Radiocarbon analysis of the Indian banyan (*Ficus benghalensis* L.) at Narora

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This article describes the radiocarbon analysis of the large Indian banyan (*Ficus benghalensis*) at Narora, Uttar Pradesh (UP). It was discovered during floristic surveys in the Upper Ganga Ramsar site in UP and ranks as the tenth largest banyan tree in the world with its 4069 sq. m crown spread. The tree has a unique architecture, with just four prop roots supporting the main stem. The oldest sample was found to be 346 ± 40 years BP, which corresponds to a calibrated age of 430 ± 35 cal years. The radiocarbon dating results indicate an age of 450 ± 50 years for the Indian banyan at Narora. This age represents the oldest accurate dating result for the species. Several protection measures are included to ensure the long-term survival of this archaic tree.

Keywords: Age determination, AMS radiocarbon dating, *Ficus benghalensis*, tree conservation, upper Ganga Ramsar site.

THE genus *Ficus* of the Mulberry family (Moraceae) is distributed throughout the tropics and subtropics, containing over 1000 species represented by vines, shrubs, epiphytes, hemiphytes and trees[1,2]. *Ficus* trees, commonly known as banyans, are the largest representatives of this family[3]. The king of the genus *Ficus* is the evergreen Indian banyan tree, *Ficus benghalensis* L., endemic to India, where it is considered to be the national tree, although it is also found in Sri Lanka, Nepal and Pakistan. Due to its multiple purposes, the Indian banyan has been introduced to other (sub) tropical areas.

As reported in the Plants of the World online catalogue[4], *F. benghalensis* has spiritual, medicinal and ornamental applications, can be used for making furniture or as construction material, plays a role in the production of shellac, and is an attractive species for cultivation due to its rapid growth and resistance to drought. Extensively used in traditional medicine, the Indian banyan is found in Siddha, Unani, Homeopathy and Ayurveda systems[5,6], being called vata vriksha in the Ayurvedic system[7]. In addition to its multiple medicinal properties and uses, the Indian banyan has mosquitocidal effects[3].

In India, banyan trees have a spiritual, mythological and religious significance, symbolizing eternal life and/or fertility, and are recommended for planting around homes and temples[5]. They are also referred to as 'Kalpavriksha', meaning wish-fulfiling trees. Several Indian banyans are also historic trees linked to ancient and mythological events[8].

Indian banyans are a superlative species, claiming the title of the largest trees in the world by canopy coverage and broadest crown spread. The largest *F. benghalensis* as measured by net covered area is Thimmamma Marrimanu in Andhra Pradesh, with a coverage of 19,107 sq. m, followed by Kabir Vad banyan tree in Gujarat, which spreads over 17,520 sq. m and the Giant Banyan tree at Majhi, Uttar Pradesh (UP), with 16,770 sq. m (ref. 8). The Great Banyan tree in the A. J. C. Bose Indian Botanic Garden in Kolkata, West Bengal, previously considered the largest banyan in the world, now ranks fourth with a coverage of 16,531 sq. m (ref. 8). Holding such records is possible not only due to the sacred status of the Indian banyan, which prohibits them from being cut down[5], but also to their singular ability to propagate aerial roots, which emerge from branches or the trunk, anchor into the ground and gradually develop into new, woody secondary stems[9,10]. Over time, a banyan tree with a single stem develops into a complex network of interconnected stems, some merging perfectly together or with the main stem, supporting the spread of the tree. Thus, Indian banyans can potentially reach advanced ages, but dendrochronological studies are problematic, especially since the tree can survive long after the mother stem has disappeared.

The study of trees using traditional dendrochronological methods in order to ascertain their ages is relatively scarce in India, although the potential of trees to serve as proxies for past climate reconstruction has been explored in recent years[11–15]. Although dendroclimatology enabled the establishment of composite tree-ring chronologies, it offered limited insight into the lifespan of the studied species, except for the study by Pandey *et al.*[16], which mentioned an incomplete juniper (*Juniperus* spp.) disc with 1200 growth rings, suggesting an even greater age for the specimen.

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Furthermore, tropical angiosperm trees show a high diversity in forming tree-ring boundaries that may vary from species to species or even intraspecific, and can be influenced by rainfall seasonality or stress factors, making ring-width studies a complex undertaking[17–20]. More research is required to fill in the existing growth-ring research gaps[21]. Concerning the genus *Ficus*, it remains unclear whether all species have non-annual growth rings. The available scientific literature revealed that for *Ficus boliviana* growth rings were harder to distinguish with age and could be blurred along some sectors of the wood[22], *Ficus virens* produced false rings[23], while *Ficus carica* and *Ficus salicifolia* showed clear rings although their annual nature was not examined[24]. By measuring the radial variation of cellulose oxygen isotopes in *Ficus semicordata*, Xu *et al.*[25] concluded that the apparent rings were not annual.

Radiocarbon analysis[26–29] or tropical dendrochemistry[30] represent alternative dating methods for tropical trees that enable precise age determination irrespective of the growth-ring periodicity.

In this article, we present the AMS (accelerator mass spectrometry) radiocarbon analysis results of the tenth largest Indian banyan in the world, which was discovered during floristic surveys in the Upper Ganga Ramsar site in UP[31].

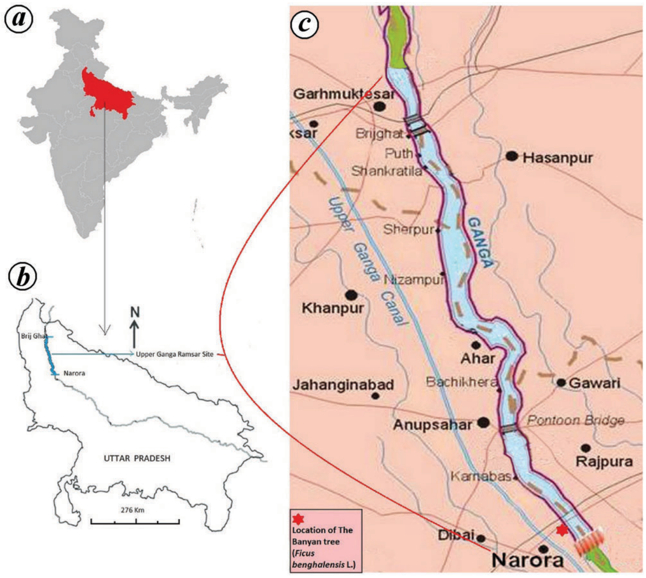

Figure 1. Map indicating the location of the Indian banyan in (***a***) Narora, Uttar Pradesh, India, (***b***) the Upper Ganga Ramsar site and (***c***) close to Narora. The location of the studied tree is marked by a star.

Methodology

The Indian banyan and its location

During floristic surveys performed by one of us (A.G.) and her team under the aegis of MOEF&CC, Government of India in the Upper Ganga Ramsar site during 2012–17, which extended from Brij Ghat in Ghaziabad district to Narora in Bulandshahr district, a gigantic Indian banyan was discovered in the Siddhwari sacred grove, Ram Ghat region, about 8 km from the Narora Atomic Power Station (Figure 1). This tree is located on the highest elevation point of the Ramsar site at 170 m amsl, on the northeastern flank of the River Ganga at 28°08.376′N, 078°26.315′E, where the mean annual rainfall reaches 902 mm (Narora station). A large family of rhesus macaques (*Macaca mulatta*) lives on and around this banyan tree.

The Indian banyan has a *cbh* = 10.5 m (circumference at breast height, i.e. at 1.30 m above ground), a height *h* = 27.7 m and covers an area of 4069 sq. m, making it the tenth largest *F. benghalensis* in the world[31] (Figure 2). The architecture is unusual; the tree has two distinct units, consisting of two main, primary stems reinforced by a mesh of roots (Figure 3) and only four large prop roots ranging from 1.00 to 4.10 m in circumference, which have developed

Figure 2. The impressive canopy of the tenth largest banyan in the world by crown spread.

Figure 3. Close-up of the two units of the Indian banyan at Narora. A mesh of roots engulfs the primary stems. Arrow indicates the sampling point.

into secondary stems (Figure 4 *a*). The prop roots can be found on the western side of the tree, promoting a unilateral expansion towards the Ganga River Basin[31] (Figure 4 *b*). The banyan is the centerpiece of the Siddhwari sacred grove, which occupies about 7 ha of the Ramsar site area and is being protected by the local community, who consider it to be a sacred wish-fulfilling tree (Siddhwari vriksha) about 500 years old[32].

Sample collection

After obtaining approval from the local guardian of the tree, a sample was extracted (using a Haglöf CH 600 increment borer; 0.60 m long and 0.0054 m inner diameter) from one of the main stems, following the methodology of Patrut *et al.*[33] for radiocarbon dating of standing, live trees. The sampling height was 3.70 m and the diameter of the stem at the corresponding height was 0.95 m. The penetration of the borer was incomplete (0.345 m into the wood) due to the hardness of the wood and the morphology of the stem. Although *Ficus* spp. possess a milky latex with significant antibacterial activity within their vasculatures, which allows for protection and self-healing[2,6], the small coring hole was additionally sealed with a special polymer sealing product to prevent infection.

Sample pretreatment, radiocarbon measurements and calibration

Three tiny segments of wood (10^{-3} m) were selected along the sample to undergo pretreatment and AMS radiocarbon dating. The segments were labelled NA-1, NA-2 and NA-3. The α-cellulose pretreatment method modified by Loader *et al.*[34] was used to obtain cellulose, which was further combusted to carbon dioxide and subsequently reduced to graphite on iron catalyst[35,36]. The resulting graphite samples were then analysed using AMS at the AMS Facility of iThemba LABS in Johannesburg, South Africa, with the 6 MV Tandem AMS system[37]. The resulting fraction of modern values was finally converted to a radiocarbon date. The reported radiocarbon dates and their corresponding errors were rounded to the nearest year.

The calibration and conversion of radiocarbon values into calendar years were performed by applying the IntCal20 atmospheric dataset[38] and using the OxCal v4.4 program for Windows[39].

Results and discussion

Radiocarbon dates and calibrated ages

Table 1 shows the radiocarbon dating results and the calibrated ages. Radiocarbon dates and errors, which are expressed in ^{14}C years BP (radiocarbon years Before Present, i.e. before the reference year 1950 CE, namely Current Era), were rounded to the nearest year. Calibrated ages and age ranges are expressed in calendar years. The 1σ probability distribution (68.3% confidence interval) was selected to derive calibrated age ranges. For NA-1 and NA-2, the 1σ probability distribution is consistent with three ranges of calendar years, while for NA-3, it is consistent with two ranges of calendar years. In such cases, the age range with the highest confidence interval (marked in bold in Table 1) was selected as the calibrated CE (cal CE) range of the sample in this study. Single calendar age values were derived by calculating the mean value of the selected age range. The sample ages represent the difference between the year 2023 and the mean value of the selected range, with the corresponding error. Sample ages and their corresponding errors were rounded to the nearest five years.

The same methodology and interpretation of results were applied to AMS radiocarbon dating of various species of baobab of Africa[28,29,40,41] and to radiocarbon studies in India, performed on African baobabs (*Adansonia digitata*), namely the baobab of Golconda Fort, Hyderābād (ca. 475 years old)[42], the baobab of Jhunsi, Allahabad, UP and the Parijaat tree at Kintoor, UP (both ca. 800 years old)[43], and on the Ceylon ironwood (*Manilkara hexandra*) at Van Khandeshwar (ca. 550 years old)[44].

Age of the Indian banyan

Sample NH-1, which originated from a depth of 10 cm along the sample, had a radiocarbon date of 92 ± 30 years BP

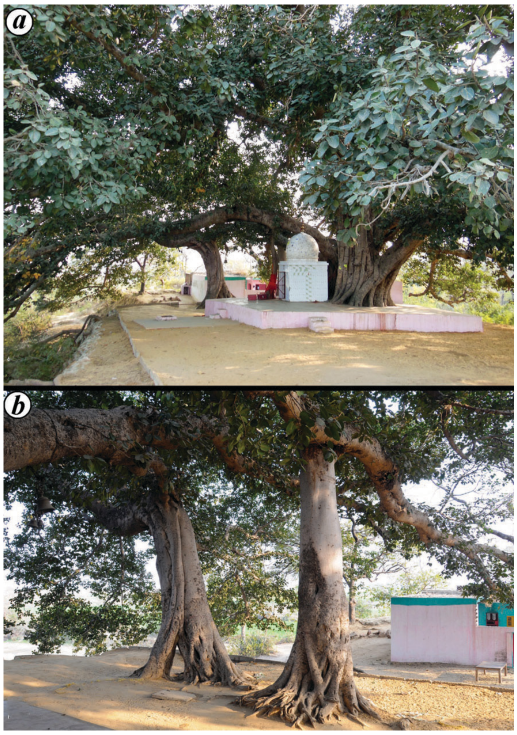

Figure 4. ***a***, Disproportionate development of the crown. ***b***, The two largest prop roots.

Table 1. Radiocarbon dating results and calibrated ages of samples collected from the Indian banyan at Narora, Uttar Pradesh

Sample/ segment code	Depth[a] (height)[b] (m)	Radiocarbon date (error; ^{14}C years BP)	Cal CE range 1σ (confidence interval)	Assigned year (error; cal CE)	Sample/segment age in 2023 (error; cal years)	Accession no.
NA-1	0.10 (3.70)	92 (± 30)	1695–1725 (21.6%) 1812–39 (19.5%) **1877–1916 (27.1%)**	1896 (± 19)	125 (± 20)	IT-C-2219
NA-2	0.20 (3.70)	212 (± 42)	1647–83 (22.4%) **1736–1803 (39.3%)** 1936– (6.6%)	1769 (± 33)	255 (± 35)	IT-C-2227
NA-3	0.345 (3.70)	346 (± 40)	1482–1525 (25.6%) **1559–1631 (42.7%)**	1595 (± 36)	430 (± 35)	IT-C-2222

[a]Depth into the wood. [b]Height above ground level.

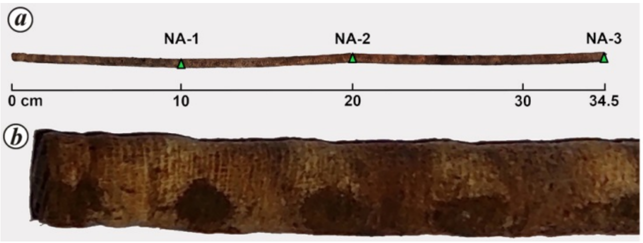

Figure 5. ***a***, Sample of length 34.5 cm. The triangles mark the area along the sample from which small segments (NA-1, NA-2 and NA-3) were AMS radiocarbon dated. ***b***, Growth rings are sufficiently visible for counting.

corresponding to a calibrated age of 125 ± 20 years. Sample NH-2, which was forfeited from the sample at a depth of 20 cm into the wood, had a radiocarbon date of 212 ± 42 years BP corresponding to a calibrated age of 255 ± 33 years. The length of the wood sample was 34.5 cm, indicating that the deepest segment NA-3 originated at a distance of 13 cm from the presumptive pith. The radiocarbon date of NA-3 was 346 ± 40 years BP corresponding to a calibrated age of 430 ± 35 years, which translates into a very old age for the Indian banyan. The total ring count revealed 481 ± 20 rings on 34.5 cm, with an average frequency of 7–8 rings/cm when the tree was younger and 10 rings/cm over the last decades. The error was due to small areas along the wood sample that showed blurred ring boundaries. Given the expected decrease in ring frequency for the distance between the presumptive pith and the original position of segment NA-3, the age of the banyan was conservatively extrapolated to 450 ± 50 years. This value confirms the presumed age attributed by the locals to the Indian banyan at Narora and represents the oldest dating result for an Indian banyan, be it by traditional dendrochronological technique or radiocarbon investigation. The result of the ring count revealed that the Indian banyan produces annual growth rings (Figure 5).

To the best of our knowledge, there is only one more age-determination study of *F. benghalensis*, conducted on introduced specimens in Ismailia, Egypt. The study resulted in a maximum age of 394 years attributed to the main stem, which had a cbh of ca. 1.80 m (ref. 10). The age was obtained by correlating the ring counts of branches with the corresponding diameters, calculating the regression equation and applying it to the diameter of the main stem. This result should be viewed with caution as the periodicity of the cambial activity was not ascertained in the study[10], the assumption that age correlates with size is not always true, and the introduction of the species to Ismailia before the construction of the Suez Canal by Ferdinand de Lesseps seems unlikely, especially since the city was founded in 1863 as a base camp by de Lesseps[10].

Conservation and protection perspectives

Indian banyan trees are essential landmarks to the Indian cultural landscape, providing shade, habitat, and historical links. They are ubiquitous as central meeting points in settlements and have a sacred status, which grants them some protection.

The Indian banyan at Narora has survived in good condition for over 400 years, withstanding variable abiotic and biotic pressures. Indian banyans in general have vast commercial potential as functional foods or pharmaceutical ingredients with important implications for human health, but centuries-old specimens also manifest valuable ancestral genetic components, allowing them to exhibit high phenotypic plasticity, with a complete set of resistant, feral genetic constituents[44]. Individual, large, old trees can be reproductively dominant in their area, acting as important nodes of regeneration[45]. In the context of climate change in particular, the pristine gene pool possesses invaluable applications in breeding, or in genetic engineering for inducing resistance traits in progenies and generating improved as well as disease-resistant cultivars. According to Murugesu *et al.*[3], *Ficus* trees also have one of the highest photosynthesis rates, enabling them to be counted among the highest oxygen generators in the world. The monumental size and high photosynthesis rate highlight the vital role banyans play in storing and accumulating carbon, thus mitigating climate change.

Furthermore, large, old trees in general are critical organisms, representing keystone ecological structures that play crucial roles in providing ecosystem services and resources to other species[26,27], while concomitantly acting as a 'micro-hotspot' containing higher species richness and abundance than the surrounding environment[45]. However, they are disproportionately vulnerable to loss in many ecosystems worldwide as a result of accelerated rates of mortality, impaired recruitment, or other intentional/incidental destruction factors[46]. Existing policies do not focus on the protection and conservation of such large, old trees, which are at risk of rapid, temporary or even permanent extinction[47].

In 2016, Garg *et al.*[31] expressed concerns regarding the unilateral canopy expansion of the banyan at Narora, which could ultimately lead to a growth imbalance by lateral dislocation of body mass. The authors noted that once the 'threshold capacity' of the main trunk is exceeded, a vertical split would be imminent, especially due to the lack of sufficient prop roots[31]. Other identified threats for the investigated banyan were modernization and globalization, dwindling religious beliefs and the dampening of sacred ethics, which would also endanger the Siddhwari sacred grove. Climate change induces an additional risk with an increase in severe weather events and changes in rainfall patterns, adding to the growing list of pressures on trees. Large, old trees have a higher sensitivity to drought than younger ones and are also a preferred target for insect attacks[48].

Lindenmayer[45] called for the protection and management of large, old trees as small natural features through targeted, fine-scale conservation strategies in order to reverse their global decline, an action that would ensure the long-term survival of the banyan in Narora. Furthermore, monitoring its growth is required to timely counteract the disproportionate gravitational pull on the tree, either through targeted pruning or hormonal treatment techniques that can stimulate aerial root growth on the eastern side. Including the specimen in gene and seed banks will ensure the conservation of the original gene pool and the sustainable future propagation of improved cultivars.

The radiocarbon analysis of the Indian banyan at Narora has added a second centuries-old landmark in the Upper Ganga Ramsar site after the identification of the 550-year-old *M. hexandra*[44]. The dissemination of information on the age, size and location of the banyan tree can contribute to popularizing the specimen, attracting tourists and pilgrims, boosting the regional economy, and thus ensuring the continuous involvement of the locals in its conservation and protection.

Conclusion

This article describes the radiocarbon analysis of the recently discovered Indian banyan at Narora in the Upper Ganga Ramsar site and presents the results of the first AMS radiocarbon dating performed on *F. benghalensis*. The Indian banyan at Narora is the tenth largest banyan tree in the world due to its 4069 sq. m crown spread. Its unusual architecture consists of two main units containing the primary stems covered by roots and four secondary stems represented by prop roots, which disproportionately support the unilateral expansion of the canopy towards the River Ganga. This unbalanced growth calls for implementing preventive protection measures to monitor and conserve this archaic botanical treasure. Dating results reveal the oldest-aged sample to be 346 ± 40 years BP, which corresponds to a calibrated age of 430 ± 35 cal years. A conservative age estimation suggests 450 ± 50 years for the Indian banyan at Narora, thus becoming the oldest dated banyan in the world.

Ethical statement: This study and sampling of the banyan was authorized by the National Biodiversity Authority of India under NBA/9/2269/18/18-19 and conducted with the assistance of the Botanical Survey of India, Central Regional Centre, Prayagraj.

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