TÜBİTAK

Turkish Journal of Botany

http://journals.tubitak.gov.tr/botany/

Review Article

Turk J Bot
(2023) 47: 89-96
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doi:10.55730/1300-008X.2748

Origin, distribution and domestication of the carob tree (*Ceratonia siliqua* L.)

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Received: 01.11.2022 • **Accepted/Published Online:** 28.02.2023 • **Final Version:** 23.03.2023

Abstract: The carob tree, which is a member of the *Fabaceae* family, is an agrosilvopastoral tree whose pre-Mediterranean tropical origin appears well established on the basis of genetic, fossil and physiological data. *C. siliqua* has recently been successfully introduced from the Mediterranean basin to other parts of the world that have a Mediterranean climate. In terms of its domestication, there is paleobotanical, philological, ecological and historical evidence to suggest that the species was spread by people from Arabia, where it took refuge during the Ice Age, to Mesopotamia and then on to the western Mediterranean. This "eastern refugium hypothesis" (ERH) postulates the existence of a single refuge for the carob tree in the eastern Mediterranean and a dissemination by humans to the west of the region concomitant with its domestication. However, recent results of phylogenetic and fossil analyses have revealed the existence of a western refuge, thus refuting the single ERH hypothesis and supporting local use and domestication of the carob tree from native populations throughout the Mediterranean. This paper advances other arguments of a historical, philological, ecological and sociocultural nature that support the existence of a western refugium and also emphasise the important role played by the Romans and particularly by the Arabs and Andalusians in the propagation and domestication of the carob tree in the western Mediterranean.

Key words: Carob tree, origin, distribution, domestication, eastern refugium, western refugium

1. Origin of the carob tree

Genetic and fossil evidence supports a pre-Mediterranean origin of the carob tree (Bessedik et al., 1984; Viruel et al., 2020). Its ancestors were probably distributed widely around the Tethys Sea during the Palaeogene, 66 Ma (Palamarev, 1989) in tropical forests that were depleted by successive extinctions during the transition to the Mediterranean climate (Suc, 1984; Mijarra et al., 2009; Suc et al., 2018). *C. siliqua* seems to have retained physiological traits specific to tropical species, notably the existence of a late flowering period (July-October), which is unusual in Mediterranean trees and shrubs, the presence of the cauliflory phenomenon (species whose flowers or fruits grow directly on the trunk), and the presence of a photosynthetic enzymatic content of the "C4 type" (characteristic of plants in hot climates) during the first stages of its development, which is subsequently inhibited when the plant matures (Catarino and Bento-Pereira, 1976). Furthermore, Lo Gullo and Salleo (1988) reported that drought is avoided by *C. siliqua* through a water-spending strategy based on compensating for water loss from the xylem to the leaves, so that RWC (relative leaf water content) decreases very little, maintaining photosynthesis at a level that allows the tree to grow. In line with this idea, in an experiment on the tropical tree *Moringa oleifera*, Echeverría et al. (2019) support the general prediction that increasing height is accompanied by compensatory changes in xylem structure that maintain hydraulic conductance constant with the leaf surface area allowing to keeps photosynthetic leaf productivity constant. In addition, the leaves of the carob tree have a longevity that is almost double that of the majority of the most common Mediterranean species (Catarino, 1993). All these arguments tend to confirm the pre-Mediterranean tropical origin of the species (Figure 1).

2. Distribution and world production of *Ceratonia siliqua*

2.1. Distribution and centre of diversity of the species

The carob tree has recently spread from Spain (Figure 2) to other regions that have a Mediterranean climate,

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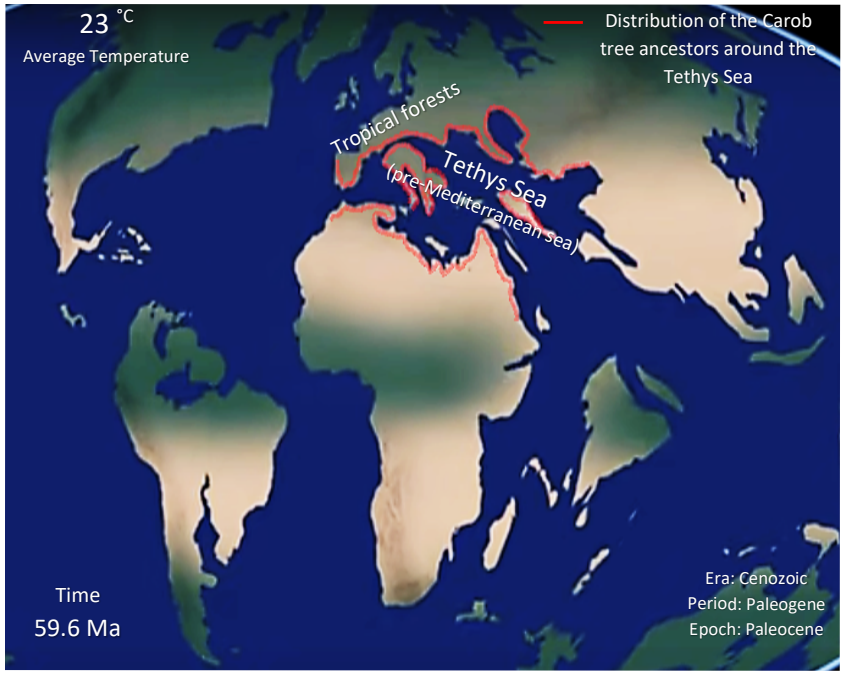

Figure 1. Pre-Mediterranean tropical origin of the carob tree. Its ancestors were probably distributed widely around the Tethys Sea during the Palaeogene in tropical forests that were depleted by successive extinctions during the transition to the Mediterranean climate.

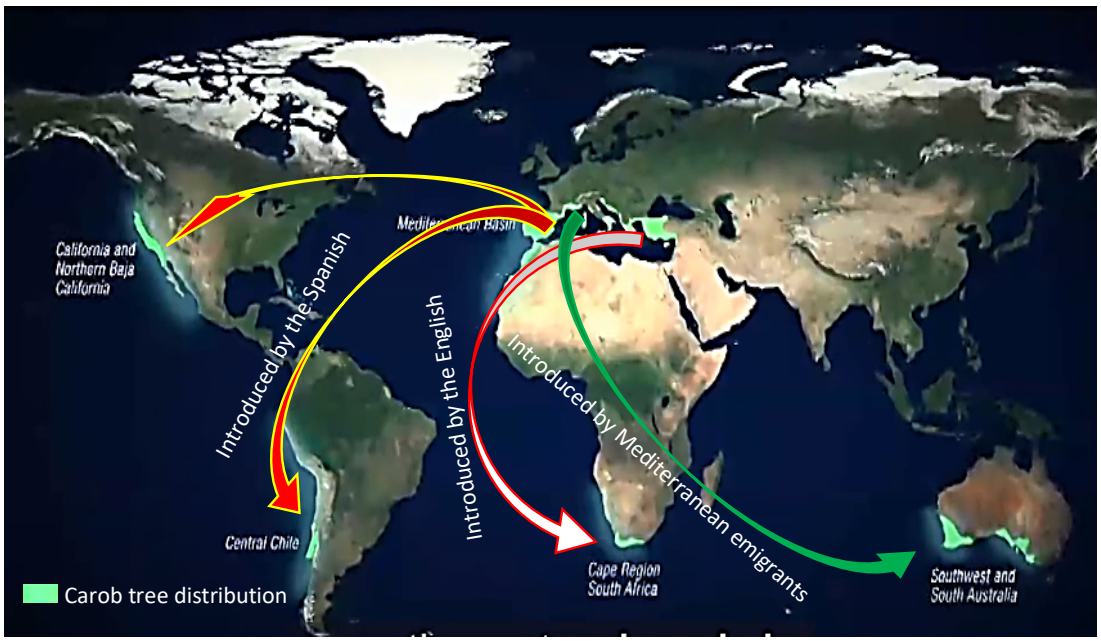

Figure 2. World distribution of *Ceratonia siliqua,* which has recently been successfully introduced from the Mediterranean basin to other parts of the world that have a Mediterranean climate.

such as California (USA), Mexico (Tijuana), Chile and Argentina, and has been introduced to parts of Australia by Mediterranean migrants and to South Africa and India by the British (Batlle and Tous, 1997). The carob tree was probably introduced to the United States from Spain in 1854. In the 1950s, budwood were introduced into California from selected Mediterranean cultivars (Tous, et al., 2013). In Australia, they were introduced

in the 19th century (Tous, 1995), mainly for agroforestry uses and recently for pod production (Tous et al., 2013). In China, carob seedlings have been planted in some forest regions, such as Sichuan and Yunnan, mainly for reforestation and animal feed (Tous et al., 2013). In Latin America, the name Algarrobo (carob tree in Spanish) is given to the species *Prosopis chilensis* (Algarrobo chileno), an autochthonous tree of the Fabaceae family, present in Chile, Southern Peru, Bolivia and Argentina; as for *C. siliqua*, recently introduced in Chile, it is called in Spanish, Algarrobo europeo (European carob tree). Furthermore, it was observed that carob cultivars adapted very well outside their area of origin. This adaptation was manifested by a good agronomic performance but also, for some cultivars, by a change of sex (Batlle and Tous, 1997; Tous et al., 2013).

The Mediterranean is undoubtedly the native and diversity area of *C. siliqua* (Batlle and Tous, 1997; Melgarejo and Salazar, 2003; Viruel et al., 2020) and consequently is the region that holds the species' most important genetic resources, which are required for the implementation of genetic improvement programmes for the species.

2.2. World carob production

The total harvested area of carob in the world during the last decade (2012–2021) is estimated at 74,229 ha (Table) of which 66,944 ha (90.18%) are distributed among Spain, Portugal, Morocco, and Italy. The average world production of carob between 2012 and 2021 is estimated at 183,915 t, and is mainly concentrated in Spain, the leading producer country with 44,114 t (Figure 3), which represents almost a quarter of world production, closely followed by Portugal with 23% of world production, Italy with 17% and Morocco with 22,031 t, i.e. 12% of world production. The four countries mentioned above alone account for more than three quarters (76%) of world carob production.

World carob production has declined drastically over the last 70 years, from 650,000 tonnes in 1945 (Orphanos and Papaconstantinou, 1969) to 183,915 tonnes (average world production from 2012 to 2021), a loss of 72%. In Spain alone, production has fallen by 88%, from 420,000 t in 1945 (AEA, 1987) to 48,756 t in 2021 (MAPA). In Algeria, carob production was reduced by 86% between 1961 (24,000 t) and 2021 (3,219 t) (FAO). This considerable drop in production is mainly due to the ageing of carob orchards throughout the Mediterranean basin, but also to the absence of renewal programmes and the installation of new plantations.

3. Domestication of the carob tree

3.1. Eastern refugium hypothesis

According to Hillcoat et al. (1980), the carob tree spread in the wild in Turkey, Cyprus, Syria, Lebanon, Palestine, southern Jordan, Egypt, Arabia, Tunisia and Libya, before reaching the western Mediterranean. Indeed, archaeological and philological evidence suggests the human spread of *C. siliqua* from Arabia, where it was

Table. Average harvested area, production and yield of the main carob producing countries over the last ten years (2012–2021).

Country**	Area harvested (ha)	Production (tonnes)	Yield (t/ha)
Spain	37330	44114	1,18
Portugal*	13599	42367	3,12
Italy	5599	31297	5,59
Morocco	10415	22031	2,12
Türkiye	1911	15489	8,11
Greece*	2580	12753	4,94
Cyprus*	1254	7932	6,33
Lebanon	348	3624	10,41
Algeria	781	3467	4,44
Tunisia	412	841	2,04
Total	74229	183915	2,48

Sources: FAO, MAPA, ISTAT.

** The countries were ranked in descending order according to their production in tonnes.

* Countries with averages of agronomic elements calculated from 2012 to 2017. Data for the last 4 years are not available.

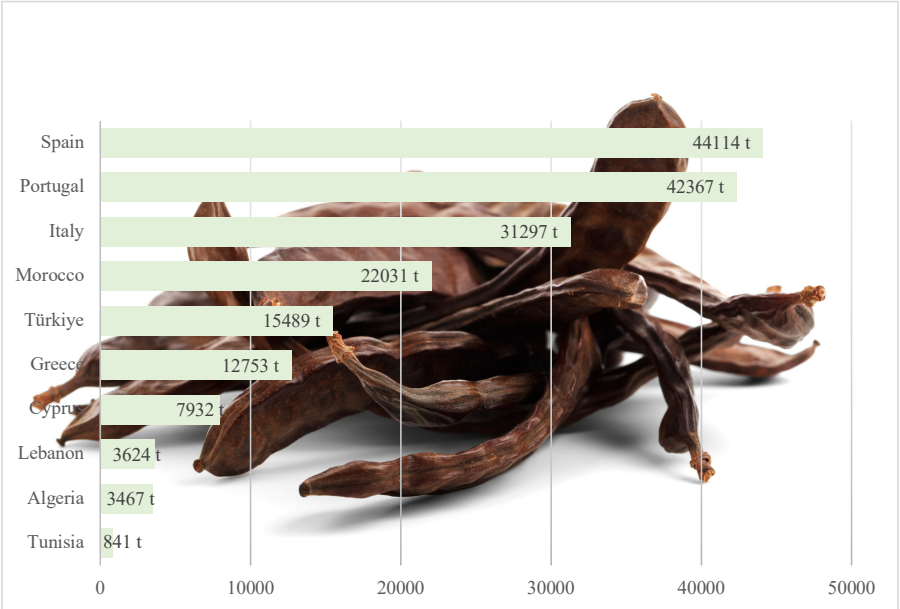

Figure 3. The main carob producing countries in the world over the last decade (2012–2021).

hypothesized to take refuge during the Ice Age, to Mesopotamia and then on to the western Mediterranean (Ramón-Laca and Mabberley, 2004). This widely accepted "eastern refugium hypothesis" (ERH) postulates the existence of a single refuge for the carob tree, located in the eastern Mediterranean, and its spread by humans concomitant with its domestication towards the west of the region. This suggests that the wild carob populations of the western Mediterranean are a recent and feral origin (Batlle and Tous, 1997; Zohary, 2002).

The arguments put forward by the proponents of the single ERH seem plausible since they are based on: i) ecological evidence, with the discovery of *Ceratonia oreothauma*, a closely related species cooccurring with the carob in Yemen (Hillcoat et al., 1980); ii) paleobotanical and archaeological evidence, supporting the existence of *C. siliqua* in the east during the late Pleistocene (12.9 to 11.7 Ka) and early Holocene (11.7 to 8.2 Ka) (Zohary, 2002); iii) philological evidence where, with the exception of Greece and southern Italy, most of the names attributed to the tree in European languages today are related to Arabic (Ramón-Laca and Mabberley, 2004), and iv) historical evidence from Jewish and Arabic documentation on the use and domestication of the carob dating from Mishnaic times (1st century BCE to 2nd century CE) (Zohary, 2002) and from the medieval period in the work *Kitāb al-Filāḥa al-Nabaṭeyya* (The Nabataean Agriculture – 10th century CE), which was the first book written on agriculture in Arabic and was the most influential not only throughout eastern Mediterranean region but also in Muslim Andalusia (Banqueri, 1802; García Sánchez, 1992). Furthermore, Amar (2000), quoted by Zohary (2002), states that carob cultivation in the Mediterranean basin appeared to peak after the Arab conquest, especially in the Levant.

However, recent results of phylogenetic and fossil analyses (Viruel et al., 2020) have revealed the existence of a western refuge, supported by both Pleistocene fossil records (2.5 Ma to 12 Ka) of *C. siliqua* found in the western and eastern Mediterranean and the identification of two major lineages of *C. siliqua*. The first encompasses two lineages, SM (southern Morocco) and SS (southern Spain), located in the westernmost part of the Mediterranean, and the second is represented by two groups, one in the central and one in the eastern Mediterranean. The divergence between these two major lineages of *C. siliqua* is estimated to have taken place 116.000 years ago (95% HPD 25–297 Ka), taking their origin back to a time that largely preceded the domestication of the species, the advent of which was between 3000 and 2000 years ago when scion grafting techniques were developed in the Mediterranean basin (Meyer et al., 2012).

Therefore, Viruel et al. (2020) concluded that the hypothesis of a single eastern refugium should be rejected and suggest in a recent study (Baumel et al., 2022) based on a genome-wide phylogeography, that the expansion of *C. siliqua* from west to east was from a single long term refugium, probably located in the foothills of the High Atlas Mountains near the Atlantic coast

(southwest Morocco). This suggestion can be supported by philological and historical evidence. Indeed, with the exception of the Chleuhs, a Berber tribe, indigenous to southwestern Morocco, who give the carob tree the name of 'Tekada' and 'Ikidu', the other Berber tribes living further north in Algeria and Morocco attribute to the carob tree names that come from the Latin name 'Siliqua' and the Arabic name 'Kharoub': 'Taslighoua', 'Taslaghwa', 'Slighwa', 'Axerrub', 'Elxarub', 'Ejert elxarrub', etc. It is not surprising that all these names have a Latin or Arabic origin, because the North of the Maghreb was conquered by the Romans (146 BC to 430 AD) whose expansion was limited to the North of Morocco and Algeria, then by the Arabs (from the middle of the 7th century) whose influence on the Chleuh tribe was late, thus explaining the genetic isolation (Viruel et al., 2020; Baumel., 2022) of the carob tree population in southwest Morocco and suggesting that this carob population has probably been domesticated by indigenous people. Furthermore, and according to the genetic data published by Di Guardo et al. (2019), Viruel et al. (2020) and Baumel et al. (2022), we suggest that the Romans did not only domesticate the carob tree but most probably introduced some cultivars, especially in northern Algeria.

Although these authors do not deny the important role played by Greek, Roman and Arab farmers in the history of the carob tree, especially in the diffusion of cultivation practices and cultivars, the results of the both studies (Viruel et al., 2020; Baumel et al., 2022) support a local use and domestication of the carob tree from native populations throughout the Mediterranean (Figure 4). This conclusion appears realistic and acceptable in view of the arguments mentioned above and those presented below.

3.2. Western refugium

In the central part of the Mediterranean basin, the carob tree was first mentioned in Rome by Columella (4 BC to 70 AD). He called it *siliqaa Graeca*, while some referred to it as *ceration*. Pliny the Elder (23–79 AD) describes the tree in detail and says that the Ionians called it *ceronia* (Meyer, 1980). These names have nothing in common with those given to the tree in the eastern Mediterranean (Kharroub in Arabic and Kharuv in Hebrew). Furthermore, paleobotanical evidence (charcoal remains and seeds) has been reported for the existence of the carob tree in northern Algeria between the Late Glacial (130 Ka) and Middle Holocene periods (6 Ka) (Carrión Marco et al., 2022). In addition, the phylogenetic study conducted by Viruel et al. (2020) using microsatellites and plastid markers estimated that the split between the central and eastern Mediterranean carob groups was 24,000 years. This period largely precedes the first records of tree crop domestication, which dates back 6000 years (Zohary et al., 2012).

As for the western part of the Mediterranean, the first and most important sources about the carob tree and its cultivation come from Muslim Andalusia, found in authoritative works on agriculture in general written by Ibn Ḥajjāj al-Ishbīlī (11th century), Abū al-Kẖayr al-Ishbīlī (11th century) and Ibn al-'Awwām (12th century).

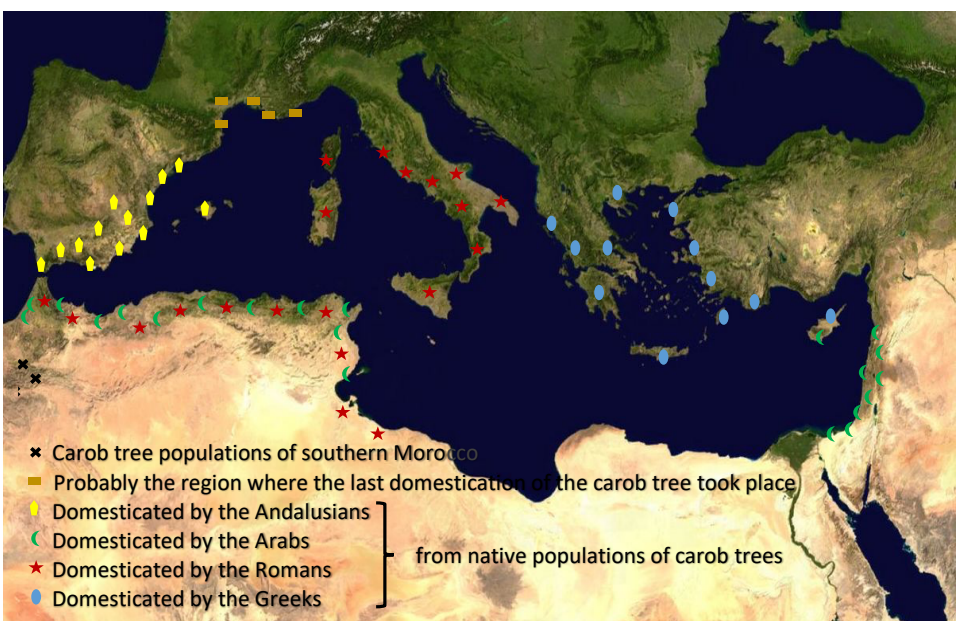

Figure 4. Domestication of the carob tree in the Mediterranean basin. *The genetically isolated populations of southwestern Morocco carob trees ('SM'; Viruel et al., 2020 and Baumel et al., 2022) has probably been domesticated by indigenous people.*

In his famous book *Kitāb al-filāḥa* (Banqueri, 1802), Ibn al-'Awwām, quoting Abū al-Kẖayr, mentions the names of carob cultivars such as 'El-Andaloussi', whose pods are wide and long (probably selected from local carob trees since its name refers to Andalusia, the name given by the Muslims to the Iberian peninsula), 'El-Amlissi' (meaning the very smooth one—it is very likely that it also resulted from a selection, as many contemporary cultivars and varieties have this trait), 'Daneb El-Fa'r' (mouse's tail), 'El-Shami' with small round fruits (a cultivar possibly introduced from Greater Syria or resembling the carobs of that region), and 'Kharoub El-Djabali', mountain or wild carob. It also includes the types of propagation of the species and is very detailed, with propagation by seedling, heel cutting and cresting (crest grafting).

Abū al-Kẖayr al-Ishbīlī's mention of the presence of wild carob in Andalusia seems to reinforce the idea of a native western carob tree. However, what explanation can there be for the lack of local names for this species in the Iberian Peninsula? The answers to this question appear to be ecological, historical, philological and sociocultural.

3.2.1. Domestication of *C. siliqua* in the Iberian Peninsula

i) Ecological answer:

The carob tree, with its intolerance to cold, cannot withstand winter temperatures below –7 °C (Batlle and Tous, 1997) which can destroy entire plantations (Albanell, 1990; Ramón-Laca and Mabberley, 2004), only grew in warm coastal regions and the southern part of the country (Valencia and the south of the country), and even if it was found in temperate regions, it could not bear fruit and did not survive in cold areas, as reported in 1513 by de Herrera, the first agronomist from the time of the Spanish Catholic kings to write about the carob tree (RSEM, 1818). It would therefore seem that the species was not common among the entire Iberian population.

ii) Historical and philological answer:

The presence of local names of Latin origin for the carob tree, particularly in the southern part of the Iberian Peninsula, cannot be ruled out, especially at the time of the Roman conquest (196 BC to 411 AD). This is the case in Algeria and Morocco, where certain Berber-speaking populations continue to use names that seem to be derived from the Latin name 'Siliqaa', such as 'Taslighoua', 'Taslaghwa' and 'Slighwa' (Baba Aissa, 1999; Bertrand, 1991). However, the invasion of the peninsula by the Visigoths (418–711 AD), western Germanic peoples from northern Europe and therefore not familiar with the species, may have led to the disappearance of the original names for the carob tree. This was followed by the Muslim conquest (710–1492 AD) where the absence of local names in the writings of Andalusian agronomists is quite noticeable. This argument is reinforced by the names given to the carob tree in the different languages of Spain, all of which derive from Arabic (algarrobo in Castilian and Basque, garrofer in Catalan and alfarrobeira in Galician). In any event, just because all the names attributed to the carob tree in Spain derive from Arabic does not mean that the species was de facto introduced by the Arabs. The same is true of the olive tree, whose presence, cultivation and use in the Iberian Peninsula are much earlier than the arrival of the Arab-Berbers, yet the name given to the wild olive tree in Spain is 'El Acebuche', a name coming from the Berber 'Azebouche' or 'Zeboudj' or the fruit of the olive tree named 'Aceituna' in Castilian, a term that comes from the Arabic 'Al-zaytūna'. These examples testify to the important agronomic heritage left by the Muslim civilisation in Spain, whether through the introduction of new species such as rice, cotton, sugar cane and aubergine (Banqueri, 1802; Ruas et al., 2015) or through ingenious and innovative cultivation techniques and practices (Hernández Bermejo and García Sánchez, 2000; García Sánchez, 2013) that allowed the enhancement and development of indigenous crops, such as the carob tree, whose cultivation undoubtedly reached its peak during the reign of the Andalusians in the peninsula of Hispania. It is highly probable that its propagation and therefore its domestication in the region were the work of Arabs and non-Arab Muslims (Figure 4).

iii) Sociocultural answer:

The carob tree has always been associated with poverty, hunger and a shortage of bread, and these pods were consumed in times of scarcity. de Herrera mentioned that once the period of scarcity was over, its pods could be used as a supplementary food for cattle and other animals (RSEM, 1818). There is every reason to believe that the Iberian population was not particularly fond of this tree, and this feeling of the species being rejected lasted until the early 19th century, as pointed out by Álvarez Guerra in one of the 17 volumes he translated from J-B François Rozier's Dictionary of Universal Agriculture (RSEM, 1818). He states that the Valencians killed off male carob trees in many regions (because they were unproductive), and calling them, as proof of their hatred, Jews, a name that continues today to be attributed to male carob trees in Spain (Albanell, 1990). Then he added it would be better if they kept those trees forbidden by their ignorance, and thus they would obtain more and more fruit. This ignorance was probably due to the expulsion of the Moors, the descendants of the Muslims of Andalusia, in 1609. They made up one third of the Valencian population and were skilled in agriculture, arts, crafts and architecture (Janer, 1857; Muñoz y Gaviria, 1861; Bahri, 2009). While *C. siliqua* is considered by Jews and Italians to be the tree of memory (Cairati, 2013), it seems that for some Iberians and

Spaniards of the time, the carob tree was "the tree of the curse". Unfortunately, this pejorative perception of this species has persisted among Spaniards, since the carob was the staple food to fight the famine that raged in Spain during and after the Civil War (1936–1939), leaving very bad memories of it among the Spanish population.

3.2.2. Domestication of *C. siliqua* in North Africa and France

In Algeria and Morocco, *C. siliqua* seems to have been present before the Roman and Arab conquests, as shown by the Amazigh names given to the species of 'Tikida', 'Tissit' and 'Ikidu' (Bertrand, 1991; Baba Aissa, 1999), but it is highly likely that its cultivation and thus its domestication in the region was the work of the Romans and of the Muslim civilisations that succeeded them (Figure 4). Indeed, Baumel et al. (2022) suggest from genetic data that the carob was mainly domesticated from locally selected wild genotypes and scattered dispersals of varieties domesticated by people over long distances to the west, along with the great historical migrations of the Romans, Greeks and Arabs. In France, *C. siliqua* was first described by the famous botanist and agronomist Rozier (1787). He mentioned that the species is suitable for cultivation in Provence (southeast France) if it is protected from the cold. Furthermore, Thouin et al. (1809) proposed the establishment of permanent grasslands with, among others, the carob tree, which makes no sense given the difficulty of seed germination. This suggestion by members of the agricultural section of the French Institute is unreasonable and shows a total lack of knowledge of carob cultivation at that time. Therefore, it is very likely that *C. siliqua* was cultivated in France very recently and that the last domestication of the species in the Mediterranean basin probably took place in the south of this country.

Conflict of interest

The authors declare that they have no conflict of interest.

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