cremaschi (2004).
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- 47 d. The line from the core nucleus of Palestine and Judea along the Jordan Valley to Egypt, and,
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49 chiefly, the Nile Valley c. 7 ka-0.5 ka (Fig. 5. C-F). Here the existence of pre-domestication
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51 evidence (Fig. 5. B) appears linked to *P. theophrasti* in the northern end and *P. reclinata* in the
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53 southern one. The presence of *P. dactylifera* is frequent along the Nile and in neighboring oases
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55 from c. 4 ka onwards, always accompanying cultivation.
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- 57 e. The line linking Cyrenaica (Libya) with north-eastern Mali and farther south, through the
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59 mountains and plateaux of southern Sahara crossing the area of modern Touareg populations and
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along the ancient Garamantes' settlements, it appears clearly defined c. 1.85 ka to 0.5 ka (Fig. 5.

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3 E-F). Possibly it is more ancient and related to a mid-Holocene wetter climate c. 6 ka but
4 evidence for this period and zone is fragmentary and controversial (Drake *et al.*, 2011; Coulthard
5 *et al.*, 2013). However at Lake Yoa (Chad) within a series of pollen analyses covering 6 ka to
6 present, *Phoenix* is significantly represented only from 0.8 ka onwards (Lézine *et al.*, 2011). At
7 the supposed Oyo oasis which was a source of sodium carbonate (NW of Merga, Sudan) a dry
8 *Phoenix dactylifera* palm leaf was dated c. 0.5 ka (Haynes, 1989).

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14 f. The line from Gabés area (Tunisia) to the Canary Islands along the northern border of the Sahara
15 Desert coinciding with the extent of Berber settlements and Berber-speaking areas, c. 1.85 to 0.5
16 ka (Fig. 5. E- F). It is likely associated to the western cluster of *Phoenix dactylifera* and to the
17 African ancestors of *P. dactylifera* of the Canary Islands. *Phoenix canariensis* seems to have
18 reached the Canary Islands long before humans arrived to the archipelago (Saro *et al.*, 2015)
19 (Fig. 5 B-D).
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26 g. The line along North Africa and southern Europe, including islands of the Mediterranean. This
27 appear well defined c. 1.85 ka, during the Roman rule of the Mediterranean. However the
28 presence of *Phoenix* is earlier. By 2.5 ka a disjunction existed between *Phoenix* populations
29 along western and eastern south Mediterranean shores, with a gap from modern Algeria to
30 eastern Libya. This gap appears filled since 2.2 ka. Although *Phoenix* pollen was documented in
31 Tertiary formations of Spain, fossil seeds were not recorded (Rivera *et al.*, 2014). The Iberian
32 Peninsula and Balearic Islands became a significant zone between 4 ka and 1.85 ka (Fig. 5. D &
33 E) which appears related to the *Phoenix dactylifera* western cluster, and includes *P. iberica*. The
34 possibility of existing *Phoenix* glacial refugia around the Strait of Gibraltar like for other genera
35 (Table 7) merits further investigation.
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46 Shannon's index of entropy confirms the above lines. These lines are, likely, a response to environmental
47 constraints but also a result of cultural and economic factors (i.e. commercial routes) extending over
48 centuries. These lines can be considered "non-centers" in the sense of Harlan (1971). Note that the onset
49 of the main structure of the *Phoenix* modern cultivation area around the Mediterranean, in North Africa
50 and West Asia is traced back to 1.85 ka and earlier (Fig. 5. E and Fig. 2) long before the expansion of
51 Islamic culture (since 1.3 ka).
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57 Genetic and archaeobotanical studies support a model for Olive (*Olea europaea* L.) with a domestication
58 in the Levant with subsequent dispersal and some introgression from wild populations in the western
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3 Mediterranean (Fuller, 2018; Khadari & El Bakkali, 2018). For (Besnard & De Casas, 2016) there is not
4
5 enough genetic or archaeological support for an independent primary domestication of the modern olive
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7 in the central or western parts of the Mediterranean Basin. In Spain the increase in size of olive stones
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9 during the first millennium BC would reflect the introduction of domesticated olive eastern cultivars
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11 (Fuller, 2018). Besnard *et al.* (2018) underline the existence of three main gene pools (west, center and
12
13 east Mediterranean) which diverged and merged along different episodes from the Pliocene to c. 6 ka,
14
15 before and during cultivation (Table 7).

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17 For grapevine (*Vitis vinifera* L.), a more cold tolerant species, which presently overlaps with *Phoenix* area
18
19 only in parts of the Mediterranean, the synthesis of diverse molecular evidence supports at least two
20
21 separate domestication events that gave rise to cultivated grape; one derived from the Transcaucasian
22
23 wild grape (c. 8 ka in Georgia) and another from the wild grape of Western Europe (McGovern *et al.*,
24
25 2017; Riaz *et al.*, 2018; This *et al.*, 2006).

26
27 Rosemary (*Rosmarinus officinalis* L.) (Mateu-Andrés *et al.*, 2013) presents a different pattern of
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29 expansion from its center in western Mediterranean southwards and eastwards across the Iberian
30
31 Peninsula and North Africa, when this occurred is not yet determined.

32 33 34 DOMESTICATION SYNDROME VERSUS WILD SYNDROME

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37 Humans have fully domesticated c. 250 species and domesticated plant species are found in 160 families,
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39 as a result of continuous interactions since 12 ka (Smýkal *et al.*, 2018). The transition from wild to crop
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41 species is the result of a succession of events and archaeological evidence suggests that cultivation
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43 preceded domestication (human selection of favorable traits). Note that the onset of plant and animal
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45 domestication in the eastern Mediterranean by 12 ka was associated to a gradual transition from foraging
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47 and hunting to farming and herding (Zeder, 2008). This led to the onset of a domestication syndrome
48
49 characterized by traits which facilitate the ease of propagation, growth and harvest, but usually have
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51 associated reduced dispersal ability of seeds and fruits (Smýkal *et al.*, 2018) and also pollen.

52
53 The existence of present wild *Phoenix dactylifera* populations has been argued as a pointer for centers of
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55 origin for date palm domestication. Gros-Balthazar *et al.* (2017 & 2018) claimed that, notably, small
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57 fruits with thin, and not very palatable mesocarp, and an ellipsoidal seed outline in palms, living
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59 unattended, in more or less natural habitats, associated to a high degree of polymorphism is enough to
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3 define several populations of Oman as “wild” and, implicitly, ancestral. This is defined as the “wild
4 syndrome” (Gros-Balthazard *et al.*, 2017). Similar syndromes were described for the wild forms of the *P.*
5 *dactylifera* western cluster, described as *P. iberica*, in south-eastern Spain (Carreño, 2017; Rivera *et al.*,
6 2014). However Obón *et al.* (2018) have shown that in each one of the three *Phoenix* species they studied
7 in the Mediterranean and the Canary Islands (*P. canariensis*, *P. dactylifera* (including *P. iberica*) and *P.*
8 *theophrasti*) exists all possible stages between “wild” and careful cultivation that were described by
9 Levadoux (1965) for grapevine: “wild” post cultural, wild subsponaneous, wild spontaneous (feral,
10 autochthonous or hybrids). Furthermore, the propagation by seedlings which is the commonest in Spain,
11 but also in parts of Africa and West Asia (Johnson *et al.*, 2013; Rivera *et al.*, 2015), favors the persistence
12 of the wild syndrome. The offspring of one or more date palm cultivars would count, after a few
13 generations, an increasing number of forms closely related to wild forms, as it occurs with grapevine
14 (Levadoux, 1956).

15
16 Likewise, the wild-like populations of Oman may also be a result of the hybridization of *P. dactylifera*
17 eastern cluster and other *Phoenix* species. The shape of their seeds shows no relation with the early
18 archaeological evidence (vid. above) and seems not directly involved in the origins of *Phoenix*
19 *dactylifera*. Further evidence is required to confirm both the wild and ancestral status of these Omani
20 *Phoenix* populations.

21
22 Seed dimensions are not conclusive in *Phoenix*, displaying notable oscillations at intervals (Table 7)
23 (Rivera *et al.*, 2014). However Fuller (2018) presented evidence of increasing dimensions through time as
24 part of the domestication syndrome (Table 8). In the case of *Phoenix* this domestication syndrome seems
25 to involve more characters: shortening and reduction in number of basal acanthophylls, shortening of
26 leaves and reduction of the number of folioles, loss of successful natural wind-pollination (requiring
27 artificial pollination), and increase of the weight of infructescences due to the greater number of dates,
28 larger dates and seeds. The increment in dimensions of date’s mesocarp and its palatability is also part of
29 this domestication syndrome (data from the National Collection of *Phoenix* germplasm of Spain,
30 Phoenix-Spain (2018)). In other genera, such as *Olea* or *Myrtus*, the domestication syndrome is more
31 tenuous (Besnard *et al.*, 2018; De la Herrán *et al.*, 2016).

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33 A multidisciplinary approach involving genomics, ecology, and techniques like the one here presented is
34 necessary to decipher which traits and genes suffered selection pressure during date palm domestication.
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3 For the genus *Olea*, in areas where intensive olive cultivation over centuries took place it was repeatedly
4 proven that the putatively “wild” individuals were the result of outcrossing between the cultivated and
5 wild forms or dissemination of seeds from cultivation areas (Kassa *et al.*, 2019).
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9 Finally grapevine (*Vitis vinifera* L.) presents genetic relationships between wild and cultivated
10 populations in the Mediterranean, Transcaucasia, and Central Asia, with a considerable amount of gene
11 flow, which limited the differentiation between the two subspecies (*V. vinifera* subsp. *vinifera* and *V.*
12 *vinifera* subsp. *sylvestris* Hegi) (Ekhvaia *et al.*, 2014; Riaz *et al.*, 2018).
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18 Therefore it is not enough to find “wild looking” populations (on phenotypic or molecular grounds) to
19 mark the population as genuine “wild”, and the area as a centre of origin. It is necessary to analyse the
20 diachronic sequence combining as many types of evidence as possible over a wider geographical range.
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24 ACCUMULATED CULTURAL AND BIOLOGICAL EVIDENCE AND DOMESTICATION

25
26 The earliest cultural evidence, c. 12 ka, appears in form of a *Phoenix* palm image in rock paintings of East
27 Africa (Leakey, 1983). This could be related to *Phoenix reclinata* (at least falls within the modern area of
28 this species) and means a southwards shift of the barycenter (Fig. 6). A further step (Fig. 7), c. 8 ka,
29 represents an increase of biological evidence and its diversity, based on archaeobotanical evidence. The
30 beginning of an acceleration of temporal accumulation of evidence within a sigmoidal pattern (Fig. 7), c.
31 6 ka, is particularly due to the increase of cultural evidence, presumably associated to the domestication
32 and wide cultivation of *Phoenix dactylifera*, notably the eastern cluster. The maximum increase rate
33 extends from 6–2.1 ka, approaching a climax by 1 ka.
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44 The global increase of *Phoenix* biological evidence, c. 8 ka, appears associated to an eastwards shift of
45 the barycenter (Fig. 6), which is more pronounced after 6.5 ka, is due to the onset for *Phoenix dactylifera*
46 eastern cluster of a wider area associated to extensive cultivation and domestication. Within the period of
47 a high rate of evidence accumulation, c. 4.5 ka, we can place the beginning of the westwards expansion of
48 *Phoenix* cultivation connected to the beginning of a wider cultural evidence (Fig. 6 and 7). Since then
49 exists a steady north-westward shift of the barycenter of accumulated evidence associated to the
50 expansion of date palm cultivation areas in the western Mediterranean and NW Africa.
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58 This westward shift was gradual (Figs. 5 and 6) and seems to have involved in some places the
59 superposition of eastern material and/or practices onto pre-existing isolated western nuclei of *Phoenix*
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3 *dactylifera*. This suggests that the main domestication events of *P. dactylifera* occurred to the east of 30°
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5 E Long. and left archaeological evidences before 7 ka. This is in agreement with the conclusions of
6
7 Tengberg (2012) for early cultivation of the date palm in the arid regions of the Middle East, but our
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9 results set focus on the Levant, Jordan Valley and NW Arabian Peninsula.

12 13 CONCLUSIONS

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15 Entropy (Shannon's index) and Bayesian analysis applied to georeferenced and chronologically
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17 referenced data from different sources (archaeobotanical, textual, numismatic, pottery, etc.) compared
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19 with modern distribution of *Phoenix* in Europe, Africa and West Asia furnish a powerful tool for
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21 modelling with relative precision, in terms of probabilities, the distribution of ancient palm groves and the
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23 date palm species. These models can be matched against others generated based on diversity of wild and
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25 cultivated palms or on molecular evidence. However, discriminating *Phoenix* species in the case of most
26
27 types of evidence is impossible.

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29 The setting up and origins of current *Phoenix* diversity can be traced through the models showing relevant
30
31 zones and periods since 50 Myr. Here we show a model of *Phoenix* expansion that could be linked to
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33 domestication processes from 8 ka onwards. Between 8 ka and 5 ka evidence gradually accumulates in
34
35 the Levant and W Asia associated to the domestication of *P. dactylifera* eastern cluster. Since 4.2 ka a
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37 westward expansion of palm groves could be associated to the increasing role of *P. dactylifera* western
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39 cluster under cultivation and the hybridization with the former.

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41 Analyzed evidence suggest that specific differentiation within *Phoenix* genus substantially occurred, at
42
43 least for the western species, in the course of Tertiary and Pleistocene, giving place to the *P. dactylifera*
44
45 eastern and western clusters, *P. canariensis*, *P. theophrasti*, *P. reclinata*, *P. sylvestris* or their ancestors.
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47 The models suggest that pre-domestication hybridization events between *P. dactylifera* and *P.*
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49 *theophrasti*, or *P. canariensis* may have occurred in the Mediterranean long before cultivation started.

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52 Comparison of the different models is useful to determine regions which merit further archaeological and
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54 paleontological research, in this case, particularly the Saharan area below 20° N Lat. The exploration for
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56 the different types of evidence in the areas of *P. reclinata*, *P. caespitosa* and *P. arabica* is still very
57
58 scarce. The lack of paleontological and archaeological excavations in this region could explain this result
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60 rather than the true absence of *Phoenix* palms in the past.

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3 The Bayesian integration of evidences chrono- and georeferenced is applicable to a wide repertory of
4 domesticated genera an species including olive, myrtle, rosemary and others.

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7 A multidisciplinary approach involving genomics, ecology, and techniques like the one here presented is
8 necessary to decipher which traits and genes suffered selection pressure during date palm domestication.
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Fig. 1 *Phoenix* modern populations: wild, cultivated and feral

A. *P. dactylifera* western cluster (*P. atlantica*), Santiago Island (Cape Verde). **B.** *P. canariensis*, San Andrés Valley, Tenerife Island (Spain). **C.** *P. dactylifera* western cluster (*P. iberica*), Abanilla, Murcia (Spain). **D.** *P. dactylifera* western cluster (*P. excelsior*), Elche (Spain). **E.** *P. theophrasti*, Preveli, Crete (Greece) **F.** *P. reclinata* (South Africa). **G.** *P. dactylifera* eastern cluster, Firmihin, Socotra Island (Yemen). **H.** *P. arabica*, Jbel Bura (Yemen).

Photos: **A,** Miguel Angel Esteve. **B,C,E,** Diego Rivera, **D,** Concepción Obón. **F,** Francisco Alcaraz. **G,H,** Joel Lode.

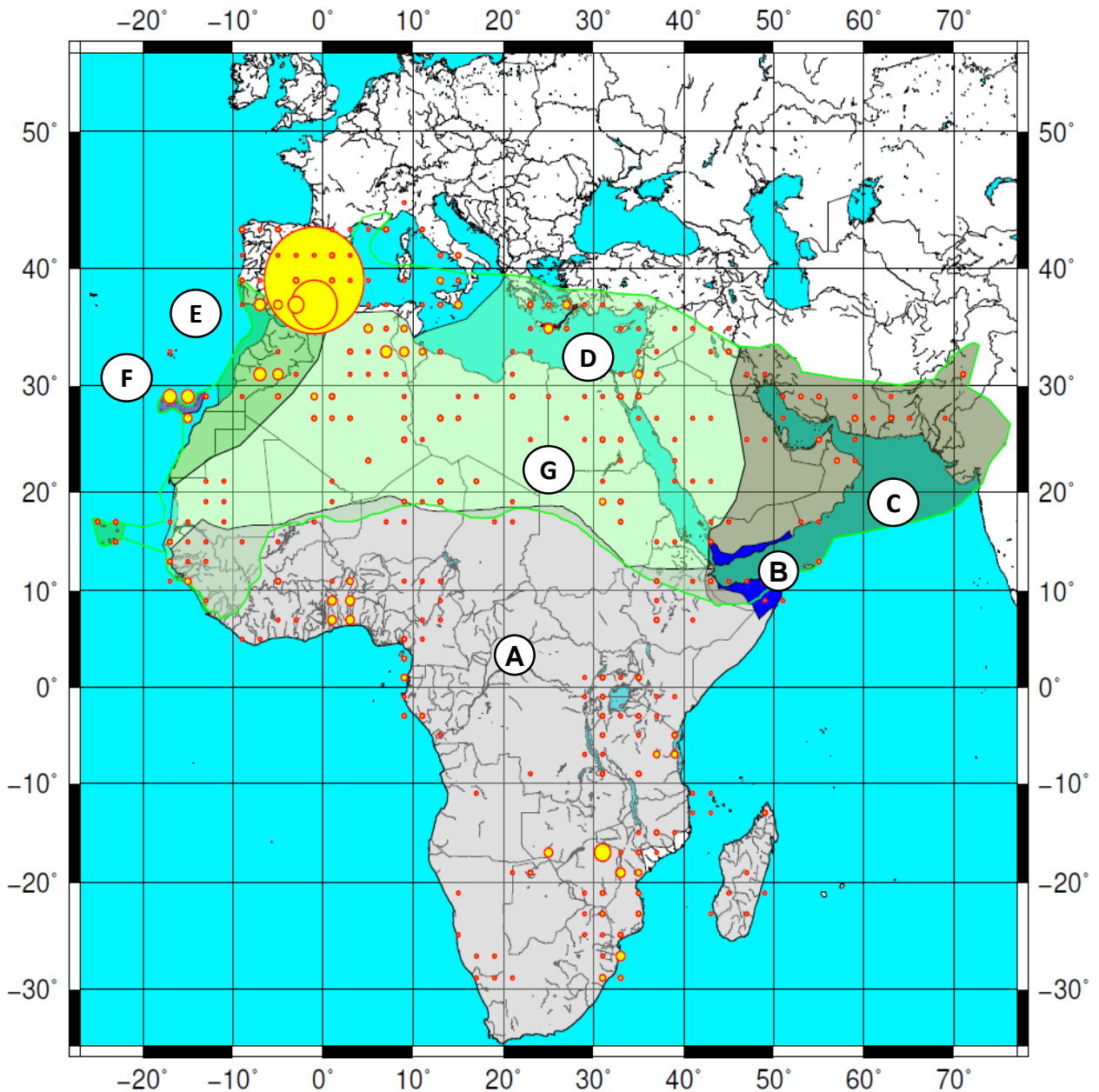


Fig. 2 Map with modern localities and areas of *Phoenix* recorded during the last hundred years

Surfaces are proportional to the number of records for each $2^\circ \times 2^\circ$ cell. Therefore circles reflect the intensity of sampling. Circles are centered in the center of the corresponding $2^\circ \times 2^\circ$ cell, thus may fall outside terrestrial areas. Main taxa: **A.** *P. reclinata*. **B.** *P. arabica* & *P. caespitosa*. **C.** *P. dactylifera* eastern cluster. **D.** *P. theophrasti*. **E.** *P. dactylifera* western cluster (including *P. iberica*, *P. excelsior* and *P. atlantica*). **F.** *P. canariensis*. **G.** *P. dactylifera* intermediate forms and western/eastern hybrid zone.



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Fig. 3 Different types of biological (paleontological and archaeobotanical) and cultural evidence analyzed for *Phoenix*

A, waterlogged *Phoenix theophrasti* seed PPNC (6000–5200 BC), Atlit-Yam structure 20. **B**, *Phoenix canariensis* pollen. **C**, trunks in ceilings, Abanilla, Murcia. **D**, Sandal with palm leaf soles, tomb of Nefertari, Egypt (Museo Egiziano, Turin). **E** *Phoenix dactylifera* male flowers, San Isidro de Albaterra, Alicante. **F**, Birds and palm tree mosaic 4th cent. AD, Jnah, Lebanon (National Museum Archaeology, Beirut). **G**, *Phoenix theophrasti* phytoliths, phase contrast micrograph, c. 1000x. **H**, Villa Livia frescoes (MNR, Rome). **I**, Carthaginian coin, c. 400 BC (Numismatic Museum, Athens). **J**, fragment of alabaster, San'a, Yemen (MNAO Rome). **K**, mosaic of Vila Romana del Casale, Piazza Armerina, Sicily. **L**, Belt plate, Amarejo, Bonete, 3rd cent. BC (Museo de Albacete). **M**, Minoan pottery Heraklion Archaeological Museum, Crete). **Photos: A**, Anat Hartmann-Shenkman. **B**, Gisela Díaz. **C, E, F, J, K**, Diego Rivera. **D, H, I, L, M**, Concepción Bobón. **G**, Francisco Torrella

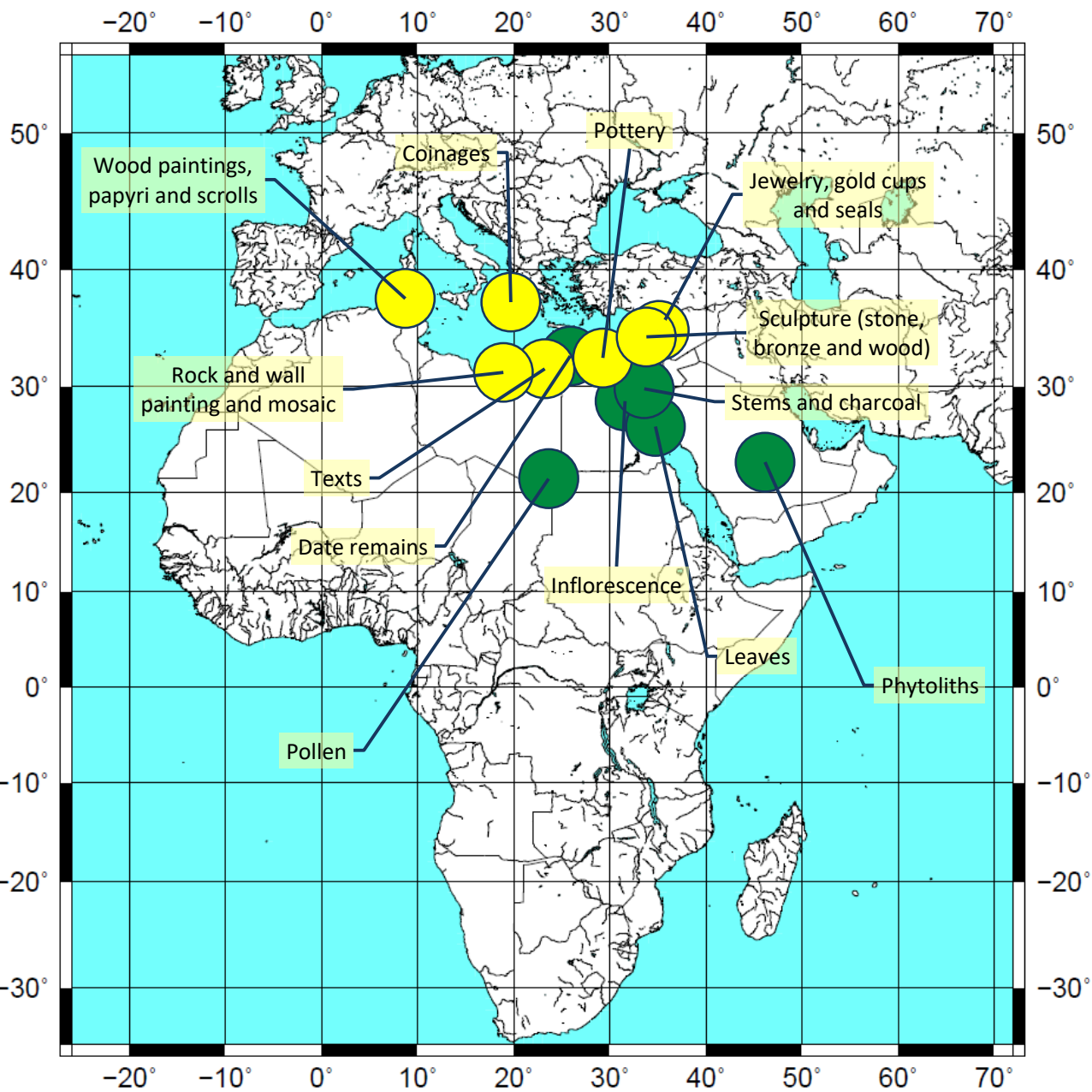
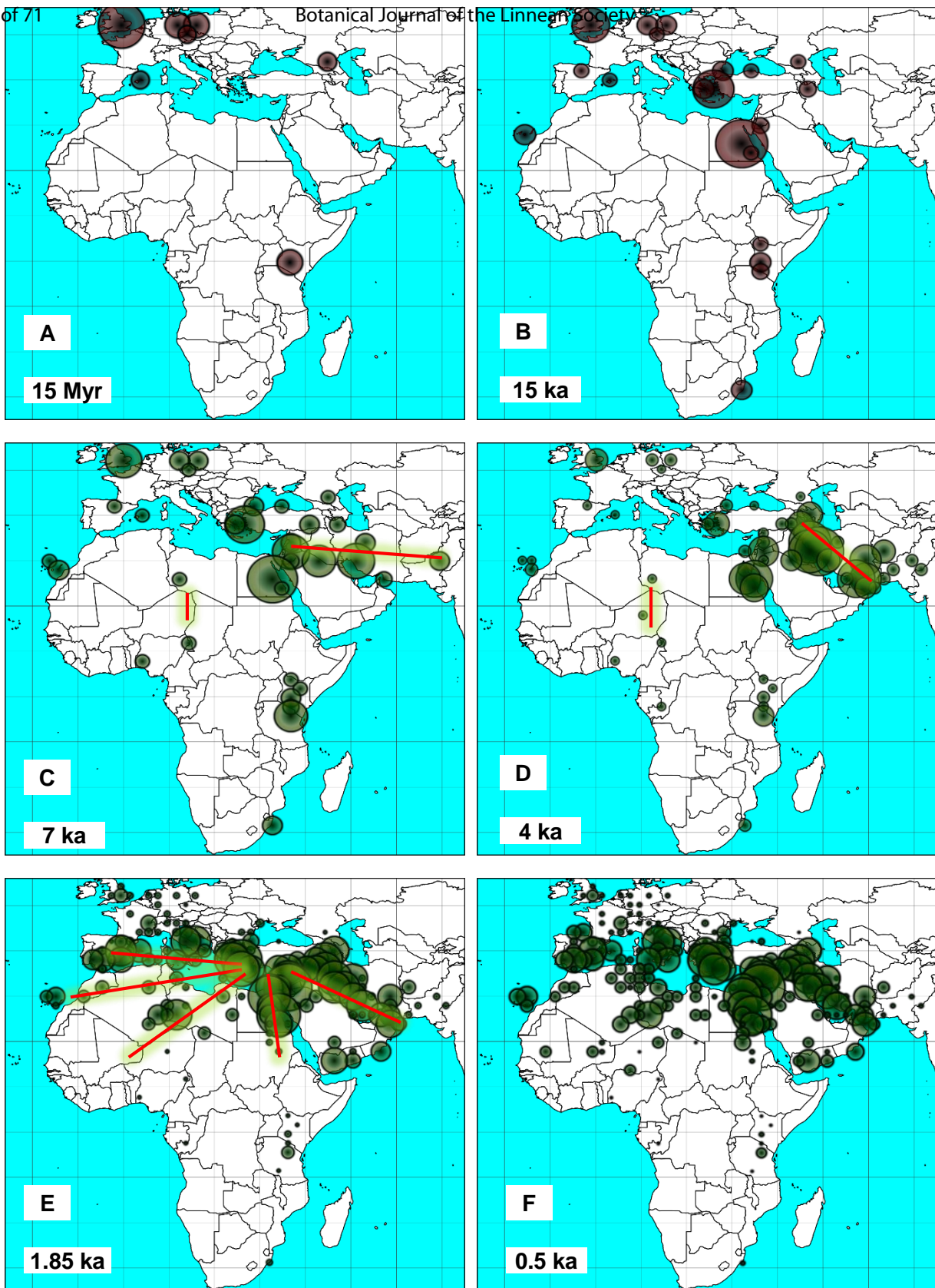


Fig. 4 Barycenter for the different types of biological and cultural of evidence
 Differential coordinates of the barycenter of each one of the biological and cultural evidence types, from the beginning to 0 BP

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51 **Fig. 5 Bayesian model for ancient *Phoenix* areas based on accumulated biological and cultural**
52 **evidence**

53 Maps are built with records of age previous or contemporary to each date. Surfaces are proportional to the \log_{10} of
54 odds of palm groves presence vs. absence (as an estimate of Bayes factor), scaled at 50%. Bubbles are colored
55 in brown for periods exclusively based on paleontological evidence. Note that here we represented the
56 accumulated evidence up to a determined date. Base map: R (2019).

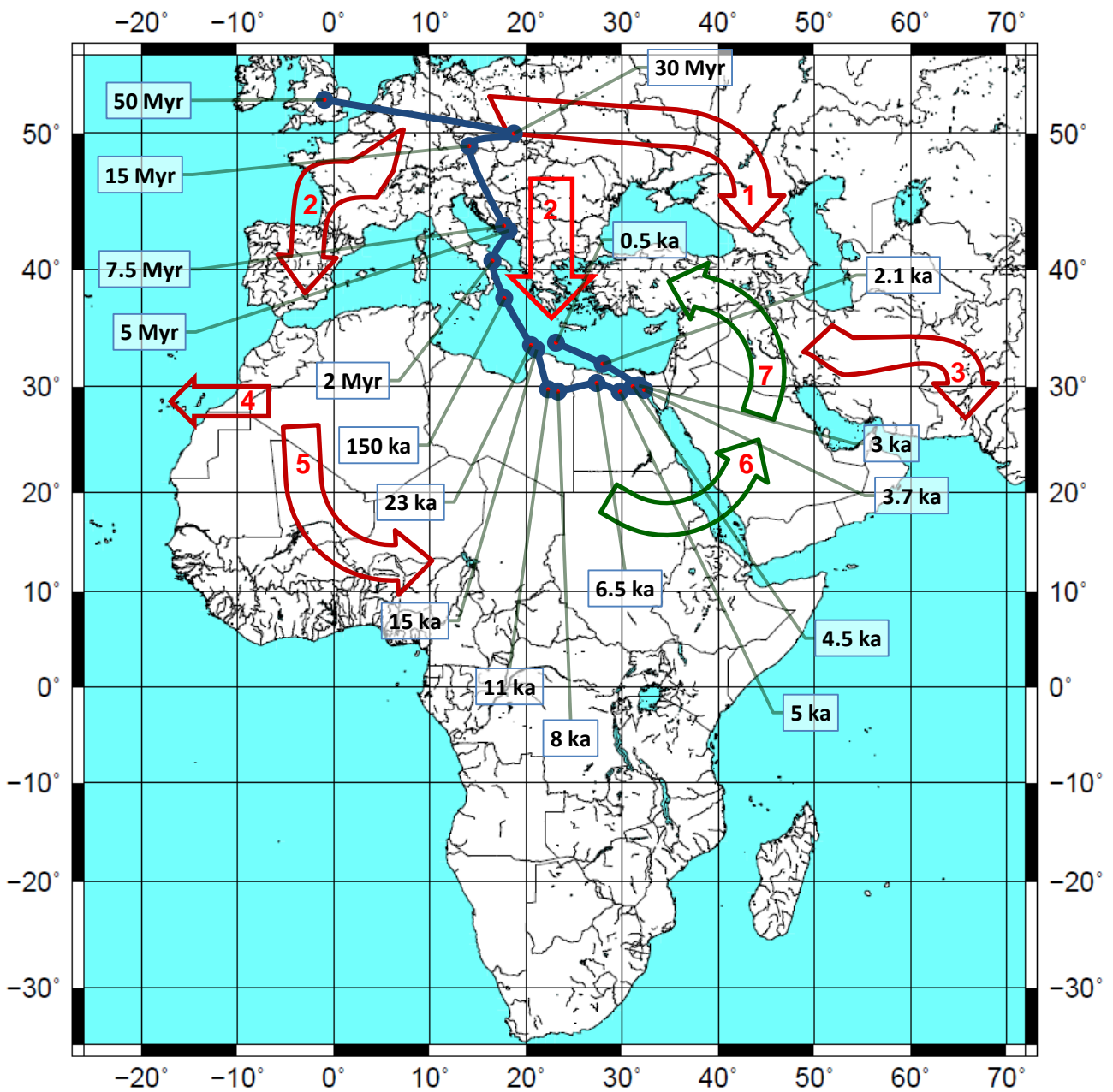


Fig. 6 Displacement of the barycenter for the *Phoenix* area in Europe, Africa and West Asia throughout the analyzed period

The barycenter is calculated with records of age previous or contemporary to each label date considering the latitude and longitude in kilometers of cells with values of the \log_{10} of Bayes factor >0 . **Milestones:** **1.** Migration from the Center of Origin to eastern Europe and the Caucasus from 50 to 15 Myr. **2.** Migrations southwards to the Iberian Peninsula, The Balkans and North Africa from 7.5 to 2 Myr. **3.** Migration to Asia. **4.** Migration to the Canary Islands, between 2 Myr and 100 ka. **5.** Increasing evidence in Africa and west Asia. Extinction in the Center of Origin in Central Europe, between 2 Myr and 11 ka. **6.** Expansion throughout SW Asia associated to the cultivation and domestication of *P. dactylifera* eastern cluster between 8 and 4.25 ka. **7.** Spread, from 3.5 ka, in the Mediterranean and North Africa of the cultivation of *Phoenix dactylifera* western cluster.

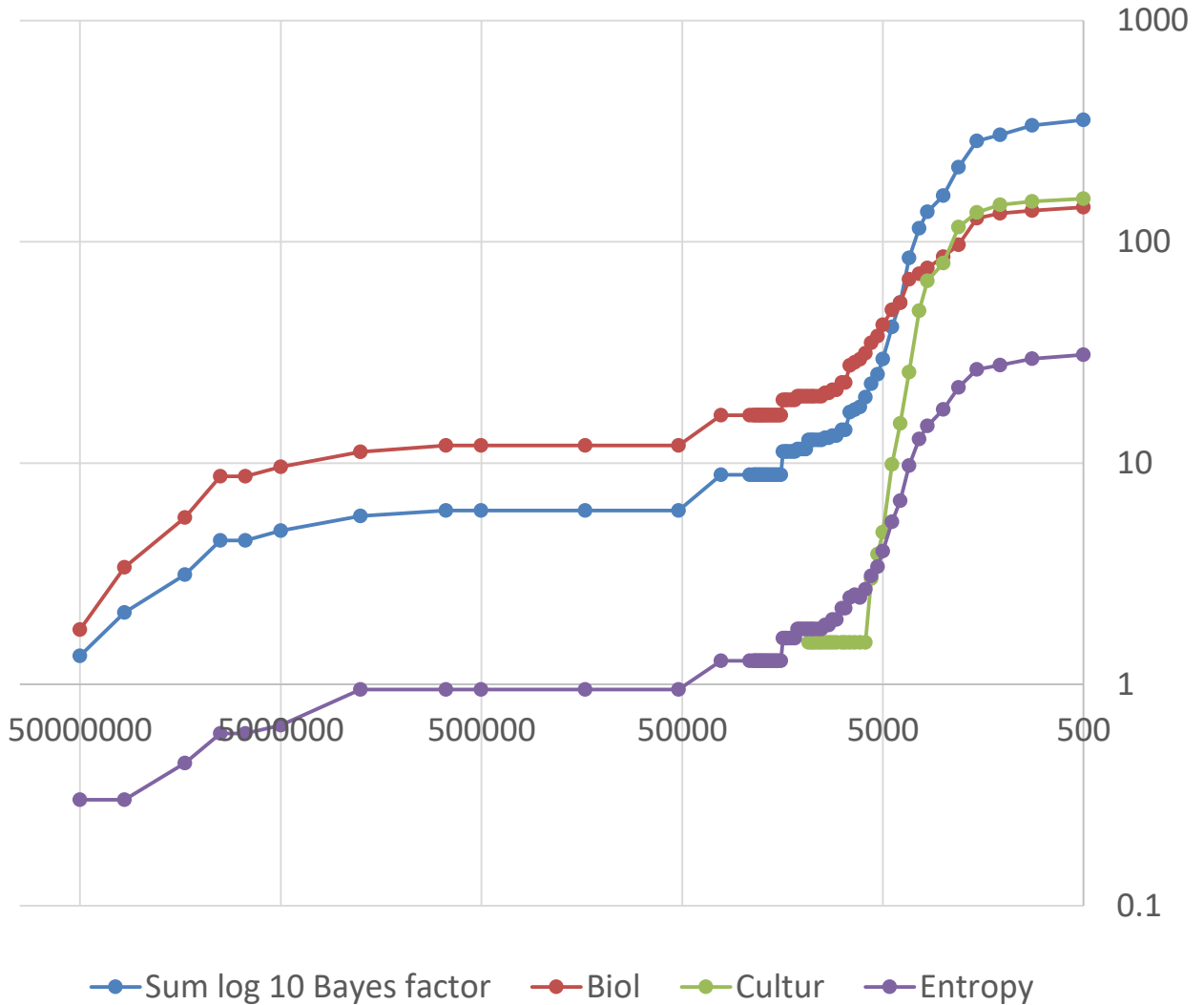


Fig. 7 Chronological sequence of the *Phoenix* expansion based on paleontological, archaeobotanical and cultural accumulated evidence

The graphic represents the increment of evidence from 50 Myr to 0.5 ka in form of records, and the number of cells where the Bayes factor is >0 within the region analyzed and the sum of accumulated entropy, from the beginning to that date.