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Assessment of Ancient Carob Germplasm of Lebanon by Morphological Traits

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Abstract

This study aimed to assess the ancient carob germplasm growing in Lebanon. A set of 59 old trees sampled from different locations across the country (between 0 and 554 m a.s.l.) were subject to morphological characterization by using 33 traits related to the tree, the leaf, the pod and the seed. Results revealed important morphological variability within the Lebanese carob germplasm. The most variable traits were the number of aborted seeds per pod, seed yield, pulp weight, pod weight and pod volume. Correlation analysis showed a negative correlation of both pod size and weight with seed yield, and a positive correlation between pod length and total seed weight. Evaluation of carob morphological characters and eco-geographic parameters revealed positive correlation of seed length, chord length and pod width with the longitude, in addition to a slight positive correlation of pod weight with latitude and longitude. Principal component analysis allowed extracting the most active and discriminant morphological variables, which were mainly represented by pod weight, width, length, thickness and shape, chord length, and individual seed weight and length. Cluster analysis revealed a clear differentiation between two main morphological groups; the first cluster was characterized by long and heavy pods and seeds, while the second cluster was distinguished by medium to small pods and seeds. Two eco-geographic sub-clusters could be differentiated, Mount Lebanon and the South, while the trees of Beirut and the North were dispersed in various subgroups. According to these results, the Lebanese carob germplasm might be a reservoir of genetic diversity that should be further investigated by complementary studies including flowering characteristics, pod chemical quality attributes and genetic analysis.

Originated in the Eastern Mediterranean and the Arabian Peninsula, the carob tree (*Ceratonia siliqua* L.) is a typical constituent of the evergreen vegetation of Mediterranean and Near East low altitude areas (Batlle and Tous, 1997; Zohary, 2002). The Mediterranean Basin is considered to be at least one of carob domestication centers and the trees were planted extensively in warmer parts of both the southern and eastern shores. Since ancient times, carob trees spread as wild seedlings, but they are regarded as feral derivatives of the fruit crop which probably evolved under domestication based on the shifting from sexual reproduction (wild forms) to the vegetative propagation (under cultivation) (Sidina *et al*., 2009; Zohary, 2002).

Historically carob has been used as feed for domesticated animals. The fruit was also eaten by peoples in times of famine while the wood was also used for fuel. Traditionally, carob trees were inter-planted with olives, grapes, almonds and even barely in low intensity farming system (Batlle and Tous, 1997). This multi-use tree cultiva-

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tion represents an age-old land use system where fruit trees are deliberately grown in the same planting with other crops and/or animals (Makhzoumi, 1997). Today, wild, naturalized, and abandoned cultivated carob trees have become an integral component of the 'thermo-Mediterranean' zone which is characterized by dense coastal woodlands of evergreen screlophyllous plant species, and is distributed at low altitudes in all warmer parts of the Mediterranean Basin, especially North Africa and the Near East (Batlle and Tous, 1997; Christodoulakis, 1992; Talhouk *et al*., 2001).

The potential multi-use value of carob in the past is still valid today and new uses have proven to be economically important. The carob bean gum extracted from carob's seeds is widely used today in the manufacture of foodstuffs as a stabilizer, emulsifier, and thickener. The ground up pod is also used as a substitute for cocoa powder. It's hardwood is used as charcoal in several Mediterranean countries (Abi Saleh *et al*., 1996; Corell *et al*., 1987). In addition, the adaptability of carob tree to all types of soils at lower and middle altitudes and its resistance to drought, makes it suitable for reforestation (Abi Saleh *et al*., 1996; Tous *et al*., 2013). Moreover, the species is considered beneficial in association with low altitude conifer trees because of its tolerance to fires (Talhouk *et al*., 2005). In Lebanon, carob grew abundantly on the lower coastal hills to the extent that a regional district was referred to by the species name 'Iklim Al Kharroub' (the carob district), and is cultivated in different agricultural systems, among olive and almond trees, where carob is mainly grafted on the remnant wild forms (Breugel and Stephan, 1999; Talhouk *et al*., 2001). By 1914, carob trees were uprooted for the expansion of agricultural alternatives causing a noticeable decrease of their populations, described as consisting of sporadic trees (Abou Nasser, 1963). Today, some centennial carob trees are still found witnessing the long history of this species in the country. Unfortunately, the remaining carob populations are threatened again by various anthropogenic pressures and more particularly by the intensive urbanization activities in the coastal zone, which are causing an alarming destruction of the remnant semi-natural habitats where carob thrives.

During the last decade, several afforestation initiatives were undertaken using carob seedlings. Also, several municipalities are investing in carob cultivation in South Lebanon for both ornamental and economic purposes. According to the statistic census of the Ministry of Agriculture of Lebanon, carob culture is occupying 241 hectares, mostly located in South Lebanon (132 ha), with an estimated average total production of 2000 tons per year. Local production is not sufficient to satisfy the local demand for molasses production. Therefore, carob pods are regularly imported by carob factories from Cyprus and Greece. Formal data regarding the imported quantities are not available yet.

Usually cultivars are described and breeding material is selected on the base of conventional phenotypic descriptors that are readily recognizable. In the Mediterranean, carob cultivars were often assessed using pod and seed morphological traits as it was the case in Algarve, Portugal (Barracosa *et al*., 2007). Also pod and seed morphological characteristics were used to study the variability within the Tunisian carob germplasm (Naghmouchi *et al*., 2009; Naghmouchi *et al*., 2009). In Morocco both morphological traits and chemical composition of pods were used for the characterization of carobs (Khlifa *et al*., 2013; Sidina *et al*., 2009). More recently, morphological traits of pods and seeds were used to characterize carob populations collected from two Croatian islands (Srečec *et al*., 2016).

To date the genetic diversity of carob trees growing in Lebanon has not been sufficiently addressed. Only a few local cultivars were differentiated across the country namely 'Ahmar', 'Makdissi', 'Khachabi', 'Sandali' and 'Barri', based on a limited number of pod characteristics (Breugel and Stephan, 1999; Haddarah et al., 2014). The genetic variability of the Lebanese carob populations was explored by using RAPD markers (Talhouk *et al*., 2005). Results from this genetic study indicated that carob trees did not cluster based on geographic proximity, and revealed a significant difference between and within populations, suggesting that the remaining trees constitute a valuable germplasm that deserves to be investigated.

In this context, the present work aims to assess the phenotypic diversity of the ancient Lebanese carob germplasm by characterizing the remaining centennial carob trees growing in the country. Germplasm characterization consisted of analyzing the variation in morphological descriptors relevant to the tree, the leaf, the pod and the seed among 59 selected trees to determine if they are related with species geographical distribution in Lebanon. This work is the first contribution in *Ceratonia siliqua* in which morphological features are analyzed to characterize Lebanese's genotypes based on their potentialities and to valorize ancient carob trees in further conservation actions and selection programs. The hypothesis was that morphological differences can be characterized, and that this analysis will provide a starting point for future molecular analysis for this important natural resource in the Mediterranean and the Near East regions.

Materials and Methods

Surveys and collected accessions

A set of 59 ancient carob trees representing most natural and domesticated Lebanese's populations was collected during June - October 2016 (Supplementary Table 1). These trees grew in family gardens, road edges, valleys and abandoned lands and were described immediately at the site prior to material collection. Trees were located at 31 sites spread over four main geographical areas, the North, the South, Mount Lebanon, and Beirut districts (Fig. 1) at altitudes between 16 and 545

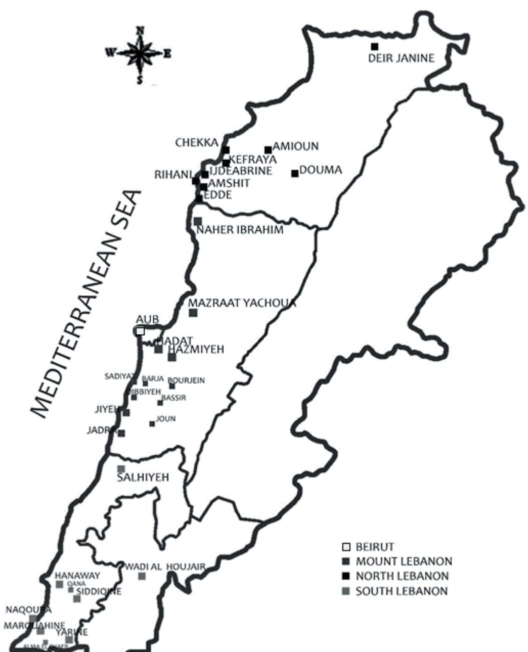

Figure 1. Distribution of the 59 centennial carob trees surveyed in 31 locations in Lebanon.

Figure 2. Examples of centennial carob trees across Lebanon considered in the study. From left to right and from top to bottom: Female carob tree with a high basal circumference in *Amioun* population; Male tree with two trunks in *Amioun* population; Female carob tree of *Joun* population with a big cavity on trunk induced by bad pruning practices; Female carob tree of Nahr *Ibrahim* population with big cavity on the basal part of trunk.

m and receiving between 920 and 491 mm of rainfall (Supplementary Table 1). Each tree was assumed to be one accession, having a trunk circumference of 2 m and above (Fig. 2). According to information given initially by the growers and elderly villagers, the trees were considered to be more than 100 years old. For each tree, samples of 20 mature leaves and pods were collected randomly on lateral branches. After seed extraction, 20 seeds were randomly chosen from 10 pods per tree.

Morphological descriptors

Globally five qualitative (scored) and 28 quantitative traits (measured) of the tree, leaf, pod and seed were examined, based on the descriptors previously developed for carob tree characterization (Barracosa *et al*., 2008 and 2007; Batlle and Tous, 1997; Gharnit *et al*., 2004; Retana *et al*., 1994; Tous et al., 2013). Tree traits included foot trunk circumference (m), trunk largest circumference (at 50 cm height from the ground) (m), crown projection diameter (m), and central cavity (length×width×depth; m^3) (Supplementary 2; Fig. 2). Leaf characteristics included leaf length (mm) and width (mm), petiole length (mm) and width (mm), and number of leaflets per leaf, leaflet length (mm) and width (mm) (Supplementary Table 3). Pod characteristics included pod shape (scored on a scale of 3=straight, 5=curved and 7= twisted); pod color (rated on a scale of 3=brown, 5=dark brown, 7=black; chord length (mm); pod length, width and thickness (mm), weight (g) and volume (ml); pulp weight (g); pod stalk length (mm) and width (mm); percentage of aborted seeds per pod; seed yield (%) and seed number per pod (Supplementary Table 4); Seed characteristics included seed): shape (1=round, 2=oval, 3=elliptic; color (1=yellowish brown, 2=brown, 3=red brown and 4=black) and surface (1=smooth, 2=rough and 3=very rough); seed length (mm); width and thickness (mm); individual seed weight and total seed weight per pod (g) (Supplementary Table 5). Seed yield (%) was calculated as the total seed weight over pod weight x 100 (Batlle and Tous, 1997).

Eco-geographical data

Climatic data used in these analyses were derived from the dataset of the meteorological stations of the Lebanese Agricultural Research Institute distributed across the country. In this study, the general climate variables considered for each location included minimum and maximum average temperatures and annual rainfall. Information on GPS coordinates and elevations of the sampled trees was also recorded in each location.

Data analysis

For each variable, means ± standard deviations and coefficients of variation were calculated. The normality test of Kolmogorov–Smirnov was used to determine if samples came from a normally distributed population (Martínez-González *et al*., 2006). When examining the distributions for the quantitative variables associated with pod, seed and leaf characteristics, the Kolmogorov-Smirnov (K-S) test indicated values of p above 0.05 for seven morphological traits which fit normality (chord length, pod width, weight, pulp weight, pod stalk length, leaflet length, leaflet width). Other variables i.e. pod volume, leaflet length and width, seed number per pod, seed length) were log10-transformed (Milton and Tsokos, 1983). When case number sample size is large, K-S test is sensitive to small deviations from normality (Milton and Tsokos, 1983). To avoid this problem, all the variables that did not fit normality with K-S test, even after Log10 transformation, were evaluated with histograms and Q-Q plots (Normal vs Expected, and Standard deviation trends), to confirm the deviation of the normal distribution. After these evaluations, data for eight traits still deviated from normality, and were excluded from the multivariable classification approach (pod stalk width, % aborted seed per pod, seed yield, seed thickness and width, leaf petiole length and width and leaflet number per leaf).

Pearson's correlation coefficients were calculated at the individual level to evaluate relationships between morphological traits. The correlation coefficients with the variables which did not fit normal distribution were analyzed using Spearman's correlation test. Additionally, the correlations between eco-geographical variables (i.e. altitude, longitude and precipitations) and the mean values of morphological traits were examined at the population level (Fig. 3) (Snedecor *et al*., 1967).

Principal Component Analysis (PCA) was performed using IBM SPSS statistics 17.0 (IBM Corp., Armonk, NY, USA) on all studied individuals of the data set except for the trees that were not productive and thereby considered to be male. All variables satisfying conditions of normality, homoscedasticity and bivariate correlations greater than

0.3 ($P < 0.05$), except for those exhibiting collinearity, were included in the PCA to select the most representative ones, according to Sleighter et al. (2010). Selected variables were identified by an optimal PCA solution that included Bartlett's sphericity test, a KMO (Kaiser-Meyer-Olkin) test, communalities, correlations with principal components, and maximum explained variance (Martínez-González *et al*., 2006). With the eight variables accounting for the maximum fraction of variance in the original dataset (Supplementary Table 6; Fig. 4), accessions were subjected to agglomerative hierarchical cluster analysis (unsupervised clustering, Ward's method) based upon squared Euclidean distance. Classification was carried out using an agglomerate algorithm (Everitt, 1980). The number of groups was judged visually based on the resulting dendrogram. After groups were defined, one-way analyses of variance were used to detect differences in quantitative traits among the previously established groups. To detect geographic patterns of variation in pod morphology, a clustering analysis following Ward's method was performed using R v.3.2.3.

Results

General status of the carob centennials

Our study included 59 centennial carob trees growing in 31 locations across the country distributed in Mount Lebanon (26 trees), North Lebanon (13 trees), South Lebanon (10 trees) and Beirut (10 trees) (Fig. 1). Trees were found along the littoral and up to 545 m of altitude (Marouahine in the South). Minimum winter temperature varied between -3.8°C and 3.5°C, while the maximum summer temperature varied between 34.8°C and 38.9°C. The annual rainfall was between 491 mm (Wadi Al Houjair in the South) and 920 mm (Douma in the North). Most of centennials are growing as scattered trees on road edges e.g. Nahr Ibrahim, family gardens and yards, and in the remaining maquis in some area e.g. Joun. On the other hand, some carobs were found in olive groves (e.g. Deir Janine and Joun), recalling the traditional Mediterranean agro-ecosystem where olive and carob trees were inter-planted. Many of these trees were in good shape while others were partially destroyed by various anthropogenic acitivities. The immense majority of these trees did not recieve irrigation or other agricultural practices.

Most of the surveyed carob trees were still productive, except seven trees found during the survey without pods and were considered by farmers as male trees. Although flower type was not addressed in this study, at least eight trees of the 59 studied and mostly located in Mount Lebanon were hermaphrodite with some inflorescences carrying pistillate flowers and others carrying staminate flowers, or with inflorescences carrying hermaphroditic flower. Normally, dried pods are harvested in September and processed to produce carob molasses also called "black honey" or "debs". According to the growers, only a few trees were grafted, such as the one found in *Kefraya* (designated as *Kefraya* NLC1) and the one called *Rihani* (designated as *Rihani* NLC1). Most of these centennial trees were thought to be subnatural and assumed to be derived initially from seedlings growing spontaneously in natural landscapes or in plantations.

Information given by the growers and municipalities indicates the carob trees considered in this study may have been 150 to 250 years old. The oldest tree might be the one found in *Amioun* (*Amioun NLC2*) which may have been more than 200 years, followed by the tree of *Deir Janine* (*Deir Janine NLC1*) and the one of *Kefraya* (*Kefraya NLC1*) with more than 150 years. Some centennials are located near some archeological troves, ruins and ancient monasteries, indicating their long history in the country.

Tree characteristics

Trees had large foot circumferences, from 2 m (e.g. *Wadi Al Houjair SLC2*) to 8.2 m (e.g. *Amioun NLC2*) (Supplementary Table 2, Fig. 2). Trunk circumferences ranged be-

Table 1. Descriptive statistics for pod, seed, and leaf variables for 59 carob centennial trees growing in Lebanon.

Morphologcal traits	Minimum	Maximum	Mean ± SD	CV (%)
Pod:				
Chord length (mm)	78.1	219.9	142.52±37.04	25.99
Length (mm)	108.3	234.2	161.93±34.43	21.26
Width (mm)	14.3	27.0	22.06±3.23	14.64
Thickness (mm)	4.6	12.2	8.26±1.58	19.13
Weight (g)	5.9	37.65	20.34±8	39.33
Volume	8.6	35.5	20.68±7.46	36.07
Stalk length (mm)	6.7	16.6	11.93±3.12	26.15
Stalk width (mm)	2.2	4.3	3.16±0.46	14.56
Color	Brown (3)*	Black (7)*	Dark brown (5)*	
Shape	Straight (3)*	Twisted (7)*	Curved (5)*	
Pulp weight (g)	4.49	34.67	18±7.73	42.94
Nº of seeds	7.86	14.3	10.93±1.47	13.45
% aborted seed/ pod	0	23	7.06±6.63	93.91
Seed yield (%)	6.7	36.6	13.13±5.86	44.63
Seed :				
Length (mm)	7.7	11.5	9.71±0.87	8.96
Width (mm)	6	8.6	7.42±0.7	9.43
Thickness (mm)	3.7	5.3	4.27±0.37	8.67
Total seed weight/ pod (g)	1.36	3.05	2.24±0.45	20.09
Individual seed weight (g)	0.152	0.295	0.22±0.03	13.64
Shape	Oval (2)*	Elliptic (3)*	Oval (2)*	
Color	Brown (2)*	Black (4)*	Red brown (3)*	
Surface	Smooth (1)*	Rough (2)*	Smooth (1)*	
Leaf:				
Length (mm)	42.7	188.9	97.8±27.9	28.5
Width (mm)	24.8	167	132.19±23.44	17.73
Leaf petiole length (mm)	18.5	69.7	37.05±9.36	25.26
Leaf petiole width (mm)	1.7	3	2.3±0.29	12.61
Leaflet length (mm)	45.6	83.4	64.31±9.36	14.55
Leaflet width (mm)	28.4	56.7	41.87±6.21	14.83
Leaflet per leaf (mm)	5.4	10.6	7.88±1.11	14.09

* Values in parentheses are scores attributed to qualitative traits.

tween 1.6 m (*Wadi Al Houjair SLC2, Debbiyeh MLC4*) and 9 m (e.g. *Baasir MLC1*), while most of the trees had trunk circumferences between 2.2 m and 4 m. Trunk cavities were present in only 44% of trees with volumes between 0.01 m^3 (e.g. *Chekka NLC1*) and 0.95 m^3 (e.g. *Nahr Ibrahim NLC4*). Crown projection ranged from 3.3 m (*Jiyeh MLC1*) to 16 m (*Baasir MLC1*) with an average of 6.61 m.

Morphological characterization

Carob centennials had a wide range of morphological variability (Tables 1; Supplementary Tables 2-5). Seed thickness, seed length and seed width were least variable with a coefficient of variation of 9%, followed by pod length and width, number of seed per pod, individual seed weight, and leaf petiole width with coefficients of variation ranging between 12 to 15%. High variation coefficients were associated with aborted seeds per pod, seed yield, pulp weight, pod weight, pod volume, leaf length, chord length, leaf petiole length and pod length with respective values of 93.91, 44.63, 42.94, 39.33 and 36.07, 28.5, 25.99, 25.26 and 21.26%.

Leaf length ranged between 42.7 mm (e.g. *Marouahine SLC7*) and 188.9 mm (e.g. *Salhiyeh SLC1*), whereas leaf width varied from 24.8 mm (e.g. *Eddeh NLC1*) to 167 mm (e.g. *Bourjein MLC3*). Leaf petiole length was short for most of the trees (19-30 mm length) and varied from medium to long for the others (up to 70 mm) such as *AUB BLC7*. Leaf petiole width ranged between 1.7 mm (*Chekka NLC1, Joun MLC*3 and *Alma El Chaeb SLC2*) and 3 mm (e.g. *Seddiqine SLC21*).

Leaflet number per leaf varied between 6 (*NahrIbrahim MLC1, Saadiyat MLC1, Qana SLC12, Hanaway SLC18, Seddiqine SLC21*) and 10 (*Baasir MLC1, Salhiyeh SLC1, Wadi Al Houjair SLC2*). Leaflet length varied between 45.6 mm (*Marouahine SLC7*) and 83.4 mm (*Hadat BLC9*), with an average width of 64.3 mm. Leaflet width ranged between 28.4 mm (e.g. *Alma El Chaeb SLC2*) and 56.7 mm (e.g. *Jiyeh MLC8*). Leaflet shape was elliptical for all trees (Supplementary Table 3). It is worthy to note that carob trees of the south were characterized by small size leaves and leaflets.

Pod characteristics were highly variable. Pod shape varied between curved to twisted with dominance to curved shape, but *Kefraya NLC1* and *Eddeh NLC6* had straight pods (Table 2). Pod color, varied from brown to black. Pod length varied from 108.3 mm (e.g. *Ijdeabrine NLC1*) to 234.2 mm (e.g. *Baasir MLC1*). Chord length varied between 78.1 mm (e.g. *Hanaway SLC18*) and 219.9 mm (e.g. *Baasir MLC1*) (Supplementary Table 4). Pod weight ranged from 5.9 g (e.g. *Marouahine SLC7*) to 37.65 g (e.g. *Jiyeh MLC1*), and pulp weight varied between 4.49 g and 34.67 g for the same trees. Pod thickness varied between 4.6 mm (e.g. *Saadiyat MLC1*) and 12.2 mm (e.g. *Eddeh NLC6*). Pods harvested in the North and Mount Lebanon had the widest pods, averaging 22.06 mm. Pod stalk length ranged between 6.7 mm (*Joun MLC2*) and 16.6 mm (*DeirJanine NLC3*), whereas pod stalk width was similar for all samples with an average of 3.17 mm. Generally, carob from the south had small and light pods whereas those of Mount Lebanon had large and heavy pods.

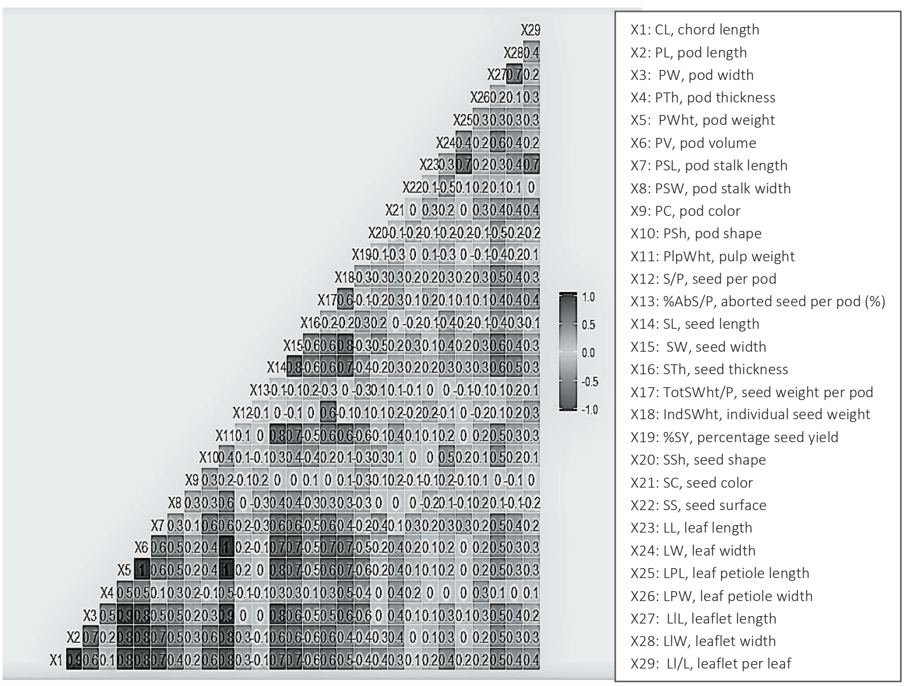

Figure 3. Correlation matrix with correlation coefficients for 28 traits of the pod, seed and leaves or carob centennial trees growing in Lebanon.

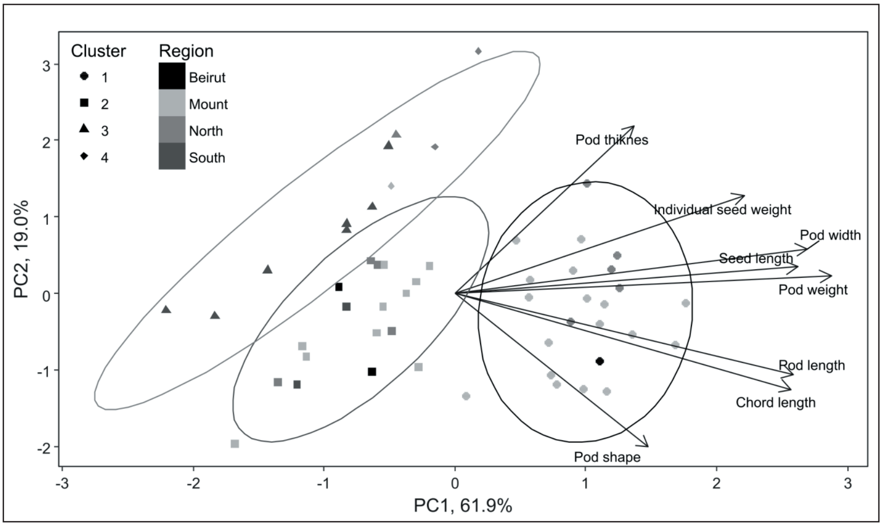

Figure 4. PCA biplot of the 52 centennial carob trees. Symbol shape represents HCA results (clustering). Accession symbols represent geographical areas. Arrows represents variable loadings, scaled to the range of PC factors (-3, 3 interval). Ellipse represents normal probability of cluster distribution with a significance level of 5%.

Seed number per pod ranged between 8 and 14 seeds with 0 to 23% aborted seed per pod, whereas total seed weight per pod varied from 1.36 g to 3.05 g (CV=20.09) (Supplementary Table 5). Seed yield per pod varied between 6.7% (e.g. *Debbiyeh MLC4*) and 36.6 % (e.g. *Jadra MLC2*) (CV= 44.63). Individual seed quantitative traits varied among trees where seed length (CV=8.96) ranged from 7.7 mm (e.g. *Qana SLC2*) to 11.5 mm (e.g. *DeirJanine NLC1*), width from 6 mm (e.g. *Qana SLC2*) to 8.6 mm (e.g. *Mazraat Yachoua MLC1*) (CV=9.43), thickness from 3.7 mm (*Amioun NLC2, Debbiyeh MLC4*) to 5.3 mm (e.g. *Barja MLC6*) (CV=8.67), and weight from 0.152 g (e.g. *Qana SLC2*) to 0.295 g (e.g. *Eddeh NLC6)* (CV=13.64).

Seed qualitative characteristics varied in color and slightly in surface and shape. Actually, seed color was yellow brown for *Chekka NLC1*, brown for *Ijdeabrine NLC1*, red brown for *Joun MLC2* and black for *Hadat BLC9*. Seed surface was smooth for all trees studied except for *Eddeh NLC1* (North Lebanon) which had rough to smooth seeds. Seed shape was oval for the majority of trees, and elliptic for *Yarine SLC6, Seddiqine SLC21* (South Lebanon), *Deir Janine NLC1, Deir Janine NLC2* (North Lebanon) and *Nahr Ibrahim MLC4* (Mount Lebanon).

Correlation between morphological traits

Pearson's correlation confidents for morphological traits are presented in Figure 3. Tree dimensions and other variables were not correlated, whereas significant correlations existed between pod and seed characteristics (data not shown). For instance, pod weight was positively significantly correlated with pod length (r=0.83), width (r=0.9) and thickness (r=0.56), chord length, total seed weight and seed length with correlation coefficients of r= 0.79, 0.65, 0.789, respectively. Similarly, individual and total seed weight were correlated with seed length (r=0.61 and 0.64, respectively) and width (r=0.76 and 0.56, respectively). On the other hand, leaflet length and width were positively and moderately correlated with pod weight (r=0.49 and 0.33, respectively), length (r=0.48 and 0.32, respectively) and width (r=0.52 and 0.37), and individual seed weight (r=0.52 and 0.43, respectively). In total, eight morphological traits were correlated, with correlation coefficients between 0.3 and 0.9, and were considered for further analysis.

Correlation between traits and eco-geographical growing areas

Correlation between the eight variables selected from the PCA analysis and the geographic parameters was performed to examine their relationship with the morphological characteristics of the carob centennials (Table 2). Results revealed slight negative correlation between pod shape and altitude (r=-0.35). Slight to moderate positive correlation was found between latitude and pod width (r= 0.318) and seed length (r=0.591). Longitude was positively correlated with seed length (r=0.606), chord length (r=0.323) and pod width (r=0.308). Slight negative correlations existed between rainfall and pod length and seed number per pod (r=-0.360 for both).

Multivariate analyses

PCA analysis showed a great variation among the carob centennials depending on the eight variables previously extracted through Pearson correlation analysis (Fig. 4). The first two components account for 80.9% of the total variance. In the first component representing 61.9%, the traits of chord length, pod weight, length and width, in addition to individual seed weight and length, were prominent as active variables. For the second component, representing 19.0% of the total variance, pod thickness and shape were the most significant variables.

Based on the active variables, the PCA biplot (Fig. 4) may allow distributing the carob centennials in three main groups; trees of the South are clustered in one group, trees of the Mount are found in a second group, while the third group clusters trees growing in Beirut, Mount Lebanon and the North in mixture with no dependency on eco-geographic growing areas.

The agglomerative hierarchical classification constructed with the squared Euclidean distance based on the eight active variables representing pod and seed traits allowed distributing the carob centennials in two large clusters at 10% dissimilarity distance (Fig. 5). Cluster I contains 13 individuals coming from Mount Lebanon, four individuals from the North and three individuals from Beirut, all characterized by big curved to twisted pod with big seeds. Cluster II contains 14 individuals coming from Mount Lebanon, nine from the South, six from the North and two individuals coming from Beirut, and all characterized by low to medium size of pod and seed with dominance of curved pods.

At 5% dissimilarity, four sub-clusters could be differentiated. Cluster I was divided into two sub-clusters. The largest sub-cluster, designated as sub-cluster I.1, contained 12 trees from the Mount, four from the North and three from Beirut. Sub-cluster I.2 was

Table 2. Pearson correlation coefficients[z] for morphological traits selected after statistical analysis (PCA) and geographical variables.

Variables	Altitude	Latitude	Longitude	Rainfall
Chord length (CL)	-.207	.297*	.323*	-.278*
Pod length (PL)	-.173	.191	.260	-.360**
Pod width (PW)	-.030	.318*	.308*	-.157
Pod thickness (PTh)	-.025	.114	.003	.096
Pod weight (PWht)	-.129	.312*	.308*	-.259
Pod shape (PSh)	-.351*	.019	.043	-.135
Seed length (SL)	-.045	.591**	.606**	.016
Individual seed weight (ISW)	-.124	.358**	.224	.076

[z]Coefficients followed by 1 or 2 astericks are significant at the 5% and 1% level, respectively.

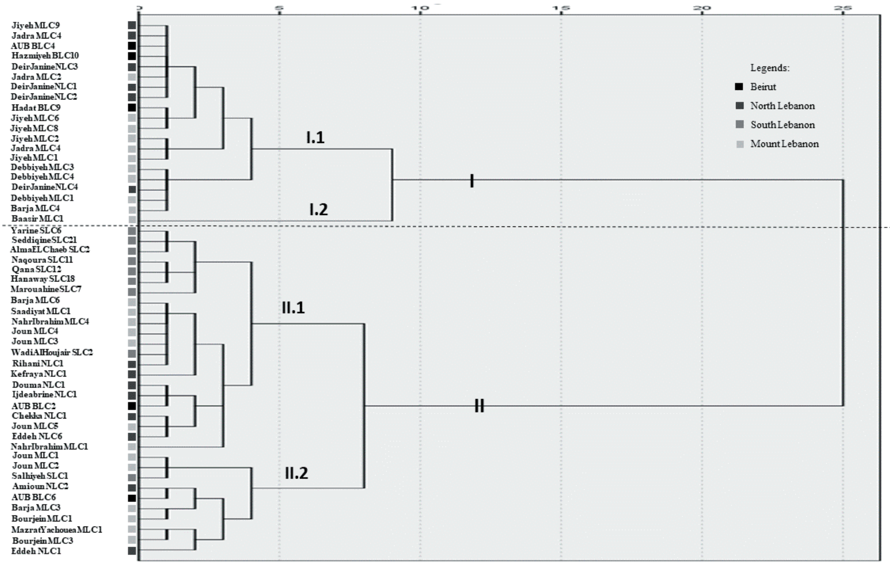

Figure 5. Dendogram of 52 centennial carob trees constructed on the base of morphological traits recorded, using rescaled squared Euclidean distance.

represented by only the *Baasir MLC1* tree, with the longest and heaviest pods with high seed number per pod. Cluster II was divided into two main sub-clusters based on pod length and width, whereas sub-cluster II.1 contained 22 trees with small to medium pod size of which seven were from Mount Lebanon, eight from the South, six from the North and one from Beirut. Sub-cluster II.2 contained 10 trees with big pods of which six were from Mount Lebanon, two from the North, one from the South and one from Beirut. At 2.5% dissimilarity and below, trees of the South (which have small and light pods and seeds) and the ones of Mount Lebanon (with heavy and long pods and seeds) are clearly differentiated, while the trees of Beirut and the North are distributed in various subgroups.

Discussion

In Lebanon, carob has always been an important component of the natural landscape and the traditional agroforestry system, but morphological variability of the species at country level has been rarely assessed (Talhouk *et al*., 2005). The present work is the first phenotypic assessment of the Lebanese carob germplasm, using a set of morphological traits related to tree, pod, seed and leaf. Morphological descriptors have been widely used to assess variability of carob germplasm and to differentiate cultivars and promising trees (Batlle and Tous, 1997; Sidina *et al*., 2009; Naghmouchi *et al*., 2009; Sidina *et al*., 2009; Tous *et al*., 2013).

The most variable traits found in this study included number of aborted seeds per pod, seed yield, pulp weight, pod weight and pod volume with respective coefficients of variation of 93.9, 44.6, 42.9, 39.3, and 36.1. These traits are mostly complex and controlled by polygenetic features, and are strongly influenced by the environmental factors (Sidina *et al*., 2009). On the other hand, seed traits varied less and seem less influenced by environmental factors, similar to the results reported previously for the Spanish cultivars, and the

Tunisia and Moroccan germplasms (Albanell *et al*., 1996; Naghmouchi *et al*., 2009; Sidina *et al*., 2009).

Data from morphological studies were used to evaluate correlations between morphological characteristics (Albanell *et al*., 1988 and 1996; Caja *et al*., 1988). In this study, pod size and weight were negatively correlated with seed yield (r=-0.427 and -0.564, respectively), confirming previous reports (Albanell *et al*., 1996; Sidina et al., 2009). The heaviest seed was the longest and widest, and seed weight ranged between 0.15 g and 0.30 g with a mean of 0.22 g. Pod length and total seed weight were previously found to be positively correlated (r= 0.567) (Albanell *et al*., 1996; Sidina *et al*., 2009).

In our study, seed length, chord length and pod width were positively correlated with the longitude (r=0.606, 0.323, 0.308, respectively; Table 5), whereas pod weight was slightly correlated with latitude and longitude. Surprisingly, pod size and weight were negatively correlated with the rainfall, indicating an unusual behavior of the Lebanese carobs to precipitation. For the Moroccan carob germplasm, significant positive and negative correlations were reported for pod thickness and pulp weight with the latitude and altitude respectively, allowing identification of different geographic patterns of carob in Morocco (Sidina *et al*., 2009). Hierarchical clustering analysis revealed an important diversity among the studied carob trees, with a differentiation of the trees of the South and the ones of Mount Lebanon which could correspond to two potential eco-geographic groups. On the other hand, carob trees of Beirut and the North were the most difficult to classify, being spread over the four clusters.

Conclusion

Using a set of morphological traits, the present work is the first morphometric assessment of the Lebanese ancient carob germplasm. Although preliminary, the results of this study identified the diversity potential of the Lebanese ancient carob germplasm. Further complementary studies involving reproduction biology characteristics (Caruso *et al*., 2008), chemical attributes (Dakia *et al*., 2007) and genetic analysis (La Malfa *et al*., 2014) are necessary to investigate the performance and real value of this heritage, prior to conserving and utilizing the germplasm in pre-breeding and breeding programs.

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Supplementary Table 1. Climatic and geographic data for the 31 locations surveyed for carob accessions. NL: North Lebanon; ML: Mount Lebanon; BL: Beirut; SL: South Lebanon.

Location (Province)	Elevation range (m)	Latitude (N)	Longitude (E)	Rainfall (mm)*	Min. mean T^a	Max. mean T^a	Avg. T^a	Accessions collected
North Lebanon								
Deir Janine (Akkar)	338-433	34°33'51.5"	36°10'36.7"	730	-3.8	37.3	19.03	NLC1, NLC2, NLC3, N
Douma (Batroun)	245	34°12'14.7"	35°50'32.3"	920	-2.9	38.3	19.37	NLC1
Chekka (Batroun)	63	34°19'28.7"	35°43'47.3"	920	-2.9	38.3	19.37	NLC1
Amioun (Koura)	318	34°18'14.5"	35°48'28.8"	920	-2.9	38.3	19.37	NLC2
Ijdeabrine (Koura)	308	34°14'36.3"	35°41'45.7"	920	-2.9	38.3	19.37	NLC1
Kefraya (Koura)	302	34°17'46.4"	35°43'06.3"	920	-2.9	38.3	19.37	NLC1
Amchit (Jbeil)	91	34°08'59.0"	35°38'17.8"	878	3.5	38.9	22.25	NLC5
Rihani (Jbeil)	169	34°35'05.1"	36°06'60.0"	878	3.5	38.9	22.25	NLC1
Eddeh (Jbeil)	239-259	34°08'24.6"	35°39'52.2"	878	3.5	38.9	22.25	NLC1, NLC6
Mount Lebanon								
NahrIbrahim (Kesrwan)	76-127	34°04'02.4"	35°38'44.4"	878	3.5	38.9	22.25	MLC1*, MLC4
MazraatYachoua (Metn)	347	33°55'50.1"	35°38'09.7"	878	3.5	38.9	22.25	MLC1
Jiyeh (Chouf)	54-184	33°40'15.3"	35°25'30.9"	615	3.2	36	21.28	MLC1, MLC2*, MLC6
Barja (Chouf)	180-398	33°38'59.7"	35°26'35.6"	737.2	-0.6	37.1	18.225	MLC3, MLC4, MLC6
Jadra (Chouf)	92-120	33°37'51.9"	35°24'27.7"	615	3.2	36	21.28	MLC2*, MLC4*, MLC(
Joun (Chouf)	398-434	33°34'53.5"	35°27'40.4"	737.2	-0.6	37.1	18.22	MLC1, MLC2, MLC3*,
Debbiyeh(Chouf)	434-438	33°39'54.9"	35°29'16.5"	737.2	-0.6	37.1	18.225	MLC1, MLC3,MLC4
Baasir (Chouf)	326	33°39'32.8"	35°26'53.0"	737.2	-0.6	37.1	18.225	MLC1*
Saadiyat (Chouf)	112	33°41'41.3"	35°25'31.5"	737.2	-0.6	37.1	18.225	MLC1
Bourjein (Chouf)	382-461	33°39'29.3"	35°29'10.7"	737.2	-0.6	37.1	18.225	MLC1,MLC3
South Lebanon								
Salhiyeh (Saida)	208	33°33'36.8"	35°25'20.8"	820	-1.4	36.4	20.18	SLC71
WadiAlHoujair (Bentjbeil)	252-315	33°15'30.7"	35°28'30.9"	491.2	-2.5	34.8	16.91	SLC1, SLC2
AlmaElChaeb (Sour)	388	33°06'17.3"	35°10'50.9"	710	2.2	34.8	20.33	SLC2
Yarine (Sour)	426	33°06'26.0"	35°13'55.9"	710	2.2	34.8	20.33	SLC6
Marouahine (Sour)	554	33°06'31.1"	35°16'28.0"	710	2.2	34.8	20.33	SLC7
Naqoura (Sour)	89	33°07'05.6"	35°08'23.4"	710	2.2	34.8	20.33	SLC11
Qana (Sour)	367	33°12'29.2"	35°18'00.6"	710	2.2	34.8	20.33	SLC12
Hanaway (Sour)	201	33°13'18.5"	35°16'38.6"	710	2.2	34.8	20.33	SLC18
Seddiqine (Sour)	372	33°11'22.8"	35°18'37.3"	710	2.2	34.8	20.33	SLC21
Beirut								
AUB (Beirut)	16-108	33°54'03.1"	35°28'51.3"	878	3.5	38.9	22.25	BLC1---- BLC8**
Hadat (Baabda)	82	33°51'00.5"	35°31'38.0"	878	3.5	38.9	22.25	BLC9
Hazmiyeh (Baabda)	195	33°51'18.8"	35°32'09.5"	878	3.5	38.9	22.25	BLC10

* Ecotypes hermaphrodies
**: BLC1, BLC2, BLC3, BLC4, BLC5, BLC6, BLC7, BLC8

Supplementary Table 2. Tree characteristics recorded for 59 carob centennials growing across Lebanon.

Accessions	Foot Circumference (m)	Trunk Circumference (m)	Crown Projection (m)	Central Cavity (m^3)
North Lebanon				
DeirJanine NLC1	6.40	5.70	4.50	0.36
DeirJanine NLC2	4.70	3.50	7.30	0.04
DeirJanine NLC3	3.60	2.40	6.50	0.04
DeirJanine NLC4	4.10	2.20	8.30	0.04
Douma NLC1	3.60	3.55	8.60	0.95
Chekka NLC1	2.40	2.10	8.10	0.01
Amioun NLC2	8.20	5.70	8.50	0.00
Ijdeabrine NLC1	4.60	4.35	9.00	0.53
Kefraya NLC1	5.00	3.60	5.10	0.00
Amchit NLC5	7.60	5.30	5.30	0.00
Rihani NLC1	4.20	3.30	6.20	0.02
Edde NLC1	3.60	3.00	7.10	0.08
Eddeh NLC6	4.60	3.50	6.30	0.00
Mount Lebanon				
Nahr Irbrahim MLC1	4.00	3.00	6.30	0.06
Nahr Ibrahim MLC4	4.20	3.60	7.00	0.95
MazraatYachouh MLC1	3.00	3.30	5.20	0.12
Jiyeh MLC1	2.20	1.63	3.30	0.00
Jiyeh MLC2	2.74	2.24	6.30	0.00
Jiyeh MLC6	3.10	2.30	4.00	0.01
Jiyeh MLC8	5.00	3.30	5.50	0.03
Barj MLC3	2.32	1.95	4.70	0.00
Barja MLC4	2.80	2.65	6.00	0.00
Barja MLC6	3.50	2.50	3.60	0.00
Jadra MLC2	3.00	2.30	5.30	0.11
Jadra MLC4	4.30	4.90	6.00	0.00
Jadra NLC6	2.60	2.30	5.00	0.00
Joun MLC1	3.15	2.26	7.80	0.00
Joun MLC2	7.70	4.30	6.40	0.17
Joun MLC3	6.20	6.00	4.00	0.00
Joun MLC4	6.70	3.50	6.50	0.59
Joun MLC5	5.50	1.68	5.30	0.00
Debbyieh MLC1	3.90	3.60	5.20	0.00
Debbiyeh MLC3	4.80	4.50	5.80	0.00
Debbiyeh MLC4	2.60	1.60	4.10	0.00
Baasir MLC1	7.10	9.00	16.00	0.00
Saadiyat MLC1	5.50	1.57	6.90	0.00
Bourjein MLC1	3.15	2.42	6.00	0.00
Boujein MLC3	3.70	3.20	6.80	0.00
Beirut				
AUB BLC1	5.50	2.60	7.10	0.21
AUB BLC2	2.50	2.00	5.70	0.00
AUB BLC3	6.63	5.40	5.90	0.00
AUB BLC4	2.90	2.45	4.40	0.06
AUB BLC5	5.50	2.10	3.80	0.00
AUB BLC6	3.80	2.50	4.70	0.00
AUB BLC7	4.70	4.00	10.5	0.00
AUB BLC8	4.30	4.90	4.70	0.00
Hadat BLC9	5.50	3.13	6.70	0.31
Hazmiyeh BLC10	2.72	2.57	6.40	1.04
South Lebanon				
Salhiyeh SLC1	7.40	4.00	9.00	0.07
WadiAlHoujair SLC1	7.24	6.30	7.10	0.00
WadiAlHoujair SLC2	2.00	1.60	6.10	0.00
AlmaElChaeb SLC2	4.40	3.00	8.00	0.05
Yarine SLC6	4.60	2.00	10.00	0.00
Marouahine SLC7	3.90	3.60	8.00	0.00
Naqoura SLC11	6.80	2.80	9.00	0.13
Qana SLC12	5.00	4.30	9.00	0.22
Hanaway SLC18	4.60	2.50	12.00	0.49
Seddiqine SLC21	4.20	2.20	4.60	0.00

Supplementary Table 3. Leaf characteristics of 59 centennial carob trees growing in Lebanon. Values were estimated from a 20-leaf sample from individual trees.

Tree code	Leaf length (mm)	Leaf width (mm)	Leaf petiole length (mm)	Leaf petiole Diam. (mm)	Leaflet length (mm)	Leaflet width (mm)	Leaflet per leaf
DeirJanine NLC1	121.9±21.7	126.6±19.8	43.1±9.8	2.3±0.2	59.8±10.9	40±6.1	9±1.1
DeirJanine NLC2	90.6±19.1	124.7±16.3	33.9±4.3	2.3±0.3	58±11.6	41±5.8	7.2±1
DeirJanine NLC3	82±19.3	130.9±8.7	37.3±6.5	2.1±0.3	60.9±4	42.1±3.8	6.8±1
DeirJanine NLC4	103±30.3	151.5±19.2	39.8±14.1	2.5±0.2	70.6±10.4	47.6±4.8	7.6±0.8
Douma NLC1	126.6±20.7	143.5±18.5	55.6±12.9	2.5±0.3	67.9±11.7	37.8±12.8	8.2±1.1
Chekka NLC1	145.2±30.1	165.3±22.8	61.7±18.5	1.7±0.3	75.2±21	43.3±6.6	8±0
Amioun MLC2	95.5±32.1	124.2±19.7	39.1±13.4	2.4±0.2	58.4±9.3	41.5±7	8.2±1.1
Ijdeabrine MLC1	98.7±24.1	126.2±24.7	40.8±7.6	2.3±0.2	62.2±6.6	42.7±4.6	7.4±1.3
Kefraya MLC1	85.4±3	112±16.9	34.5±2.7	25.4±0.2	57.8±14.3	3.3±3.2	8±0
Amchit MLC5	125.6±26	122±11.8	33.3±7.3	2.4±0.2	57.3±6.1	38.3±3.4	10.6±1.3
Rihani NLC1	115.8±19.3	131±14.4	44.2±12.4	2.4±0.1	60.9±6.9	41.4±4.3	9±1.4
Eddeh NLC1	114.9±24.7	24.8±2.5	37.5±11.9	2.5±0.2	77.1±7.8	48.1±6.2	8.4±0.8
Eddeh NLC6	138.9±23.4	155.7±14.3	51.8±13.4	2.8±0.2	77.1±7.3	51.5±10.1	9.4±1
NahrIrbrahim MLC1	63.8±7.1	122.1±11.1	29.4±7.9	2.1±0.7	71.9±23.4	45.9±5.2	6.2±0.6
NahrIbrahim MLC4	96.3±12.1	136.1±9.6	36.5±3.9	1.8±0.2	63.4±5.4	47.4±6.1	7.4±1
MazraatYachoua MLC1	100.4±31.7	159.7±25.4	39.3±9	2.4±0.3	82±11.5	46.5±4.9	7.2±1
Jiyeh MLC1	89.6±16.3	146±19.3	29.4±6.4	2.3±0.3	77.7±5.7	44.5±2.9	8±0
Jiyeh MLC2	91.9±22.2	149.3±15.9	34.8±7.4	2.4±0.5	74.6±16.1	53.4±16	8.4±0.8
Jiyeh MLC6	75±16.7	137.3±16.2	31.6±7.3	2.2±0.3	80.4±4.8	47.1±3	6±0
Jiyeh MLC8	63.8±15.7	128.5±13.5	29.6±6	1.9±0.1	70.2±10.9	56.7±15.7	9.2±1
Jiyeh MLC9	83.2±16.2	155.3±16.7	37.4±8.3	2.4±0.1	71.7±7.5	40.7±4.1	8±0.9
Barja MLC3	88.4±15.8	153.6±13.5	42±12.4	2.7±0.2	69.6±8.8	42.1±4.7	8.4±1.3
Barja MLC4	93.2±7	158.3±18.2	34.8±4.3	2.5±0.2	74.4±9.4	42.9±5.1	8.2±0.7
Barja MLC6	107.2±15	106±13	32.4±7.7	2±0.3	54.2±4.2	35.6±2.7	9.6±1.3
Jadra MLC2	141.2±12.4	129.6±11.3	38.1±7	2.5±0.3	61.5±7.5	41.4±4.1	9.8±0.6
Jadra MLC4	90.9±18	154.1±22.8	43.4±10.2	2.3±0.3	71.8±10.8	44.1±5.1	8±1.3
Jadra NLC6	91±22.5	153.2±13.6	37.9±6.2	2.6±0.2	69.6±4.4	38.8±4	8±0
Joun MLC1	105.3±20.2	128.6±14.3	40.5±7.9	2.2±0.2	60.2±6.2	40.3±2.5	9±1.1
Joun MLC2	85.7±15.6	133.5±10.5	28.5±6.1	2.4±0.1	60.7±4.8	40.9±3.4	8±0
Joun MLC3	82.8±14.4	103.8±9.5	21.5±5.1	1.7±0.2	64.9±5.8	44.9±3.5	7.8±0.6
Joun MLC4	85.2±13.6	126.9±15.7	27.5±5.7	2.1±0.2	60.8±5.5	43.3±3.1	8±0
Joun MLC5	70.4±20.4	129±15.8	28±3.9	2±0	67.3±7.1	47.8±3.2	6.8±1
Debbyieh MLC1	76.8±11.8	148.6±8.7	34.7±4.1	2.5±0.1	70.1±3.7	41±2.4	7.8±0.6
Debbiyeh MLC3	63.2±12.2	139.3±15.3	31±6.5	2.5±0.2	63.9±7.5	39.6±4.9	7±1.1
Debbiyeh MLC4	70.8±18.5	140.6±16.5	27±7.1	2.2±0.3	60.8±9.1	36±5.9	8±0
Baasir MLC1	140.3±29.8	132.7±12.8	35.2±10.8	2.1±0.2	66.6±5.8	43.3±4.5	10±0.9
Saadiyat MLC1	95.8±16.2	120.1±7.7	39.6±12.7	1.9±0.4	51±6	34.8±4.2	6.4±0.8
Bourjein MLC1	71±16	132.9±13.3	29.6±9.7	1.9±0.2	59.1±9.3	35.1±6.7	7±1.1
Bourjein MLC3	108.7±15	167±23.5	46.9±9.8	2.6±0.2	77.1±10.7	45.6±3.5	8.2±0.6
AUB BLC1	125.9±10.9	129.7±10.6	46.7±8	2.2±0.3	59.6±5.5	42±4.6	8±0
AUB BLC2	90.5±36.1	126.7±18.4	40.2±8.7	2.2±0.2	55.5±8.1	37.5±4.2	7.3±1.6
AUB BLC3	114.5±20.9	151.4±14.2	52.4±9.8	2.2±0.2	70.6±7.7	43±5.3	7±1.1
AUB BLC4	92.4±20.8	159.6±16	45.9±4.8	2.7±0.2	73.7±8.1	41.7±6.1	7.4±1
AUB BLC5	114.1±19.8	109.1±12.7	42.6±9.9	2.7±0.4	48.9±6.7	37.1±4.6	8.6±1.3
AUB BLC6	74.1±14.4	133.6±11.9	33±13.1	2.1±0.1	58.8±7.5	35.9±4.2	7.2±1
AUB BLC7	165±28.6	140.5±17.5	69.7±14.9	2.4±0.3	64.1±8.1	49.7±6.3	7.8±1.5
AUB BLC8	88.5±11.4	126.9±10.8	32.4±8.2	2.9±0.3	60.9±9.4	47±9.2	8.6±1
Hadat BLC9	139.5±49.1	163.1±18.8	38±16.9	2.5±0.3	83.4±8.7	50±6.5	8.8±1
Hazmiyeh BLC10	95.1±14.1	151.5±7.5	42.1±6.4	2.4±0.2	70.1±3.5	42.4±3.6	8±0.9
Salhiyeh SLC1	188.9±17.4	154.5±9.6	48±8.2	2.4±0.2	69.9±4.8	50.1±3.9	10±0
WadiAlHoujair SLC1	124.5±15.3	150.7±15.4	39.1±6.6	2.4±0.3	69.7±10	53.8±5.1	8±0
WadiAlHoujair SLC2	115.5±16.8	126.8±13.6	35.5±9.9	2.6±0.3	55.9±5.6	46.1±3	9.6±1.3
AlmaElChaeb SLC2	64.7±14.2	105.6±16.6	22.5±5.4	1.7±0.2	50.1±9	28.4±5.9	6.8±1
Yarine SLC6	82.4±13.2	114.1±10	29.5±4.5	1.9±0.3	54.2±5.2	34.5±4.1	6.9±0.9
Marouahine SLC7	42.7±11.6	87.2±19.9	26.8±4.6	2.3±0.3	45.6±7.4	30.2±5.5	5.4±1
Naqoura SLC11	87.9±20.7	120.8±7.1	26.3±4.6	2.1±0.1	52±6.2	37±7.8	6.8±1.4
Qana SLC12	66.4±11.7	100.7±9.8	33.4±6.9	2±0.2	49±5	31.7±3.2	6±0
Hanaway SLC18	52.4±18.2	99.9±9.9	18.5±3.4	2.1±0.3	49.9±5.4	31.1±5.1	6.2±1.5
Seddiqine SLC21	67.5±9.9	110.6±10.2	30.1±9.9	3±0.5	49.4±9.6	31.3±4.5	6.5±1.1

Supplementary Table 4. Pod characteristics of 52 centennial carob trees (the non-productive trees considered as male were excluded). Values were estimated from a 20-leaf sample from individual trees.

Tree code	Chord length (mm)	Pod length (mm)	Pod width (mm)	pod thickness (mm)	Weight (g)	Volume (ml)	Pod stalk length (mm)	Pod stalk width (mm)	Pod color	Pod shape	Pulp weight (g)
DeirJanine NLC1	183.4±20.7	199.6±18.9	26±1.5	8.5±1	31.32±5.5	26.4±6.2	15.6±1.5	3.7±0.3	Dark brown	Curved twisted	28.41±5.4
DeirJanine NLC2	181.6±31.7	210.8±24.9	25.3±2.2	8.8±1.2	31.29±6.5	31±7.7	16.4±2.4	3.7±0.4	Dark brown	Curved	28.63±5.87
DeirJanine NLC3	174.6±23.9	202.4±21.6	27±1.9	9.1±1	31.19±6.2	31±5.7	16.6±1.7	3.4±0.3	Dark brown	Curved	28.66±5.8
DeirJanine NLC4	169.2±24	189.4±17.4	25.3±2.1	7.7±1.2	24.51±3.4	18±4.7	15.4±3	3.3±0.4	Dark brown	Curved twisted	22.15±3.51
Douma NLC1	106.5±18.4	111.5±17.8	17.7±1.5	7.1±1	7.95±1.9	11.4±3.4	12.7±1.5	2.2±0.2	Brown	Curved twisted	6.55±1.53
Chekka NLC1	115.6±18.9	130.5±16.4	23.6±3.5	5.8±1.5	16.16±5.7	15.5±6	12.8±1.6	3±0.2	Dark brown	Curved twisted	14.16±5.19
Amioun MLC2	142.3±16.9	149.1±18.5	18.9±1.5	7.6±0.6	14.28±2.3	15.5±2.8	9.2±0.5	3.2±0.2	Brown	Curved	12.04±1.98
Ijdeabrine MLC1	104.3±16.2	108.3±15.5	19.6±2.7	6.4±1.8	9.36±3.6	12.1±4.9	11.1±1.3	2.9±0.2	Dark brown	Curved twisted	7.7±3.23
Kefraya NLC1	120.8±11.5	127±11	22.8±2.5	10±1.1	21.6±3.8	20±3.3	6.7±0.7	2.5±0.3	Dark brown	Straight curved	19.9±3.5
Rihani NLC1	118.5±20.1	137.2±36	22±1.8	10.9±0.7	18.65±3	19.1±3.5	13.4±1.5	2.8±0.2	Dark brown	Curved	15.99±2.68
Eddeh NLC1	142.9±19.2	181±18.7	25.1±3.3	10.8±1.7	32.21±9.2	32.2±8.8	16.4±2.2	3.1±0.2	Dark brown	Curved	28.59±7.98
Eddeh NLC6	119.1±14.5	116.6±14.2	22±1.8	12.2±0.8	20.2±4	20±4.7	11.6±1.1	2.9±0.2	Dark brown	Straight curved	16.61±4.08
NahrIrbrahim MLC1	87.5±16.2	121±13.9	21.1±2	9.2±2	17.29±2.9	17.8±2.7	12.2±1.9	3±0.2	Dark brown	Curved	14.82±2.62
NahrIbrahim MLC4	127.5±21.5	137±18.1	21.9±2.4	8±1.6	20.24±3.9	20.6±1.7	7.9±1.2	2.8±0.2	Dark brown	Curved twisted	17.74±3.56
MazraatYachoua MLC1	149.1±17.1	153.4±18.4	24.2±2.1	8.4±1.8	22.52±3.6	23.1±3.4	13.4±1.4	3.3±0.3	Dark brown	Curved twisted	20.35±2.92
Jiyeh MLC1	191.6±22.6	217±25.9	26.8±2.5	9.8±1.4	37.65±6.9	33.2±6.3	14.3±2	3.7±0.5	Dark brown	Curved twisted	34.67±6.65
Jiyeh MLC2	200.9±19.2	207.9±19.6	25.2±2.7	7.3±1.7	27.78±5.5	29.3±6.4	14.5±1.3	3.7±0.3	Black	Twisted	25.18±5.16
Jiyeh MLC6	182.1±29.3	203.1±28.6	24.2±2.9	7.6±1.6	26.69±5.3	27±6.3	15.9±1.7	3.5±0.3	Dark brown	Twisted	24.37±4.73
Jiyeh MLC8	184.3±23.3	194.6±20.4	23.9±2.6	7.7±1.8	25.62±5	26.1±5.9	14.7±1.1	3.2±0.4	Dark brown	Curved twisted	23.42±4.8
Jiyeh MLC9	189±15.1	204±17.3	23.8±2.2	8.1±1.2	27.78±4.7	28.7±4.7	16.6±2.5	3.2±0.4	Black	Twisted	24.43±4.05
Barja MLC3	155.7±16.5	162.3±16	19.6±1.7	6.1±1.1	12.75±3.2	14.5±4.4	14.4±2.6	3.2±0.4	Black	Curved twisted	10.32±2.77
Barja MLC4	164.6±23	181±21.7	25.4±2.1	9.6±1.3	25.99±4.8	27.2±5.3	13±1.5	3.2±0.3	Black	Curved twisted	23.59±4.33
Barja MLC6	128±6.8	132.3±6.6	16.1±1.6	7.4±1.7	11.73±1.7	15±4.1	10±0.7	2.3±0.2	Dark brown	Curved twisted	9.28±1.83
Jadra MLC2	175±20.2	193.8±33.3	25.1±1.9	8.8±1	30.97±7.6	30.5±9.6	12.1±1.1	3.7±0.5	Dark brown	Curved	27.79±7.05
Jadra MLC4	208±19.7	219.5±24.2	24.5±2.4	8.6±1.6	30.62±7.7	32.4±7.4	12.1±1.2	3.5±0.3	Dark brown	Curved twisted	28.3±5.24
Jadra NLC6	189.1±35.4	204.5±28.4	24.8±2.4	9.6±1.2	30.81±6.7	31±6.6	15.6±1.9	3.6±0.4	Black	Curved twisted	27.71±6.08
Joun MLC1	119.6±21.3	159±37.6	21.6±1.8	7.3±0.6	15.96±2.7	14.3±5.1	8±0	2.4±0	Black	Curved	11.21±3.31
Joun MLC2	109.6±22.7	164.3±21.7	22.6±1.7	8.4±1.5	19.38±2.3	17.1±3.1	6.7±1.3	2.5±0.5	Black	Curved twisted	17.45±2.11
Joun MLC3	121.4±26.6	140±23.6	16.9±1.7	5.6±0.8	10.16±2.3	12.5±2.6	10.8±0.8	2.9±0.4	Brown	Curved	7.7±1.89
Joun MLC4	134.1±15.8	141.2±10	23.5±2.2	6.7±1	22.2±2.2	21.5±2.4	8.4±0.6	2.7±0.3	Dark brown	Curved	19.95±1.88
Joun MLC5	111.9±19.3	127.9±16.8	22.7±2.2	6.6±1.1	18.2±4.5	15.5±4.4	7.5±1.1	2.9±0.4	Dark brown	Curved	16.46±4.11
Debbyieh MLC1	176.5±25.6	188.5±27.3	26.5±3	8.7±1.4	27.24±5.1	27.5±5.9	13.6±1.7	3.8±0.5	Black	Twisted	25.64±4.63
Debbiyeh MLC3	168.1±32.9	179.2±31.8	26.1±2.7	9.2±1.5	28.9±6.8	29.5±6.9	13.6±2.2	3.4±0.3	Black	Twisted	26.43±6.07
Debbiyeh MLC4	162.7±19.3	170.8±13	25.8±3	8.8±1.5	25.71±4.9	26.5±4.7	13.8±2.3	3.5±0.4	Black	Curved twisted	23.87±4.6
Baasir MLC1	219.9±26	234.2±29.7	24.7±3	9.7±1.6	35.67±7	35.5±8	16.1±2.5	3.5±0.2	Black	Twisted	32.87±6.26
Saadiyat MLC1	130.3±18.1	141.8±12.4	15.1±2.3	4.6±0.9	8.9±0.8	9.5±1.6	15.4±1.8	2.4±0.3	Dark brown	Curved twisted	6.69±0.76
Bourjein MLC1	155.6±28.5	171.8±25.1	16.9±1.7	7.2±1.2	15.37±5.1	18.5±5.3	11.5±1.2	2.8±0.4	Dark brown	Curved	12.76±4.89
Bourjein MLC3	145.2±31	165.5±36.7	25.4±2.2	9.8±1.1	22.73±5.7	21±7	13.8±3.1	3.3±0.3	Dark brown	Curved twisted	20.83±5.2
AUB BLC2	110±17.5	120±12.4	18.7±2	8.8±2	12.6±3.1	16±4.6	11.9±1.4	2.7±0.3	Black	Curved twisted	11±2.6
AUB BLC3	184.4±27.9	201.3±34.5	24±2.4	8.6±1.1	28.6±7.9	30±8.2	12.7±0	4.3±0	Black	Twisted	25.5±7.3
AUB BLC6	147.7±8.9	152.2±9.4	18.6±2.8	7.4±1.2	13.78±3.1	15.8±5.8	14.3±1.1	3.9±0.4	Black	Curved twisted	12.14±2.92
Hadat BLC9	182.7±41	201.6±30.2	20.4±2.2	7.5±0.9	17.12±5.5	19.7±7.3	12.9±1.1	2.7±0.3	Black	Curved twisted	15.33±4.39
Hazmiyeh BLC10	180.6±19.8	199±18.2	23.4±2.3	8.7±1.1	23.49±4.2	21.2±4.8	15.3±2.4	3±0.5	Black	Twisted	20.87±3.72
Salhiyeh SLC1	115.8±16.8	166.1±16	20.4±0.8	7.6±0.9	13.39±2	12.6±3.2	8.4±0.8	2.8±0.4	Black	Curved	11.2±1.61
WadiAlHoujair SLC2	123.2±15.3	131.3±13.7	19±1.4	5.3±0.9	11.08±1.5	12.1±2.2	10.2±0.9	2.7±0.2	Brown	Curved twisted	8.68±1.24
AlmaElChaeb SL2	106.4±11.3	146.3±10.3	21.8±2.1	10.3±1.1	15.81±2.7	19.2±1.8	8±0.9	3.2±0.8	Black	Curved	13.62±2.42
Yarine SL6	96.8±6.5	139±20.2	21.3±2.2	9.7±0.9	15.34±2.9	15.2±3.5	7.9±1.3	3.4±0.2	Black	Curved	13.62±2.75
Marwahine SL7	94±16.1	112.5±10.9	14.3±1.6	6.2±1	5.9±1	8.6±1.6	7.2±0.8	3±0.3	Dark brown	Curved	4.49±0.81
Naqoura SL11	85.6±14	127.5±18.4	21.3±2.1	10.3±1.1	16.45±3.9	16.6±4.3	7.5±1	3.4±0.3	Black	Curved	14.74±3.59
Qana SL12	84.7±10.5	129.5±18	17.6±2.2	7.2±0.9	10.65±2.2	10.1±1	8.6±0.7	3.7±0.3	Black	Curved	8.94±2.05
Hanawey SL18	78.1±14.2	121.5±21.4	19.3±2.1	7.9±0.8	9.74±3.1	8.9±2.8	7.2±0.8	3.5±0.5	Dark brwon	Curved	7.95±2.51
Seddiqine SL21	95.6±14.6	131.2±22	21.5±1.3	10.6±2.2	17.31±4.2	17.6±4.1	7.9±0.9	3.8±0.4	Dark brown	Curved	15.32±4.19

Supplementary Table 5. Seed characteristics of 52 centennial carob trees growing in Lebanon. Values were estimated from a 20-fruit sample from individual trees.

Seed characteristics	Seed number per pod	% aborted seed per pod	Seed length (mm)	Seed width (mm)	Seed thickness (mm)	Total seed weight (g)	Individual seed weight (g)	Seed yield	Seed shape	Seed color	Seed surface
DeirJanine NLC1	11.4±0.97	0.9±2.9	11.5±0.4	7.8±0.4	3.8±0.3	2.7±0.26	0.238±0.027	8.8±1.3	Elliptic	Red brown	Smooth
DeirJanine NLC2	10.9±2.69	0.8±2.6	11.3±0.7	7.8±0.5	3.9±0.3	2.58±0.69	0.239±0.029	8.2±1	Elliptic	Red brown	Smooth
DeirJanine NLC3	10.8±2.57	0±0	11±0.8	7.5±0.6	3.8±0.4	2.58±0.64	0.247±0.022	8.2±1	Oval elliptic	Red brown	Smooth
DeirJanine NLC4	10.4±1.43	2.9±4.6	11.3±0.3	7.8±0.3	3.9±0.3	2.3±0.38	0.233±0.021	9.6±2.7	Oval elliptic	Red brown	Smooth
Douma NLC1	8±2.4	2.8±6	8.6±0.5	6.9±0.5	4.2±0.4	1.36±0.38	0.177±0.021	17.4±4.7	Oval	Red brown	Smooth
Chekka NLC1	11.8±1.75	0.9±2.9	10±0.5	7±0.4	3.8±0.2	2.28±0.54	0.206±0.021	14.7±3.3	Oval	Yellow brown	Smooth
Amioun NLC2	10.7±1.42	1.7±3.7	9.8±0.5	7.8±0.4	3.7±0.3	2.12±0.37	0.222±0.014	14.9±2.1	Oval	Red brown	Smooth
Ijdeabrine MLC1	7.86±1.07	8.3±8.6	10.5±0.6	8.2±0.4	4.4±0.5	1.87±0.42	0.267±0.019	21.5±5.7	Oval	Brown	Smooth
Kefraya NLC1	8.4±2	20.5±13.5	9.4±0.3	7±0.6	4.7±0.3	1.6±0.4	0.23±0.05	7.8±2	Oval	Brown	Smooth
Rihani NLC1	12±1.41	0.8±2.4	9.7±0.4	7.3±0.7	4.8±0.3	2.99±0.46	0.25±0.02	16.2±2.5	Oval	Red brown	Smooth
Eddeh NLC1	12.6±1.84	10±15.7	10.7±0.5	8±0.4	4.4±0.3	3.02±0.75	0.261±0.028	9.7±2.7	Oval	Red Brown	Rough
Eddeh NLC6	11±1.41	1.8±3.9	10.5±0.4	8.1±0.5	4.6±0.4	2.99±0.58	0.295±0.024	14.6±2.6	Oval	Red brown	Smooth
NahrirIbrahim MLC1	10.5±1.18	2.7±4.3	10±0.3	7.5±0.7	4.5±0.3	2.51±0.4	0.242±0.021	14.6±1.5	Oval	Red brown	Smooth
NahrIbrahim MLC4	13.2±2.62	23±14.5	9.3±0.7	6.8±0.5	4.6±0.4	2.23±0.6	0.212±0.026	7.2±5.3	Elliptic	Red brown	Smooth
MazraatYachoua MLC1	9.8±3.65	12.5±31	10.4±0.6	8.6±0.4	4.1±0.2	2.39±0.77	0.267±0.022	10.4±2.3	Oval	Red brown	Smooth
Jiyeh MLC1	12±1.56	5±8.1	10.9±0.7	8.3±0.5	4±0.3	2.98±0.74	0.256±0.034	8±1.5	Oval	Red brown	Smooth
Jiyeh MLC2	11.2±1.93	3.9±5.1	10.4±0.6	8.2±0.4	4±0.2	2.76±0.58	0.244±0.019	10±1.6	Oval	Red brown	Smooth
Jiyeh MLC6	10.6±2.72	5.2±9.2	10.1±0.9	7.8±0.5	4±0.3	2.16±0.62	0.22±0.04	8±1.3	Oval	Red brown	Smooth
Jiyeh MLC8	12.4±1.65	7.9±9.5	10.2±0.5	8±0.5	4±0.1	2.64±0.42	0.234±0.025	10.5±2.1	Oval	Red brown	Smooth
Jiyeh MLC9	12.3±2.67	0±0	10.3±0.5	7.7±1	4±0.1	2.82±0.62	0.229±0.023	10.1±1.2	Oval	Red brown	Smooth
Barja MLC3	12.5±1.35	17.9±9.8	9.9±0.3	7.4±0.3	4.4±0.2	2.36±0.59	0.235±0.014	18.7±2.9	Oval	Red brown	Smooth
Barja MLC4	9.7±1.89	3.7±6.2	10.3±0.6	8.4±0.5	4.2±0.2	2.36±0.54	0.254±0.033	9±0.9	Oval	Red brown	Smooth
Barja MLC6	12.25±0.5	1.9±3.8	8.2±0.4	6.7±0.4	5.3±0.4	2.47±0.16	0.208±0.018	21.5±4.1	Oval	Red brown	Smooth
Jadra MLC2	11.2±2.66	0.8±2.6	10.4±0.5	8.5±0.6	4.3±0.4	1.12±2.66	0.262±0.024	36.6±6.1	Oval	Red brown	Smooth
Jadra MLC4	11.2±3.33	0.8±2.6	10.5±0.6	8.2±0.5	4.1±0.3	2.58±1.08	0.258±0.037	8.5±3.2	Oval	Red brown	Smooth
Jadra NLC6	12.6±2.41	2.9±3.7	10.2±0.6	7.9±0.4	4±0.3	3.05±0.66	0.243±0.024	9.9±1.4	Oval	Red brown	Smooth
Joun MLC1	10±3.08	16.3±12.4	9.3±0.9	6.6±0.3	4.3±0.3	1.84±0.57	0.204±0.01	13.7±0.5	Oval	Red brown	Smooth
Joun MLC2	10.14±1.35	22.9±8.9	9.5±0.5	6.8±0.7	4.7±0.2	1.96±0.38	0.227±0.023	10.1±1.8	Oval	Red brown	Smooth
Joun MLC3	13.1±1.85	8±10.8	9.4±0.7	7±0.3	3.9±0.2	2.42±0.47	0.201±0.025	24.1±1.9	Oval	Brown	Smooth
Joun MLC4	11.2±1.48	16.9±15.3	9.5±0.4	6.9±0.3	4.4±0.4	2.2±0.42	0.219±0.019	9.8±1.4	Oval	Red brown	Smooth
Joun MLC5	9.6±2.12	21.9±19.2	9.8±0.3	6.9±0.2	4.6±0.7	1.69±0.56	0.222±0.014	9.3±2.1	Oval	Red brown	Smooth
Debbyieh MLC1	10.6±2.63	6.8±7.9	10.2±0.5	8.3±0.4	3.8±0.2	2.29±0.73	0.256±0.021	8.3±1.4	Oval	Red brown	Smooth
Debbiyeh MLC3	10.3±2.63	6.7±6.5	10.2±0.6	8.4±0.4	3.9±0.2	2.35±0.59	0.250±0.03	8.1±0.7	Oval	Red brown	Smooth
Debbiyeh MLC4	8.1±2.85	9.6±16.7	10±0.7	8.2±0.6	3.7±0.3	1.72±0.33	0.220±0.032	6.7±0.7	Oval	Red brown	Smooth
Baasir MLC1	13.4±2.59	16.3±18	10.4±0.4	8±0.4	4±0.1	2.79±0.93	0.250±0.017	7.7±1.8	Oval	Red brown	Smooth
Saadiyat MLC1	12.6±1.26	2.5±4.1	7.9±0.5	6.4±0.3	4.8±0.8	2.05±0.21	0.166±0.011	23.2±2.6	Oval	Red brown	Smooth
Bourjein MLC1	12.3±1.77	10.6±12.5	9.1±0.4	7.9±0.4	4.2±0.4	2.48±0.48	0.219±0.018	17.1±3.7	Oval	Red brown	Smooth
Bourjein MLC3	8.6±2.46	10.4±17.5	10.4±0.6	8.1±0.4	4±0.3	1.77±0.58	0.224±0.032	7.9±1.7	Oval	Red brown	Smooth
AUB BLC2	8.9±2.3	10.5±11.5	9.3±0.6	7.1±0.6	4.2±0.4	1.6±0.5	0.200±0.028	12.7±1.6	Oval	Brown	Rrough
AUB BLC4	10.33±2.1	4.8±6.2	10.3±0.5	7.9±0.5	3.9±0.2	2.3±0.7	0.244±0.020	8.1±1.6	Oval	Red brown	Smooth
AUB BLC6	10.5±1.38	12.2±14.1	8.9±0.3	6.9±1.3	4.7±0.8	1.88±0.43	0.202±0.023	14.5±5.9	Oval	Brown	Smooth
Hadat BLC9	11.33±3.2	3.3±5.2	9.7±0.4	7.1±0.3	4.3±0.4	1.96±0.58	0.199±0.027	11.9±2.9	Oval	Black	Smooth
Hazmiyeh BLC0	10.6±2.91	4.6±6.6	9.9±0.8	7.7±0.5	3.8±0.3	2.25±0.67	0.225±0.024	8.6±3.5	Oval	Red brown	Smooth
Salhiyeh SLC1	12.3±1.89	16.2±11.5	8.7±0.4	6.7±0.3	4.3±0.2	1.95±0.34	0.196±0.021	14.7±1.9	Oval	Red brown	Smooth
WadiAlHoujair SLC2	14.3±1.57	4.2±3.7	9.2±0.4	6.4±0.4	4±0.2	2.32±0.3	0.170±0.012	21±1.5	Oval	Red brown	Smooth
AlmaElChaeb SLC2	11.4±1.84	1.7±3.7	8.9±0.3	6.8±0.4	4.7±0.2	2.22±0.27	0.203±0.017	14.4±3.4	Oval	Red brown	Smooth
Yarine SLC6	11±2.58	2.25±4.8	8.8±0.6	6.6±0.6	4.7±1	2.01±0.46	0.193±0.018	13.1±2	Elliptic	Red brown	Smooth
Marwahine SLC7	8.8±1.14	0±0	7.9±1	6.9±0.8	4.2±0.4	1.38±0.18	0.166±0.018	23.6±1.7	Oval	Brown	Smooth
Naqoura SLC11	9.7±2.58	6.5±10.8	8.6±0.7	6.5±0.5	4.7±0.5	1.64±0.47	0.279±0.424	10±1.6	Oval elliptic	Red brown	Smooth
Qana SLC12	11.1±1.1	1.8±3.8	7.7±1.1	6±0.9	4.6±0.6	1.66±0.2	0.152±0.022	15.8±1.8	Oval	Brown	Smooth
Hanaway SLC18	10±3.5	0.8±2.6	8.7±0.4	6.3±0.4	4.6±0.2	1.76±0.61	0.181±0.012	17.7±2.3	Oval elliptic	Brown	Smooth
Seddiqine SLC21	11.4±2.07	3.4±4.4	8.7±0.4	6.4±0.7	5±1.2	1.99±0.37	0.177±0.026	11.9±2.3	Elliptic	Red brown	Smooth

Supplementary Table 6. Statistics of the PCA analysis. A: Communalities of the 8 variables accounting for the maximum variability range. B: Statistic test to sample adequacy and PC vectors. MO: Kaiser-Meier-Olkin test of sample adequacy ($KMO<0.5$: Unacceptable; $0.5\leq KMO<0.7$: Acceptable; $0.7\leq KMO<0.8$: Adequate; $0.8\leq KMO<0.9$: Meritorious; $0.9\leq KMO$: Marvelous).

A		B	
	Communalities		Eigeen values
Chord length	0.91	*PC1*	4.95
Pod length	0.87	*PC2*	1.52
Pod width	0.84		Sample adequacy
Pod thiknes	0.74	*KMO*	0.78
Pod weight	0.92		Bartlett test
Pod shape	0.69	χ^2	420.00
Seed length	0.78	*DF*	28
Individual seed weight	0.72	*Sig.*	<0.001

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