Tree Physiology 27, 1569–1574

Radiocarbon dating of a very large African baobab

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Received February 26, 2007; accepted March 30, 2007; published online August 1, 2007

Summary In late 2004, Grootboom, probably the largest known African baobab (*Adansonia digitata* L.), collapsed unexpectedly in northeastern Namibia. Ten wood samples collected from different areas of the trunk were processed and investigated by accelerator mass spectrometry radiocarbon dating. The radiocarbon dates of three samples were greater than 1000 years BP (radiocarbon years before present, i.e., before AD 1950). The corresponding calibrated calendar age of the oldest sample was 1275 ± 50 years, making Grootboom the oldest known angiosperm tree with reliable dating results. Variations in radiocarbon dates among the wood samples indicated that, morphologically, Grootboom was a quintuple tree, whereas genetically, it was a single individual. Ages of extreme lateral samples revealed that, over the past 500–600 years, Grootbooom had almost ceased growing, providing information about climate changes in central southern Africa. The sudden demise of Grootboom coincided with the spread of the poorly studied baobab disease, which has become epidemic in Namibia.

Keywords: Adansonia digitata, age determination, dendrochronology, dendroclimatology, tropical trees.

Introduction

As of today, 16 trees species have been accurately dated to over 1000 years, all of which are gymnosperms. No angiosperm tree with a scientifically proven age of at least 1000 years is reported on the current oldlist (Brown 1996, 2006). Although Chambers et al. (1998) reported ages of over 1000 years for two tropical trees of the Amazonian rain forest, their study was based on single samples of each tree and on single radiocarbon measurements. Furthermore, their findings contradict other studies on the age limit of similar tree species from the Amazonian rain forest and have been questioned by several researchers (Worbes and Junk 1999, Williamson et al. 1999, Fichtler et al. 2003).

The African baobab (*Adansonia digitata* L.), which is a tropical angiosperm belonging to the Malvaceae family, is the largest and best-known of the eight *Adansonia* species. It is widespread south of the Sahara, especially in savanna regions. The African baobab is a relatively short tree, with a mean height of about 20 m, but some individuals can reach over 20 m in girth (Wickens 1983, Baum 1995, Mullin 2003). The tremendous size of certain specimens has led many observers to conclude that the baobab lives to a great age. The age of the oldest baobabs remains a controversial topic that has generated two competing hypotheses: the long-lived baobab hypothesis and the short-lived baobab hypothesis.

The long-lived baobab hypothesis (baobabs as millenarian trees) is based on local traditions, the statements of pioneer explorers and the study of several large specimens. Early African explorers ventured to extrapolate the low growth rate of old baobabs over their entire life cycle, thus claiming incredible ages of up to 5150 years for the largest individuals (Adanson 1771, Livingstone 1857). Several modern measurements also evinced very low growth rates for large baobabs of southern Africa, suggesting ages of well over 1000 years (Swart 1963, Guy 1970, Wickens 1983, Mullin 2003).

The short-lived baobab hypothesis (baobabs as centenary trees), promoted by many contemporary researchers, is based on several relatively recent studies that reveal surprisingly high growth rates, especially for young baobabs of central Africa (Caughley 1976, Barnes 1980, Breitenbach 1985, Barnes et al. 1994). These researchers consider that the age limit of the African baobab is only 500–800 years, possibly reaching values up to 1000 years for huge individuals (Breitenbach 1985, Wilson 1988, Esterhuyse et al. 2001, Pakenham 2004).

Reliable dating of a large baobab is a challenging opportunity because few such specimens exist, and they are usually isolated in arid or semi-arid areas. Furthermore, they decay shortly after death, usually disappearing without a trace within a year. The faint growth rings, believed by many researchers to be annual rings (Wickens 1983, Esterhuyse et al. 2001), cannot be used for aging fallen large trees for two reasons: first, growth rings may no longer be visible in certain areas of the trunk of old baobabs; and second, the presence of large internal hollows prevents a hypothetically correct ring count. Hence, the sole available technique for determining the age of old baobabs appears to be radiocarbon dating of wood samples collected from a recently fallen tree, namely by measuring their ^{14}C (or radiocarbon) content relative to their stable carbon content. The only radiocarbon dated baobab is a specimen with a circumference of 14.4 m, felled in 1960 at Lake Cariba, in today's Zimbabwe. Swart (1963) and Robins and Swart (1964) reported an adjusted radiocarbon date of 1010 ± 100 years BP for the core sample, corresponding to a calibrated calendar age of 950 ± 20 years.

"Die Grootboom" ("The Big Tree" in Afrikaans, also named Homasi by the native San people), a very large African baobab (Figure 1), was located in the Nyae Nyae Conservancy in Eastern Bushmanland, 15 km east of Tsumkwe, northeastern Namibia. The Grootboom site is located at 19°38′57.5″ S, 20°39′23.7″ E, 1149 m a.s.l. Mean annual rainfall in the area is 451 mm.

Considered a Namibian national symbol, Grootboom was, at the end of the 2003–2004 rainy season, in full foliage and apparently healthy. In late June 2004, however, it suddenly started dying and its large trunk collapsed successively into six stems. The last stem fell around January 1, 2005. Its huge size offered a unique chance to clarify the age of the largest baobabs.

Materials and methods

Measurements

The circumference and base diameter of Grootboom were measured in November 2001, several years before it collapsed. The original height of the tree was accurately estimated in December 2004 from the measured dimensions of the broken and unbroken fallen branches.

Sample collection

Several sets of wood samples were collected from the fallen stems C and D (samples Nos. 5–10, and from the remaining stumps of stems A and B (samples Nos. 1–4; Figure 2). Stems E and F were unavailable for sampling. Samples Nos. 2–10 were collected in December 2004, and sample No. 1 was collected in May 2005. The sampling of Grootboom was recorded on videotape, photographs were taken and several measurements were performed on the remains of the collapsed tree. This allowed us to establish the location of each sample in the trunk before its collapse.

Sample preparation

Cellulose samples were prepared by the standard acid-base-acid pretreatment method (Olsson 1986), except for sample No. 7. Because Sample No. 7 included decayed material and, therefore, a proportion of microbial biomass, it was processed by the α-cellulose pretreatment method, as described by Jayme and Wise (Green 1963) and modified by Loader et al. (1997). The cellulose samples were combusted to CO_2 by the closed tube combustion method (Sofer 1980). The CO_2 was then reduced to graphite with an iron catalyst in a hydrogen atmosphere (Vogel et al. 1984). The graphite samples were analyzed by accelerator mass spectrometry (AMS).

Figure 1. The southern flank of Grootboom, the largest known African baobab, before its collapse in late 2004 (Nyae Nyae Conservancy, Eastern Bushmanland, Namibia). Photo: R. Wittmann.

Accelerator mass spectrometry measurements

Radiocarbon measurements were performed at the National Ocean Sciences AMS Facility of the Woods Hole Oceanographic Institution with a 3 MV Tandetron (TM) AMS system. Each graphite sample was compressed into a small cavity in an aluminum target, which acted as a cathode in the ion source. The graphite surface was sputtered with cesium ions and the secondary negative ions were extracted and accelerated in the AMS system. After acceleration and removal of electrons, the emerging positive ions were magnetically separated by mass. The ^{12}C and ^{13}C ions were measured in Faraday cups. Simultaneously, ^{14}C ions were determined with a gas ionization counter and instantaneous ratios of ^{14}C to ^{13}C and ^{14}C to ^{12}C were calculated. These raw signals were ultimately converted to a radiocarbon date (or radiocarbon age). Radiocarbon dates and errors were rounded to the nearest 5 years.

Calibration

The radiocarbon dates were calibrated to calendar (cal) ages with the software program OxCal v3.10 for Windows and the atmospheric data from Reimer et al. (2004), i.e., the IntCal04 terrestrial calibration data set. Our choice was made based on the following reasons: (1) The SHCal Southern Hemisphere calibration (McCormac et al. 2002, 2004) is based on a relatively small number of dating results of wood samples from mid-latitude areas, which suggest a mean inter-hemispheric offset of several decades. Alternative studies (Barbetti et al. 1992, 1995, Sparks et al. 1995) show little or no inter-hemispheric offset. Recent research (Guilderson, Lawrence Livermore National Laboratory, Livermore, CA, unpublished data) on Tasmanian huon pine (*Lagarostrobos franklinii* (Hook. f.) Quinn) decadal samples documented no distinguishable offset from the Northern Hemisphere for the time period 1550–2100 cal years BP. (2) Grootboom's site is located at a relatively low latitude, about 19° S, right in the intertropical area, for which there are some calibration uncertainties. We emphasize that all results used for the Southern Hemisphere calibration originate from wood samples collected from greater latitudes. Several studies have suggested intra-hemispheric offsets between samples collected from different latitudes of the same hemisphere (Damon et al. 1989, 1992, Damon 1995*a*, 1995*b*, McCormac et al. 1995, 1998, Stuiver and Braziunas 1998). Calibration of the samples using the SHCal04 data set (McCormac et al. 2004) leads to lower calendar age values, with an offset of several decades. The 1-σ probability distribution for the radiocarbon dates, with a relative area corresponding to the 68.3% confidence interval, was chosen to calculate the calendar ages. Each 1-σ probability distribution corresponds to one or several ranges of calendar years. From these values, the 1-σ range with the highest probability was selected as the cal AD range of each sample. The mean cal BP ages and errors were calculated from the cal AD ranges. Calendar ages of samples (at Grootboom's demise) were derived from mean cal BP ages extrapolated (from AD 1950) to AD 2005. Calendar ages and errors were rounded to the nearest 5 years.

Results and discussion

Dimensions of Grootboom

Size measurements of Grootboom (Wittmann 2003) indicated a maximum base diameter of 12.1 m and a gross circumference at breast height (cbh; 1.30 m above ground) of 30.6 m, corresponding to a diameter at breast height (dbh) of 9.74 m, assuming a hypothetical circular approximation. The trunk ramified into seven branches, with the four tallest pointing straight upward, reaching a maximum height (h) of 32.0 m and a mean crown spread of 32 m. These values made Grootboom the largest known African baobab.

Age of Grootboom

The six fallen stems of Grootboom were marked A to F, in reverse order of their collapse (Figures 2a and 2b). Ten wood samples collected from four stems (A–D) and labeled 1–10 (Figure 2c) were processed and analyzed by AMS radiocarbon dating. Three samples (Nos. 1, 4 and 8), collected from three different stems (A, B and D), produced radiocarbon dates greater than 1000 years BP (radiocarbon years before present, i.e., before AD 1950); namely, 1255 ± 35, 1045 ± 20 and 1090 ± 55 years BP, respectively (Table 1).

The conventional radiocarbon dates were then calibrated to calendar (cal) ages. The corresponding calibrated 1-σ calendar ages of the three old samples are 1275 ± 50, 1000 ± 15 and 1050 ± 65 years (Table 1). These old samples were collected between 0.40 and 1.00 m from the calculated positions of the true cores of the corresponding stems, which were hollow.

Grootboom's true age can be estimated from the age of the oldest sample and its position in the respective stem. Sample No. 1, with a calendar age of 1275 ± 50 years, was collected from the stump of the relatively small stem A (west to east and north to south dbh of 2.5 and 1.2 m, respectively), at a height of 1.2 m above ground and a distance of 0.4 m from the calculated position of its core. These results reveal Grootboom to have been more than 1275 years old; our estimate being 1350–1500 years. This estimate is based on the variation in growth rate during the life cycle of baobabs in general (Breitenbach 1985), and for Grootboom's stems in particular, as determined from the age sequence of the dated samples. Thus, Grootboom is the oldest known angiosperm tree with reliable dating results.

The results provide evidence for the long-lived baobab hypothesis. Furthermore, shortly before its demise, Grootboom looked healthy and did not not have the appearance of a decrepit tree nearing its end. It was probably attacked and killed by the poorly studied baobab disease.

Structure of Grootboom

Owing to its irregular shape, bearing deep incisions and fissures, some researchers believed that the trunk of Grootboom consisted of several fused stems. Variation in sample ages and the presence of three millenarian samples in three different stems confirm this supposition. Dating results, as well as the location and dimensions of the oval stems, indicate that the

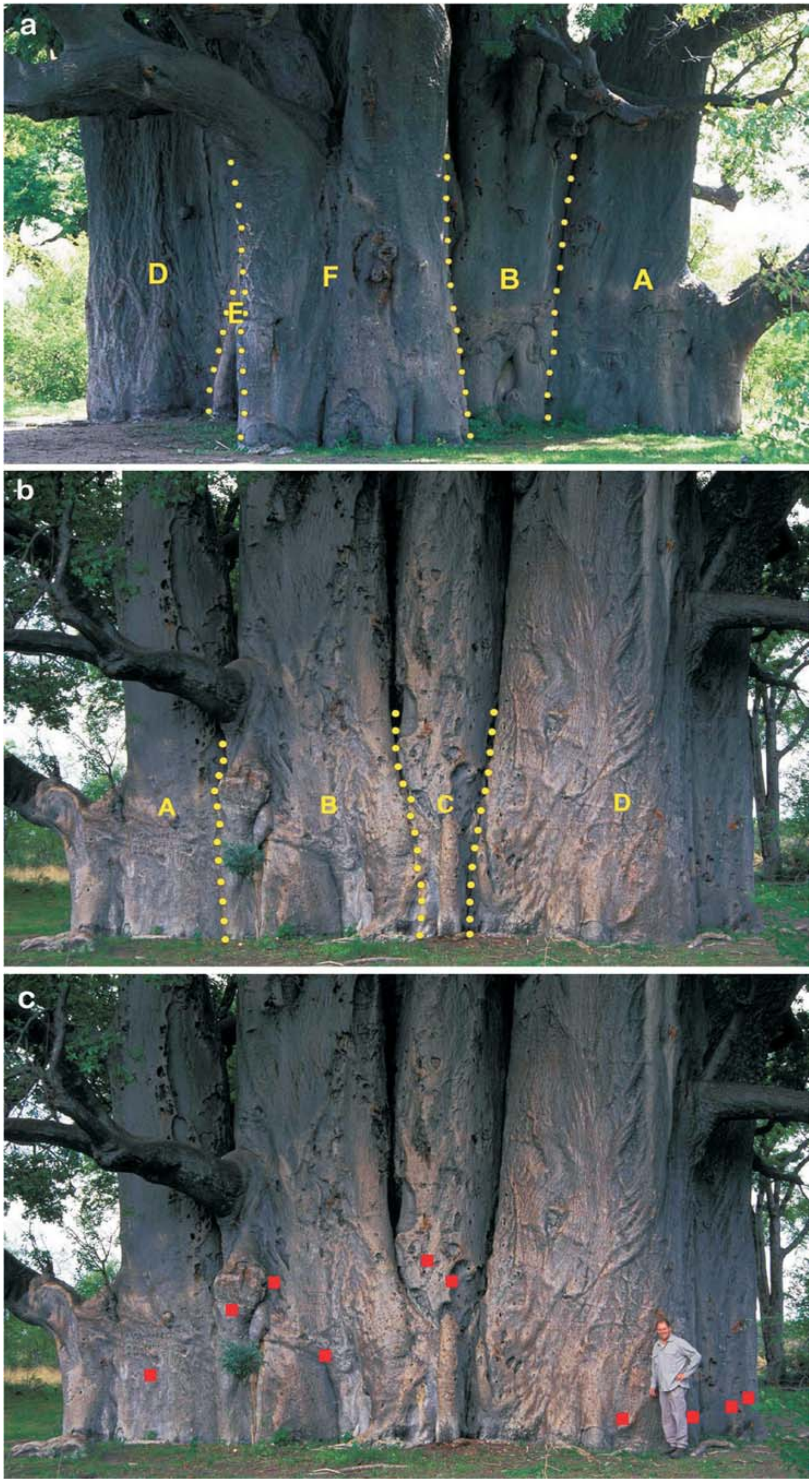

Figure 2. Stem locations (A–F) and sample positions (Nos. 1–10) before Grootboom's collapse. (a) Location of stems on the northern and northeastern flanks. (b) Location of stems on the southern flank. (c) Original positions of samples (marked with red squares) projected on the southern flank. Samples Nos. 1–10 are ordered from left to right. Photo: R. Wittmann.

Table 1. Radiocarbon dates and calibrated calendar (cal) ages of Grootboom stem samples. Radiocarbon dates were calculated from Fraction modern corrected with $\delta^{13}C$ for isotopic fractionation. The highest probability 1-σ range for each sample is in bold type. The relative areas of 1-σ ranges for a radiocarbon date correspond to the 68.3% confidence interval. The sample ages (at Grootboom's demise) were calculated from the mean cal BP ages extrapolated (from AD 1950) to AD 2005. Abbreviations: AD is Anno Domini; BP is before present, i.e., before AD 1950; and ^{14}C years BP is the radiocarbon-dated years before AD 1950. Errors are shown in parenthesis.

Sample No. and stem	Fraction Modern	$\delta^{13}C$ (‰)	Radiocarbon date (^{14}C years BP)	1-σ age ranges (cal years AD)	Relative area (%)	Mean cal BP age (cal years BP)	Sample age (cal years)
1 A	0.8555 (± 0.0042)	–23.60	1255 (± 35)	**680–780**	68.2	1220 (± 50)	1275 (± 50)
2 B	0.9559 (± 0.0036)	–24.89	360 (± 30)	**1460–1530**	39.0	455 (± 35)	510 (± 35)
				1570–1630	29.2		
3 B	0.9551 (± 0.0024)	–26.14	370 (± 20)	**1450–1520**	51.0	465 (± 35)	520 (± 35)
				1600–1620	17.2		
4 B	0.8778 (± 0.0023)	–25.56	1045 (± 20)	**990–1020**	68.2	945 (± 15)	1000 (± 15)
5 C	0.9334 (± 0.0032)	–24.31	555 (± 25)	1325–1345	26.4	545 (± 15)	600 (± 15)
				1390–1420	41.8		
6 C	0.9466 (± 0.0030)	–24.24	440 (± 25)	**1430–1460**	68.2	505 (± 15)	560 (± 15)
7 D	0.8981 (± 0.0026)	–25.66	865 (± 20)	**1165–1210**	68.2	765 (± 25)	820 (± 25)
8 D	0.8734 (± 0.0071)	–24.54	1090 (± 55)	**890–1020**	68.2	995 (± 65)	1050 (± 65)
9 D	0.9361 (± 0.0053)	–23.54	530 (± 45)	1320–1350	13.3	535 (± 25)	590 (± 25)
				1390–1440	54.9		
10 D	0.9419 (± 0.0025)	–24.69	480 (± 20)	**1420–1440**	68.2	520 (± 10)	575 (± 10)

stems with old samples (A, B and D) and the stems that were unavailable for sampling (E and F) can be considered independent and belong to Grootboom's original structure.

The sixth stem (C) turned out to be much younger, probably the result of the fusion of three independent neighboring stems. The multiple-stem structure of baobabs can be ascribed to: (1) multiple sprouting from the remains of a fallen parent tree; or (2) simultaneous germination of several seeds (Esterhuyse et al. 2001). In the former case, stems are genetic clones of the parent tree and look similar to one another. In the latter case, stems are genetically different and may differ in appearance, date of bud burst, and leaf and bark coloration. However, no such variation has been observed among the stems of Grootboom, indicating that all five independent stems sprouted simultaneously, later fusing into a single trunk. We therefore conclude that, morphologically, Grootboom was a quintuple tree, whereas genetically, it was a single individual. The time of complete fusion can be determined from ages and positions of samples collected from the fusion stem C (Nos. 5 and 6) and near the fusion area in between stems A and B (No. 2). Results show that the five independent stems fused into a single trunk about 600–800 years ago.

Growth rate of Grootboom

For trees with multiple stems, the classic concept of growth rate of the whole trunk is meaningless. One can evaluate the growth rates of only the independent stems by taking into account that the growth of each stem is limited in at least one direction by other stems. Ages of extreme lateral samples (Nos. 3 and 10) show that, over the past ~520 years, stem B grew by only 0.10 m toward the south, whereas stem D grew by 0.25 m toward the east in ~575 years, even though there was enough room in both directions (no neighboring stem). The calculated growth rates of stems B and D are low: 0.19 and 0.43×10^{-3} m year^{-1} (corresponding to mean annual increases in radius of only 0.19 and 0.43 mm, respectively). Such values reveal that, over the past 500–600 years, Grootbooom almost ceased growing. When compared with historic records of similar trees, measurements of several huge individuals from Botswana and Mozambique also show only a small increase or even a decrease in girth during a time span of ~110 years, from about 1850 to 1966 (Guy 1970). These results were attributed to a pronounced decrease in rainfall in central southern Africa. Our dating results for Grootboom suggest that the period of prolonged drought may have begun several centuries earlier, probably around 1400–1500.

Baobab disease

The demise of Grootboom was most likely a result of baobab disease, which raises serious concerns about the threat this disease poses to the remaining giant trees. Rumors about a disease affecting baobabs emerged in Zimbabwe in the 1980s, and there have been isolated reports of the occurrence of the disease in South Africa since 1991 (Anonymous 1991, Piearce et al. 1994, Wingfield 2002). So far, no pathogenic agent responsible for baobab disease has been identified.

In 2004, baobab disease appeared in the Nyae Nyae Conservancy of northeastern Namibia, causing the death of Grootboom. The finding that Grootboom almost stopped growing over the past 500–600 years suggests that it could have been vulnerable to disease. Only a few months after the collapse of Grootboom, the disease affected many other baobabs in the Nyae Nyae Conservancy and appears to represent a threat to the survival of the African baobab.

Acknowledgments

We thank Mike Elliott, Stacey Main, Gunther Friedrich, Ken Grabowski, David Knies, Edward Fletcher and Eugene Gergely for help and useful discussions. Special thanks to the Ministry of Environment and Tourism of Namibia for facilitating the research and providing export permits for the samples. Authors are grateful to Russell Jeffries from Nova Research. (Alexandria, VA) for supporting this project. This material is based, in part, on work supported by the National Science Foundation under Cooperative Agreement OCE-0228996. Part of this research was supported by a research grant from the Romanian Academy.

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