Agroforest Syst
DOI 10.1007/s10457-012-9568-7

# Opportunities for domesticating the African baobab (*Adansonia digitata* L.): multi-trait fruit selection

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Received: 5 April 2012 / Accepted: 5 September 2012

**Abstract** Among the priority species identified for domestication in the Sahel region of Sub-Sahara Africa is the baobab (*Adansonia digitata* L.) tree. The quantification of the variation in nutrient content and fruit morphological traits of trees is one of the most important steps in identifying superior planting material for domestication. Ten provenances in Mali covering all the different agro-ecological zones were selected and the fruit morphological traits, vitamin C, calcium, iron and colour were studied. Mean pulp content was 2,149 ± 1,117 , 2,406 ± 776 and 25 ± 17 mg $kg^{-1}$ for vitamin C, calcium and iron, respectively. Fruit pulp colour varied from white, creamy to pink and a significant correlation between pulp vitamin C content and reflectance in the green and blue bands was observed. Significant negative correlations were found between rainfall and pulp vitamin C content and between mean annual temperature and fruit and pulp weight and pulp fraction, suggesting that these traits are influenced by the environment. Pulp iron content correlated positively with topsoil sodicity and base saturation. Similarly, pulp vitamin C content correlated positively with topsoil sand fraction. Pulp reflectance in the blue and green bands correlated negatively with topsoil pH water and base saturation, respectively. The variation in nutritive and morphological traits offers the opportunity for selecting plus trees with a combination of desired traits for domestication.

**Keywords** Baobab · Calcium · Domestication · Fruit pulp · Iron · Pulp colour · Vitamin C

## Introduction

Nutrient deficiencies are a common problem confronting people in both the developing and developed world, with iron deficiency being the most wide spread, affecting about two billion people worldwide (Ramakrishnan 2002). Vitamin C, whose natural sources are from fruits and vegetables, is important in the diet, not only because of its physiological functions in the body, but also because it is associated with enhanced absorption of nonheme iron (Péneau et al. 2008). Therefore, the consumption of fruits rich

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in nutrients and vitamin C is important for nutritional balance. The fruit pulp of the African baobab is known to be rich in nutrients and vitamins (Chadare et al. 2009). It is consumed throughout the Sahel region of Africa from Senegal in the west and extending to Sudan in the east, including regions in Eastern and Southern Africa. Recently, the Food and Drugs Board approved the use of baobab fruit pulp as an ingredient in the United States of America while the European Union also certified the sale of baobab fruit products as a novel food (Cuni Sanchez et al. 2011).

The African baobab is a stem-succulent tree, native to areas with low rainfall (Wickens and Lowe 2008). The baobab is widely used, with uses ranging from the provision of food, shelter and medicine among others (Buchmann et al. 2010). Its drought resistance and size makes it one of the most prominent trees in the Sahel region of West Africa (De Smedt et al. 2012), serving as a habitat to several mammals and bird species which feed on its large fruits (Wickens and Lowe 2008). The succulent stems store water during the dry season while faecal matter from animals and birds inhabiting the tree contribute to soil fertility in an area where organic matter is low (Wickens and Lowe 2008). The rooting system of baobab enhances water infiltration while organic matter from its leaf litter increases the soil nitrogen content (Belsky et al. 1989). These attributes render the baobab tree into an important eco-service provider in the Sahel. In addition, baobab fruit pulp is very important since it has the greatest variety of uses compared to other plant parts (Buchmann et al. 2010). It has been described as nutritive, contains proteins, phosphorous, iron and high amounts of calcium and vitamin C (Chadare et al. 2009). Rural communities in Mali, and in other parts of the Sahel, depend on the baobab fruit pulp as a source of nutrients. The commercialization of the fruit pulp provides income to many people across Africa (Venter et al. 2011). The fruit pulp of the baobab is the most important part of the tree with the highest commercial value in the international market because of its nutritive value (Chadare et al. 2009). The authorization to sell baobab fruit products in both the EU and US food markets (Cuni Sanchez et al. 2011) has further fuelled interest in the species. Though seeming to offer some opportunities for local farmers, concerns have been raised because international trade in the species may result in an overexploitation of the natural population which will have a negative impact on the nutrition and livelihoods of the millions of rural poor who depend on it (Buchmann et al. 2010).

In order to protect the natural population and at the same time meet the demands in both the local and international markets, the baobab tree should be domesticated (Cuni Sanchez et al. 2011). One of the essential features for selecting trees for domestication is the identification of elite plus trees with superior desirable characteristics (Tchoundjeu et al. 2006). To achieve this, a quantitative study to describe the morphological variations in fruit traits including nutritional traits (Leakey et al. 2005a) should be undertaken. Furthermore, knowledge of the interaction between the various fruit traits and between these traits and the environment will be useful for the selection of plus trees with the best combination of traits for domestication (Tchoundjeu et al. 2006).

Vitamin C content has been related to colour in a few fruits, providing consumers with an indication of the vitamin C content based on the colour of the fruit (Simonne et al. 1997). Carotenoids and anthocyanin are two classes of pigments which give colour to fruits and have some additional health benefits, as they are associated with scavenging reactive oxygen species, reducing the risk of cancer and the occurrence of heart diseases (Sass-Kiss et al. 2005). However, for baobab the variation in colour and its relation to other fruits traits and environmental characteristics have not been addressed.

Some studies reported fruit morphological variations in baobab fruits from Mali (De Smedt et al. 2011). Sidibé et al. (1996) reported on vitamin C content in fruit pulp while Parkouda et al. (2011) studied vitamin C and sugar contents across some countries including few provenances from Mali. Recently, Assogbadjo et al. (2012) reported on the biochemical composition of baobab plant parts in relation to soil type. To the best of our knowledge micronutrient content, vitamin C content and pulp colour of baobab fruits from Mali are not yet reported in the scientific literature. Therefore, the objective of this study is to investigate micronutrient content, vitamin C content and colour of baobab fruit pulp from ten provenances in Mali and correlate these traits with environmental data and fruit morphological traits already reported by De Smedt et al. (2011) with the aim of identifying plus trees with superior desirable characteristics which could be domesticated for fruit production.

## Materials and methods

### Plant material

The methodology for fruit collection is as outlined in De Smedt et al. (2011). Provenances for fruit collection were selected based on the presence of a fruit-bearing baobab population along a rainfall gradient in the country as shown in Table 1. In total about 1,300 fruits from 269 trees, located at a minimum distance of at least 100 m, to avoid sampling of genetically related trees (De Smedt et al. 2011), were collected. From the total dataset, 14 trees were randomly selected, and from these trees all five fruits were analysed for vitamin C in order to determine within tree variation. Based on the results (see results section), further analyses were done at tree level. Mixed pulp samples at tree level were obtained by putting together equal amounts of fruit pulp from each of the five fruits from a tree in a mortar and grinding them using a pestle. After sieving, a fine powder with uniform texture was obtained. Vitamin C, calcium and iron contents were analyzed from these mixed samples and results were expressed on a fresh weight basis. The number of trees which were analysed for each trait is shown in Table 2.

### Determination of water and nutrient content

Pulp water content was determined by drying a bulk sample of fruit pulp in an oven at 100 °C for 12 h according to the method of Lockett et al. (2000).

Vitamin C was determined according to the procedure described by Vandekinderen et al. (2009) using HPLC. From each provenance between 20 and 28 trees were analysed giving a total of 260 trees.

Trees whose fruit pulp colour appear visually pink, cream or white were selected and analysed for calcium and iron contents after ashing according to Van Ranst et al. (1999). Contents of calcium and iron in the extracts were analysed using inductively coupled plasma optical emission spectroscopy (ICP-OES, Vista MPX, Varian Inc., USA).

### Colour analysis

A tissue culture dish Cell Star (Cat. No. 627160) was filled with pulp obtained from a mixed sample as described above and then smoothed with a sheet of paper to ensure a uniformly smooth surface. Reflectance spectra between 340 and 1,000 nm were obtained using an advanced, portable hand held, near infrared spectroradiometer (Handheld 2TM, ASD Inc., USA). The same background was used for all the samples and it was ensured that the spectroradiometer was focused towards the centre of the dish containing the samples.

The spectrum was separated into distinct wavelength bands corresponding to red (600–699 nm), green (500–599 nm) and blue (400–499 nm) bands. Means and standard errors associated with each waveband were calculated.

### Selection of plus trees with superior fruit traits

The results from the nutrient analyses (see above) were used to identify superior plus trees with a combination of multiple desirable traits which could

**Table 1** Geographic location, annual precipitation, mean annual temperature in the studied provenances

| Provenance | Latitude (N) | Longitude (W) | Precipitation (mm) | Mean annual temperature (°C) |
|---|---|---|---|---|
| Katon | 10°35′ | 5°55′ | 1,145 | 27.0 |
| Banko | 11°05′ | 7°25′ | 1,097 | 26.8 |
| Kita | 12°48′ | 9°35′ | 1,042 | 27.6 |
| Kerela | 12°45′ | 6°50′ | 823 | 27.5 |
| Massadji | 14°04′ | 11°41′ | 763 | 28.5 |
| Wataga | 14°31′ | 9°35′ | 703 | 27.5 |
| Seribougou | 13°20′ | 6°05′ | 691 | 27.8 |
| Bendjiely | 14°29′ | 3°35′ | 509 | 26.7 |
| Bandjougoula | 15°17′ | 10°31′ | 453 | 28.9 |
| Tatakarat | 15°04′ | 0°53′ | 336 | 29.7 |

**Table 2** Number of trees characterized for each of the fruit traits measured from each provenance

| Provenance | Number of trees characterized | | | |
|---|---|---|---|---|
| | Morphological traits | Vitamin C content | Calcium and iron content | Reflectance measurements |
| Katon | 25 | 24 | 3 | 24 |
| Banko | 22 | 22 | 4 | 22 |
| Kita | 28 | 28 | 9 | 28 |
| Kerela | 24 | 22 | 5 | 22 |
| Massadji | 27 | 27 | 4 | 27 |
| Wataga | 26 | 25 | 7 | 25 |
| Seribougou | 28 | 28 | 12 | 28 |
| Bendjiely | 28 | 28 | 6 | 28 |
| Bandjougoula | 24 | 23 | 5 | 23 |
| Tatakarat | 28 | 27 | 2 | 27 |
| Total | 260 | 254 | 57 | 254 |

be selected for domestication for fruit production. When selecting superior plus trees, vitamin C content was used as the most important trait since it's content is higher in baobab fruit pulp compared to other tropical fruit (Chadare et al. 2009), followed by pulp weight, pulp fraction, iron content and calcium content. Pulp weight and pulp fraction are important since they indicate how much pulp will be available from the fruits while iron and calcium are important nutrients. A web diagramme was drawn using these fruit traits. The tree with the lowest value for each trait was considered the zero baseline for that trait, while the one with the highest was considered to be one (an 'ideotype' for that particular trait). All other trees were ranked accordingly.

## Environmental data

The annual precipitation and mean air temperature were extracted from GIS maps of climatic variables of the Worldclim climate and altitude database (Hijmans et al. 2005) which is based on the means for a 50 year period between 1950 and 2000 (Table 1). Soil data was obtained from Harmonized World Soil Database (version 1.2) (HDSW) (FAO/IIASA/ISRIC/ISS-CAS/JRC 2012). Topsoil characteristics such as sodicity (exchangeable sodium percentage), pH (a measure of alkalinity or acidity of soil), base saturation (a measure of exchangeable cations) and sand fraction (percentage sand in the soil) (FAO/IIASA/ISRIC/ISS-CAS/JRC 2012) were used in the analysis (Table 3) because they were found to influence at least one fruit trait.

**Table 3** Topsoil sand fraction, pH, base saturation and sodicity in the studied provenances

| Provenance | Sand fraction (wt%) | pH water ($-\log(H^+)$) | Base saturation (%) | Sodicity (%) |
|---|---|---|---|---|
| Katon | 56 | 6.3 | 85 | 2 |
| Banko | 56 | 6.3 | 85 | 2 |
| Kita | 73 | 7.5 | 75 | 3 |
| Kerela | 56 | 6.3 | 85 | 2 |
| Massadji | 47 | 6.4 | 79 | 1 |
| Wataga | 56 | 6.3 | 85 | 2 |
| Seribougou | 56 | 6.3 | 85 | 2 |
| Bendjiely | 90 | 5.7 | 80 | 3 |
| Bandjougoula | 43 | 7.6 | 100 | 4 |
| Tatakarat | 90 | 5.7 | 80 | 3 |

## Statistical analyses

Traits averaged per tree were used to calculate the mean for each provenance. Analysis of variance was used to compare the differences between provenances while Tukey's Honest Significance Difference was used for pair wise comparisons between the means. Spearman rank correlation coefficients were used to assess the correlation among fruit traits and also between fruit traits and the environmental variables. A $P$ value of less than 0.05 was used as a threshold for statistical significance. Data analyses were done using R statistical software (R Development Core Team 2010).

## Results

### Variation in fruit traits

Phenotypic variations in fruit morphological traits have been reported in De Smedt et al. (2011), so here we report the other fruit traits investigated. The mean water content of a bulk sample of baobab fruit pulp was found to be 2.1 %. For 14 trees, all the individual fruits were analyzed for vitamin C content. The coefficient of variation in vitamin C content between fruits from the same tree was found to be between 0.06 and 0.16.

Pulp vitamin C content at the tree level ranged from 107 mg kg$^{-1}$ in one tree in Kerela to 5,469 mg kg$^{-1}$ in another in Bendjiely, with a mean value of 2,149 mg kg$^{-1}$ across all provenances (Fig. 1). Vitamin C content of the fruit pulp varied significantly between provenances ($P < 0.001$). Baobab fruits from Bendjiely, with a mean vitamin C content at provenance level of 3,100 mg kg$^{-1}$, were found to contain on average the highest amount of vitamin C followed

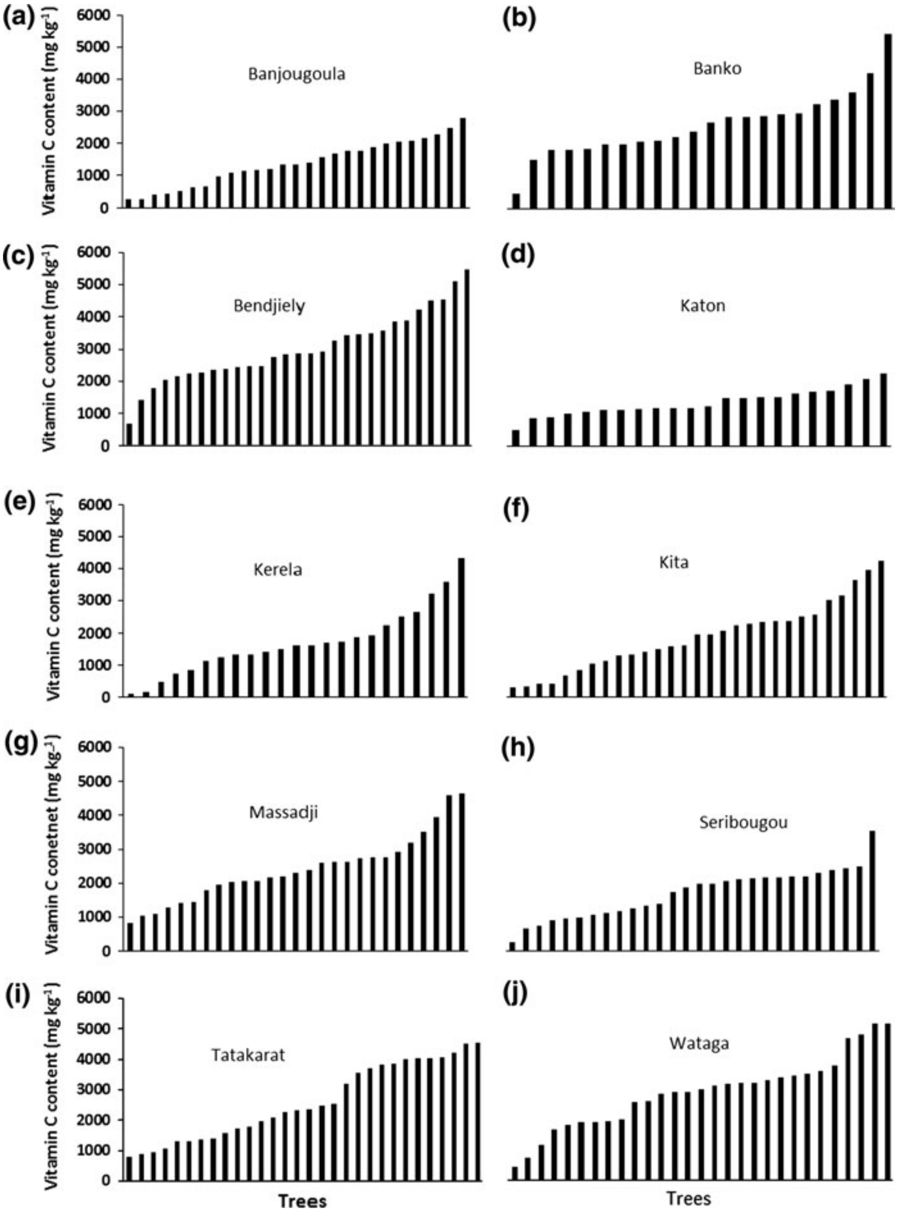

**Fig. 1** Vitamin C content (fresh weight) in baobab fruit pulp for all individual trees of the sampled provenances: **a** Bandjougoula, **b** Banko, **c** Bendjiely, **d** Katon, **e** Kerela, **f** Kita, **g** Massadji, **h** Seribougou, **i** Tatakarat, **j** Wataga

**Table 4** Characteristics of baobab fruits from different provenances in Mali

| Provenance | Fruit weight* (g) | | | Pulp weight** (g) | | | Pulp fraction | | | Vitamin C content (mg kg$^{-1}$) | | | Calcium content (mg kg$^{-1}$) | | | Iron content (mg kg$^{-1}$) | | | Reflectance blue | | | Reflectance green | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Katon | 304.9 | ± | 20.1c | 76.2 | ± | 5.4c | 0.25 | ± | 0.01d | 1152 | ± | 103a | 2526.0 | ± | 232.7ab | 10.0 | ± | 1.6a | 0.417 | ± | 0.008a | 0.585 | ± | 0.006ab |
| Banko | 191.4 | ± | 18.7a | 46.5 | ± | 4.4ab | 0.24 | ± | 0.01d | 2393 | ± | 203cdef | 2682.8 | ± | 288.6ab | 16.4 | ± | 2.4ab | 0.529 | ± | 0.008c | 0.662 | ± | 0.006f |
| Kita | 207.0 | ± | 21.6ab | 39.3 | ± | 4.8a | 0.18 | ± | 0.01ab | 1824 | ± | 188abcde | 3090.0 | ± | 373.3b | 12.8 | ± | 1.4a | 0.444 | ± | 0.014a | 0.627 | ± | 0.007cde |
| Kerela | 222.6 | ± | 24.4ab | 46.7 | ± | 4.9ab | 0.21 | ± | 0.01c | 1713 | ± | 216abc | 2884.6 | ± | 441.9ab | 23.8 | ± | 3abc | 0.454 | ± | 0.011ab | 0.607 | ± | 0.009bcd |
| Massadji | 167.7 | ± | 14.1a | 34.2 | ± | 3.2a | 0.20 | ± | 0.01abc | 2356 | ± | 249bcdef | 2314.3 | ± | 497.2ab | 14.8 | ± | 2.4a | 0.489 | ± | 0.01bc | 0.626 | ± | 0.007cde |
| Wataga | 215.6 | ± | 15.3ab | 40.1 | ± | 3.2a | 0.18 | ± | 0.01abc | 2826 | ± | 212f | 1760.3 | ± | 169.2a | 19.5 | ± | 3.4ab | 0.454 | ± | 0.009ab | 0.601 | ± | 0.007abc |
| Seribougou | 165.3 | ± | 11.2a | 31.3 | ± | 2.4a | 0.19 | ± | 0.01abc | 1638 | ± | 133abcd | 2237.3 | ± | 133.1ab | 31.2 | ± | 3.4bc | 0.451 | ± | 0.01ab | 0.598 | ± | 0.008abc |
| Bendjiely | 282.2 | ± | 22.4bc | 58.4 | ± | 5.3b | 0.20 | ± | 0.01abc | 3100 | ± | 209f | 2366.8 | ± | 181ab | 41.5 | ± | 7.4c | 0.500 | ± | 0.005c | 0.638 | ± | 0.006def |
| Bandjougoula | 238.6 | ± | 19.6ab | 43.0 | ± | 4.1ab | 0.18 | ± | 0.01a | 1485 | ± | 138ab | 2328.4 | ± | 204.9ab | 54.0 | ± | 11.4c | 0.414 | ± | 0.008a | 0.573 | ± | 0.007a |
| Tatakarat | 207.0 | ± | 16.3ab | 43.5 | ± | 4.2ab | 0.21 | ± | 0.01bc | 3039 | ± | 221f | 1666.5 | ± | 601.5a | 24.6 | ± | 1.4abc | 0.515 | ± | 0.006c | 0.647 | ± | 0.005ef |

Values followed by the same letters on the same vertical column are not significant different from each other. Values are mean and standard errors. * and ** have been published in De Smedt et al. (2011)

by Tatakarat (3,040 mg kg$^{-1}$) while those from Katon (1,152 mg kg$^{-1}$) were found to contain the least (Table 4).

Pulp calcium content at tree level varied more than fivefold ranging from 1,065 mg kg$^{-1}$ (Tatakarat) to 5,212 mg kg$^{-1}$ (Kita) with an average of 2,406 mg kg$^{-1}$ for all provenances sampled. The lowest mean calcium content at provenance level was observed at Tatakarat (1,666 mg kg$^{-1}$) while Kita contained the highest amount (3,090 mg kg$^{-1}$), being significantly different from Tatakarat (Table 4).

Pulp iron content at tree level ranged from 7 mg kg$^{-1}$ (Katon) to 87 mg kg$^{-1}$ (Bandjougoula), with an average of 25 mg kg$^{-1}$ over all sampled trees. The highest mean iron content at provenance level was found in Bandjougoula (54 mg kg$^{-1}$), being more than five times the average amount observed in Katon (10 mg kg$^{-1}$) where the lowest mean value was observed (Table 4).

Reflectance of the fruit pulp in the blue and green bands ranged from 0.3 to 0.71.

## Correlations between fruit traits

Spearman's rank correlation coefficients among the considered fruit traits studied are presented in Table 5. Fruit weight was found to be positively correlated with pulp weight ($P < 0.001$) and pulp weight fraction ($P < 0.05$). Both latter traits also significantly correlated with each other ($P < 0.001$). Fruit pulp fraction was negatively correlated with iron content of the fruit pulp ($P < 0.05$) and positively correlated with the reflectance in the blue ($P < 0.01$) and green ($P < 0.001$) bands. Reflectance in both bands was highly, and positively, correlated ($P < 0.001$) to each other. A positive and highly significant correlation was found between vitamin C content and reflectance in both the blue and green bands ($P < 0.001$). A significant correlation was also found between iron content and reflectance in the green band ($P < 0.01$).

## Correlations between fruit traits and environmental characteristics

Precipitation was found to be positively correlated with pulp weight, pulp fraction and calcium content, and negatively correlated with vitamin C and iron content ($P < 0.001$) (Table 6). The relationship between precipitation and pulp fraction, precipitation

**Table 5** Spearman's rank correlation coefficients among fruit traits from ten provenances in Mali

| Fruit traits | Pulp weight | Pulp fraction | Vitamin C | Calcium | Iron | Reflectance in blue band | Reflectance in green band |
|---|---|---|---|---|---|---|---|
| Fruit weight | __0.92***__ | __0.15*__ | 0.05 | −0.17 | 0.09 | −0.09 | −0.05 |
| Pulp weight | | __0.50***__ | 0.08 | −0.11 | −0.03 | −0.01 | 0.03 |
| Pulp fraction | | | 0.10 | 0.10 | __−0.31*__ | __0.18**__ | __0.23***__ |
| Vitamin C | | | | −0.26 | 0.13 | __0.45***__ | __0.43***__ |
| Calcium | | | | | −0.06 | 0.08 | 0.06 |
| Iron | | | | | | −0.23 | __−0.40**__ |
| Reflectance in blue | | | | | | | __0.95***__ |

Figures in bold are significant * $P < 0.05$ ** $P < 0.01$ *** $P < 0.001$

**Table 6** Spearman's rank correlation coefficients between fruit traits and mean annual precipitation, mean annual air temperature and some topsoil characteristics

| Fruit traits | Precipitation (mm) | Mean annual temperature | Sodicity | Base saturation | pH water | Sand fraction |
|---|---|---|---|---|---|---|
| Fruit weight | 0.03 | __−0.21***__ | 0.41 | 0.29 | −0.14 | 0.11 |
| Pulp weight | __0.15*__ | __−0.30***__ | 0.17 | 0.22 | −0.48 | 0.30 |
| Pulp fraction | __0.28***__ | __−0.24***__ | −0.36 | 0.05 | −0.51 | 0.17 |
| Vitamin C | __−0.24***__ | −0.08 | 0.1 | −0.49 | −0.60 | __0.61*__ |
| Calcium | __0.27*__ | −0.14 | 0.05 | −0.09 | 0.32 | 0.03 |
| Iron | __−0.73***__ | 0.16 | __0.53*__ | __0.38*__ | −0.21 | 0.02 |
| Reflectance in blue | −0.12 | −0.06 | −0.23 | −0.35 | __−0.64*__ | 0.43 |
| Reflectance in green | −0.02 | −0.11 | 0.02 | __−0.60*__ | −0.47 | 0.62 |

Figures in bold are significant * $P < 0.05$ ** $P < 0.01$ *** $P < 0.001$

and vitamin C and precipitation and iron content was stronger than that between precipitation and pulp weight, precipitation and calcium content (Table 6). An inverse relationship was observed between mean annual temperatures and fruit weight, pulp weight and pulp fraction ($P < 0.001$). Vitamin C content correlated positively with topsoil sand fraction ($P = 0.05$) while pulp iron content correlated positively with topsoil sodicity and topsoil base saturation ($P < 0.05$). Topsoil base saturation and topsoil pH water correlated negatively with reflection in the green and blue bands respectively ($P = 0.05$).

### Selection of plus trees with superior fruit traits

Three trees (Ban 26, Ben 2 and Ben 26) could be identified with the best combination of the most desirable fruit traits which could be selected for domestication (Fig. 2). These trees performed better than the average for at least three of the five fruit traits studied.

## Discussion

### Variations in fruit traits

The range in fruit weight in Mali (165–305 g) was found to be very similar to the range reported by Assogbadjo et al. (2005) for Benin. The range was, however, higher than reported for Malawi (Cuni Sanchez et al. 2011). This may be because a larger ecological range was sampled in Mali compared to Malawi. It could also be one of the differences between baobabs from West and East Africa.

The low coefficient of variation (0.06–0.16) in vitamin C content in fruits from the same tree indicates a low intra-tree variation. Based on this low intra-tree variation it was decided to consider vitamin C content at tree level for further analysis. The low within tree variation in vitamin C content has important implications for domestication since knowing the vitamin C content of one fruit of a tree is indicative of the vitamin C content of other fruits of that tree.

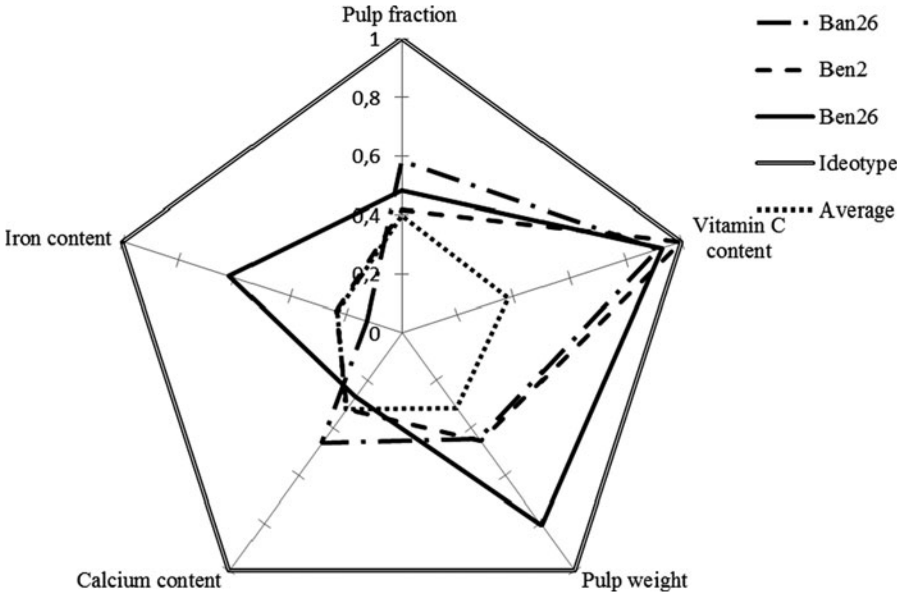

**Fig. 2** Multi-trait web diagramme of tree-to-tree *variation* in fruit traits from ten provenances in Mali. Trees superior in the fruit traits studied are shown here

A range of 1,500–5,000 mg kg$^{-1}$ has been reported in baobab fruit pulp from Mali with a mean of 2,800 mg kg$^{-1}$ (Sidibé et al. 1996), very close to the average value (2,830 mg kg$^{-1}$) found by Chadare et al. (2009). In this study, the observed mean vitamin C content (2,149 mg kg$^{-1}$) is lower than the average reported for Mali (Sidibé et al. 1996; Parkouda et al. 2011) but close to the average value (2,090 mg kg$^{-1}$) found by Diop et al. (1988) in Senegal. It is noteworthy to state that the reports by Diop et al. (1988) and by Sidibé et al. (1996) did not state clearly if vitamin C contents were calculated on a fresh weight or dry weight basis. Vitamin C content as reported by Parkouda et al. (2011) was done on a dry weight basis. Baobab fruit pulp contains higher amounts of vitamin C when compared to *Borassus eathiopum* (vitamin C content of 1,340–1,710 mg kg$^{-1}$) (Ali et al. 2010) and *Tamarindus indica* (vitamin C content of 197 mg kg$^{-1}$) (Saka 1995) which grow in the same area.

Our results confirm the large variability in vitamin C content of baobab fruit pulp within and between provenances as was also observed in an earlier study in Mali (Sidibé et al. 1996). The range in baobab fruit pulp vitamin C content found in this study (107–5,469 mg kg$^{-1}$) was considerably larger than reported by Sidibé et al. (1996) (1,500–5,000 mg kg$^{-1}$). The scale of our field collection, harvesting about five fruits from 269 trees resulting in more than 1,300 sampled fruits from all the areas where the baobab grows in Mali, was more extensive and could cover more of the possible genetic and phenotypic variations within the species compared to the 120 fruits from 24 trees analysed earlier by Sidibé et al. (1996). Therefore, the larger variability reported in this study may be a more correct indication of the actual variability within the species. For some of the provenances (Banko, Bendjiely, Kerela, Seribougou), however, the bar charts (Fig. 1) of vitamin C contents do not level off at the high values but shows some abrupt increases. This might indicate that the whole range of vitamin C content was not completely sampled and that even more intensive sampling might identify trees with even higher vitamin C contents.

As mentioned before our results of baobab fruit pulp vitamin C content (2,149 mg kg$^{-1}$) were lower than those reported by Sidibé et al. (1996) and by Parkouda et al. (2011) for Mali. The difference between this study and the previously mentioned studies might be explained by differences in methods of analyses (titrimetric method versus HPLC method in this study), as a higher vitamin C content (33 % more) was obtained by the titrimetric method compared to HPLC method by Diop et al. (1988) on the same sample. Determination of vitamin C using HPLC with fluorescent detection, a methodology which involves derivatization of DHA and the conversion of AA to DHA, gives the highest selectivity and sensitivity (Novakova et al. 2008) and thus could be considered a better method compared to other methods.

A water content of 2.1 % is at the lower end of values reported for baobab fruit pulp in literature, between 2 and 27 % with an average of 11 % (Chadare et al. 2009). As a consequence of its lower moisture content compared to other fruits from the semi-arid lowlands of West Africa such as *B. eathiopum* (water content of about 80 %) (Ali et al. 2010) and T. indica (water content of between 15 and 47 %) (FAO 1998), the baobab fruit pulp can be stored for long period without significant loss in vitamin C content.

The calcium content in our samples ranged from 1,065–5,212 mg kg$^{-1}$ with an average of 2,406 mg kg$^{-1}$. This is slightly lower than the average of 3,020 mg kg$^{-1}$ reported by Chadare et al. (2009) but higher than the range (600–725 mg kg$^{-1}$) found in Benin (Assogbadjo et al. 2012), and thus, our results fall within the range reported in the literature (30–6,550 mg kg$^{-1}$) (Chadare et al. 2009). Mean pulp iron content (25 mg kg$^{-1}$) was also within the range of 12–86 mg kg$^{-1}$ found in earlier studies (Chadare et al. 2009). However, a slightly wider range (7–87 mg kg$^{-1}$) was found in this study than reported in the literature.

Besides the different environmental conditions, including soil type, also the genetic make-up could account for the large intra- and inter-provenance variation in nutritive value (Lee and Kader 2000; Chadare et al. 2009), since fruits were collected in such a manner as to avoid collecting closely related trees. However, this should be confirmed by experimental evidence. Nevertheless, according to Leakey et al. (2005b), variation in fruit parameters at the level of the provenance indicates that genetic variation exists within the species since the environment is similar.

## Correlations between fruit traits

The positive correlation between fruit and pulp weight (Table 5) found in this study is similar to the findings in Benin and Malawi (Assogbadjo et al. 2005; Cuni Sanchez et al. 2011). This positive correlation between fruit and pulp weight and between fruit weight and pulp fraction indicates that if one is interested in the amount of fruit pulp, the heaviest fruits should be selected. A similar relationship was reported by Leakey (2005) for marula (*Sclerocarya birrea*).

Fruit pulp which appears visually white was found to contain more vitamin C compared to those with a creamy or pinkish colour. Pulp reflectance in both the green and blue bands correlated positively with pulp vitamin C contents. The pinkish fruit colour may be the result of the presence of anthocyanins (Bacchella et al. 2008) which have been found in baobab fruit pulp (Shahat 2006). Ascorbic acid has been reported to be inversely related to anthocyanin content (Bacchella et al. 2008), and although we did not measure anthocyanin content, this seem to be in agreement with the fact that pinkish pulp contained less vitamin C. The observed relationship between reflectance and vitamin C content might be a handy first tool for selecting plants with a high vitamin C content since reflectance is cheaper, less laborious and time consuming to measure than the common chemical determination and allows even a first determination in the field. While visual colour estimation is easy and cheap, it may, however, be subjective. Therefore, reflectance measurements could offer a more objective approach with comparable advantages in relation to visual evaluation. Reflectance measurements have also been used as a method to determine vitamin C non-destructively in tangerine (*Citrus* sp.) (Liu et al. 2008).

## Correlations between fruit traits and environmental characteristics

Correlations between annual rainfall and mean annual air temperature with fruit morphological characteristics (Table 6) have earlier been reported for baobab in Benin (Assogbadjo et al. 2005), and more recently in Malawi (Cuni Sanchez et al. 2011). Higher rainfall favoured the production of fruits with higher pulp weight and pulp fraction in southern provenances (Table 6) compared to northern provenances which experience lower rainfall. Similar results have been reported for *Vitellaria paradoxa* in Burkina Faso (Maranz and Wiesman 2003) and in Nigeria (Ugese et al. 2010). The negative correlations between mean annual temperature and fruit morphological traits may exist because higher temperatures constitute a more adverse environment for the production and development of larger fruits (Ugese et al. 2010). For *V. paradoxa*, Maranz and Wiesman (2003) reported that adaptation to a drier and warmer climate resulted in an increased formation of fat in the seeds to protect against drought and the production of fruits with lower pulp weight.

The negative correlation ($P < 0.001$) between pulp vitamin C content and rainfall found in this study is similar to the findings of Parkouda et al. (2011) who reported higher vitamin C contents in baobab fruit pulp from the drier sites. Some studies in other species have reported similar relationships between vitamin C content and rainfall or irrigation (Lee and Kader 2000). Vitamin C, one of the most common antioxidants in plants, increases in the warmer and drier northern sites, most probably as a reaction to increasing drought stress. Drought experienced by plant results in an increase in the production of reactive oxygen species, leading to increases in the antioxidant system which controls the intracellular antioxidant concentrations protecting the cell (Smirnoff 1993). According to Munné-Bosch and Alegre (2002), for mutant *Arabidopsis thaliana* vitamin C content is positively related to drought tolerance. Contrary to our results, Assogbadjo et al. (2012) reported for Benin higher vitamin C in the pulp of fruits from the Guineo-Congolian zone with a higher rainfall compared to those from Sudanian zone characterized with a lower rainfall. However, these latter authors used less trees and provenances (three trees per climatic zone), compared to the number used in this study.

Top soil sand fraction was found to influence vitamin C content, while iron content was influenced by topsoil sodicity and base saturation. Similarly, Assogbadjo et al. (2012) reported the influence of soil physico-chemical characteristics on baobab pulp nutrient contents. Cultural practices affecting soil nutrient content have earlier been described as one of the factors influencing composition and concentration of compounds such as vitamin C content in plants (Lee and Kader 2000). This means that a tree with a high vitamin C content, for example, growing in one place may not produce the same high vitamin C content if grown in another area with a different soil type, a factor which should be considered when domesticating trees for fruit production.

## Selection of plus trees with superior fruit traits

The lack of correlation between fruit morphological traits and pulp nutritional value (except for the case of the negative correlation between pulp iron content and pulp fraction) indicates that it is possible to identify a few important traits which could be combined to form superior plus trees endowed with the most advantageous and desirable traits for nutritional and commercial values (Leakey et al. 2000). For the selection of these plus trees with superior fruit traits (Fig. 2) vitamin C content might be one of the most important traits since it has been reported to be significantly higher in baobab fruit pulp than in other tropical African fruits (Chadare et al. 2009). Due to the low water content of the fruit, it can also be stored for a long time providing a source of vitamin C during the dry period when less fresh fruits are available. In addition, vitamin C in the diet enhances the absorption of dietary iron (Péneau et al. 2008). It is unknown whether selecting for vitamin C as the main trait of interest will reduce some other traits by chance or through genetic linkages between them, and could be a topic for future research.

However, possibilities exist for the selection of individual trees with several fruit traits of interest well above the average. Two trees from Bendjiely and one from Bandjougoula have the best combination of superiority for most of the traits studied (Fig. 2) and might be considered superior plus trees. Although low in calcium content, Ben 26 contains the best combination of vitamin C, high pulp weight and iron content. Choosing these trees for domestication in regard to fruit production will increase average fruit pulp fraction between 35 and 50 %, vitamin C content by 80–87 %, pulp weight by 47–83 % and iron content by 34–90 % of the average.

The intra-specific variation observed in our study, has also been observed for another indigenous West African fruit, *V. paradoxa* (Ugese et al. 2010), opening the possibility of selecting trees with superior fruit traits. This might suggest that a similar domestication strategy can be followed for baobab as for the other species. Tree selection could be done at provenance level since the environment has an influence on fruit morphological and nutrient traits (Table 6). At the provenance level within each climatic zone, there are plus trees with superior fruit traits offering the possibility of local domestication.

## Domestication

After identifying trees with superior desirable traits, these could be multiplied vegetatively since such a method of propagation assures the conservation of the traits of interest (Tchoundjeu et al. 2006). For baobab, such vegetative multiplication can be accomplished by grafting. Sidibé et al. (1996) successful grafted baobab superior in vitamin C content in Mali. A similar approach could be used for other underutilized multipurpose tree species. In contrast to concerns highlighted by Kalinganire et al. (2008) that strategies to produce genetic gain by selecting for certain traits may decrease genetic variation within a population, Ugese et al. (2010) demonstrated for *V. paradoxa* that such selection instead resulted in a higher genetic diversity.

A domestication programme for baobab could be carried out in Sudano-Sahelian zones of Sub-Sahara Africa stretching from Senegal in the west to Sudan in the east, including portions of Southern and East Africa where the species already grows (Cuni Sanchez et al. 2011). A study to identify the global potential for cultivating the baobab using ecological niche modelling by Cuni Sanchez et al. (2010) suggests India, Madagascar, Mexico, North-West Australia and North-East Brazil as potential areas where the species can be cultivated base on annual rainfall and temperature, thus bringing the potential benefits of the species to a larger population.

For baobab different ethnic groups have been reported to view different traits as important (Cuni Sanchez et al. 2011). So, the selection of plus trees for domestication should be done in collaboration with farmers and local communities since they have their perception of desirable fruit characteristics. Cuni Sanchez et al. (2011) proposed a list of desirable traits when selecting baobab trees for domestication. Domesticating the baobab tree for fruit production will be beneficial to the local communities. As baobab fruits are ready for harvesting during the dry season when most other crops are not available and because its low water content makes it possible to store the fruit for a long time, it can serve as a buffer against hunger and can be a source of income during periods of scarcity. Reported to be rich in minerals, vitamins, proteins and oils, domesticating the baobab will increase the availability of these nutritional component leading to an improvement in nutritional security and health of the communities (Leakey et al. 2005b).

Besides the traits preferred by the local market, preference of the international markets should also be taken into consideration when domesticating the species (Cuni Sanchez et al. 2011) since domestication of indigenous fruit trees should be a market driven process which simultaneously alleviates poverty and preserves the environment (Leakey et al. 2005b). For domestication to be successful, it should be linked to market expansion and commercialization (Tchoundjeu et al. 2008) in order to encourage domestication to such levels that it can reduce economic problems (Leakey et al. 2005b). The acceptance of baobab products in the EU and US markets and its use in the pharmaceutical industries points to the existence of a market.

## Conclusion

There is a significant variability in baobab fruit traits from different provenances in Mali offering opportunities for tree selection for domestication. Trees from the drier northern provenances produced smaller fruits with higher vitamin C content. Reflectance correlated positively with vitamin C content which is a highly desirable trait, opening the possibility to select fruit pulp with high vitamin C content based on colour, a trait that can easily be measured. A few trees were identified with a good combination of the most desirable traits which could be selected as plus trees for domestication. Our findings show that topsoil characteristics influenced the nutritive composition of baobab fruit pulp. Knowledge of the environmental and genetic heritability of the traits is important for the selection of cultivars since this will make the selection to be done on sound data. A common garden with superior baobab from different provenances superior in specific traits could be established to determine if they will reproduce the trait of interest in a different environment. Concerted international efforts should be exerted to search for baobab trees superior in fruit traits for domestication.

**Acknowledgments** The authors are thankful to Litsa Bogaerts for assisting with the vitamin C analysis. We are also thankful to Ria Van Hulle for assisting in analyzing calcium and iron. Katrijn Alaerts is thankfully acknowledged for assisting in the fruit collection. We are also grateful to the assistance provided by Yu-Ting Chen, Siege van Ballaert and Kathleen Wuyts who assisted with the colour analysis. Our thanks also go to Hilde Vanderstappen for making practical arrangements for the laboratory analysis to be carried out.

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