New Forests (2011) 41:113–125
DOI 10.1007/s11056-010-9214-z

Natural variation in fruit characteristics, seed germination and seedling growth of *Adansonia digitata* L. in Benin

A. E. Assogbadjo · R. Glèlè Kakaï · S. Edon · T. Kyndt · B. Sinsin

Received: 23 April 2009 / Accepted: 28 June 2010 / Published online: 11 July 2010

Abstract *Adansonia digitata* (baobab tree), a multipurpose tree species, occurs throughout semi-arid and arid zones of Africa. Its survival is, however, threatened by bush fire, over-exploitation, grazing and a lack of natural regeneration. The extent of variation in fruit characteristics, seed germination and seedling traits of the baobab tree in Benin, was evaluated at climatic zone level. 1,200 fruits were sampled in each of the three climatic zones of Benin for morphological assessment and to assess germination rate and seedling growth dynamics according to the climatic zones, the used substrate and the scarification of the seed coat. There were significant differences in fruit characteristics not only between climatic zones but also between individuals from the same zone and within-trees. Using mechanical scarification on freshly-collected baobab seeds negatively affected the germination rate of baobab seeds sampled in the Guinean and Sudano-Guinean zones of Benin. The best-germination rate was recorded for non-treated seeds from the Guinean zone, up to 57% on day 25. All seeds germinated best on the sand substrate, but supplying organic matter promoted further seedling growth after 11 days of germination. Based on these observations we propose some strategies for efficient ex situ conservation of baobab in Benin.

Keywords Climatic zones · Seed scarification · Germination substrate

Introduction

The multipurpose baobab (*Adansonia digitata* L.) is a key economic species used daily in the diet of rural communities in West Africa (Assogbadjo et al. 2005a, b; Codjia et al.

A. E. Assogbadjo (✉) · R. Glèlè Kakaï · S. Edon · B. Sinsin
Laboratory of Applied Ecology, Faculty of Agronomic Sciences, University of Abomey-Calavi, 05 BP 1752 Cotonou, Benin
e-mail: assogbadjo@yahoo.fr

T. Kyndt
Department of Molecular Biotechnology, Faculty of Bioscience Engineering, Ghent University (UGent), Coupure Links 653, 9000 Ghent, Belgium

2001, 2003; Sidibé and Williams 2002). The species contributes to rural incomes (Diop et al. 2005) and has various important medicinal and food uses (Assogbadjo et al. 2005a; Diop et al. 2005; Codjia et al. 2001, 2003; Sidibé and Williams 2002; Sena et al. 1998; Sidibe et al. 1996; Yazzie et al. 1994).

A recent study by our research group (Kyndt et al. 2009) showed that the human influence on baobab populations in agroforestry systems has an effect on the genetic structure of the species. A spatial aggregation of related genotypes and therefore a risk for future inbreeding depression was observed. However, at present, high levels of genetic diversity are still present within populations.

A number of local baobab forms differing in habit, vigor, size, quality of the fruits and foliar vitamin content, are recognized by the local people (Assogbadjo et al. 2006, 2008; Gebauer et al. 2002; Sidibé and Williams 2002). An ethnobotanical survey of the perceptions and human/cultural meaning of morphological variation, use forms, preferences and links between traits (Assogbadjo et al. 2008) showed that local people apply a morphological classification system for baobab trees and are able to guide in selecting and collecting germplasm from trees with preferred combinations of traits. However, we found that genetic fingerprinting using AFLP markers did not completely correlate with this traditional morphological identification of *Adansonia digitata* (Assogbadjo et al. 2009). In Beninese baobab populations, we did observe a link between morphological diversity and abiotic, environmental factors as well as a genetic basis for some specific traits (Assogbadjo et al. 2005a, 2006). However, since general morphological diversity and genetic diversity are not completely correlated to each other (Assogbadjo et al. 2008), baobab phenotypic traits and certainly the fruit characteristics seem to be significantly influenced by environmental factors. Therefore, a detailed study of the morphological variation in baobab fruit characteristics, is needed to be able to include a wide range of natural diversity in conservation strategies.

Next to human disturbance, the lack of natural regeneration is one of the main risk factors for baobab extinction. In order to design efficient conservation management, a study on the propagation of the species is needed. Studying the germination rate, the effect of seed pre-germination treatment and seedling growth from seeds collected in different climatic zones will give insights into the best options for propagation to obtain an efficient restoration and conservation both within and outside the natural habitat of the species.

A previous study done by Assogbadjo et al. (2005b) described the morphological traits and productivity of *A. digitata*, using data from four well-known and locally recognized types of capsules in rural areas of Benin. The present study, supplementary to the previous one, aims at understanding the variation of fruit morphology and seed germination according to the climatic zones. Differences in germination characteristics depending on climatic zone are commonly observed for widely distributed plant species like baobab (e.g. Keller and Kollmann 1999; Andersen et al. 2008; Hamasha and Hensen 2009).

With the present study, the following questions will be answered: (i) Could quantitative descriptors based on morphological characteristics help to statistically distinguish baobab capsules sampled in the same and different climatic zones? (ii) Are there differences in terms of seed germination rate and seedling growth according to their origin, the used substrate and the seed coat scarification? As such, the study will allow selecting the trees having a good combination of quantitative traits as well as the best seed germination method for different climatic zones for future species improvement, restoration and conservation.

Materials and methods

Study areas and sampling

The study was conducted in the three climatic zones of Benin, located between 6° and 12°50′ N and 1° and 3°40′ E in West Africa (Fig. 1). The climatic zones studied are: the Sudanian zone (zone 1) located between 9°45′ and 12°25′ N, the Sudano-Guinean zone (zone 2) located between 7°30′ and 9°45′ N and the sub-humid Guinean zone (zone 3) located between 6°25′ and 7°30′ N. In the Sudanian zone, the mean annual rainfall is often less than 1000 mm and the relative humidity varies from 18 to 99% (highest in August). The temperature varies from 24 to 31°C. The Sudanian zone has hydromorphic soils, well-drained soils, and lithosols. The vegetation of this zone is mainly composed of savannas with trees of smaller size. The rainfall in the Sudan-Guinean zone is unimodal, from May to October, and lasts for about 113 days with an annual total rainfall varying between 900 and 1,110 mm. The annual temperature ranges from 25 to 29°C, and the relative humidity from 31 to 98%. The soils in this zone are ferruginous with variable fertility. The vegetation of the Sudan-Guinean transition zone is characterized by a mosaic of woodland, dry dense forests, tree and shrub savannas and gallery forests. In the Guinean zone the rainfall is bimodal with a mean annual rainfall of 1,200 mm. The mean annual temperature varies between 25 and 29°C and the relative humidity between 69 and 97%. The soils are either deep ferrallitic or rich in clay, humus and minerals. Our previous study showed that baobab is distributed throughout the whole country at various densities according to the climatic zones (Assogbadjo et al. 2005a, b). In the Sudanian zone, a mean population density of 5 baobabs per km^2 was recorded. In the Sudano-Guinean zone, a mean density of 2–3 baobabs per km^2 was recorded while in the Guinean zone a density of only 1 baobab per km^2 was recorded.

From each climatic zone of Benin, 30 individuals of baobab have been randomly sampled. For each sampled baobab, 40 fruits were randomly collected. This corresponds to a total of 1,200 fruits sampled in each climatic zone.

Morphological analysis of fruit characteristics

For each capsule, length (Lcaps), width (Wcaps), thickness (Tcaps), length/width (Lcaps/Wcaps) ratio and total weight (TWcaps) was assessed. In addition, weight of pulp (Wp), seeds (Ws), pulp-seed (Wps), kernels (Wk), number of seeds (Ns) and length of peduncle (Pl) of each capsule were assessed as indicated by Assogbadjo et al. (2005b) and their means were evaluated.

Measured data on baobab capsules were used to perform an univariate analysis of variance with three factors using a linear nested model (capsules in trees and trees in climatic zones). In addition, a variance components analysis (Goodnight 1978) was executed on each morphological trait to analyze the variability of the capsules in baobab trees and the variability of trees within climatic zones. For these two statistical analyses, "zone" was considered as fixed whereas "capsules" and "trees" were considered as random. The factor "zone" is considered as fixed in the analysis because its levels constitute the entire population in which we are interested. Least square means of the traits of baobab capsules were estimated for trees of each climatic zone. Multivariate analysis of variance followed by canonical discriminant analysis (Rao 1973) was performed on the least square means in order to describe the difference between climatic zones according to the traits of baobab fruits.

All the analyses were done using SAS software (SAS Inc. 2003).

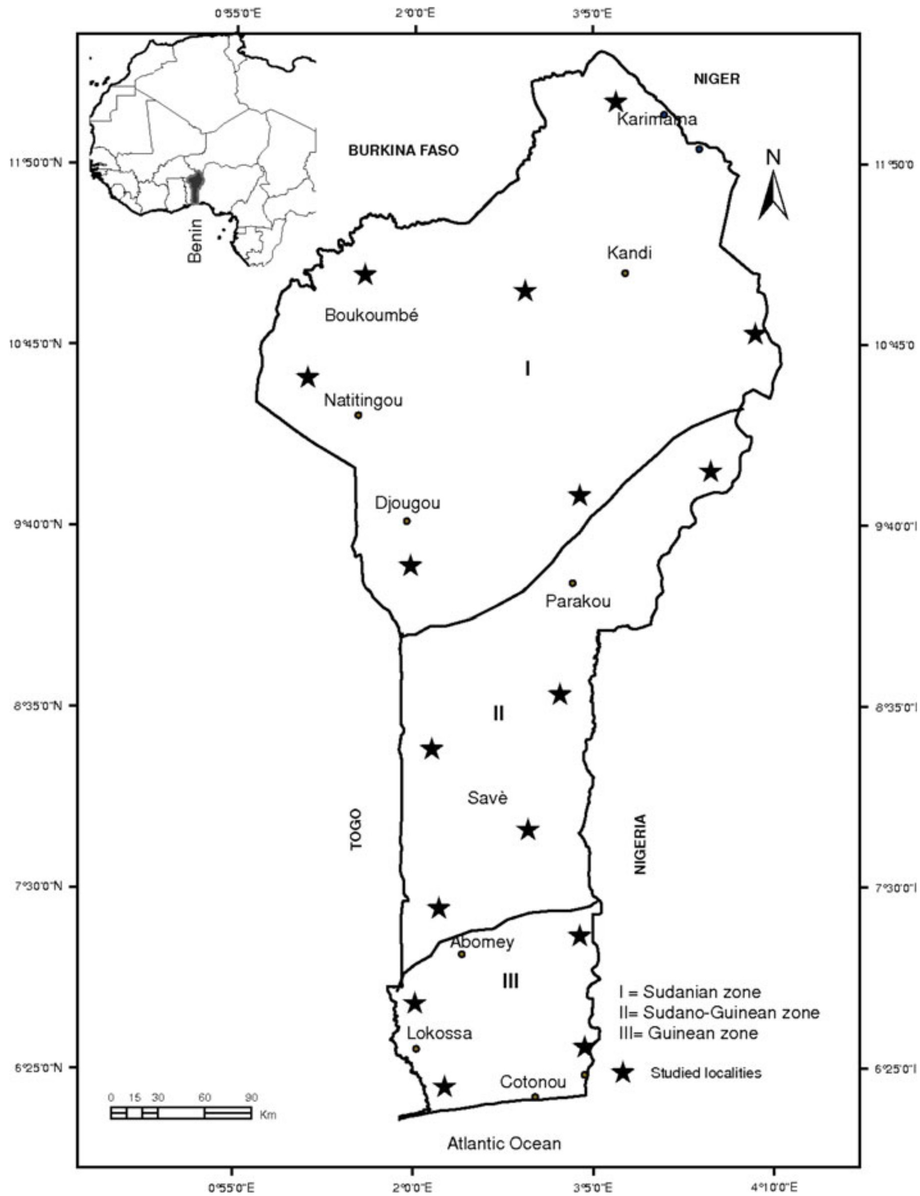

Fig. 1 Map showing the main towns of Benin and the sampling locations for evaluation of baobab fruit characteristics and germination

Germination and seedling growth dynamics

Seeds used for germination tests have been sampled on 30 baobab individuals selected in the three climatic zones of Benin. For each climatic zone, three germination substrates have been evaluated: S1: 100% sand; S2: sand (1/3) + organic matter (2/3); S3: sand (1/4) + organic matter (3/4). To test the hypothesis that germination is inhibited by the seed coat and hence pre-treatment by scarification would promote germination (Razanameharizaka et al. 2006), we have compared the germination capacity of intact seeds (NS) with that of seeds from which a 5–10 mm^2 fragment of coat has been removed with pruning shears (S). The factors tested were arranged in split plots within homogenous randomised blocks that were replicated three times.

Percentage of germinated seeds was recorded from day 7 (when the first seed germination occurred) and then every 2 days till the 31st day. Analysis of variance with repeated measures (Crowder and Hand 1990) was performed, using a mixed model. In this model, the factor "Block" was considered as random whereas all the others ("zone", "substrate" and "pre-treatment") were considered as fixed. No data transformation on the germination rate was used because multinormality and homoscedasticity were checked using the test of Rao and Ali and the generalized Bartlett test, respectively (Glèlè Kakaï et al. 2006). With this statistical method the effect of climatic zone, substrate and pre-treatment on the germination rate of the capsules was evaluated. Least square means of the germination rate were estimated from the analysis and used to draw figures showing the evolution trend of germination percentage of capsules according to the factors considered.

Growth rate has been recorded for each of the above mentioned treatments. Variability in height, diameter, number of leaves at 11, 18, 25 and 32 days was analyzed using analysis of variance with repeated measures (Crowder and Hand 1990). We analyzed the effect of climatic zone, substrate and seed coat scarification on these variables. Least square means of the variables were estimated from the analysis of variance with repeated measures and used to draw figures showing the evolution trend of each of them according to the factors in consideration.

Results

Variation in baobab fruit characteristics according to climatic zones and baobab individuals

The variance components analysis (Table 1) revealed that baobab fruit variability is generally lower between zones than within zones. The length, width, thickness, length/width ratio and weight of the capsules, as well as the weight of the pulp and the length of the peduncle has more variability between baobab trees than within the same tree, whereas the other traits revealed more variability within trees than between trees (Table 1). Between capsules of the same tree, a large variation (>40%) was observed for the weight of the capsules, seeds, and kernels as well as for the number of seeds.

The multivariate analysis of variance and canonical discriminant analysis performed on the least square means of the traits of baobab capsules indicated significant differences between climatic zones (Wilks' Lambda = 0.067; $P = 0.0003$) and between individuals from the same zone (Wilks' Lambda = 0.002; $P < 0.0001$). Capsules from trees in the Guinean zone generally have the largest dimensions and weight, while the Sudanian capsules are smaller and more lightweight. The capsules from the Sudanoguinean zone show intermediate characteristics.

Effect of climatic zone, substrate and seed coat scarification on the germination dynamics of baobab

Results of the analysis of variance with repeated measures performed on the germination rate of baobab seeds according to the level of factors considered in the experimental design

Table 1 Results of the variance components estimation procedure on capsule traits from baobab fruits collected in the three climatic zones of Benin

Variance component	Lcaps	Wcaps	Tcaps	Lcaps/Wcaps	TWcaps	Wps	Ws	Wp	Wk	Ns	Pl
Zone	1.5 (9.38%)***	0.2 (7.14%)***	0.001 (11.11%)**	0.01(2.38%)***	612.7 (4.73%)**	822.6 (15.09%)**	335.9 (12.12%)**	124.1 (21.14%)**	37.3 (12.11%)**	1626.0 (13.31%)*	3.0 (6.25%)***
Trees (zone)	13.3 (83.13%)***	2.0 (71.43%)***	0.006 (66.67%)**	0.34 (80.95%)***	7305.7 (56.41%)*	2304.3 (42.27%)*	1117.3 (40.31%)*	337.5 (57.49%)**	124.1 (40.31%)**	4902.1 (40.13%)*	43.0 (89.58%)***
Capsules (trees)	1.2 (7.50%)***	0.6 (21.43%)***	0.002 (22.22%)**	0.07 (16.67%)***	5032.5 (38.86%)*	2324.3 (42.64%)*	1318.7 (47.57%)*	125.5 (21.38%)**	146.5 (47.58%)**	5688.8 (46.57%)*	2.0 (4.17%)***

Legend: *Lcaps* Length of capsule, *Wcaps* Width of capsule, *Tcaps* Thickness of capsule, *Lcaps/Wcaps* Length/width ratio of capsule, *TWCaps* Total weight of capsule, *Wps* Weight [pulp + seed], *Wp* Weight of pulp, *Ws* Weight of seed, *Wk* Weight of kernel, *Ns* Number of seeds, *Pl* Length of peduncle

Percentages in parentheses are the variance components expressed as a percentage of the sum of the three variance components; *** significant at 0.001; ** significant at 0.01; * significant at 0.05; *ns* non significant

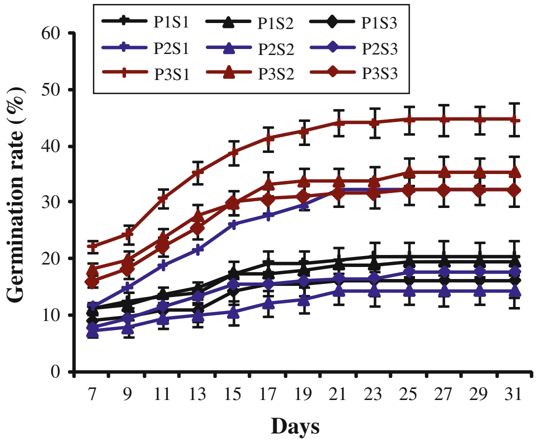

Fig. 2 Evolution trend of the germination percentage according to climatic zone and substrate. *Legend*: PiSj = Seed from climatic zone i sown on substrate j [i = 1 for Sudanian zone; i = 2 for Sudano-Guinean zone; i = 3 for Guinean zone; j = 1 for substrate 1 (sand); j = 2 for substrate 2: sand (1/3) + organic matter (2/3); j = 3 for substrate 3: sand (1/4) + organic matter (3/4)]

showed that all three main factors (substrate, climatic zone climatic zone and seed coat scarification) had a significant effect on the germination rate of the baobab seeds ($P < 0.05$; results not presented). Moreover, some of the interactions between these factors were also significant (climatic zone*substrate, climatic zone*pre-treatment) showing that the effect of a given main factor on the germination rate was influenced by another factor. In addition, the effect of the main factors on the germination rate and their interaction changed over time.

Curves showing the evolution of the interaction effect of climatic zone climatic zone and substrate on the germination rate over time are shown in Figs. 2 and 3. In general, seed germination reached its maximum after 25 days. Figure 2 shows that seeds from the Guinean zone (Climatic zone 3) when sown on substrate S1, gave the highest germination rate (from 25% to 35–45%). Seeds from the Sudano-Guinean zone (Climatic zone 2) gave the lowest germination rate. However, when substrate S1 was applied, their germination rate increased rapidly from 10% the 7th day to 30% on the 21st days. Seeds from the Sudanian zone (Climatic zone1) also had low germination rates, but this did not significantly differ from one substrate to another.

Figure 3 shows the interaction between climatic zone climatic zone and seed coat scarification on the germination rate of baobab seeds over time. We noticed that there is a highly significant negative effect of seed coat scarification on the germination rate of seeds from climatic zones 1 and 3 (Fig. 3). For the best-germinating seeds, from climatic zone 3, the germination rate of non-scarified seeds increased from 27% the 7th day to 57% the 25th day after sowing. For the scarified seeds of the same climatic zone, we only recorded a germination rate of 10% on the 7th day after sowing and this number did not significantly increase in time. Scarified seeds of climatic zone 1 showed the lowest germination rate. For climatic zone 2, however, scarification had a positive effect on the germination rate.

Effect of climatic zone, substrate and scarification on the growth dynamics of baobab seedlings

Results of the analysis of variance with repeated measures performed on the baobab seedling height, diameter and number of leaves according to the factors considered in the experimental design (Table 2) indicate that, regardless to the time of measurement, substrate and climatic zone had a significant effect on seedling growth (height and

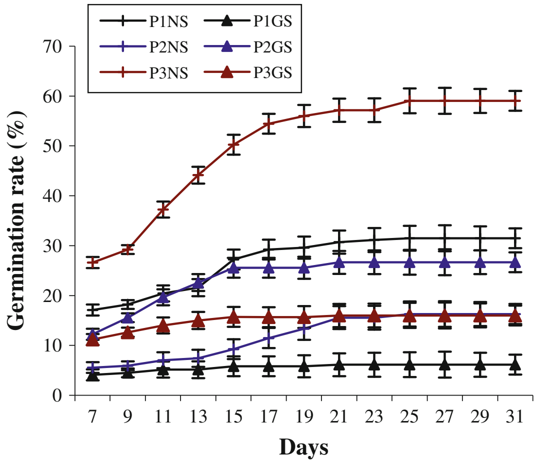

Fig. 3 Evolution trend of the germination percentage according to climatic zone and pre-treatment of baobab seed. *Legend*: Pi = seed from climatic zone i (i = 1 for Sudanian zone; i = 2 for Sudano-Guinean zone; i = 3 for Guinean zone); *NS* non scarified seeds; *GS* scarified seeds

Table 2 Summary of the analysis of variance with repeated measures on the height, diameter and number of leaves of baobab seedlings

Source	Height		Diameter		Number of leaves of baobab seedlings	
	df	*F* value	*df*	*F* value	*df*	*F* value
Time*block	8	5.89***	8	1.81ns	8	2.59**
Time*climatic zone	8	16.86***	8	0.72ns	8	0.98ns
Time*substrate	8	28.27***	8	6.00**	8	18.39***
Time*seed	4	2.38ns	4	0.71ns	4	4.18*
Time*block*climatic zone	16	0.45ns	16	0.62ns	16	0.49ns
Time*block*Substrate	16	0.88ns	16	0.62ns	16	0.63ns
Time*block*pre-treatment	8	1.30ns	8	0.32ns	8	0.32ns
Time*climatic zone*substrate	16	0.76ns	16	0.46ns	16	0.75ns
Time*substrate*pre-treatment	8	0.57ns	8	0.32ns	8	0.89ns
Time*climatic zone*pre-treatment	8	1.08ns	8	1.15ns	8	2.10ns
Time*block*climatic zone*substrate	32	1.09ns	32	1.17ns	32	1.34ns
Time*block*climatic zone*pre-treatment	16	1.02ns	16	0.48ns	16	1.21ns

Legend: *df* degree of freedom, *MS* Mean square, *F* Fisher, *Pr* probability

*** Significant at 0.001; ** significant at 0.01; * significant at 0.05; *ns* non significant

diameter) as well as on the number of leaves ($P < 0.05$). None of the interactions between the considered factors is significant ($P > 0.05$). Results in Table 2 show that the time significantly impacted the effect of substrate and climatic zone on the seedling growth and number of leaves.

Figure 4 shows the curves describing the evolution trend of these factors on the seedling growth (height and diameter). Seedlings obtained from seeds sampled in the Sudanian zone (Climatic zone 1) have the highest height and diameter whereas seedlings from the Sudano-Guinean zone (climatic zone 2) have the lowest height and diameter at all time points. Regarding the substrate, we observed that the seedlings are smaller in height and

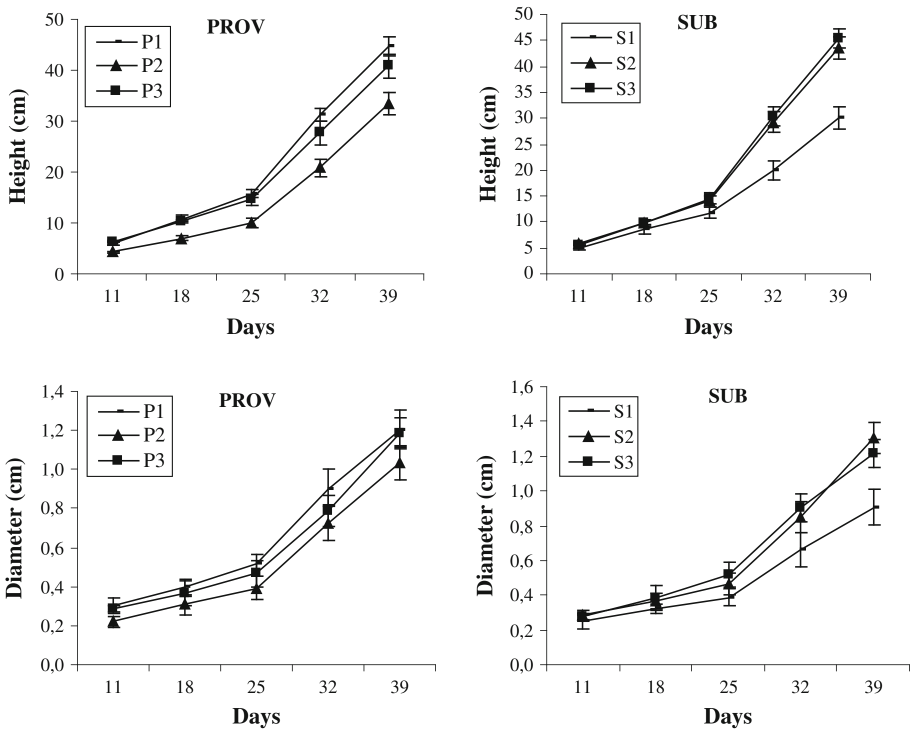

Fig. 4 Evolution trend of the seedling growth (height in *top* and diameter in *bottom*) according to the climatic zones and substrate. *Legend*: Pi = seed from climatic zone i [i = 1 for Sudanian zone; i = 2 for Sudano-Guinean zone; i = 3 for Guinean zone); S1 = sand; S2 = sand (1/3) + organic matter (2/3); S = sand (1/4) + organic matter (3/4)]

diameter on substrate 1 (sand) while substrates 2 and 3, including organic matter, result in a faster seedling growth.

Discussion

In the present study, the variation in capsule morphological traits, germination rate and seedling growth was registered among baobab seeds sampled in the three different climatic zones of Benin. Some studies dealing with different plant species already reported that morphological characteristics vary with climatic region and ecological gradients. Maranz and Wiesman (2003) revealed a significant relationship between trait values (fruit size and shape, pulp sweetness and kernel content of the species) and abiotic variables (temperature and rainfall) in sub-Saharan Africa north of the equator for the shea tree (*Vitellaria paradoxa*). Moreover, Soloviev et al. (2004) reported a significant influence of different climatic zones of Senegal on fruit pulp production for *Balanites aegyptiaca* and *Tamarindus indica* (savanna trees).

For the baobab tree, the current study revealed that variation in capsule morphological traits is higher within the same climatic zone than among climatic zones and hence no eco/morphotypes can be distinguished based on capsule traits. The observed big variation in fruits is probably influenced by both genetic and environmental factors. Phenotypic differences observed between capsules might be due to genetic drift, natural selection or plastic responses to differences in micro- habitat factors. A high influence of soil composition on the morphological characteristics of baobab tree was already observed by Assogbadjo et al. (2005a). Given the degree of variation reported in this study, selection for improvement of fruit traits would be more effective among trees within the same climatic zones than among zones.

Between capsules of the same tree very little difference was observed in capsule shape (length, width, thickness, length/width ratio) while more significant differences were observed for the weight of the capsules, seeds, pulp, and kernels as well as for the number of seeds. The low within-tree morphological variability in capsule shape could be due to a high heritability of this trait. Although in some studies a low to moderate narrow-sense heritability has been reported for fruit shape (Abe et al. 1995; Gusmini and Wehner 2007), no detailed studies have been performed on long-living tropical tree species like baobab up till now. Next to heritability, maternal effects could also explain our observations. While generally strong maternal effects are reported for seed size and seed numbers (e.g. Byers et al. 1997; Lipow and Wyatt 1999; ProvenanceWaser et al. 1995; Castellanos et al. 2008), for baobab it is rather the capsule shape that seems to be maternally determined.

The high within-tree variation in weight of capsules, seeds, pulp and kernels could be determined by the position of the capsule in the tree or, since baobab is generally outcrossing, by paternal effects.

The use of local seed provenances is often recommended in restoration and conservation strategies because they are thought to be better adapted to local habitat conditions. For these kind of programmes germination studies are important to gain insights into the effect of pretreatments, optimal conditions for germination and the influence of seed provenance.

It was reported by Danthu et al. (1995) that seeds from *A. digitata* germinated entirely after soaking in concentrated sulphuric acid for periods ranging from 3 to 12 h or by boiling for 15 s. This drastic treatment can be applied in a laboratory setting but cannot be recommended in rural areas because of the dangerous effect which may be caused by the use of concentrated acid. Mechanical scarification, as recommended by Razanameharizaka et al. (2006), which showed that the removal of the seed coat of Malagasy baobab increased the germination rate, might then be more practical. However, our study unexpectedly revealed that using mechanical scarification on freshly-collected baobab seeds negatively affects the germination rate of baobab seeds sampled in the Guinean and Sudano-Guinean zones of Benin. Whereas the non-treated seeds from the Guinean zone were already 27% germinated on day 10 and attained up to 57% on day 25, the scarified seeds from this zone merely reached 14% germination rate. Our results demonstrate that baobab seed can germinate without scarification of its seed coat. Baobab seeds from Benin do not seem to have a strict physical dormancy compared to the Malagasy ones and the observed differences may be due to a physiological response lead by genetic and/or environmental factors.

It is important to note that in our experiment, regardless of the climatic zone of origin, the seeds germinated best on sand, the germination of the freshly-collected seeds began 7 days after sowing, and was at its maximum after 25 days. While it is possible that non-germinated seeds were still viable, they were not particularly vigorous.

For species with a wide distribution range, differences in germination characteristics depending on seed climatic zone are commonly observed (e.g. Keller and Kollmann 1999; Strandby Andersen et al. 2008; Hamasha and Hensen 2009). Variations between populations are probably due to the presence of different ecotypes with different germination strategies. However, this is a hypothesis that requires additional research to test.

In our study, the percentage of germination was generally higher for baobab seeds from the Guinean zone than for those from the Sudanian zone or Sudano-Guinean zone. This might be due to differences in temperature and rainfall between the relatively dry and hot Sudanian zone and the colder and more humid Guinean climate. In many species from dry and hot regions, the loss of dormancy rate increases with the temperature to which the seeds are exposed (Baskin and Baskin 2001). In addition, for Jordanian and Central Asian *Stipa* spp. (Hamasha and Hensen 2009) rainfall had a negative influence on the germination of seeds collected in dry areas. It is then logical that in our experiments, executed in the humid and colder Guinean zone the highest rate of germination is observed for the seeds from this particular zone. Seeds collected in dryer climates are probably germinating less efficiently because the applied conditions fail to break their dormancy. This indicates a strong response of baobab germination to ecological conditions like humidity and temperature. The use of local seed provenances is hence of high importance in baobab restoration strategies. It has to be noted that next to environmental factors, also genetic factors can have an influence on seed germination traits. Wulff (1995) and Gutterman (2000) reported that maternal factors, such as position of the seed in the fruit/tree and the age of the mother plant influence seed germination ability. In this study, such effects have been not studied. Next to germination, significant differences were also observed in baobab seedling growth among the different climatic zones and between the substrates on which the seeds were sown. Emerging seedlings mainly depend on seed reserve for initial growth, which explains why seedling height and diameter for the 11-day-old seedlings was the same. However, the same variables significantly varied after 11 days according to the used substrate and climatic zone of origin. Regarding the substrate, it is not surprising to notice that the seedlings grow faster when organic matter is supplied. Seedlings obtained from seeds sampled in the Sudanian zone have the highest height and diameter whereas seedlings from the Sudano-Guinean zone have the lowest height and diameter at all time points. Parker et al. (2006) and Rai and Tripathi (1982) reported a positive influence of large seed size and seed reserve on the establishment and early growth of seedlings. Indeed, baobab from the Sudanian zone generally have a higher weight of seeds (Assogbadjo et al. 2005a, b) and this results in a faster seedling growth as well as a higher diameter at breast height in mature state (Assogbadjo et al. 2006).

The baobab species is facing a high risk of extinction because of the lack of its natural regeneration, and hence practical ex situ conservation measures are urgently needed to preserve genetic diversity and maintain multiple specimens. As a very big variation is observed in morphological characteristics of capsules between various climatic zones, between trees within the same zone and even between capsules within the same tree, there is little to be gained by selecting the "best" climatic zone based on the measured variables. However, taking into account the potential adaptation of baobab to the latitudinal rainfall gradients in Benin (Assogbadjo et al. 2006), collection can be made from a large number of capsules of different individuals in each climatic zone, to ensure to capture the widest range of biological diversity. Since seeds from the Guinean zone showed the highest germination rate compared to the ones from the Sudano-Guinean and Sudanian zone, we suggest for ex situ conservation to collect more seeds from the latter zones than in the Guinean zone. Moreover, home gardens should be developed to limit the pressure on the natural population of the species. For that, propagation through seeds is preferred and we suggest germinating on sand and then transferring the seedlings to a substrate including organic matter for further growth. No seed scarification is required for germination and we propose to use autochthonous seeds for the species propagation within specific zones.

Acknowledgments This work is financially supported by the International Foundation for Science (IFS) provided to Dr. Ir. Achille Assogbadjo in 2006. We thank IFS and its donors.

References

Abe K, Sato Y, Saito T, Kurihara A, Kotobuki K (1995) Narrow-sense heritability of fruit characters in japanese pear (Pyrus Pyrifolia Nakai). Breed Sci 45:1–5

Andersen US, Córdova JPP, Bräuner Nielsen U, Kollmann J (2008) Provenance variation in germination and seedling growth of Abies guatemalensis Rehder. For Ecol Manag 255:1831–1840

Assogbadjo AE, Sinsin B, Codjia JTC, Van Damme P (2005a) Ecological diversity and pulp, seed and kernel production of the baobab (*Adansonia digitata*) in Benin. Belg J Bot 138(1):47–56

Assogbadjo AE, Sinsin B, Van Damme P (2005b) Caractères morphologiques et production des capsules de baobab (*Adansonia digitata L.)* au Bénin. Fruits 60(5):327–340

Assogbadjo AE, Kyndt T, Sinsin B, Gheysen G, Van Damme P (2006) Patterns of genetic and morphometric diversity in baobab (*Adansonia digitata* L.) populations across different climatic zones of Benin (West Africa). Ann Bot 97:819–830

Assogbadjo AE, Glèlè Kakaï R, Chadare FJ, Thomson L, Kyndt T, Sinsin B, Van Damme P (2008) Folk classification, perception and preferences of baobab products in West Africa: consequences for species conservation and improvement. Econ Bot 62(1):74–84

Assogbadjo AE, Kyndt T, Chadare FJ, Sinsin B, Gheysen G, Eyog-Matig O, Van Damme P (2009) Genetic fingerprinting using AFLP cannot distinguish traditionally classified baobab morphotypes. Agrofor Syst 75:157–165

Baskin CC, Baskin JM (2001) Seeds: ecology, biogeography, and evolution of dormancy and germination. Academic Press, San Diego

Byers DL, Platenkamp GAJ, Shaw RG (1997) Variation in used characters in Nemophila menziessi: evidence of a genetic basis for maternal effects. Evolution 51:1445–1456

Castellanos MC, Medrano M, Herrera CM (2008) Subindividual variation and genetic versus environmental effects on seed traits in a European Aquilegia. Botany 86:1125–1132

Codjia JTC, Fonton-Kiki B, Assogbadjo AE, Ekue MRM (2001) Le baobab (Adansonia digitata), une espèce à usage multiple au Bénin. CECODI/CBDD/Veco/SNV/FSA, Cotonou, Bénin

Codjia JTC, Assogbadjo AE, Ekué MRM (2003) Diversité et valorisation au niveau local des ressources forestières alimentaires végétales du Bénin. Cahiers Agric 12:321–331

Crowder MJ, Hand DJ (1990) Analysis of repeated measures. Chapman and Hall, New York

Danthu P, Roussel J, Gaye A, El Mazzoudi EH (1995) Baobab (*Adansonia digitata* L.) seed pretreatments for germination improvement. Seed Sci Technol 23:469–475

Diop AG, Sakho M, Dornier M, Cisse M, Reynes M (2005) Le baobab africain (*Adansonia digitata* L.): principales caractéristiques et utilisations. Fruits 61(1):55–69

Gebauer J, El-Siddig K, Ebert G (2002) Baobab (*Adansonia digitata* L.): a review on a multipurpose tree with promising future in the Sudan. Gartenbauwissenschaft 67(4):155–160

Glèlè Kakaï R, Sodjinou E, Fonton HN (2006) Conditions d'application des méthodes statistiques paramétriques. Bibliothèque Nationale, Cotonou

Goodnight JH (1978) Computing MIVQUE0 estimates of variance components, SAS technical report R-105. SAS Institute Inc, Cary, NC

Gusmini G, Wehner TC (2007) Heritability and genetic variance estimates for fruit weight in watermelon. Hortscience 42:1332–1336

Gutterman Y (2000) Maternal effects on seeds during development. In: Fenner M (ed) Seeds: the ecology of regeneration in plant communities, 2nd edn. CABI Publishing, Wallingford, pp 59–84

Hamasha HR, Hensen I (2009) Seed germination of four Jordanian *Stipa* spp.: differences in temperature regimes and seed provenances. Plant Spec Biol 24:127–132

Keller M, Kollmann J (1999) Effects of seed provenance on germination of herbs for agricultural compensation sites. Agric Ecosyst Environ 72:87–99

Kyndt T, Assogbadjo AE, Hardy OJ, Glele Kakaï R, Sinsin B, Gheysen G, Van Damme P (2009) Spatial genetic structuring of baobab (*Adansonia digitata* L.) in the traditional agroforestry systems of West Africa. Am J Bot 96(5):950–957

Lipow SR, Wyatt R (1999) Diallel crosses reveal patterns of variation in fruit-set, seed mass, and seed number in Asclepios incarnate. Heredity 83:310–318

Maranz S, Wiesman Z (2003) Evidence for indigenous selection and distribution of the shea tree, Vitellaria paradoxa, and its potential significance to prevailing parkland savanna tree patterns in sub-Saharan Africa north of the equator. J Biogeogr 30:1505–1516

Parker WC, Noland TL, Morneault AE (2006) The effects of seed mass on germination, seedling emergence, and early seedling growth of eastern white pine (*Pinus strobus* L.). New For 32:33–49
ProvenanceWaser NM, Shaw RG, Price MV (1995) Seed set and seed mass in Ipomopsis aggregata: variance partitioning and inferences about postpollination selection. Evolution 49:80–88
Rai JPN, Tripathi RS (1982) Adaptive significance of seed reserves in ray achenes of Galinsoga parviflora Cav. Cell Mol Life Sci 38:804–805
Rao CR (1973) Linear statistical inference. John Wiley & Sons, Inc., New York
Razanameharizaka J, Grouzis M, Ravelomanama D, Danthu P (2006) Seed storage behaviour and seed germination in African and Malagasy baobabs (*Adansonia* species). Seed Sci Res 16:83–88
SAS Institute Inc. (2003) SAS OnlineDoc® 9.1. SAS Institute Inc., Cary, NC
Sena LP, Vanderjagt DJ, Rivera C, Tsin ATC, Muhamadu I, Mahamadou O, Millson M, Pastuszyn A, Glew RH (1998) Analysis of nutritional components of eight famine foods of the Republic of Niger. Plant Food Hum Nutr 52(1):17–30
Sidibé M, Williams JT (2002) Baobab: *Adansonia digitata*. International Centre for Underutilised Crops, Southampton, UK, p 100 ISBN 0854327762
Sidibe M, Scheuring JF, Tembely D, Sidibe MM, Hofman P, Frigg M (1996) Baobab—homegrown vitamin C for Africa. Agrofor Today 8(2):13–15
Soloviev P, Niang TD, Gaye A, Totte A (2004) Variabilité des caractères physico-chimiques des fruits de trois espèces ligneuses de cueillette, récoltés au Sénégal: *Adansonia digitata*, *Balanites aegyptiaca* et *Tamarindus indica*. Fruits 59:109–119
Wulff RD (1995) Environmental maternal effects on seed quality and germination. In: Kigel J, Galili G (eds) Seed development and germination. Marcel Dekker, Inc., New York, pp 491–505
Yazzie D, Vanderjagt DJ, Pastuszyn A, Okolo A, Glew RH (1994) The amino acid and mineral content of baobab (*Adansonia digitata* L.) leaves. J Food Compos Anal 7(3):189–193