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Shea (*Vitellaria paradoxa* C. F. Gaertn.) at the crossroads: current knowledge and research gaps

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Abstract Shea (*Vitellaria paradoxa* C. F. Gaertn.) is arguably socio-economically and environmentally the most important plant species in the semi-arid and arid zones of Africa where it is widely distributed. Apart from the economic gains in international export markets where shea butter is valued for use in luxury cosmetic, pharmaceutical and confectionary industries, locally the fat (butter) is the main cooking oil for over 86 million inhabitants. Research during the past decades has acknowledged the chemical and nutritional composition as well as the ethnobotanical uses of shea which has resulted in its butter being used in a wide array of products. This review summarizes the current knowledge of the morphological and genetic diversity; propagation, initial growth, and management; ecology and population structure; chemical and nutritional composition as well as the socioeconomic and livelihood empowerment potential of shea. Little is known about the fruiting behaviour and the responses of shea to the inevitable changes in climate. We suggest ecophysiological and dendrochronological studies as an option to predict how the domestication of this multipurpose tree species can be sustained even under the prospects of global climate change.

Keywords Shea · Climate change · Parkland · Savanna and ecophysiology

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Introduction

The Shea tree (*Vitellaria paradoxa* C. F. Gaertn., synonyms: *Butyrospermum paradoxa* (C. F. Gaertn.) Hepper. or *Butyrospermum parkii* (G. Don.) Kotschy.), is native to the savanna belt of the Sudanian region centre of endemism from Senegal to the foothills of the Ethiopian highlands (White 1983) covering a 6000 km belt (Okullo et al. 2004; Sanou et al. 2006) across 21 countries (Boffa 2015; Naughton et al. 2015) as shown in Fig. 1. Except in Ghana and Nigeria, where it occurs within 50 km off the coast, shea is generally an inland tree (Hall et al. 1996). It belongs to the plant family Sapotaceae and is the only species of the genus *Vitellaria*. Two sub-species are recognised: *V. paradoxa* subsp. *paradoxa* found in West and Central Africa (from Senegal to the Central African Republic) occurring at elevations of 100–600 m above sea level (Hall et al. 1996; Boffa

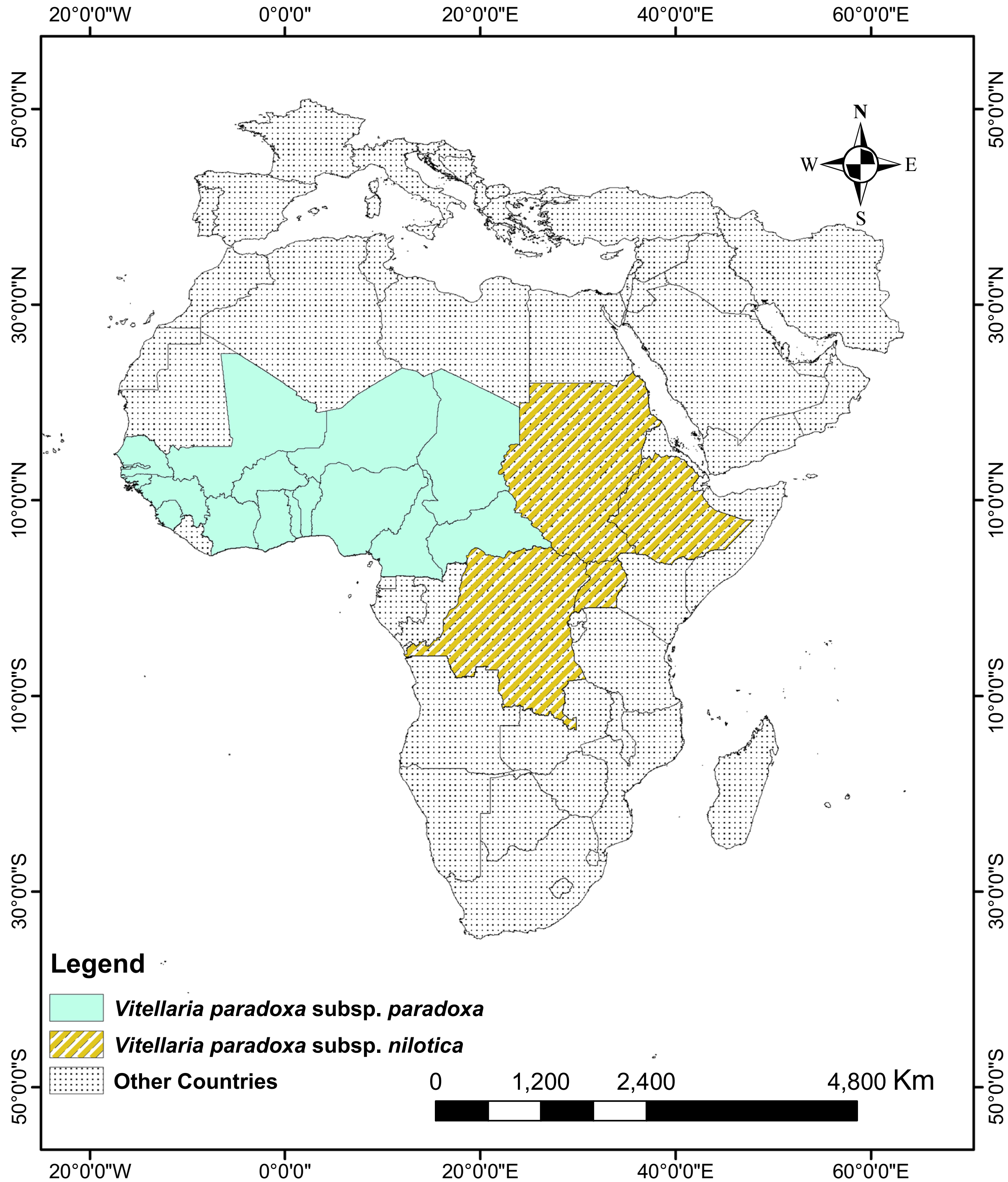

Fig. 1 Distribution map of shea showing the occurrence of the two sub-species. *Source*: Damian Tom-Dery

1999) and *V. paradoxa* subsp. *nilotica* in Eastern Africa (Ethiopia, Sudan, Democratic Republic of Congo and Uganda) which occurs at higher altitudes between 1200–1600 m above sea level, except for a few populations in Sudan at 500 m (Vermilye 2004; Okullo et al. 2004; Byakagaba et al. 2011). A geographical distance of 175 km separates the two sub-species along the different watersheds in the area: the Lake Chad basin is home to subsp. *paradoxa* and the Nile drainage basin is home to subsp. *nilotica* (Hall et al. 1996). Analyses of genetic diversity of shea trees across Sub-Saharan Africa have indicated the Adamawa Highlands along the border of Cameroon and Nigeria as the geographical divider of the two sub-species rather than the watersheds (Allal et al. 2011).

The deciduous, medium size tree attains a height of 10–20 m, occasionally reaching 25 m (von Maydell 1990; Yidana 2004) and stem diameters between 0.3 and 1.0 m (Chevalier 1946). It is a slow-growing tree and generally produces smaller and fewer fruits from 15–20 years of age, with maximum fruit production after 25–40 years of growth (Sanou et al. 2004). Shea tree can reach an age of up to 300 years (Delolme 1947; Ruyssen 1957; Jøker 2000). The elliptically shaped fruit is 4–8 cm long and 2.5–5 cm wide (Hall et al. 1996; Moore 2008) and weighs 10–57 g with an annual production of 15–30 kg per tree (Greenwood 1929; Ruyssen 1957; Agbahungba and Depommier 1989). The fruit is highly nutritious with a thin fleshy pericarp which has a sweet pear-like taste enclosing the oval, reddish-brown seed, the so-called ‘shea nut’. The seed has a shiny, smooth surface and constitutes about 50% of the weight of the fresh fruit (Maranz and Wiesman 2003). The pericarp of the ripe fruit is eaten by both humans and livestock. Parts (bark, roots, wood) of the tree are used for medicine, construction materials, fuel wood and carving wood (Hall et al. 1996; Boffa 1999). The shea tree is highly valued by farmers, mostly because of its fatty acids rich seeds which are sold both locally and internationally. The commercialization of shea products represents an important source of income for the local community and even entire countries such as Burkina Faso and Ghana (Bonkoungou 1992; Elias and Carney 2007; Moore 2008).

Internationally in the export market, shea butter is valued for use in luxury cosmetics or pharmaceutical goods. Roughly 90% of export volume goes for confectionary applications and 10% for cosmetic uses (Rousseau et al. 2015). Between August 2014 and September 2016, the Global Shea Alliance facilitated the export of 121,000 MT dry shea kernels with a market value of US $43 million from Africa (GSA 2016). Due to the economic importance of the species, an up-to-date summary of the knowledge and research carried out on shea is needed. Research so far covers predominantly ethnobotanic utilization as well as the chemical and nutritional quality (Chevalier 1946; Ruyssen 1957; Bonkoungou 1987; Abbiw 1990; Hall et al. 1996; Maranz et al. 2004a; Maranz and Wiesman 2004; Honfo et al. 2014). We review state-of-the-art knowledge of the morphology and genetic diversity; germination and initial growth; ecology and population structure; chemical composition and nutritional values; and socio-economic and poverty alleviation potential of shea. We also seek to identify knowledge gaps and explore future research possibilities into the adaptation of shea to climate variables in this era of global climate change.

Morphological characteristics, genetic diversity and domestication

The unique socio-economic and ecosystem services provided by shea have elevated it into the priority list of African genetic resources (FAO 1988). Though the species is wild, it can conveniently be termed a semi-domesticated species because of centuries of association with humans and the resultant anthropic selection the species has undergone (Pullan 1974; Lovett and Haq 2000a). The leaves and flower parts (sepals, filaments and styles) of subsp. *nilotica* are larger compared to subsp. *paradoxa* (Osei-Amaning 1996). The shape of nuts of subsp. *nilotica* are described as oval (Eggeling and Dale 1951) while that of subsp. *paradoxa* are described variously as spherical, ovoid and fusiform (Ruyssen 1957). High intra-specific variation exists among shea trees from different African regions (Chevalier 1948; Ruyssen 1957; Lovett and Haq 2000b; Sanou et al. 2006; Diarrassouba et al. 2006; Ugese et al. 2010b; Okullo et al. 2011; Gwali et al. 2011, 2012a, 2012b; Enaberuel et al. 2014; Djekota et al. 2014; Souberou et al. 2015). The leave and fruit characteristics of shea across its geographical range are illustrated in Table 1.

Understanding the variability within the gene pool of shea is crucial to facilitate its domestication, conservation and future improvements. Lovett and Haq (2000b) suggested with isoenzyme analysis of shea from Ghana, the existence of moderate to high heterozygosity and high gene flow. They inferred that past climatic changes and nonexistent methods of seed selection were the causes. They also proposed seed and leaf lamina shape as possible indicators of genetic diversity. There have also been studies of shea genetic

Table 1 Morphological characteristics of shea leaves and fruits in various countries

Country	Leaves (cm)		Fruits (cm)		References
	Length	Width	Length	Diameter	
Ghana	9.2–22.5	3.7–5.2	1.7–3.7 s	1.7–2.7 ws	Lovett and Haq (2000b), Moore (2008), Nyarko et al. (2012), and Issaka (2013)
Benin	17.3–19.4	7.0–7.2	4.3–4.7	3.4–3.7	Souberou et al. (2015)
Nigeria	12.8–17.3	5.3–7.7	3.9–5.2	3.2–3.7	Ugese et al. (2010c), Okullo et al. (2011), and Enaberuel et al. (2014)
Mali	13.7–14.9	3.9–4.9	3.6	3.1	Sanou et al. (2006)
Chad	15.5–26.3	3.0–5.4	1.0–3.3	2.3–4.4 w	Djekota et al. (2014)
Cameroon	10.0–25.0	4.0–12	3.7–8.2	2.9–5.3	Vivien (1990) and Diarrassouba et al. (2006)
Uganda (sspn)	28.69	8.6–9.2	2.95s	2.06s	Gwali et al. (2011)

w Width, *s* seed, *sspn* sub-species *nilotica*

variability using biochemical composition by analysing for fatty acids (Maranz and Wiesman 2003; Maranz et al. 2004b; Di Vincenzo et al. 2005; Allal et al. 2013), phenolic compounds (Maranz et al. 2003) and tocopherols (Maranz and Wiesman 2004; Allal et al. 2013).

Microsatellite DNA has widely been utilized in population genetics because of its ability to detect differences among closely related species. Kelly et al. (2004) used ten microsatellite loci to examine the effect of anthropogenic activity on the spatial and temporal genetic structure of shea population, concluding that differentiation was very limited at the microsatellite loci, perhaps because of the buffering effect of extensive gene flow between unmanaged and managed populations. Microsatellites have been used to illustrate within population diversity (Sanou et al. 2005) and to differentiate between ethno-varieties (Gwali et al. 2015). Past climatic conditions and anthopogenic activities have been cited as the causes of these variations. Random amplified polymorphic DNA (RAPD) and chloroplast markers analysis from several populations distributed across West and Central/Eastern Africa suggested genetic distinction between West and Central/Eastern African populations (Fontaine et al. 2004; Bouvet et al. 2004; Allal et al. 2011). Recognising there are distinctive gene pools between the two sub-species occurring in different regions implies they might differently adapt to future climate changes. The diversity of the shea gene pool within and between countries and even regional populations calls for a concerted organized collection and assessment of superior germplasm, building on previously separated stand-alone research across the region (Boffa 2015).

Shea propagation, initial growth and management

Typical for shea as an indigenous savanna species is its demand for light, especially in the early years of growth. Seed dispersal is mainly by birds, ungulates and primates, including humans that eat the fruits. Long distant seed dispersal is mostly by fruit bats (Fujita 1991; Djossa et al. 2008a). The phenological events of shea are timed with regards to seasons; leaf fall, leaf flushing and flowering (December–March) are notably dry season events while fruiting (April–September) coincides with the raining season (Jøker 2000; Okullo et al. 2004). The maturing of fruits and ripening during the rainy season possibly is an adaptation for maintenance of the species (Okullo et al. 2004) because the seeds are recalcitrant (Hall et al. 1996; Jøker 2000) with seed viability generally limited to a week and at most a month (Ruyssen 1957) depending on storage conditions (Jøker 2000). Fallow periods offer shea opportunities for regeneration, but these are continuously being shortened because of pressure for land (Boffa 1999; Lovett and Haq 2000a) and land hunger. The wild species traits that impede shea cultivation include problems with germination (Jøker 2000; Ugese et al. 2005), the extended gestation period (Awoleye 1995) and slow growth rate (Jackson 1968) which makes its cultivation less attractive to farmers (Yidana 2004).

Although in savanna ecoregions shea regenerates unaided, the complete process of germination is cumbersome because the seed looses its viability quickly and it takes a long period for the shoot to emerge which is a major challenge for shea to be planted by farmers. The peculiar germination and seedling morphology of shea is described as cryptogeal (Fig. 2) and involves the burying of the plumule (Jackson 1968). The fallen seeds as a result of its shape turn to have the scar area facing downwards to enable water uptake. This causes the testa to crack towards the micropyl and the pseudo-radicle which is positively geotropic emerges and grows into the soil. This grows to a depth of 7–8 cm before a swelling arises at 5–7 cm away from the testa, which splits for the shoot to emerge and push upwards. The pseudo-radicle continues to grow and develop into the tap root (Osei-Amaning 1996). After germination the shea seedling first produce a long tap root before growing any leaves (Yayock et al. 1988) which can be considered as an adaptive mechanism against drought. Frimpong and Adomako (1987) established that about 74% of the dry matter of seedlings is found in their roots, indicating that shoot development is suppressed in the early stages of shea seedling growth. The time it takes for the appearance of the shoot above ground when seeds are planted takes between one to more than 2 months under favorable conditions (Delolme 1947; Ruyssen 1957; Awoleye 1995; Jøker 2000; Yidana 2004; Ugese et al. 2005; Ugese et al. 2010a, 2010b, 2010c). Depulping is known to facilitate seed germination (Ruyssen 1957; Osei-Amaning 1996), while optimal and uniform germination as well as seedling production is enhanced by soaking of seeds in concentrated H_2SO_4 for 10 min or Stenberg solution and removing the seedcoat (Jatto et al. 2012; Iroko et al. 2013; Iddrisu 2013). Early seedling emergence correlates with faster growth rates (Ugese et al. 2005) and seed size is positively correlated to emergence, growth and seedling development (Kolawole et al. 2011).

Fig. 2 Cryptogeal germination of shea showing the burying of the plumule. *Source*: Damian Tom-Dery

Grafting as a vegetative means of propagation is defined by Sanou et al. (2004) as 'a method of vegetative propagation that allows the production of individuals of the same genetic constitution as the original plant, and hence facilitates the multiplication of desirable genotypes'. This can be employed to improve the development of trees in the reproductive stage (Grolleau 1989; Hartmann et al. 1997), by taking scions from the ontogenetically mature crowns of older trees and thereby avoiding the extended juvenile phase (Hackett 1985; Hartmann et al. 1997). Grafting as a method of achieving early maturity on four year old shea seedlings was reported to have a success rate of only 25% due to the wilting of the scions in dry and hot conditions of the Sahel (Grolleau 1989). Even with successful grafts, fruit production has been shown to be restricted (Kambuo 2001; Sanou et al. 2004).

Experiments with stem cutting propagation of shea have reported that root formation depends on the concentrations of applied phytohormones (Zerbo 1987; Bonkoungou et al. 1988; Frimpong et al. 1993; Yidana 2004; Yeboah et al. 2009, 2011). Up to a 100% survival after planting of cuttings was reported depending on the time of the year and the environmental conditions (Opoku-Ameyaw et al. 1997). Developing in vitro systems for shea shoot and root regeneration of explants taken from mature materials might aid in shortening the long juvenile phase. However, rather few efforts in the somatic embryogenesis of shea calli have been made, and shoot or root production has been successful in some cases (Fotso et al. 2008; Adu-Gyamfi et al. 2012; Lovett and Haq 2013). Yeboah et al. (2014) found in survival trials that, the mist propagator was the most appropriate propagating structure for weaning rooted cuttings with planting depth of 52 cm producing higher survival rates and better growth. They also suggested the beginning of the rainy season for establishment, as this is vital for the survival of transplanted propagules.

Layering, which is generally the growth of roots on a stem while the stem is still attached to the mother plant, has achieved minimal but nevertheless encouraging results. Zerbo (1987) and Bonkoungou et al. (1988) reported 2% survival for air layering and 15% for ground layering during the raining season using substantial amounts of hormones. This technique has the advantage that the resulting plants grow better than those directly from seed, thus air layering with epicormic shoots produced roots within 51 days (Yidana 2004). Also a container layering technique holds promise for the rooting of shea trees with rooting performance of 40.9% for four year-old seedlings and 27.9% for mature shea trees (Amissah et al. 2013). Pruning has no effect on shea growth (Kessler 1992), nevertheless in agroforestry systems it increases yield of inter crops like millet (Bayala et al. 2002) and is recommended to farmers as a way to rejuvenate aging trees (Bayala et al. 2008a). Girdling as a method to regulate fruiting irregularity is reported to increase fruit yield by 100% (Lamien et al. 2006).

Water logging has detrimental effects on seedling growth (ICRAF 2000) but wide spacing, good site preparation and weeding are vital for plant survival (Jøker 2000). There are conflicting reports of the response of shea growth to NPK fertilization. Shea growth has been shown to benefit from residue effects of NPK fertilizers applied to the intercropped foods in rotations of maize, cowpea and yam (Osei-Bonsu et al. 1995). Seedlings grown in N and P deficient sand cultures recorded stunted growth (Dianda et al. 2009; Ugese et al. 2012). In contrast, Yakubu et al. (2015) reported no significant effect of NPK fertilization on seedling growth. Shea propagation needs protection from herbivore grazing (Chevalier 1946) and competing vegetation (Delolme 1947). Neighbouring grasses are not only competitors for space, light and nutrients but also a source of combustible matter which intensifies the periodic bush fires (Osei-Amaning 1996). Phytosanitary problems associated with shea include the larvae of *Mussidia nigriolla* and *Ceratitis silvestrii* feeding on the pulp of fruits (Jøker 2000). A plant hemiparasite of the genus *Tapinanthus* (African mistletoe) is a major cause of tree mortality by reducing the growth of the distal ends of the branches, thereby affecting wood quality and increasing susceptibility to attack by pathogens (Hall et al. 1996). The shoot and fruit borer *Salebria* sp. infests mostly the reproductive phenophases of flowering and fruit production (Lamien et al. 2008).

Tree ecology, distribution and population structure

Shea preferably grows in loamy and sandy soils but not clayey, anaerobic, volcanic soils; however the soils should be well drained with a good water-holding capacity (Hall et al. 1996; Moore 2008; Naughton et al. 2015). There are reports of a significant correlation of sand content and phosphorus levels to tree density (Moore 2008). Annual leaf abscission probably plays a major role in nutrient recycling through the decay of leaves and fine roots at the soil surface (Bayala et al. 2006). The species generally thrives in the arid and semi-arid areas where annual rainfall amounts range between 400 and 1500 mm (von Maydell 1990; Hall et al. 1996) and it tolerates an extended drought of up to eight months (Vermilye 2004). Agroforestry parklands (Fig. 3) defined as a dispersed arrangement of scattered trees within which annual crops are cultivated (Pullan 1974; Boffa 1999) are considered the most widespread farming system in the Sahelian zone (Bayala et al. 2015). In these parklands, shea trees constitute a high-percentage of standing biomass thereby protecting the environment against soil degradation and possessing significant carbon stores with high potential for future C-sequestration for climate change mitigation (Luedeling and Neufeldt 2012). Shea also has the ability to clean-up atmospheric pollutants and is thus recommended for use in green belt development (Ogunkunle et al. 2015).

Few studies have investigated shea phenology, with Okullo et al. (2004) reporting that, for sub-species *nilotica*, the pattern of leafing and leaf loss, flowering and fruiting are unimodal although rainfall is bimodal in the studied area. However, Kelly et al. (2007) investigated the effect of human practices on the flowering of sub-sp. *paradoxa*, concluding that cultivated fields provided better conditions for flowering than fallow lands and there was a positive correlation

Fig. 3 Shea parkland in Northern Ghana with maize grown under scattered shea trees. *Source*: Damian Tom-Dery

of flowering and fruiting with higher rainfall. Lamien et al. (2007) reported higher fruit yields in highland than lowland shea populations and were able to simultaneously predict number of fruits, fruits fresh and dry weights with selected dendrometric and fruiting variables. Bushfire during flowering has a negative effect on fruiting (Chevalier 1948; Ruyssen 1957; Abbiw 1990) while harmattan winds cause flower abscission (Ruyssen 1957). Delolme (1947) reported the amount and timing of rainfall to slightly impact fruit maturation, but Ruyssen (1957) found no correlation between rainfall and fruit yield. On the contrary, Kakaï et al. (2011) reported that high rainfall and relative humidity reduced fruit production. There are also suggestions that fruit set formation is limited by pollination (Osei-Amaning 1996). It is, however, generally accepted that fruit production is cyclical with 2–3 years cycles (Delolme 1947; Agbahungba and Depommier 1989; Masters 2002; Yidana 2004). Research is, required on the effects of annual climatic conditions, future projected climate variations (increased atmospheric CO_2 concentration and increased global average temperatures), the effects of different soil constituents and drought stress on flowering and fruit production, and the interaction of these abiotic factors with the age of shea trees.

Shea represent up to 70% of the woody vegetation in areas of Benin (Agbahungba and Depommier 1989; Djossa et al. 2008b) and may constitute about 80% in parts of northern Ghana (Lovett and Haq 2000a) and Burkina Faso (Boffa 1999). Shea is often the dominant species in parklands and mostly associated with tree species such as *Parkia biglobosa*, *Terminalia avicennioides*, *Acacia senegal* and *Annona senegalensis* (Boffa 1999). There is evidence of hydraulic redistribution in shea which may suggest facilitation for associated plants in parklands (Bayala et al. 2008b) and might even explain the co-existence of tree and grass in savanna ecosystems. The Sudanian savanna zone which recorded the highest population of Shea trees in the 1940s with estimates of 230 trees ha^{-1} (Chevalier 1946) has decreased densities since then to only 11 trees ha^{-1} (Nikiema et al. 2001), while West Africa has numbers dwindling to 5 tree ha^{-1} (Djossa et al. 2008b). The decline in shea populations may be due to a number of factors which include short fallow periods, inappropriate agricultural methods, annual bushfires, overgrazing and the cutting of trees for firewood and charcoal production (Lovett and Haq 2000a, b; Djossa et al. 2008b; Byakagaba et al. 2011; Aleza et al. 2015). Population studies on shea compared populations on cultivated lands to those on fallow land, as opposed to wild populations on unmanaged spots, reporting larger trees on cultivated fields (Boffa 1995). Importantly, in these studies trees with small diameter indicating regeneration were not found, a lack of which has been used as evidence for the degradation of West African parklands (Gijsbers et al. 1994).

Lovett and Haq (2000a) compared shea populations on sites with different intensities of landuse and concluded that populations in farmed parklands are a direct result of anthropic selection resulting from many centuries of traditional cultivation and fallow. Odebiyi et al. (2004) reported shea and *Parkia biglobosa* as being co-dominant with the occurrence of only big trees and regeneration, recording no saplings. Djossa et al. (2008b) reported shea trees being well preserved in parklands under traditional farming that advances the growth of young shea trees resulting in a random age distribution. The population structure as documented in the distribution pattern of trunk diameter and regeneration status of both subspecies *niloticus* and *paradoxa* are affected by land management regimes in East and West Africa, respectively (Osei-Amaning 1996; Okullo 2004; Byakagaba et al. 2011; Aleza et al. 2015). The population structure (Fig. 4) of shea on parklands is composed of a good adult and regeneration population with very few number of or even no saplings (Osei-Amaning 1996; Okullo 2004; Aleza et al. 2015).

Platts et al. (2010) used climate, topography, agro-ecological data, fire radiative power and IPCC scenarios to predict an increase in areas climatically suitable for shea in the 21st century, indicating the moisture index as the best environmental predictor of shea distribution. Therefore, shea will most likely grow in reasonably dry climates, but not too dry as in deserts. Allal et al. (2011) employed DIVA-GIS ecological niche modeling to predict the shea distribution focusing on genetic diversity and comparisons of the present distribution through the Last Glacial Maximum and last interglacial periods. The authors concluded that there was a strong geographical separation of the western and eastern populations indicating climatic variations as the major factor for the genetic patterns. Naughton et al. (2015) predicted the possible shea distribution and production using Geographic Information Systems via merging binary and suitability layers developed from

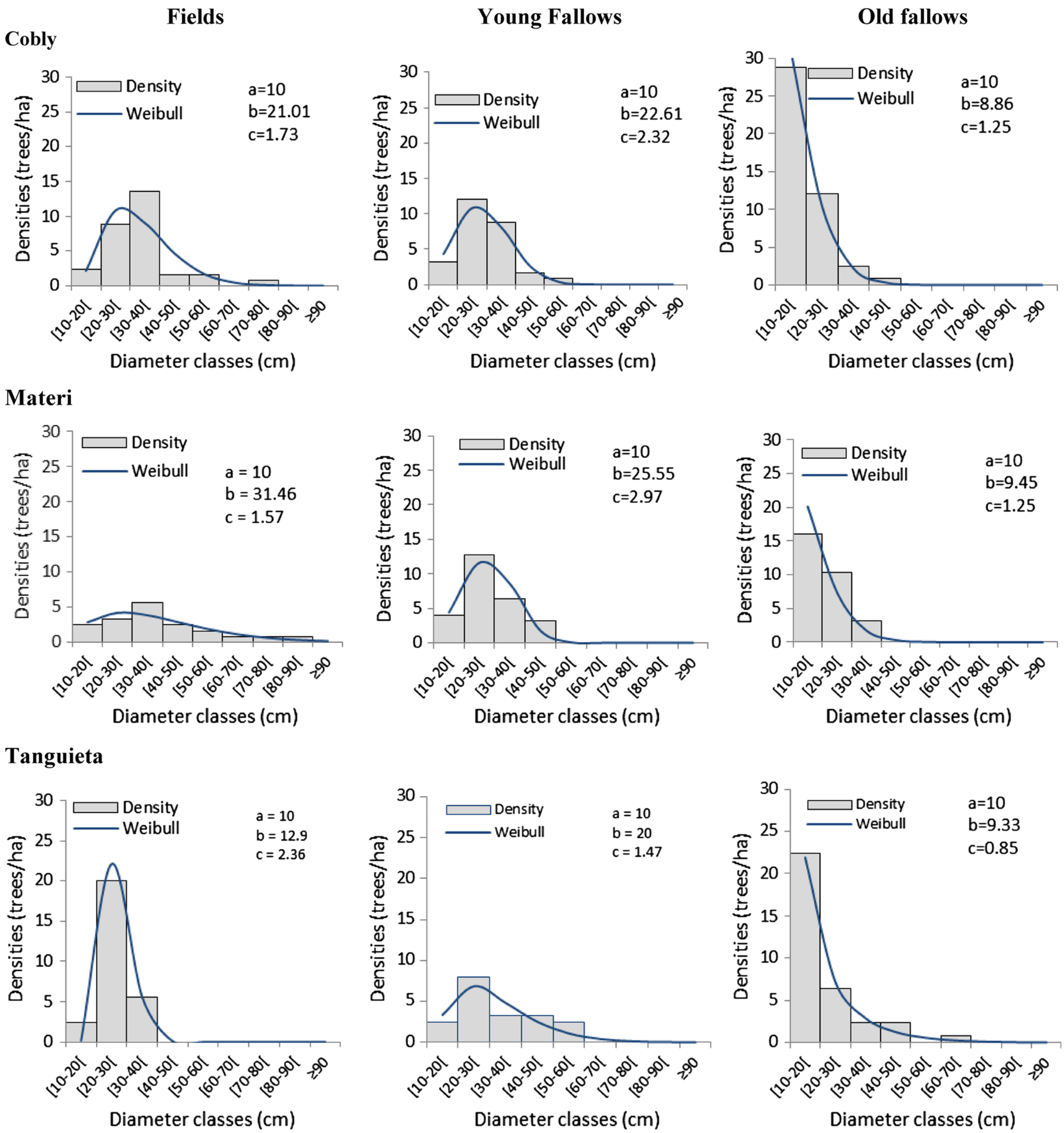

Fig. 4 Diameter class distribution of shea according to land use types in three localities of Benin. *Source*: Aleza et al. (2015)

eight factors (Land-use, temperature, precipitation, elevation, fire, normalized difference vegetation index, soil-type and soil drainage) concluding that the potential shea distribution area will increase in the future. Models of shea in general lack the imput of ecophysiological parameters such as properties of leaves and photosynthetic rates.

Chemical and nutritional composition

The monumental ascend in the trade of shea has led to state-of-the-art research on the chemical and nutritional properties of shea. The sweet pulp is four times richer in ascorbic acid than ripe orange (Eromosele and Kuzhhuzha 1991) and a rich source of sugars, proteins, calcium, and iron (Maranz et al. 2004a). The composition of macronutrients and minerals in the kernel and pulp of shea are illustrated in Table 2. Different methodology used for the analysis of the various nutrients, minerals and vitamins is a possible cause of the high variation of information about the nutritional values (Honfo et al. 2014). Shea kernels are particularly loaded with crude lipids with amounts ranging between 17.4 and 59.1 g/100 g dw (Tano-Debrah and Ohta 1994) and also contain a considerable amount of carbohydrate in the range 25 g/100 g dw (Busson 1965) to 34.8 g/100 g dw (Tano-Debrah and Ohta 1994). The pulp is rich in potassium (K) that varied between 21.7 mg/100 g dw (Mbaiguinam et al. 2007) and 1686 mg/100 g dw (Maranz et al. 2004a) while calcium (Ca) ranged between 2.5 mg/100 g dw (Ugese et al. 2008b) and 426 mg/100 g dw (Maranz et al. 2004a), representing the two most abundant nutrients found in the pulp.

The most treasured product of the shea tree is its butter extracted from the kernels which is not only highly valued by the confectionary and pharmaceutical industries but also used locally for culinary purposes. The solidified shea oil is referred to as 'butter' which consists basically of tryglycerides (stearic acid, oleic acid) and is more or less solid at room temperature (Hall et al. 1996). Nutrient and chemical composition of shea butter is illustrated in Table 3, where the carbohydrate content of the butter is remarkably high (22.3 g/100 g dw) (Chukwu and Adgidzi 2008). Calcium and Sodium were the most abundant minerals in the butter, with mean concentrations of 17.2 and 5.3 mg/100 g dw, respectively (Megnanou et al. 2007). Fat content of shea butter across its distribution range varies between 28.0 and 61.6% (Kershaw and Hardwick 1981; Davrieux et al. 2010; Gwanli et al. 2012b; Allal et al. 2013), depending on various factors including climatic conditions, genetic variation, age, size, as well as water stress. Three groups of triglycerides have been identified, namely mono-unsaturated, diunsaturated and polyunsaturated (Kapseu et al. 2001; Di Vincenzo et al. 2005), with Maranz et al. (2004b) reporting 1,3-distearoly-2-oleoyl-glycerol (SOS) and 1-stearoly-2,3-dioleoyl-glycerol (SOO) as the major triglycerides. Sixteen fatty acids have been identified in shea butter (Di Vincenzo et al. 2005) with the main fatty acids reported in Table 4. Several authors (Maranz et al. 2004b; Di Vincenzo et al. 2005; Akihisa et al. 2010a; Allal et al. 2013) report that oleic acid is dominant in butters from Eastern Africa, while stearic acid is dominant in samples of West African provenances. While stearic acid is particularly good for use as an industrial base in confectionary and food products (Ming 2008), oleic acid is purposely best as a raw material for cosmetics (Maranz et al. 2004b). The current market prefers butter of the following quality: Free Fatty Acids (FFA) $<7\%$ and impurities $<1\%$. Butter quality for the cosmetic industry varies depending on end use, low FFA, white to yellow colour, low water content, low odour, low melting point, and high unsaponifiable fraction (Lovett 2004).

Unsaponifiable matter of shea butter is mainly constituted by triterpene alcohols (α-amyrin, β-amyrin lupeol and butyrospermol) (Alander and Andersson 2002; Akihisa et al. 2010b) with α-amyrin being the most abundant with a mean value of 36.2% (Akihisa et al. 2010b) while β-amyrin is the least abundant with a mean value of 10.2% (Peers 1977). The unsaponifiable matters are attributed to anti-inflammatory and antioxidant properties which is one reason that makes shea butter attractive for cosmetic industries (Alander 2004; Maranz and Wiesman 2004). Tocopherol content, which is influenced by climatic factors varies between 13 and 112 μg/g (Maranz and Wiesman 2004; Allal et al. 2013) with α tocopherol being the majority accounting for 64% (112 μg/g) (Maranz and Wiesman 2004). The quantity of tocopherol type has been used as basis to distinguish between shea from the Eastern and the Western regions of its distribution with γ-tocopherols significantly higher in Eastern than Western shea (Allal et al. 2013). However, Maranz and Wiesmann (2004) posit the amount of α and total tocopherols will increase in shea butter with increasing mean regional temperature. Four sterols have been identified in shea butter namely β-sitosterol, Cholesterol, Δ7-Stigmasterol and stigmasterol (Peers 1977; Njoku et al. 2000). The major phenolic compounds are gallic acid, gallocatechin, epigallocatechin gallate, epigallocatechin, epicatechin and epicatechin gallate (Maranz et al. 2003). Further non-glyceride elements of shea butter consent its use in cosmetic product formulations because the triterpene alcohols of cinnamates possess anti-inflammatory effects, particularly lupeol and α/β-amyrin in their esterified forms (Alander and Andersson 2002; Alander 2004; Akihisa et al. 2010a).

Table 2 Chemical and nutritional composition of the kernels and pulp of shea (Extracted from: Honfo et al. 2014)

Micronutrient	Kernels	References	Pulp	References
Crude lipids (g/100 g dw)	17.4–59.1	Greenwood (1929), Busson (1965), Tallantire and Goode (1975), Duke and Atchley (1986), Tano-Debrah and Ohta (1994), Maranz and Wiesman (2003), Di Vincenzo et al. (2005), Mbaiguinam et al. (2007), Nkouam et al. (2007), and Akihisa et al. (2010a)	1.3	Ugese et al. (2008a)
Carbohydrate (g/100 g dw)	25.0–34.8	Greenwood (1929), Busson (1965), Tallantire and Goode (1975), Duke and Atchley (1986), Tano-Debrah and Ohta (1994), and GRET (2007)	8.1–37.2	Mbaiguinam et al. (2007) and Ugese et al. (2008a)
Crude fibre (g/100 g dw)	3.2–20.4	Greenwood (1929), Ruyssen (1957), Duke and Atchley (1986), and Tano-Debrah and Ohta (1994)	42.2	Ugese et al. (2008a)
Crude protein (g/100 g dw)	6.8–9.0	Greenwood (1929), Busson (1965), Tallantire and Goode (1975), Duke and Atchley (1986), Tano-Debrah and Ohta (1994), and GRET (2007)	4.2–5.6	Maranz et al. (2004a)
Moisture (%)	5.0–8.1	Busson (1965), Tallantire and Goode (1975), GRET (2007), and Mbaiguinam et al. (2007)	67.0–80.3	Maranz et al. (2004a) and Mbaiguinam et al. (2007)
Ash (g/100 g dw)	1.8–3.0	Greenwood (1929), Ruyssen (1957), Duke and Atchley (1986), Tano-Debrah and Ohta (1994), and GRET (2007)	4.7–5.4	Mbaiguinam et al. (2007) and Ugese et al. (2008a)
Energy (Kcal/100 g dw)	–	–	179.5	Ugese et al. (2008a)
Vitamins (mg/100 g)				
C	–	–	196.1	Eromosele and Kuzhhuzha (1991)
B	–	–	7.0	Maranz et al. (2004a)
Minerals (mg/100 g dw)				
Mg	142.6	Megnanou et al. (2007)	11.1–129.0	Eromosele and Kuzhhuzha (1991), Maranz et al. (2004a), Mbaiguinam et al. (2007), and Ugese et al. (2008b)
Ca	0.1–215.2	Tallantire and Goode (1975), Duke and Atchley (1986), Megnanou et al. (2007) and Alhassan et al. (2011)	2.5–426.0	Eromosele and Kuzhhuzha (1991), Maranz et al. (2004a), Mbaiguinam et al. (2007), and Ugese et al. (2008b)
Na	0.9–73.9	Megnanou et al. (2007) and Alhassan et al. (2011)	19.3	Ugese et al. (2008b)
Fe	0.01–3.1	Duke and Atchley (1986) and Megnanou et al. (2007)	0.4–16.0	Eromosele and Kuzhhuzha (1991), Maranz et al. (2004a), and Megnanou et al. (2007)
Zn	0.9	Megnanou et al. (2007)	0.5–4.0	Eromosele and Kuzhhuzha (1991), Maranz et al. (2004a), Ugese et al. (2008b)
Mn	0.1–0.7	Alhassan et al. (2011)	0.5–4.0	Eromosele and Kuzhhuzha (1991), and Maranz et al. (2004a)

Table 2 continued

Micronutrient	Kernels	References	Pulp	References
Cu	0.3	Megnanou et al. (2007)	0.0–1.1	Eromosele and Kuzhhuzha (1991), Maranz et al. (2004a)
K	0.1–0.2	Alhassan et al. (2011)	21.7–1686.0	Maranz et al. (2004a), Megnanou et al. (2007), and Ugese et al. (2008b)
P	0.04	Tallantire and Goode (1975) and Duke and Atchley (1986)	1.0–71.4	Eromosele and Kuzhhuzha (1991), Maranz et al. (2004a), Mbaiguinam et al. (2007), and Ugese et al. (2008b)

Socioeconomic and rural livelihood empowerment

Shea is an important oleaginous plant that provides unprecedented opportunities to mitigate rural communities' vulnerability to food insecurity and alleviate rural poverty across the 21 Sub-Saharan countries in which it is distributed. The possible uses of the multipurpose shea are illustrated in Table 5. Generally, the regions within which shea occurs are bereft of poverty and inhabitants are mostly subsistent farmers dependent on rain-fed agriculture. Rainfall is the major determinant of farming patterns in the savanna and the rainy season where land preparation and sowing takes place, is referred to as the hungry season (Maranz et al. 2004a; Pouliot et al. 2008) because the food barns are low or almost exhausted. Shea which bears fruits during the hungry season becomes an important gap-filling environmental tree both as food and sold for cash (Pouliot 2012). Shea is believed to be the main cooking oil for more than 86 million rural people across its range (Naughton et al. 2014) and is also widely regarded as an important melliferous species throughout the savanna zones (Chevalier 1948; Hall et al. 1996).

The local shea industry is controlled by women who are involved in fruit and nut collection, processing and commercialization (Lovett and Haq 2000a; Maranz et al. 2003; Chalfin 2004; Elias and Carney 2007). Elias (2015) posits women as being more knowledgeable about the shea tree than men. Traditionaly in the past, shea and its products were not sold and was generally a secondary activity for women to farming. During the period of harvest, women picked shea which was stored for processing at their leisure time. Processed shea was principally for household use and meant for gifts and only rarely sold when money was required for abrupt expenses (Ziba and Yameogo 2002). With the emergent prominence of shea, the picking and processing of shea has now become a full time activity for women and part of the proceeds rather used to employ labour for their farms. Reports in Bukina Faso estimated 300,000–400,000 women participating in shea picking and processing in the year 2000 (Harsch 2001). Shea generally contributes between 2.8 and 66% of household income (Becker 2001; Schreckenberg 2004; Pouliot 2012). Based on the prices of shea in 2008, an average monthly income of 53–173 USD is attainable per picker and 97–279 USD per butter extractor in Ghana (Hatskevich et al.

Table 3 Chemical and nutritional composition of shea butter (Extracted from: Honfo et al. 2014)

Nutrients	Butter	References
Crude lipids (g/100 g dw)	75.0	Chukwu and Adgidzi (2008)
Carbohydrate (g/100 g dw)	22.3	Chukwu and Adgidzi (2008)
Moisture (%)	0.1–8.4	Greenwood (1929), Megnanou et al. (2007), Olaniyan and Oje (2007), Chukwu and Adgidzi (2008), and Davrieux et al. (2010)
Ash (g/100 g dw)	1.6–3.2	Adomako (1985) and Chukwu and Adgidzi (2008)
Minerals (mg/100 g dw)		
Ca	0.2–34.1	Megnanou et al. (2007)
Na	1.0–9.6	Megnanou et al. (2007)
Mg	0.0–8.9	Megnanou et al. (2007)
Fe	0.5–6.7	Megnanou et al. (2007)
Zn	1.9–3.4	Megnanou et al. (2007)
Cu	0.0–1.5	Megnanou et al. (2007)
K	0.0–0.4	Megnanou et al. (2007)
Mn	0.0–0.14	Alhassan et al. (2011)

Table 4 Fatty acids composition of shea butter (Extracted from: Honfo et al. 2014)

Fatty acid	Gram fatty acid/100 g fat	References
Oleic 18:01	37.2–62.0	Kershaw and Hardwick (1981), Tano-Debrah and Ohta (1994), Tholstrup et al. (1994), Kapseu et al. (2001), Alander and Andersson (2002), Maranz et al. (2004b), Di Vincenzo et al. (2005), Mbaiguinam et al. (2007), Letchamo et al. (2007), Akihisa et al. (2010a), Okullo et al. (2010), Ugese et al. (2010c), Allal et al. (2013), Davrieux et al. (2010), and Gwali et al. (2012b)
Stearic 18:00	29.5–55.7	Kershaw and Hardwick (1981), Tano-Debrah and Ohta (1994), Tholstrup et al. (1994), Kapseu et al. (2001), Alander and Andersson (2002), Maranz et al. (2004b), Di Vincenzo et al. (2005), Mbaiguinam et al. (2007), Letchamo et al. (2007), Akihisa et al. (2010a), Okullo et al. (2010), Ugese et al. (2010c), Allal et al. (2013), Davrieux et al. (2010), and Gwali et al. (2012b)
Linoleic 18:02	4.3–8.9	Mendez and Lope (1991), Tano-Debrah and Ohta (1994), Tholstrup et al. (1994), Kapseu et al. (2001), Alander and Andersson (2002), Maranz et al. (2004b), Di Vincenzo et al. (2005), Mbaiguinam et al. (2007), Letchamo et al. (2007), Akihisa et al. (2010a), Okullo et al. (2010), Ugese et al. (2010c), Davrieux et al. (2010), and Gwali et al. (2012b)
Palmitic 16:00	3.3–7.5	Tano-Debrah and Ohta (1994), Tholstrup et al. (1994), Alander and Andersson (2002), Maranz et al. (2004b), Di Vincenzo et al. (2005), Mbaiguinam et al. (2007), Letchamo et al. (2007), Akihisa et al. (2010a), Okullo et al. (2010), Ugese et al. (2010c), Davrieux et al. (2010), and Gwali et al. (2012b)
Arachidic 20:00	0.8–1.8	Kapseu et al. (2001), Maranz et al. (2004b), Di Vincenzo et al. (2005), Letchamo et al. (2007), Akihisa et al. (2010a), Okullo et al. (2010), Davrieux et al. (2010), and Gwali et al. (2012b)
Linolenic 18:03	0.2–1.7	Tano-Debrah and Ohta (1994), Tholstrup et al. (1994), Akihisa et al. (2010a), Davrieux et al. (2010), and Gwali et al. (2012b)
Vaccenic 18:01	0.08–0.90	Davrieux et al. (2010) and Gwali et al. (2012b)

Table 5 Potential uses of shea in industry and local communities

Usage (part/ extract)	Pharmaceutical/medicinal/cosmetic	Culinary/other uses
Butter	Care of sprains (Bonkoungou 1987)	Cooking oil (Lamien et al. 1996; Hall et al.1996)
	Treating wound (Abbiw 1990; Wallace-Bruce 1995; Egunyomi et al. 2009)	Illuminant (Greenwood 1929; Dalziel 1937)
	Child birth (Moore 2008)	Anointing oil in traditional ceremonies (Goreja 2004; Sturges 2008)
	Dermatitis/dermatoses (Bonkoungou 1987)	Waterproofing of mud Houses (Boffa 1999)
	Massage pregnant women/children	Soap making (Abbiw 1990; Boffa 1999)
	Skin lotion and moisturizer, hair lotion (Dalziel 1937)	
	Pomade (Marchard 1988; Bonkoungou 1987)	
Leaves	Analgesic for head, stomach ache (Millee 1984)	Spituality and Covering the dead (Agbahungba and Depommier 1989)
	Jaundice (Bonkoungou 1987)	Fish meal (Obirikorang et al. 2015)
	Eye drops/care of eyes (Bonkoungou 1987; Abbiw 1990)	Source of saponin used for washing (Abbiw 1990)
	Malaria (Bonkoungou 1987)	
Bark/Latex	Bleeding gums (Bognounou 1988)	Latex is heated mixed with palm oil and used as glue (Hall et al. 1996)
	Diarrhoea/dysentery (Soladoye et al. 1989)	Latex used to mend drums (Millee 1984)
	Cure for jaundice (Ampofo 1983)	
	Stomach ulcers (Hall et al. 1996)	
	Eye wash to neutralize venom of cobra (Soladoye et al. 1989)	
	Infusions used to treat leprosy (Dalziel 1937)	
	Used as a bath to facilitate delivery (Abbiw 1990; Soladoye et al. (1989)	
Roots	Cough (Bonkoungou 1987)	Chewing stick (Isawumi 1978)
	Cure for jaundice (Ampofo 1983; Hall et al. 1996)	
	Stomach ache (Millee 1984)	
	Chronic sores in horses (Dalziel 1937)	
Wood		Fuelwood and Charcoal (Dalziel 1937; Abbiw 1990)
		Wood work (Dalziel 1937; Abbiw 1990)
		Local tools (Dalziel 1937; Abbiw 1990; FAO 1988)
		Construction (Millee 1984; Abbiw 1990)
Presscake/nut residue		Soap making(Hall et al. 1996; Boffa 1999)
		Cooking fuel (Hall et al. 1996)
		Termite repellent (Dalziel 1937)
		Animal feed (Hall et al. 1996)
		Fish meal (Obirikorang et al. 2015)
		Used as mulch/Fertilizer (FAO 1988)
		Removal of heavy Metals from water (Eromosele and Otitolaye 1994)
Caterpillers (*Cirina butyrospermi*)		Eaten fried and a rich source of protein (Greenwood 1929; Ruyssen 1957)

2011). Income generated from the shea trade by women is generally used for sustenance and improvements of the household living standards. Shea thus ultimately has the prospects to offer value addition for women and is a vehicle to improve their livelihoods ensuing the promotion of rural development.

Shea is considered sacred in many rural communities and is seen as blessed by God and a symbol of a maternal tree. As a result it is utilized at birth and death thereby occupying a key position in various cultural and religious ceremonies (Hall et al. 1996; Bayala et al. 2002; Goreja 2004; Sturges 2008). In the Dagomba ethnic group of Northern Ghana, where funerals are performed during the rainy season, the wood of shea is mostly used for firewood because of the scarcity of wood and the hard corky dried bark which easily lights up even when freshly cut during the rainy season. The importance of shea to local communities is further manifested by its use in local poetry, song and dance (Fardon 1990; Kuwabong 2004).

Future research prospects

The future of research on *Vitellaria paradoxa* should hinge on the following themes: towards a better understanding of the phenology relating to fruiting in order to produce a high, fairly predictable annual yield, domestication of shea by reducing the long juvenile phase of growth, and towards the future distribution of the species in the face of global climate change. To maximize the benefits of the shea resource necessitates that processed shea rather than raw nuts are exported to the international markets. Processing entails the establishment of medium to large scale production centers which would not only create jobs but eventually lead to the sustainable development of the shea belt. But, assurance of a fairly constant supply of nuts on a yearly basis is vital and the yearly production potential of shea needs to be scientifically understood and predictable. There is therefore the need for research to understand the biological and ecological basis for productivity parameters of shea. In this regard, research questions should include (1) the role of shea pollinators and the factors that limit these pollinators, (2) the role of soil nutrients and also bushfire in shea fruiting, and (3) the role of rainfall (moisture) during flowering and subsequent fruiting.

Overcoming the long juvenile phase of growth is important for the domestication of the wild species and ultimate cultivation in plantations which would lead to higher and reliable productivity of the shea resource. The way forward in over-coming the long juvenile phase of shea lies in improving the grafting methods and the promising in vitro technology. Research in this regards has come a long way and merely a perfection of the techniques are needed, as well as a need to investigate the management of the grafting environment, as the rainy season could be the best season for grafting in terms of curtailing physiological stress. Studies of the eco-physiology of planted/grafted shea seedlings could be a starting point to understand how the species will adapt to climatic variations like increased CO_2 and drought as proposed by climate change projections. This would provide data for improving models to forcast also the future distribution of shea. Much as the fight towards domestication of the wild species continues on several methodological fronts, in the interim there should be research to test the effect of shea-grass/crop competition under current and predicted future levels of CO_2. Ecologists have used stable isotopes to investigate the effects of past climate variability on species and therefore interpret present change in climate. This tool together with dendrochronological research of shea should aid in the accurate prediction of the future distribution of the species. This could also help in matching the age of shea trees with past climate events and production data.

In conclusion, the establishment of a harmonized methodology for determining the distribution, density, chemical and nutritional analysis as well as characterization of country/regional populations is timeously required. Though the results of vegetative propagation are a basis of hope, optimization and perfection of the techniques are needed for the much desirable benefits to be derived for domestication. We propose research into eco-physiology of shea seedlings under current and projected climate scenarios as well as dendrochronology as the way forward. We also propose eco-physiological studies of the phenophases flowering and fruiting.

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