Genet Resour Crop Evol (2016) 63:377–399
DOI 10.1007/s10722-015-0360-1

REVIEW PAPER

Africa's wooden elephant: the baobab tree (*Adansonia digitata* L.) in Sudan and Kenya: a review

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Received: 23 May 2015 / Accepted: 21 December 2015 / Published online: 13 January 2016

Abstract Wild edible fruits hold great potential for improving human diets, especially in agricultural societies of the developing world. In Africa, a well-known supplier of such fruits is the baobab (*Adansonia digitata* L., Malvaceae), one of the most remarkable trees of the world. Several studies in different African countries have highlighted this indigenous fruit tree as a priority species for domestication and expanded use. However, internationally available information on baobab in East Africa, particularly in Sudan and Kenya, remains scarce. This review aims to shed light on the ecology, diversity and current level of utilization of baobab in East Africa in order to facilitate

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domestication and conservation of the species. A list of priority research areas is provided at the end of the review to encourage further studies and investment in this unique plant taxon.

Keywords *Adansonia digitata* · Agroforestry · Ethnobotany · Fruit · Indigenous fruit tree (IFT) · Nutrition · Up-side down tree · Sub-Sahara

Introduction

According to recent estimates, about 805 million people around the world are chronically undernourished (FAO 2014) and 162 million children under five years of age are stunted, particularly in poor families living in rural areas (UNICEF 2014). Out of the 21 high-burden countries with child stunting rates of >40 %, as many as 15 are located in sub-Saharan Africa (UNICEF 2013). This frightening situation coincides with rapid biodiversity loss (Jackson et al. 2005; Chappell and La Valle 2011). Great potential exists in supplementing agriculture-based food supply by promotion of edible wild foods (Chaudhary and Sthapit 2013). This also implies potential for the exploration and utilization of the rich diversity of flavours, textures and aromas available in plants (Collins and Qualset 1999).

In many rural communities of the developing world, livelihoods depend on exploration of natural resources for income, food and other products. In time of hardship, wild products often constitute security options, for example when shortfalls in agricultural crop production are compensated through gathering and processing of wild edible fruits or other products from woodlands and forests (Becker 1986; Mithöfer and Waibel 2003; Akinnifesi and Leakey 2008; Vinceti et al. 2013). Worldwide, only about 50 fruit tree species have been highly domesticated so far (Leakey and Tomich 1999) and are produced on a commercial scale. Compared to tropical America and Asia, Africa has the highest number of wild edible fruit species (about 1200 species; Paull and Duarte 2011). The diversity of Africa's wild edible fruits indicates high horticultural potential and valuable genetic resources that—after their domestication—could become the basis for integrating new commercial high-value species and cultivars into existing farming systems. Their use and conservation belong to the most important tasks for mankind within the international CWR (Crop Wild Relatives) initiative (Ford-Lloyd et al. 2011).

Across sub-Saharan Africa wild indigenous fruit trees (IFTs) are used for a wide range of purposes, fulfilling subsistence as well as commercial objectives (Bennett 2006; Jamnadass et al. 2011; Leakey 2003, 2012). IFTs improve nutrition, boost food security, foster rural development and support sustainable landscape management (Gebauer et al. 2007; Mithöfer and Waibel 2008; Saied et al. 2008; Pye-Smith 2010; Ræbild et al. 2011). Especially during periods of famine and food scarcity, IFTs provide crucial services to rural communities through the provision of energy and nutrients, including vitamins, minerals and proteins.

Many IFT species are well adapted to harsh environmental conditions and yield also in drought years, when crops often fail (Haq et al. 2008). In many areas, IFTs are intensively harvested, which

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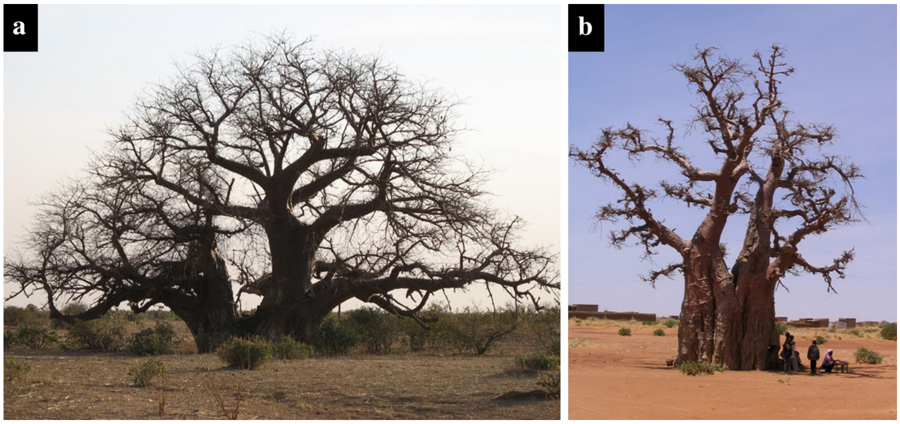

Fig. 1 Natural growth habit (unpruned; however, lower branches are browsed by livestock and/or wildlife) of the baobab (*A. digitata*) in Kordofan, Sudan (**a**) and heavily pruned baobab north-east of El Obeid, Sudan, due to fresh leaf harvest (**b**)

sometimes leads to overexploitation of natural stands. Domestication of IFT species and integration into agricultural systems would allow producing a diverse range of fruits on farms to promote food and nutritional security. At the same time, this would reduce the harvesting pressure on natural stands, facilitating conservation of the species' genetic resources (Kehlenbeck et al. 2013). Despite their potential and importance at local scale, IFTs are neglected by science and therefore remain underutilized. Recently the growing importance of IFTs such as marula (*Sclerocarya birrea* A. Rich.) and the shea butter tree (*Vitellaria paradoxa* C. F. Gaertn.) have exemplarily shown the great potential such species may have for international food and pharmaceutical markets. The fruits of *S. birrea* for example are used in South Africa to make the cream liqueur 'Amarula', a major export product that is traded worldwide (Ham et al. 2008; Saka et al. 2008).

The baobab (*Adansonia digitata* L., Malvaceae, subfamily Bombacoideae, Baum et al. 2004; Fig. 1) is one of the most remarkable trees of the world (Pakenham 2002; Lewington and Parker 2013, Bynum and Bynum 2014). It is an important IFT throughout the drylands of Africa and a representative of the wooden "Big Five" (Jama et al. 2008). Several studies in different African countries such as Benin (Assogbadjo et al. 2010, 2011), Malawi (Cuní Sanchez 2011), Mali (De Smedt et al. 2011), Nigeria (Okafor 1980), Tanzania (Maduka 2004) and South Africa (Modiba et al. 2014) have highlighted this deciduous stem-succulent taxon as priority species for further domestication and enhanced utilization.

Due to its bulky appearance, its greyish wrinkled bark at the massive trunk and its widely visible appearance in many African savannahs, one of the common names is wooden or vegetative elephant (von Maydell 1990; Isomäki 2009; Pakenham 2004). The baobab is also known as Africa's up-side down tree due to its gnarled boughs which are leafless for many months of the year and appears like a root system straightened toward the sky (Wickens 1982; NRC 2008). The eye-catching profile of this unique tree has attracted many travellers and tourists and it is widely used as a motif on postcards, calendars and postage stamps.

In recent years, international interest in the species has intensified following the acceptance of baobab fruit pulp as food ingredient by the European Union (EC 2008) and the US Food and Drug Administration (FDA 2009), which was initiated by PhytoTrade Africa. A recent study by Gebauer et al. (2014) revealed more than 300 baobab products or products with baobab parts as an ingredient that are already available in Europe. The products range from foodstuffs, such as soft drinks, sandwich spreads, cereal bars, sweets and chocolates, to pharmaceutical products, including after-shave, shampoo and foot spray.

In the arid and semi-arid areas of sub-Saharan Africa, the baobab provides a variety of foodstuff (van Wyk 2006, Kabore et al. 2011) to local communities, as well as fodder (Venter and Venter 1996; De Caluwé 2011; Bekele-Tesemma 2007), fibres for weaving and rope-making (Teel and Hirst 1990; DAFF 2012), gum (Roberts 1990; Nussinovitch 2010), seed oil (Osman

2004; Kamatou et al. 2011), natural medicine (Mueller and Mechler 2005; Iwu 2014; Lim 2012), materials for dishes (Schütt and Wolf 2004) and water storage (Walsh 1991). It also often constitutes shelter and a gathering point for humans and their livestock (Gebauer and Ebert 2002). All across the African continent, the sight of a baobab has inspired tale, poetry, songs and legends. Baobabs have often commanded compassion and even devotion (NRC 2006; Buthelezi 2013; Wenkel 2014).

Fruits, leaves, flowers, bark, seeds, wood and roots are used in different ways. Buchmann et al. (2010) compiled 300 traditional uses in Benin, Mali and Senegal across eleven ethnic groups and four agroecological zones. In West Africa, both baobab fruits and leaves contribute to human diets in a major way (Gebauer et al. 2014), while in East and South Africa the fruits are the most important plant part used (NRC 2006; Esterhuyse et al. 2001). A review paper by Stadlmayr et al. (2013) indicated that baobab fruit pulp is of high nutritional value, as it had the lowest water content but the highest energy, available carbohydrate, fibre, ash, vitamin C, calcium, magnesium and potassium contents compared with 9 other important IFTs from sub-Saharan Africa.

In the last 10 years several baobab studies have been conducted in western and southern Africa on different aspects, such as morphological diversity (e.g. Cuní Sanchez et al. 2010, 2011a,b), genetic characterisation (Assogbadjo et al. 2006; Kyndt et al. 2009), population stability/vitality (Schumann et al. 2010, 2012; Venter and Witkowski 2013a), nutritional value (Osman 2004; Chadare et al. 2009), germination (Danthu et al. 1995; Razanameharizaka et al. 2006), age determination (Patrut et al. 2007, 2011, 2013), ecophysiology (De Smedt et al. 2012), diseases (Cruywagen et al. 2010) and socio-economy (De Caluwé 2011; Venter and Witkowski 2013c). However, peer-reviewed publications on baobabs in East Africa, particularly Sudan and Kenya remain scarce (North et al. 2014). According to modelling results obtained by Cuní Sanchez et al. (2011c), baobab populations in East Africa, particularly in Sudan, will shrink under the predicted levels of climate warming. To prevent irrevocable losses of genetic material, information on these threatened populations is urgently needed to define research needs and to develop sustainable utilization and conservation strategies.

This review presents currently available information on the ecology, diversity and utilization of the baobab in East Africa. Information presented here was obtained from the literature, gathered during field surveys and collated during stakeholder workshops held in 2013 at Rhine-Waal University of Applied Sciences in Kleve, Germany and in 2014 at Jomo Kenyatta University of Agriculture and Technology in Juja, Kenya. The overall aim of this paper is to identify some of the challenges and opportunities in utilization, promotion and conservation of the baobab resources of Sudan and Kenya and to encourage further research and investment in this remarkable plant taxon.

Historical background

The name baobab is probably derived from the Arabic words ‘bu hibab’ meaning ‘fruits with many seeds’ (Mshigenro and Paull 2008). Its scientific name *Adansonia digitata* was given by Carl von Linné in 1753 in honour of the French scientist Michel Adanson who lived from 1727 to 1806. Adanson was the first European botanist to see and describe the baobab tree in its native habitat (Orwa et al. 2009), while the term ‘digitata’ refers to the shape of the tree’s leaves. In Sudan, the common Arabic vernacular name is ‘tabaldi’, more rarely ‘humeir’ and the fruit is known as ‘gungolez’ (Vogt 1995). The fact that there exists a different name for the fruit indicates its specific importance to local people in Sudan. In Kenya, vernacular names for the tree are ‘mbuyu’ (Swahili), ‘mwamba’ (Kamba), ‘olmisera’ (Maasai) and ‘muru’ (Bajun) (NRC 2008).

In Sudan, it is well known that old trees often have natural or artificial cavities, in which up to 10,000 litres of water can be stored for months or even years without spoiling, if properly covered (von Maydell 1990). This capacity may also be one reason why the baobab is also called ‘bottle tree’ (Gruenwald and Galizia 2005; NRC 2006). Nachtigal (1971 cited by Wickens and Lowe 2008) recorded several examples of Sudanese villages without wells, where people relied entirely on water stored in hollow baobabs for their survival during the dry season. It appears that baobabs provided important preconditions for the establishment of these settlements. The value of baobabs as water cisterns to both villagers and long-

Fig. 2 Toothbrush stored at the wrinkled bark of a baobab (*A. digitata*) trunk in Kordofan, Sudan, indicating the use of the tree as washing place of herdsmen

distance travellers is also illustrated by the large number of water-storing trees that were deliberately destroyed during the time of the Mahdist war in Sudan of 1881–1898 (Wickens and Lowe 2008). According to Wickens (1982), hollow trees filled with water in the former North Eastern Province of Kenya were used by slave and ivory raiders from Ethiopia, enabling them to cross water-poor areas. Furthermore, in eastern Africa hollow trunks have been used as shelters, stables and stores for centuries. Even the enormous trunk of the baobab itself provides important shelter, especially in the almost tree-less regions of North Kordofan, Sudan. Herdsmen occasionally fix a mirror and store sanitary items such as soap, towel and toothbrush (Fig. 2) in the wrinkled bark of a stand-alone baobab and use the shade of the trunk as temporary washing place. Hollow trees are occasionally used as stables for livestock which is also known from West Africa (Guy 1971).

The bark of many large baobab trunks shows inscriptions and carvings from the past, making these trees living witnesses of history (Erb 2004, Watson 2007). However, damage by fire, livestock and human visitors as well as natural attrition seems to have reduced the number of historical engravings.

Due to its visibility from a long distance and the distinctive shape of individual trees, baobab has been an important landmark for travellers in savannah areas for centuries. Individual trees were even marked on early 1:250,000 maps of Sudan (Wickens 1982). Furthermore in many cases boundaries were demarcated or sites of new villages established with reference to a baobab tree.

Natural distribution

In Sudan, baobabs are most frequently found in the southern part of the country (Fig. 3). They thrive on sandy and rocky soils, from the short-grass savannah (El Amin 1990) to the deciduous savannah woodlands (Wickens and Lowe 2008). They often occur as widely spaced individuals or small groups of individuals scattered over large areas. Baobabs are also common on mountain slopes such as the Jebel ed Dair in central Sudan. Wiehle et al. (2014a) sampled baobabs up to an elevation of 1013 m in the Nuba Mountains. In the eastern foothills of the Jebel Marra massif, baobabs are known to occur up to 1250 m (Wickens 1982). Along wadis and in depressions, where water collects during the rainy season, baobabs are found even in the very dry northern parts of Darfur and Kordofan with 100–200 mm annual rainfall. On heavy soils, such as the flat clay plains around Habila (600 mm annual rainfall) in the Nuba Mountains, baobabs are almost absent, mostly found as monumental individuals or in clumps on rocky outcrops that give this area a characteristic feature. According to El Amin (1990), baobabs form belts in Kordofan, Darfur, Blue Nile, Upper Nile (South Sudan) and Bahr El Ghazal (South Sudan).

In Kenya, the baobab is a conspicuous feature of different vegetation types such as deciduous bushland, woodland and wooden grassland (Wickens and Lowe 2008). It is distributed only in the eastern part of the country in two belts, one in the inland from the Tanzanian border east of Mt. Kilimanjaro towards the north-east around Kitui town and a second one along the whole coastal region (Fig. 3), even directly at the seashore on fossil corals (Fig. 4) and in areas with high annual rainfall up to 2000 mm (NRC 2006). In Tsavo National Park scattered trees exist over a large area on sandy clays and are often damaged by elephants (Wickens and Lowe 2008). Pettigrew et al. (2012) recently surveyed baobabs from the eastern slopes of Mt. Kilimanjaro (Tsavo West National Park) to the south Kenyan coast. Surprisingly, they found in addition to other locations in eastern and southern Africa the new baobab species *Adansonia kilima* Pettigrew et al., which has a diploid nature in contrast to the tetraploid *A. digitata*. Within the survey areas,

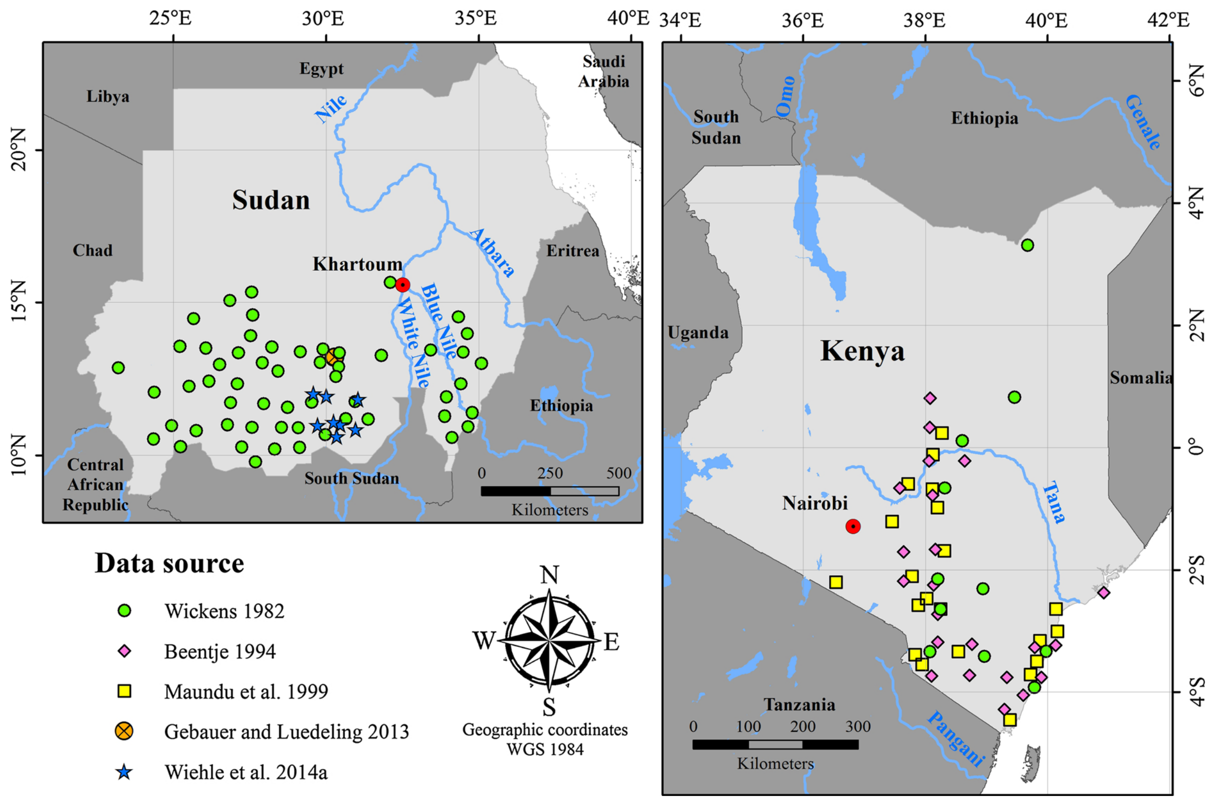

Fig. 3 The distribution of baobab (*A. digitata*) in Sudan and Kenya

Fig. 4 Baobab (*A. digitata*) at the sea shore (low tide) near Shimoni, Kenya

A. kilima was restricted to elevations between 650 and 1500 m, while *A. digitata* occurred primarily at elevations below 800 m.

The baobabs of Kenya are geographically disjunct from the baobab stands in Sudan, and it is possible that the alluvial clays with rather undrained soil conditions of the White Nile and Bahr el Arab flood plains effectively isolated the baobab populations in Sudan and Kenya (Wickens and Lowe 2008). The Sudanese baobab population in western Sudan extends into a very small part only of eastern Chad (Wickens 1982), whereby palaeo-environmental conditions were deemed responsible for the absence of the species from the remainder of the country (Wickens and Lowe 2008).

In general, information about the mode of seed dispersal is still largely anecdotal (Wickens and Lowe 2008). In the Nuba Mountains, Sudanese baboons have been observed to extensively feed on baobab fruits, and undigested seeds were found in their faeces (Fig. 5). The presence of baobabs in places difficult to access, such as the summit of a hill or the crest of a rocky outcrop, may be the result of baboons transporting the fruit or carrying seeds in their digestive tracts (Wickens and Lowe 2008). It can be assumed that seeds passing through the intestinal tract have a lower dormancy (Vogt 1995) and therefore improved germination rates (Mabberley 2008) due to the softening of the hard seed coat, which increases its water permeability (Razanameharizaka et al. 2006; Sacande et al. 2006). However, baboons are also known to pick immature fruits, taking one or two bites and then discarding the remains. As those fruits contain undeveloped seeds, baboons therefore also contribute to seed destruction, which has also been reported from South Africa (Venter and Witkowski 2011).

Other mammal species such as rodents and ruminants as well as birds, are also known to feed on baobab fruits and are probably also engaged in the zoochory (seed dispersal by animals; Wickens and Lowe 2008; Assogbadjo and Loo 2011; Kupika et al. 2014). When fruits fall to the ground, the woody husk often fractures, enabling termites to enter and eat the fruit pulp. By doing so, they bring soil into the fruit which becomes moist at the onset of rains, providing a favourable environment for in situ germination.

Likely one of the predominant dispersal vectors for baobab seeds are humans. Nomads and travellers commonly carry fruits as food supply. When eating the sweet pulp, they spit out the seeds, and thereby disseminate them along the wayside or in the shade of trees (Wickens and Lowe 2008). It is also possible that fruits from riverine trees are water-dispersed which explains the fact that baobabs are frequently found on banks of the Nile (Sahni 1968) and along wadis (El Amin 1990) in Sudan.

Utilisation and yield

Several studies have highlighted baobab as one of the most important IFTs, with considerable ethnobotanical significance, in Sudan (e.g. Bella et al. 2002; Gebauer et al. 2002a, b; El Tahir 2004; El Tahir and Gebauer 2004; Gebauer and Osman 2004; Adam et al. 2012, 2013) and in Kenya (e.g. Muok et al. 2000; Mbabu and Wekesa 2004; Muok 2005; Simitu and Oginosako 2005; Simitu et al. 2009; Mwema et al. 2012; McMullin and Kehlenbeck 2015).

In these two East African countries, the most important benefit of baobab is derived from the fruit, using different parts in various ways. Fruits, which are generally well attached to the branches, are picked by hand or with a long rod with a hook. They are smashed on a stone or cut with a machete (Fig. 6). The capsules contain cream-coloured farinaceous pulp, which is rich in vitamin C, calcium, magnesium and potassium (Stadlmayr et al. 2013). Due to its naturally low water content, the fruit can easily be stored for months under dry conditions (FAO 1988). The pulp is eaten raw, dissolved in water or milk or added to porridge (Maundu et al. 1999). In some areas of Kenya, such as Nairobi and Taita-Taveta, where refrigeration is available, sweetened water-diluted pulp is frozen in small polythene packets and used as an ice lollipop as also described by Ruffo et al. (2002) from Tanzania. The Akamba people of Kenya use the pulp in local

Fig. 5 Undigested baobab (*A. digitata*) seeds in baboon faeces on the slope of Jebel ed Dair Mountain, Sudan

Fig. 6 Harvester opens baobab (*A. digitata*) fruits by using a machete in Kilifi, Kenya

beer production (Orwa et al. 2009), while in coastal Kenya, chunks of dried pulp with the seeds embedded are coloured and sugar-coated and sold as 'mabuyu' sweets (Fig. 7a) in many kiosks and supermarkets (Karmann and Lorbach 1996; Bosch et al. 2004). Ndabikunze et al. (2011) documented high pectin content in baobab fruit powder, which makes it suitable for jam production. The Kenya Forestry Research Institute (KEFRI) recently produced baobab jam (Fig. 7k) for testing its market potential.

The kidney-shaped seeds of baobab have a hard testa, which is not readily separated from the kernel (Wickens 1980). The endosperm has a pleasant almond-like taste (NRC 2008) and is rich in oil (Kamatou et al. 2011). Seeds can be eaten fresh, dried or roasted and edible oil for cooking and cosmetic use can be pressed from them. In Sudan, whole seeds are pounded into a coarse meal, fermented and added to the traditional dish 'Kurundu' (Dirar 1993). In drought-prone areas, baobab pulp and seeds still act as important supplementary food during famine times, which has also been reported by Robinson (2004, 2005) from South Sudan. The woody fruit shells are used in different ways as dishes, vessels, etc. and in the manufacture of curio items and souvenirs such as mouse traps, jewel cases, lamp shades and music instruments (Fig. 7m, o, p).

In recent years, regional and international interest in baobab products has increased and more and more baobab pulp and seeds are processed at a commercial scale. For example at the Wild Living Resources Business Park in Kilifi, Kenya, sweetened baobab powder pellets (Fig. 7h) and seed oil (Fig. 7j) are produced mainly for tourists and the local high-end market. In Sudan baobab pulp powder (Fig. 7b, c, f) and seed oil are produced by e.g. the Kordofal Taste Factory for Fruit Trees Extraction in El Obeid for the local market. According to the available information, no baobab fruit pulp or seed oil is exported from Sudan or Kenya so far, while some countries of western Africa such as Senegal are well integrated into the baobab export business to Europe (Gruenwald and Galizia 2005).

Little information is available on fruit yield of baobab trees in Sudan and Kenya. In Kordofan, Sudan, Gebauer (unpublished data) counted fruits of six mature trees which resulted in an average of 381 fruits per tree with a range between 145 and 595 fruits per tree. In Kenya, Muchiri and Chikamai (2003) assessed baobab trees in Kibwezi. Fruit counts of the 25 randomly selected trees yielded between 12 and 2675 fruits per tree with an average of 360 fruits per tree. Kehlenbeck et al. (unpublished data) assessed yields of 96 trees along a transect from Kibwezi to the Kenyan coast. According to the interviewed 64 tree owners, average number of fruits per tree was 707 with a range of 140–1800 fruits per tree. However, alternate bearing, removal of immature fruits, e.g. by baboons, and early harvests of mature fruits are challenges to accurate yield assessments.

As mentioned above, baobab leaves are rarely used in East Africa. In many parts of western Sudan in contrast, young tender leaves are mixed with peanuts and used as salad (Bella et al. 2002). In Kenya, leaves are also reported to be used as vegetable in certain parts of the country (Muthoni and Nyamongo 2010) and prepared like spinach or mixed and cooked with coarser vegetables like cassava leaves (Maundu et al. 1999). However, during the interviews of 64 farmers along a transect from Kibwezi to the coast, only two farmers mentioned a potential use of the leaves as vegetable (Kehlenbeck, unpublished data). Leaves and young shoots are also palatable to domestic animals and therefore harvested for fodder (Sahni 1968). Fallen leaves are browsed by livestock at the beginning of the dry season in the Sudanian zone. The fodder value of the leaves is very good, with 1 feed unit kg^{-1} DM (or 6.9 MJ kg^{-1} DM) and 110 g kg^{-1} of digestible crude protein (DCP) (Toutain 1980). In general, baobab leaves are of limited importance as food in East Africa, especially compared to West Africa where they are part of daily dishes and sold fresh or dried in large amounts on rural and urban markets (Sidibé et al. 1998; Gebauer et al. 2014). However, where lack of water limits the production of vegetables, baobab trees are also heavily pruned (Fig. 1b) for fresh green leaves in Sudan. To our knowledge, no scientific data on leaf yields are available for East Africa. However, Dhillion and Gustad (2004) estimated that more than 130 kg of fresh leaves per tree and year are harvested in Mali.

The stringy inner bark of the baobab trunk yields a strong and durable fibre. In Sudan, the bark is stripped off at the lower trunk of the trees (Fig. 8a) and used for the production of string and cordage (Fig. 7e), which is then used to cover furniture, such as the traditional rope stool 'bambar' (Fig. 7n) or the traditional rope bed 'angareb'. The trees are not seriously damaged

Fig. 7 Products made from the baobab (*Adansonia digitata*). **a** 'mabuyu' sweets‡, **b**, **c** and **f** natural fruit powder†, **d** colored fruit powder‡, **g** uncolored fruit powder‡, **e** rope†, **h** fruit powder pellets ‡, **i** 'kiondo' basket‡, **j** seed oil‡, **k** fruit jam‡, **l** massage oil‡, **m** lamp shade‡, **n** 'bambar' rope stool†, **o** toy drum‡, **p** jewel cases‡ (†from Sudan, ‡from Kenya)

and even after repeated use the bark regenerates and can be stripped again some years later. In Kenya, the fibre is used for making the famous 'kiondo' baskets (Fig. 7i; Orwa et al. 2009). However, sisal and more recently nylon strings have replaced traditional baobab fibre. In Kenya, many baobab trunks show scars (Fig. 8b) of intensive debarking in former times that have completely healed over, while in Sudan, bark harvest is still common.

According to Sahni (1968), the wood has little use except for floats of fishing nets instead of cork. Trials at the Forest Research Institute in Soba, Sudan, have shown that if the wood is left in water for about two months it will disintegrate, producing a long fibrous substance that could be used as a packing material. Due to its high water content, the wood is chewed by humans and animals in case of extreme water scarcity (Simitu and Oginosako 2005). However, the low value of baobab wood for humans has saved many trees from being cut down for construction, firewood and charcoal in Sudan and Kenya.

In East Africa, a soluble red dye is obtained from baobab roots (Beentje 1994; Sidibé and Williams 2002; Dharani 2011). In some parts of Kenya, soft tuber-like root tips are cooked and eaten in times of famine (Kabuye 1986; Maundu et al. 1999; Muok 2005).

Regarding baobab's medicinal value, there are many claims and applications. For example in Sudan, dysentery and diarrhoea are treated with a maceration or decoction of baobab fruit pulp (El Ghazali et al. 1997; El-Kamali and El-Khalifa 1999). If this remedy shows no effect, dough made from baobab bark or roasted seeds are fed to patients several times a day (Wickens and Lowe 2008). In Kenya, a tisane of fruit pulp and a steam bath of the bark decoction are used to treat high fever (Maundu et al. 1999).

Intra-specific diversity

Wickens (1982) distinguished four types of baobabs with regard to the trunk shape (1: trunk tapering, branching from low down; 2: bottle-shaped trunk; 3: stout, cylindrical trunk, branching from the top; 4: trunk short, squat). He further stated, that the bottle-shaped baobabs appeared to be a common shape in East Africa. However, our own observations suggest that in Sudan and Kenya bottle-shaped baobabs are less frequent. Cylindrical and squat-trunked baobabs are the most common in Sudan while Kenya is dominated by the cylindrical and tapering trunk types.

In Sudan, bark colour was observed to be predominantly grey-green, grey-yellow and silver-grey

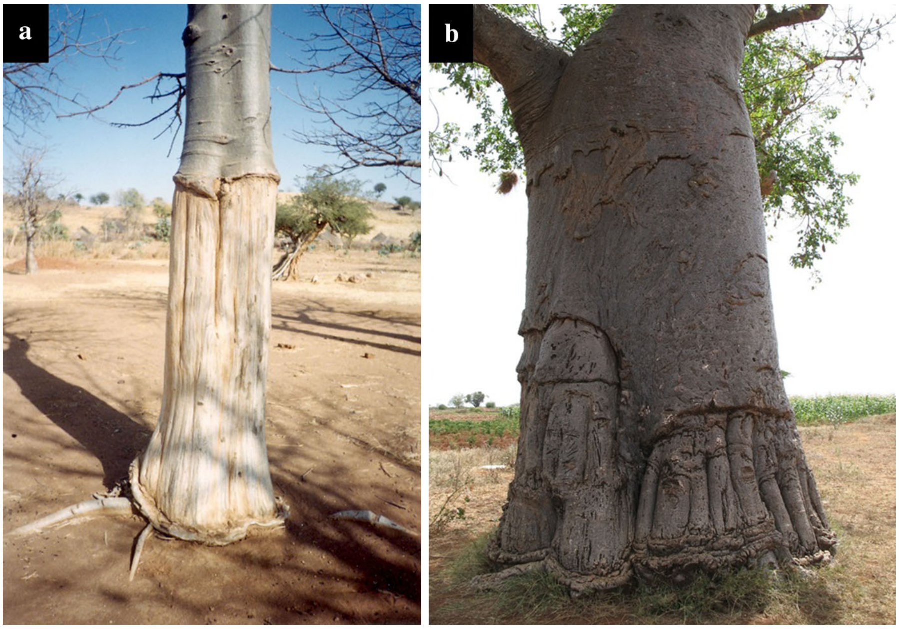

Fig. 8 Ring-debarked baobab (*A. digitata*) trunk in the Nuba Mountains, Sudan (**a**) and signs of debarking in former times on a baobab trunk near Makindu, Kenya (**b**)

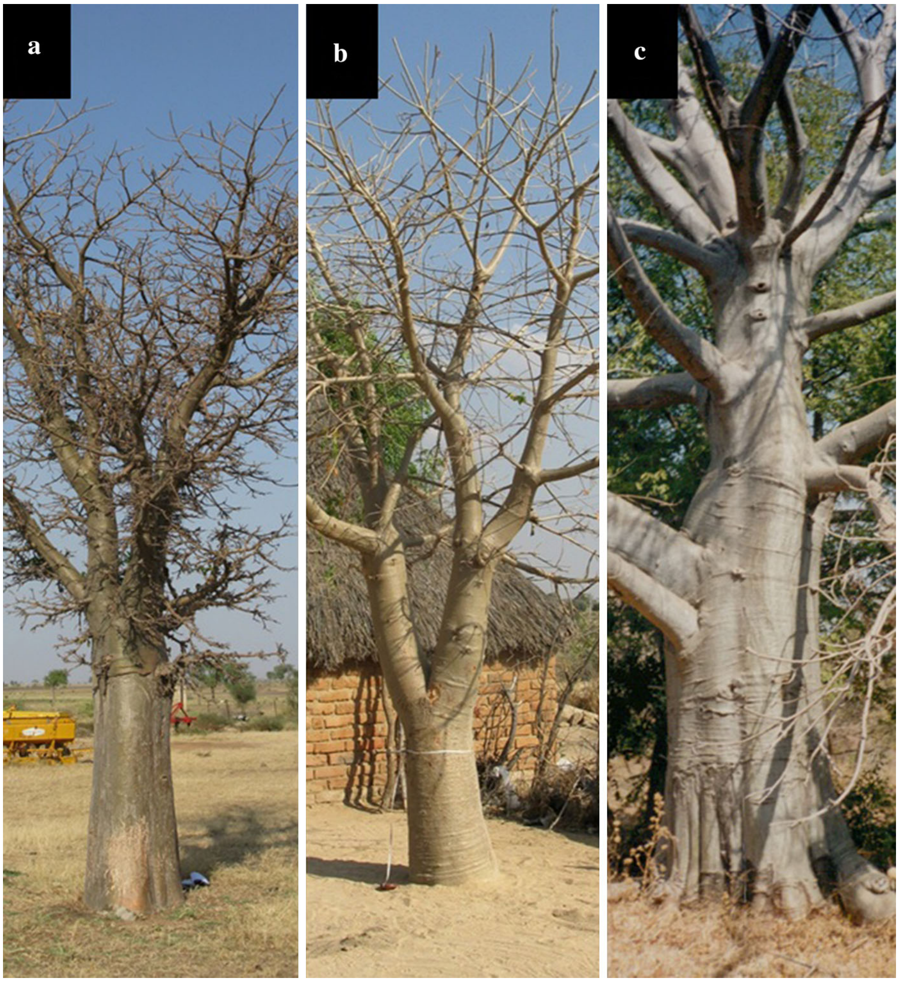

Fig. 9 Baobab (*A. digitata*) morphotypes in Sudan with different bark color: grey-green (**a**), grey-yellow (**b**) and silver-grey (**c**)

(Fig. 9). In Kenya, silver-grey, dark-grey and reddish brown barks seem to be more common. In the West African Sahel, folk classification recognizes three morphotypes: black, red and grey bark baobabs (NRC 2006). Local farmers there often assert that bark colour is related to fruit and leaf quality (Parkouda et al. 2012).

In Sudan and Kenya baobabs exhibit a considerable diversity of leaf morphology. Leaf colour ranges from light to dark green, and leaves appear dull or shiny (Fig. 10). Furthermore, considerable variation in hairs at the underside of the leaves could also be observed. Gurashi et al. (unpublished data) studied leaf shape and size of baobabs from different locations in Blue Nile and North Kordofan, Sudan, and recorded a considerable diversity. Leaflet shape and apex ranged

Fig. 10 Leaves of two baobab (*A. digitata*) seedlings from Sudan grown under controlled environmental conditions in a greenhouse in Germany. Leaflets on the *left side* are showing undulated leaf margins. Scale in centimeter

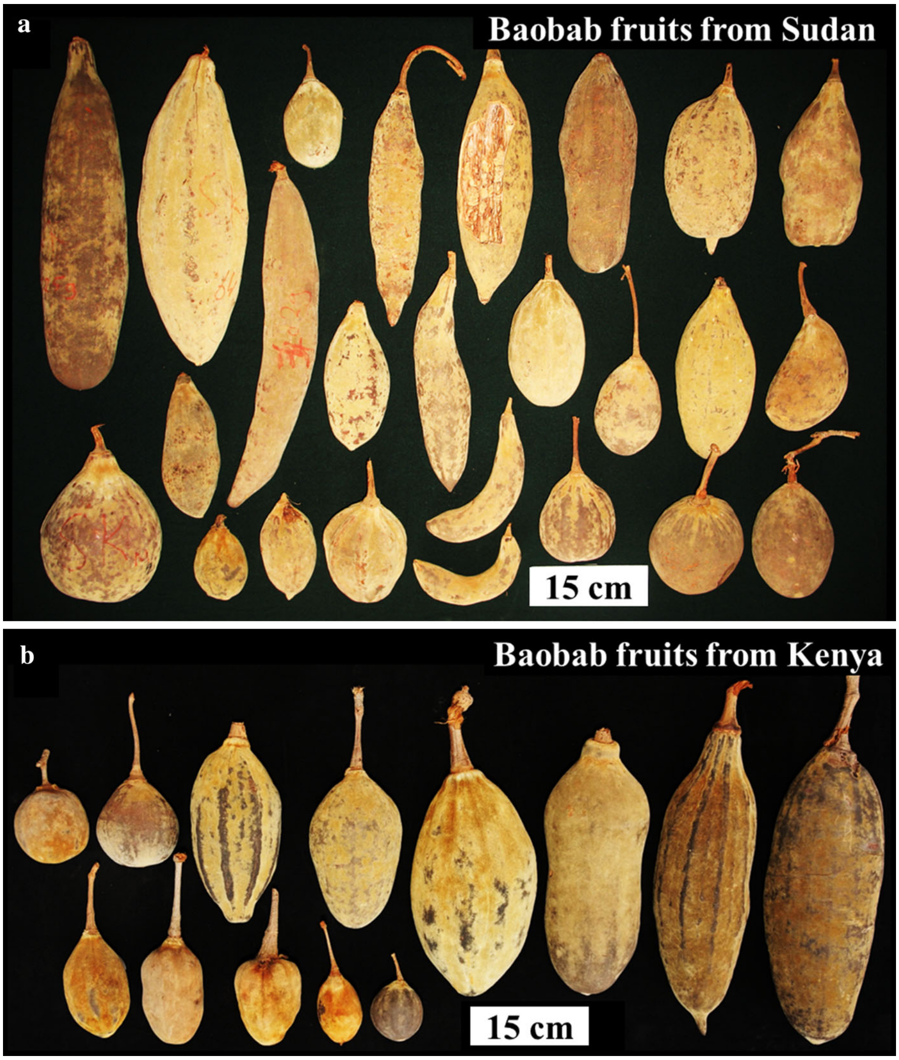

Fig. 11 Morphologically diverse baobab (*A. digitata*) fruits collected in Sudan (**a**). *Second upper left most fruit* 648 g dry weight, 15 cm width; *first upper left most fruit*: 44 cm length. Morphologically diverse baobab (*A. digitata*) fruits collected in Kenya (**b**). *Right most fruit* 683 g dry weight, 13 cm width, 37 cm length

from lanceolate to obovate and caudate to obtuse, respectively. Furthermore, the screening of baobab seedlings from different locations in Kordofan, Sudan, in greenhouses in Germany under controlled environmental conditions revealed some seedlings with undulated leaflet margins (Fig. 10). Leaf shape assessments of baobabs from Kenya are still on-going. In West Africa, several studies have reported that local people distinguish baobabs by leaf colour and smoothness (Assogbadjo et al. 2008) and recognise bitter and delicious (Assogbadjo et al. 2008) or tasty leaves (Dhillion and Gustad 2004). However, such folk classifications seem not to be available for eastern Africa, possibly due to the rare utilization of baobab leaves for food.

Substantial variability in fruit size and shape has been observed in *A. digitata* for Sudan and Kenya, with fruit shapes ranging from globose to fusiform (Fig. 11). In Sudan, Gurashi and Kordofani (2014) categorized 486 fruit samples into 12 fruit shape classes. Gebauer and Luedeling (2013) described four distinctive fruit types, with significant differences in percentage of pulp per total fruit, ranging from 14 to 21 %. Recent surveys in Kordofan recorded fruit lengths of up to 44 cm, widths of up to 15 cm and weights of up to 647 g (Fig. 11). Considerable variation in the flavour of the creamy pulp is widely known and people commonly taste crushed fruits on local markets prior to purchasing them. Maundu et al. (1999) reported for Kenya that farmers can distinguish the taste of the fruits by the fruit shapes. Elongated fruits are supposedly sweeter than short fruits (Simitu and Oginasako 2005). Kehlenbeck et al. (unpublished) documented 64 baobab trees in eastern Kenya and collected fruit samples. Average fruit length and weight ranged from 9 to 30 cm and from 62 to 627 g, respectively, while the average proportion of pulp ranged from 7 to 34 % of total fruit weight. In a recent survey in Kilifi, Kenya, fruit lengths, widths and weights of up to 37 cm, 13 cm and 683 g, respectively were measured (Fig. 11).

Maximum fruit size and weight records from Sudan and Kenya exceed reports from Benin (Assogbadjo et al. 2005b), Malawi (Cuní Sanchez et al. 2011a; Munthali et al. 2012), Mali (Cuní Sanchez et al. 2011a), Niger (Parkouda et al. 2012) and Senegal (Soloviev et al. 2004). However, fruit lengths of up to 54 cm reported by Wickens (1982) for Angola exceeded the records from Sudan and Kenya.

Our observations in Sudan and Kenya also show clearly that fruit shape varied between trees but was consistent within each individual tree. Assogbadjo et al. (2011) also reported a low within-tree morphological variability in capsule shape of baobabs in Benin and suggested a high heritability of this trait.

Baobab phenology displays considerable variation. During our field trips in Kenya, we observed some ecotypes that do not shed their leaves at the beginning of the dry season (Fig. 12), as has also been reported from Sudan (Gebauer and Luedeling 2013; Wiehle et al. 2014a). Maranz et al. (2008) evaluated baobab germplasm of different origin in field trials in Mali and also observed some dry-season leaf retention of individual trees. The flowering season for *A. digitata* is usually at the start of the rainy season, although some flowers can also be observed in the dry season leading to off-season fruits. Main harvest season for fruits in Sudan and Kenya is November to December and September to November, respectively. However, regional differences exist and sometimes mature fruits could be found on individual trees at different times of the year.

Wiehle et al. (2014a) studied the genetics of baobabs from seven different locations in the Nuba Mountains, Sudan, by applying nine microsatellite markers. The study revealed a substantial amount of genetic variation with the appearance of two distinct gene pools. Nei's genetic diversity was slightly higher in Malawian populations (Munthali et al. 2012) compared to the Sudanese locations. However, higher numbers of rare and private alleles in the Nuba Mountains might indicate hidden genetic resources. To our knowledge, studies on genetic diversity of Kenyan baobab populations are not yet available, and thus, gene flow among countries is largely unknown. However, Prinz and Kehlenbeck recently started to investigate the genetic diversity of Kenyan baobab accessions and preliminary results suggest a rather high level of diversity.

Fig. 12 Two baobab (*A. digitata*) trees in a sisal field in Kilifi, Kenya, showing differences in phenology. *Left tree* is showing dry-season leaf retention

Cultivation and conservation

High baobab abundance in many settlement sites in Africa suggests a strong relationship between trees and people (Duvall 2007). However, in some sites it remains unclear whether people naturally settled close to these useful trees or vice versa (NRC 2006). For Sudan, our observations indicated that baobabs are integral parts of human settlements. In the town of El Obeid they grow in urban gardens (Gebauer 2005), are signs of market places and planted as avenue trees (Fig. 13). Wiehle et al. (2014b) studied 61 homegardens in four villages of the Nuba Mountains and found *A. digitata* in 46 % of the gardens with a total of 74 individuals. With baobab fruits collected from the wild

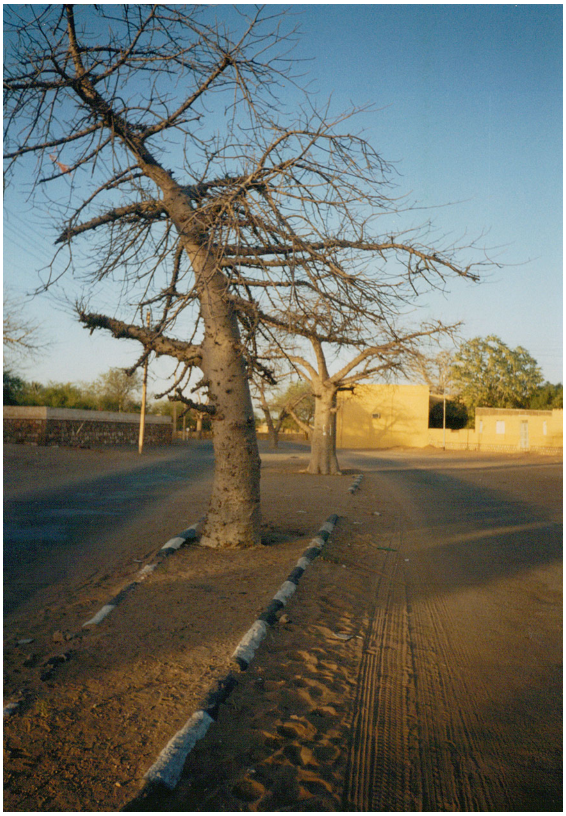

Fig. 13 Three baobab (*A. digitata*) trees planted in the divide of a road in El Obeid, Sudan

by the gardeners, seeds are extracted from the nearby woodlands in the Nuba Mountains, transferred to homesteads, disposed in the gardens and often spontaneously germinate in place. In the village of Sama, in South Kordofan, Goenster et al. (2011) found baobab trees in homegardens, where they were not actively planted, but had been retained during land clearance for crop planting. Beentje (1989, 1994) also reported for Kenya that baobab trees are often left standing in cultivated areas. This is in line with our observations of remaining monumental baobabs in crop lands such as sisal plantations in Kilifi near the Kenyan coast (Fig. 12). Karmann and Lorbach (1996) suggested that baobabs are usually not cut when clearing woodlands for agriculture because of their spiritual significance. In inland Kitui, Kenya, baobabs can also be found scattered all over the farms with an average of seven trees per farm, with farmers taking care of the trees by clearing bushes around them and protecting young trees from destruction by domestic or wild animals (Simitu and Oginosako 2005).

In general, baobab trees in Sudan and Kenya appear to be rarely planted but commonly protected by households. In the last few years awareness of the benefits of planting baobab seedlings has increased and planting material has been provided by, e.g. Wild Living Resources Business Park in Kilifi, Kenya. Outside of its natural range of distribution, individual baobabs have been successfully planted in places such as Khartoum, Sudan (Korbo et al. 2012), or near Moyale at the border between Kenya and Ethiopia (Vollesen 1995).

Low recruitment rates and bell-shaped or positively skewed size class distribution (SCD), which are typical of baobab populations across Africa, have led many authors to express concern about the long-term survival of baobab populations. Various causes, such as livestock browsing, recent expansion of baobab fruit harvesting and the drop in rainfall due to climate change have been discussed extensively (Assogbadjo et al. 2005a; Venter and Witkowski 2010; Cuní Sanchez et al. 2011c). Wiehle et al. (2014a) confirmed the importance of 'protected areas', such as homegardens and parklands, as survival strategy for future baobab populations in Sudan, echoing findings by Venter and Witkowski (2013b) for South Africa and Mpofu et al. (2012) for Zimbabwe. Wilson (1988) recorded a lack of regeneration in baobab populations in Darfur and Kordofan. However, Gebauer and Luedeling (2013) were able to identify a viable population pattern with high recruitment rates of a natural baobab stand in North Kordofan, Sudan. Venter and Witkowski (2010, 2013b) argued that recruitment of the baobab is an episodic event of the long-lived trees, and therefore relatively low numbers of juveniles, compared to other species, are normal for baobab. 'Sheets of seedlings' with a number of same age baobab individuals under the canopy of a mature baobab were observed by Gebauer near Damazin in eastern Sudan (Fig. 14). While natural regeneration in most African countries is lacking, Sudan seems to offer unique possibilities for studying population dynamics of baobabs at the northernmost limit of the East African distributional range.

In Kenya, little information is available on population patterns of natural baobab populations. According to Wilson (1988) and Muchiri and Chikamai (2003), SCD curves are constricted bell-shaped with a low number of individuals in the young age class indicating that tree populations are not self-maintaining. However, recent observations by Fischer and Kehlenbeck indicated

Fig. 14 Evenly aged baobab (*A. digitata*) seedlings under the canopy of a mature baobab near Damazin, Sudan

significant rejuvenation of baobab populations in parts of Taita-Taveta County (unpublished data). Baobabs have long been noted as being attacked and seriously damaged by elephants, and their population has been drastically reduced in wildlife conservation areas, such as Tsavo National Park (Leuthold 1977; Wickens and Lowe 2008). Mainly in the dry season, elephants strip the bark, eat any fruit and branches they can reach and gouge out the soft wood with their tusks for moisture extraction from the trunk, thus causing heavy damage or the collapse of the tree. Young baobabs are particularly palatable and elephants invariably select young trees for feeding. In that process, they often push them over (Wickens and Lowe 2008). The phenomenon of declining baobab populations due to increasing abundance of elephant in game reserves and national parks has also been reported from South Africa (Edkins et al. 2007; Whyte et al. 2003), Tanzania (Barnes 1980; Weyerhaeuser 1985), Zambia (Guy 1982) and Zimbabwe (Swanepoel 1993; Kupika et al. 2014,). In Sudan, no such damage on baobabs has been reported in the recent decades due to the usual absence of elephants since the beginning of the twentieth century.

Knowledge gaps and research needs

The baobab tree is a key multipurpose species with considerable importance as a model fruit tree species for domestication and pan-African multi-disciplinary research cooperation. Compared to western and southern Africa, scientific information on baobab from East Africa is fragmentary but would serve as an important contribution to the overall picture of the "wooden elephant" on the African continent. Combining the traditional knowledge of local communities in East Africa with modern scientific research methods could boost the species' utilization, promotion and conservation.

The following list highlights important research areas for Sudan and Kenya. We do not claim that this list is comprehensive; it is rather a selection and aims at supporting the development of research strategies.

Phenotypic variation

Morphological and phenological characterisation needs to be further elaborated by using consistent coding schemes. How much variation in tree growth habit and in size and shape of leaves and fruits has been discovered and described so far? How much of this variation is influenced by the environment? Which key characteristics can be used to distinguish different ecotypes within *A. digitata* and *A. kilima*? How widespread is *A. kilima* in Kenya and is *A. kilima* also present in Sudan? The descriptor list for baobabs developed by Kehlenbeck et al. (2015) is a first important contribution to provide internationally standardized formats and a universally understood language for the characterisation of the intra-specific diversity of baobab, and the list needs to be tested across Africa's baobab populations.

Genetic variation

More individuals from various locations need to be genetically studied to verify and support morphological results, characterize ecotypes, depict patterns of genetic variation and to identify hidden valuable genetic resources with rare and private alleles. Moreover, knowledge of genetic patterns allow for identification of different species or types of unknown taxonomic status. This is especially relevant, if morphological characterization is difficult (*A. digitata* vs. *A. kilima*) or differentiation of genotypes or even species remains unclear (*A. digitata* in West Africa vs. East Africa). Analysis of gene flow among Sudan and Kenya is important to evaluate the differentiation of these regions assumed to be unconnected. However, in a large biogeographic investigation of chloroplast DNA variation, both populations share the same haplotype (Pock Tsy et al. 2009). How much genetic variation occurs within and between Sudanese and Kenyan populations on a more regional scale and compared to other populations on the African continent? How much genetic exchange exists between Sudan and Kenya via South Sudan or Ethiopia, and which vectors are responsible for pollen (e.g. fruit bats, Fig. 15) and seed dispersal (e.g. birds, mammals and humans)? How unique and valuable are the isolated Sudanese baobabs?

Population status versus uses

The conservation status of baobab stands in eastern Africa and the quantity of materials extracted from wild baobab stands are largely unknown. How many baobab populations exist in Sudan and Kenya and how viable and resilient are they? How do these populations regenerate? What are the effects that different harvesting methods and the increased demand for baobab products in Europe and the US have on the health and survival of populations? Many baobab stands in Sudan are probably heavily overexploited. For Kenya, on the other hand, NRC (2008) estimates that less than 10 % of the potential inherent in its existing baobabs are utilized, but this statement needs verification, particularly if commercial use is to be promoted for improving livelihoods of local communities. Aerial tree identification and mapping of baobab populations, as already suggested by Wickens (1966), in combination with ground referencing as conducted by Vieilledent et al. (2013) on Malagasy baobab species may help to assess the sizes and distributions of baobab populations in Sudan and Kenya.

Fig. 15 A baobab (*A. digitata*) flower from a tree in Kilifi, Kenya, showing laceration traces of pollinating fruit bat claws on the white petals indicating their nocturnal visits for nectar

Socio-economics of baobab management, processing and trade

There exist significant knowledge gaps with regard to the current economic contribution of baobab to the smallholder farm-household systems in East Africa, as well as the national economy in Sudan and Kenya at large. Which contribution can baobab make to household livelihoods and income, reduced vulnerability of rural communities and poverty alleviation? How economically viable are the various baobab management, processing and marketing options? What is the comparative advantage of East African baobab compared to other areas of origin globally? It is important to quantify total production, losses and supply of baobab products at various scales, as well as their actual subsistence consumption and demand from domestic and international markets in order to carefully assess the potential for further commercialization of the resource in Sudan and Kenya. Studies are needed to better understand the functioning of baobab value chains in both countries, as well as success factors and limitations for the development of commercial baobab products.

Nutritional value

There is substantial uncertainty about the regional variation of nutrient contents in baobab leaves, fruit pulp and seeds from East Africa. Are differences caused by the environment or by genetics, or are both important? Does *A. kilima* differ from *A. digitata* with regard to the nutritional value of its products? How do soil and climate affect the nutritional value and flavour of leaves, fruit pulp and seeds? Plants with high polyphenol content, such as baobab avail their micronutrients, particularly critical minerals such as iron, calcium and zinc, only poorly. This can be clarified by tests of availability. What are the compositional differences of young and mature leaves and immature and ripe fruits? How do post-harvest handling, storage conditions, storage time and processing techniques affect the flavour and nutritional value of leaves, fruit pulp and seeds? These are some fundamental questions for further elucidating the various reported differences in baobab products and for enhanced development of high quality products, particularly for markets in Europe and the US. However, possible negative impacts of intensive fruit harvest for pulp export on food and nutrition security of local communities need to be assessed and, if necessary, sustainable and socially responsible resource use strategies should be developed together with the affected communities.

Horticultural production

The selection of ecotypes with desired traits and the application of vegetative propagation techniques such as cutting, grafting, budding, tissue culture and micropropagation (Hartmann et al. 2011) needs to be further refined in laboratory experiments and nursery trials in order to produce 'true-to-type' progeny from the selected genetic resources. In addition, vegetative propagation can reduce the time to first fruiting. Is it possible to select rootstock germplasm to induce, e.g. dwarfing, adaptation to specific soils and management conditions? If such attempts are successful, this would allow setting up commercial orchards, as has been done with, e.g. apple trees in Europe. By keeping the trees to relatively low heights, the leaves and fruits would be easier to access during harvest. In addition, research on potential pests and diseases of baobabs should be performed to address current concerns on the existence of severe damage of young baobab trees showing 'stunted growth' in certain parts of south-eastern Kenya (Fischer and Kehlenbeck, personal observation).

Ecophysiology

Further studies are required on the effect of salinity on the growth, photosynthesis, leaf chlorophyll concentration and ion distribution of baobab germplasm of different local origins. Baobab seedlings from Kordofan, Sudan, are salt-sensitive (Gebauer et al. 2003), whereas in Kenya baobab trees can be found along the seashore (Fig. 4). How tolerant are the latter baobab provenances to salinity, and what are the physiological mechanisms underlying their adaptation? Salt-tolerant seedlings could be used for reforestation and may serve as rootstocks for baobab cultivation on arable salt-affected soils, on which cultivation of annual crops is often increasingly difficult.

Root system

Very little is known about the root development of baobabs. Under which environmental conditions are tuberous roots developed and how long do they last? Seedlings grown in greenhouses under suitable conditions did not develop tuberous taproots while seedlings grown in saline soils did so (Fig. 16). Maundu et al. (1999) reported tuber-like root tips and Sidibé and Williams (2002) mentioned that lateral roots ended in tubers. Greenhouse experiments and field trials are needed to understand the root and tuber development in relation to abiotic stresses. The nutritional content of these tubers needs to be assessed. Knowledge about juvenile and mature tree root development and competition or complementarity with adjacent crops would also be valuable for sound integration of baobabs in agroforestry systems.

Fig. 16 Six month-old baobab (*A. digitata*) seedling from Sudan grown in saline soil under controlled environmental conditions in a greenhouse in Germany showing a tuberous taproot

Further thoughts about the "unfinished business" of *Adansonia* in Africa, Madagascar and Australia can be obtained from NRC (2006, 2008), Wickens and Lowe (2008), Jensen et al. (2011).

In conclusion, baobab could have a high potential for enhancing nutrition security and income generation of rural communities in Sudan and Kenya, but several knowledge gaps need to be addressed to enable domestication and sustainable use of this valuable plant resource.

Acknowledgments This review is an output of the project "BAOFRUIT-Partnership for developing the use of Baobab in the African and European food industry to improve sustainable resource utilisation and livelihoods of poor farmers in the drylands of Sub-Saharan Africa" (01DG13015) funded by the German Federal Ministry of Education and Research (BMBF).

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