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RESEARCH ARTICLE

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# Large trees in tropical rain forests require big plots

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**Societal Impact Statement**

Globally, the conservation value of big trees is linked to biodiversity and carbon sequestration. We studied trees, greater than 80 cm in diameter, in a forest in the Republic of Congo. We found that more than 100 species reach this size and the most abundant species is Sapele (*Entandrophragma cylindricum*), which is exploited for global timber markets. More than 40% of the large tree species are used by local people for food. Our results show that big trees are important to local people in the Congo Basin in addition to being the focus of industrial logging and in many areas the basis for the formal economy.

**Summary**

- The main aim of this paper is to establish standard techniques for surveying the biggest trees in tropical rain forests.
- One hundred and thirty hectares (13 plots of 10 ha) of unlogged mixed species terra firma forest in the Republic of Congo were surveyed for trees greater than 80 cm in diameter.
- More than 100 species of tree exceed 80 cm in diameter and one species, *Entandrophragma cylindricum* (Sapele or Sapelli), dominates this size class.
- Obtaining comparable data of big trees from different sites across the tropics is a priority. We propose a standardised plot size of 10 ha, replicated 10 times for each forest type at different study sites and a minimum trunk diameter of 70 cm at breast height or above buttresses.

## 1 | INTRODUCTION

The largest trees in the world are exceptional, and in tropical rain forests, these long-lived individuals especially stand-out, forming the emergents that tower over the multistoried forest canopy below. The tallest recorded tropical tree is just over 100 m tall (Shenkin et al., 2019). Such big trees occur at much lower densities, but play important roles in the ecosystem and face increased threats compared to the other trees (Clark et al., 2019; Lindenmayer & Laurence, 2017; Lutz et al., 2018; Pinho et al., 2020). However, in many tropical forests, little is known about the largest trees, including their species composition and distribution.

There are two reasons for this lack of information on one of the most dramatic features of tropical rain forests. First, big trees are much harder to measure accurately than smaller ones. When using the standard 10 cm diameter at breast height (dbh) as a minimum, the smaller trees are measured quickly and accurately. However, due to buttresses and other trunk anomalies, the diameters of the largest trees take much longer to measure. The second reason is the relative rarity of the largest trees in the forest compared to smaller trees. In a previous study in the lowland rainforest of the Central African

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Republic, all trees above 10 cm dbh were measured in forest plots covering 11 hectares (Hall et al., 2003; Hall et al., 2019). Out of the 4,560 trees surveyed, only 118 (2.6%) were greater than 80 cm in diameter.

## 2 | THE DEFINITION OF BIG TREES IN THIS STUDY

To gain an initial sense of the representation of big trees, we analysed the data from 11 ha of plots in different terra firma forest types, logged and unlogged from the Sangha Trinational in central Africa where Cameroon, Republic of Congo and the Central African Republic meet (Hall et al., 2003). In this forest over the previous 20 years, we had occasionally encountered remarkably large individuals of species such as *Ceiba pentandra*, *Pachylesma tessmannii*, *Autranella congolensis*, *Nauclea diderrichi*, *Entandrophragma utile* and *Entandrophragma candollei*. When we analysed the data from the 11 ha, we found no individuals of any of these species above 50 cm dbh. From this, we concluded that we had to drastically increase the area sampled to pick up some of the exceptionally large-diameter trees of these species. Measuring a big tree accurately takes time, so we had to make a trade-off between the lower limit dbh and the amount of area we could sample. We decided to use a lower limit of 80 cm dbh so that we could reduce the number of trees that needed to be measured in a 10-ha plot to a number that we thought manageable with the time available to us. This would also to allow us to make at least 10 random samples and sample 100 ha in the first instance. We could, of course, have made the lower limit higher but as we knew how few individuals above 80 cm (118 in 11 ha) had been sampled for a fixed area we settled for that as the lower limit in this study.

## 3 | AIMS

Our first aim in this study was to set up permanent monitoring plots of big trees to establish a baseline for monitoring the growth, recruitment and mortality of big trees in the Sangha Trinational area. These permanent plots will allow us to understand the dynamic nature of these forests at a time when they face threats from logging, land-use conversion and climate change. Our second aim was to test whether 10-ha plots are a practical size, and what area of sampling is necessary to adequately survey big trees in a tropical forest. Our third aim was to answer two simple questions:

1. How many species become big trees?
2. Which species of big tree are the most abundant?

## 4 | STUDY SITE

This study took place in the Nouabalé-Ndoki National Park (NNNP; 2°05'-3°03' N; 16°51'-16°56' E) and the Kabo Forestry Concession that forms the southern border of the park in the north of the Republic of Congo (Figure 1). The NNNP is part of the Sangha Trinational that was declared a UNESCO Natural World Heritage Site in 2012. It is formed by a transborder series of protected areas in the Republic of Congo, Cameroon and Central African Republic.

The main vegetation type on non-flooded ground (terra firma) has been described as semi-evergreen (White 1983) and semi-deciduous (Letouzey, 1968) forest. However, it is important to recognise that both the authors describe the same forest type, in which most of the trees are evergreen; at any point in the year the forest is green and only a few individual trees have lost their leaves. This forest type has been described from Ivory Coast to Ghana, Nigeria, through Cameroon and across the Sangha Trinational area to the Democratic Republic of Congo. A comprehensive comparison of this broad tract of forest across its entire range of 4,000 km has yet to be conducted, but it has been well documented in Ghana (Hall & Swaine, 1981) and Cameroon (Letouzey, 1968).

In the Sangha Trinational area, this forest type occurs in what is probably its most extensive and most natural state (Potapov et al., 2017) with very low human population densities since 1891, documented in the oral histories of the people who live there and maps and written descriptions from the first Europeans to arrive in the area (Kretsinger & Zana, 1996). It appears from pollen core data (Brncic et al., 2007) that the previous two centuries (1700–1900) also had low human population densities. There are large areas of forest that have not been industrially logged.

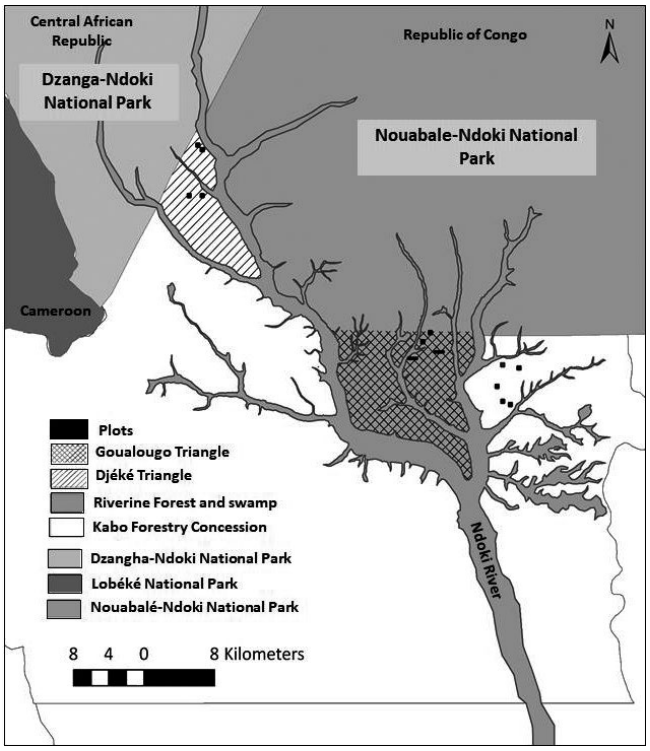



**FIGURE 1** Map showing the location of the plots in the Sangha Trinational study site

In addition to mixed-species, semi-evergreen terra firma forest, other vegetation types in the Sangha Trinational Area are monodominant evergreen *Gilbertiodendron dewevrei* forest, swamp forest and seasonally flooded forest.

We know that there are 429 species of tree that reach 10 cm dbh on terra firma in the Sangha Trinational area. This list is derived from the cumulative results of botanical inventories which started in 1987 (Harris, 2002), forest ecology studies with herbarium specimens as vouchers (Hall et al., 2003; Hall et al., 2019; Medjibe et al., 2011; Ndolo Ebika et al., 2018; Thenkabail et al., 2003); taxonomic revisions (Hyam et al., 2012; Wellsow et al., 2019) and a tree identification manual (Harris & Wortley, 2008).

## 5 | METHODS

We established permanent plots at three different sites within our study area (Figure 1), all of which represented intact forest that had not been logged at the time of data collection. The first site was located in the Goualougo Triangle, which is inside the NNNP. A second site was established to the south-east of the National Park in the Kabo Forestry Concession. The third site was also located in the Kabo concession in an area known as the Djéké Triangle to the west of the National Park (Figure 1).

At each of the three different sites, grids of 500-m squares were laid out on a classified vegetation map (Laporte, 2002) using the geographic information system software QGIS (QGIS Development Team, 2019). The intersection points of the grid lines were selected and assigned a number if they occurred on terra firma mixed-species forest according to the vegetation map. Points were rejected if they occurred on other vegetation types, such as swamp forest or monodominant forest. A random number generator was then used to select five points at the Goualougo, Djéké sites and six points in the Kabo Forestry Concession to the east of the NNNP. At each of the selected points (totalling 16), a 10-ha plot was drawn in QGIS with the south-west corner of the plot on the point. The first three plots were rectangular (500 × 200 m) and then the remaining 13 plots were square (316.2 × 316.2 m). The shape files of the plots were then uploaded onto hand-held GPS units.

On the ground, the plots were approximately delineated using string or thread to orient the survey teams. The teams of six people 4–5 m apart, swept through the plots in parallel paths searching for trees over 80 cm dbh and measuring candidate trees with a dbh tape. The team leader followed behind checking that no trees were missed. The trees were measured and marked using the RAINFOR protocol (Phillips et al., 2009; Phillips et al., 2018; see Figure 2). The locality of each tree was recorded as a waypoint, which when taken on the west side of the trunk once the GPS unit reported accuracy between 8 and 12 m. For big trees within 10 m of the plot's boundary up to an extra 10 min were taken recording the locality so that the precision reading on the units was within 5–8 m. After the waypoints of the trees were downloaded onto a laptop and projected using QGIS, the trees were scored as inside or outside of the plot, depending on which side of the plot border they occurred. Figure 3 shows an example plot at this stage after all the trees close to the boundary were allocated as "in" or "out" and only those inside the plot are shown.



**FIGURE 2** Base of *Autranella congolensis*, tree number 920, diameter 252.3 cm, point of measurement 170 cm. Nouablé Ndoki National Park, Sangha Trinational, Republic of Congo

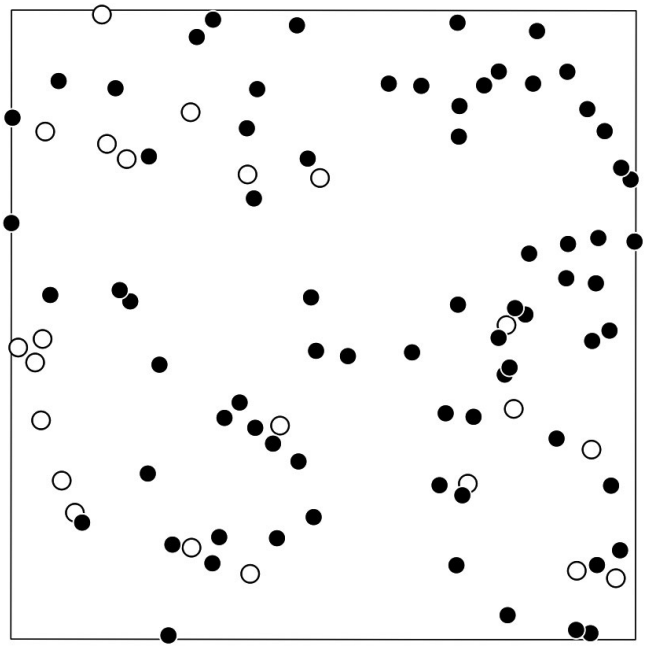


**FIGURE 3** An example of a 10-ha plot with big (>80 cm dbh) trees, *Entandrophragma cylindricum* (Sapele), open circles 22 individuals, other species, closed circles 73 individuals. Plot BT20

The survey team consisted of a parataxonomist, technicians and local field assistants. The trees were identified using a combination of local, commercial and Latin names when there was any doubt within the team as to the identity of the trees. The parataxonomist has spent 15 years in NNNP identifying trees using the tree identification manual (Harris & Wortley, 2008) written at the study site. Multiple herbarium vouchers have been collected at the study site for each of the species recorded in the plots and these have been deposited at the National Herbarium in Brazzaville (IEC) and the Royal Botanic Garden Edinburgh (E). Individual vouchers for the 1,221 trees identified in the plots were planned for 2020 but this was cancelled due to COVID 19 travel restrictions and will be made at the first re-census. All identifications reported here were made by David Koni and David Harris across the entire series of plots.

Three plots (BT 1, BT 7 and BT 19) were characterised as a mosaic of monodominant *G. dewevrei* forest and mixed species terra firma forest (see Table 1). Each of those three plots had more than 30% of their large trees were of that particular species and so were not analysed further in this study. The monodominance of *G. dewevrei* is unique on a global scale, and in the Sangha Trinational, it is a very different vegetation type from the adjacent mixed species forest (Harris, 2002). In addition to monodominance, the differences are in species composition, leaf phenology, basal area, canopy structure, species turnover over a millennial scale (Tovar et al., 2019) and soil (Hall et al., 2019). This is a highly unusual forest type that is not representative of mixed species tropical rain forest on terra firma. Of the remaining 13 plots, 6 plots had no *G. dewevrei* big trees and 7 plots had only a few big *G. dewevrei* trees (counts in those plots: 2, 3, 5, 8, 11, 18 and 22 big individuals of that species).

We extrapolated our results using the non-parametric estimator Chao1 (Chao, 1984) using the following formula.

$$s_1 = s_{obs} + \frac{F_1^2}{2F_2}$$

where $S_{obs}$ is the number of species in the entire sample of 130 ha, $F_1$ is the number of singletons (i.e. the number of species with only a single occurrence in the sample) and $F_2$ is the number of doubletons (the number of species with exactly two occurrences in the sample).

**TABLE 1** An overview of the large tree plots and the number of *Gilbertiodendron dewevrei* trees in each plot. Plots 1, 7 and 19 were rejected for having more than 30% of big trees of *G. dewevrei*

| Plot number | Big trees in plot | Big *Gilbertiodendron dewevrei* trees in plot | % big trees *Gilbertiodendron dewevrei* |
|---|---|---|---|
| BT 1 | 125 | 71 | 57% |
| BT 2 | 92 | 0 | 0 |
| BT 3 | 101 | 0 | 0 |
| BT 4 | 117 | 0 | 0 |
| BT 5 | 89 | 2 | 2.2% |
| BT 6 | 94 | 5 | 5.3% |
| BT 7 | 81 | 33 | 40.7% |
| BT 8 | 101 | 8 | 7.9% |
| BT 9 | 110 | 0 | 0 |
| BT 10 | 107 | 0 | 0 |
| BT 11 | 104 | 22 | 21.1% |
| BT17 | 64 | 18 | 28.1% |
| BT18 | 94 | 3 | 3.2% |
| BT19 | 93 | 52 | 55.9% |
| BT20 | 96 | 11 | 11.5% |
| BT21 | 52 | 0 | 0 |

## 6 | RESULTS

The total number of big trees greater than 80 cm dbh sampled in 13 plots, each of 10 ha, was 1,221. The number of big trees per plot ranged from 52 to 117. The mean number of big trees in a 10-ha plot was 94 and the variance was 314.4 (*SD* 17.7).

We recorded 92 species in the big tree category of greater than 80 cm dbh surveyed over 130 ha ($n$ = 1,221 trees). The 92 species were in 32 families and 71 genera. The 12 most abundant big tree species are listed in ranked order in Table 2.

Of the 92 species represented in our sample, 17 of them were represented by a single tree (singletons) and 8 of them as two individuals (doubletons). The ranked species abundance curve is presented in Figure 4. Using Chao1 as an estimator, we obtained an estimate of 110 species of tree reaching 80 cm dbh.

*Entandrophragma cylindricum* (Meliaceae), known by its commercial name of Sapele (English) or Sapelli (French), was the most abundant species in this sample. A total of 177 trees of that species were recorded out of the 1,221 trees measured (14.5%). The largest 81 of the big Sapele trees were greater than 125 cm in diameter and 89 of them were taller than 45 m.

**TABLE 2** Ranked species abundance of the most abundant 12 species of trees greater than 80 cm dbh across 130 ha

| Species name | Number of individuals above 80 cm in 13 plots, ranked |
|---|---|
| *Entandrophragma cylindricum* | 177 |
| *Petersianthus macrocarpus* | 124 |
| *Terminalia superba* | 104 |
| *Gilbertiodendron dewevrei* | 69 |
| *Pentaclethra macrophylla* | 53 |
| *Triplochiton scleroxylon* | 52 |
| *Erythrophleum suaveolens* | 45 |
| *Blighia welwitschii* | 30 |
| *Sterculia oblonga* | 26 |
| *Entandrophragma candollei* | 22 |
| *Celtis mildbraedii* | 21 |
| *Entandrophragma utile* | 21 |

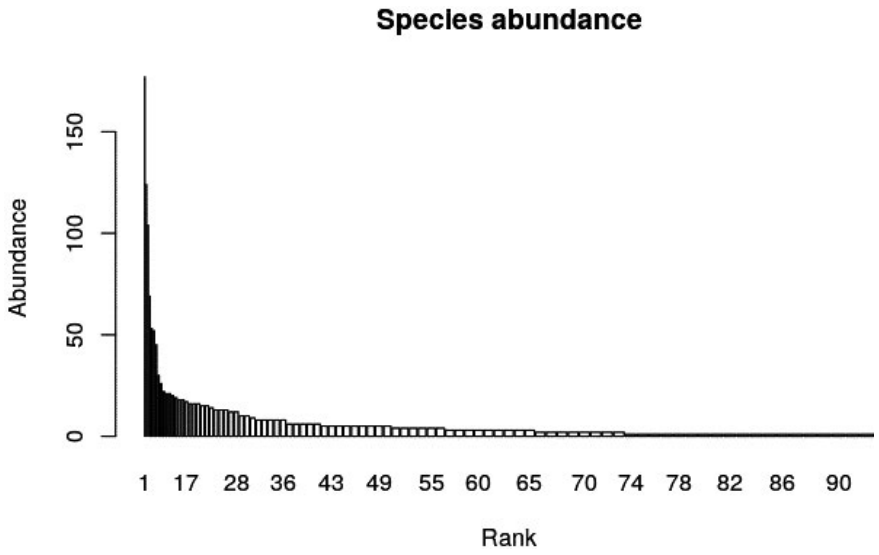



**FIGURE 4** Ranked species abundance curve for 92 species of tree (>80 cm dbh) in 130 ha of plots in the Sangha Trinational, Republic of Congo. The commonest species is *Entandrophragma cylindricum* with 177 individuals, the rarest 17 species are represented by a single individual and $N = 1,221$

**TABLE 3** Number of big Sapele trees (>80 cm dbh) in thirteen 10-ha plots

| Plot number | Number of big Sapele |
|---|---|
| BT 2 | 10 |
| BT 3 | 18 |
| BT 4 | 10 |
| BT 5 | 14 |
| BT 6 | 12 |
| BT 8 | 20 |
| BT 9 | 8 |
| BT 10 | 14 |
| BT 11 | 11 |
| BT17 | 12 |
| BT18 | 14 |
| BT20 | 22 |
| BT21 | 12 |

In each of the 13 plots, Sapele was in the top four species ranked by abundance. In seven of the plots it was the commonest tree above 80 cm dbh. Other species that were consistently in the top 10 species for each plot were *Terminalia superba* and *Petersianthus macrocarpus*.

Across the 13 plots, the mean density of big Sapele individuals was 1.4 stems stem ha$^{-1}$. The highest density of Sapele was 2 stems ha$^{-1}$. In 12 of the 13 plots, the density of big Sapele trees was greater than 1 stem per hectare (Table 3). In the only plot with Sapele stem density less than 1 per ha, the density was 0.8 stem ha$^{-1}$. *P. macrocarpus* had an average stem density of 0.95 ha$^{-1}$ and *T. superba* had a density of 0.8 stems ha$^{-1}$. Figure 3 shows an example of a 10-ha plot with the individuals of Sapele distributed across the plot as open circles and the closed circles of the individuals of other species.

### 6.1 | "How many species reach the class of big tree?"

A total of 92 species were shown to reach the big tree class (>80 cm dbh) in this forest and 110 species are estimated to reach this size.

### 6.2 | "Which species of big tree are the most abundant?"

Unequivocally, *E. cylindricum* (more widely known by its trade names of Sapele or Sapelli) is the most abundant big tree in the terra firma mixed species forest of this region.

## 7 | DISCUSSION

We were able to answer our two main questions about big trees with clarity.

### 7.1 | Question 1—How many species reach the class of big tree?

We knew that over 400 species of tree above 10 cm dbh occurred on terra firma in the Sangha Trinational area, but we never imagined that 92 species, almost 25% could grow to be such large trees. We were aware from previous research (Harris & Wortley, 2008) that many species grew to be bigger than 60 cm dbh, but quantitative published data were not available to say how many species become really big trees. Previous sampling in the Sangha Trinational of 11 ha of 0.09-ha plots (Hall et al., 2003) when reanalysed for this study provided only 48 species greater than 80 cm dbh. If standard 1-ha plots had been used, for the same sampling effort then probably even fewer species would have been recorded.

In addition to the 92 species that we now know reach 80 cm, it was possible to estimate, using Chao1, that there are 110 species reaching that size in the Sangha Trinational. Due to the number of the species that we have seen (personal observations) to reach this size outside of any sampling plot in the area, the estimate of 110 species appears plausible. We think it is safe to assert that more than 100 species reach the big tree class (>80 cm dbh) in this forest.

We were able to find only a limited set of data on species numbers in our size class (dbh 80 cm and larger) for tropical rain forest trees from other locations. Few studies have focused on the large trees and asked the question of "how many species get very big"? Richards (1952), for example, gives the largest size class as above 41 cm diameter for mixed species forest (tables 25 and 28 in that book). In his second edition, Richards (1996) says "Trees of girth greater than 1 m [=dbh of 32 cm] are uncommon." One notable early study recorded all the species of large trees, in a 38-ha total sample from Bobiri Forest Reserve in Ghana. Taylor (1960) reported 46 species with diameters greater than 87 cm. Our sample of 130 ha compared to Taylor's 38 ha is the simplest explanation of our much longer species list. When we reanalysed the first 40 ha of our plots for trees greater than 87 cm diameter to approach Taylor's sampling we found 56 species. Of the 46 species of Taylor, 27 were in our big tree species list and most of the commonest trees at each site were present at the other. The two sites are 2000 km apart. The concept of the hyperdominance in trees, reported from Amazonia (Ter Steege et al., 2013) and from central Africa (Bastin et al., 2015), may be even more striking for the very big trees.

When researchers realise that the species abundance and distribution can be so different between medium and very big trees, we predict that they will begin to ask the simple question across tropical forests: how many species of big trees are there? An immediate and straightforward way to facilitate systematic comparisons between sites would be for the authors to present data for all of the 10-cm size classes. Widely used databases for plot data such as ForestPlots.net record individual tree diameters and are available on request. This database has been used by the plot networks such as DRYFLOR, RAINFOR and SEOSAW (Moonlight et al., 2020; The SEOSAW partnership, 2020).

We found one recent, directly comparable data set in the published literature which reported trees over 80 cm dbh from 119 ha of plots in Costa Rica (Clark et al., 2019). At La Selva, they recorded 39 species of big trees in 119 ha. By contrast, in our study we identified 90 species in the first 120 ha of plots in the Sangha Trinational of central Africa (our total was 92 species for 130 ha). The density of big trees was 3.5 per ha in Costa Rica, in comparison to 10.7 big trees per ha in the Sangha Trinational. Clearly, there was a difference in big tree density and species richness in these two studies which had comparable sample sizes and are both in old growth lowland tropical rainforest. We found more than twice as many big tree species in the Sangha Trinational compared to La Selva. Furthermore, there were twice as many individuals of big trees per hectare in the Congo Basin forest compared to old growth forest in Central America.

Comparisons with data presented by Thomas et al., (2003) from a 50-ha plot in Korup, Cameroon were harder to compare. Apart from the smaller sample size, the main difficulty is that they report the largest tree class as 60 cm dbh and above and we cannot calculate the larger size classes because diameters are not given for individual trees. The number of species in that size class is 84 and the density of stems is 11 per ha in Korup. Hall et al., (2003) had a mean of 20.4 trees greater than 60 cm per ha for the Sangha Trinational. Although very limited, this initial comparison indicates the Sangha Trinational may have more species of big tree and more individuals per hectare than other forests in Africa.

## 7.2 | Question 2—Which species of big tree are the most abundant?

*Entandrophragma cylindricum* or Sapele is the most common species to reach big tree status. Before this study, we might have expected that *P. macrocarpus*, *T. superba* or *Celtis mildbraedii* would be more abundant than *E. cylindricum* from general observations in the forest and from samples of trees above 10 cm dbh. The data from plots less than 1 ha recording all trees above 10 cm dbh showed that *E. cylindricum* is not common in this forest, with a density of only 3.5 stems $ha^{-1}$ in unlogged forest (Hall et al., 2003, Table 1). How can this be? How does one reconcile our observations that *E. cylindricum* is the commonest species in this study of big trees but quite rare in plots that encompass smaller tree size classes?

An explanation can be seen in the size class distribution of Sapele in Figure 5 (from Hall et al., 2003) that shows the size class distribution of Sapele in a 100 ha plot in which all stems above 10 cm dbh of that species were recorded. Each 10 cm size class from 30 to 80 cm dbh has fewer individuals than any of the size classes from 90 to 130 cm dbh. Small individuals of Sapele grow very slowly in the shade, and then some of them in the 10- to 20-cm dbh class get extra light (Hall et al., 2003). These "released" individuals grow faster, receive more light and increase their growth rates even more. They continue to increase their rate of growth as they move up through the size classes. The decreasing "travel time" from the bottom to the top of each 10-cm dbh class from 20 through to 100 cm dbh explains their rarity in those classes compared to below 20 cm and above 100 cm. This explanation illustrates the need for large areas, such as 100 ha, to be sampled to understand the population structure of the big tree species. Big trees need big plots.

Prior to this study, there were three groups of people who knew, and had data to show it, that this forest and similar ones across Africa are full of large Sapele trees. These are the government ministries who allocate forestry concessions, the logging companies that extract timber and a handful of forest ecologists (Hall et al., 2004; Hawthorne, 1995; Lourmas et al., 2007; Réjou-Méchain et al., 2011; Taylor, 1960). Sapele alone makes up 28% of the entire industrial timber production from the Congo Basin (Ruiz Perez et al., 2005). In addition to being the commonest big tree species in this forest,

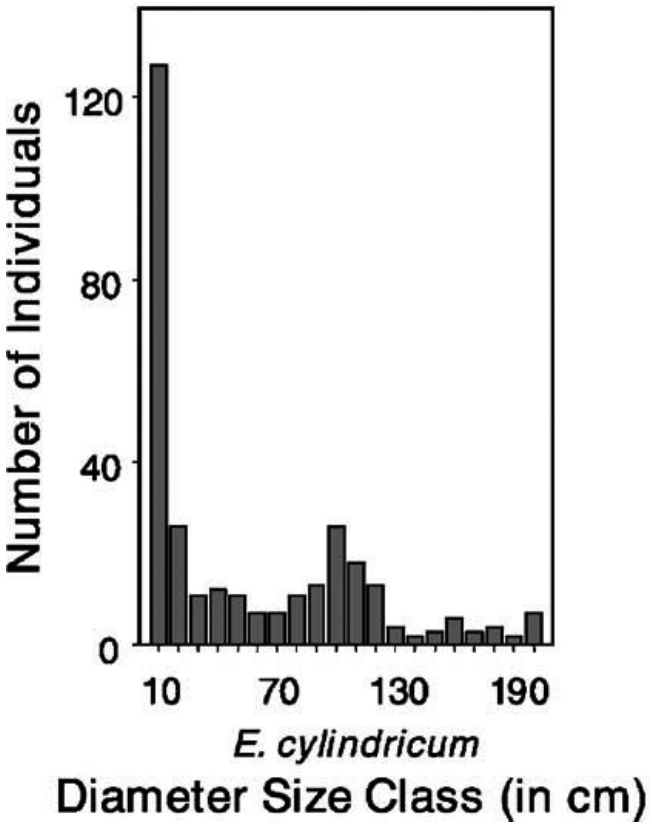



**FIGURE 5** Size class distribution of *E. cylindricum* >10 cm dbh on the 100-ha Eleme ya Ngombe plot in the Dzanga-Sangha Dense Forest Reserve, Sangha Trinational, Central African Republic, modified from Figure 3 of Hall et al., (2003)

Sapele has been a high value commodity on the international timber market for over 100 years.

Richards, 1996 (table 1.1) lists Sapele as the species with the largest diameter of any tropical tree. Two large diameter Sapele trees were reported from Nigeria by Kennedy (1936), one measured on the ground was 4.83 m in diameter above buttresses, and a second tree had a diameter of 4.27 m. Both these trees were approximately double the size of the largest Sapele in our results which was 2.16 m in diameter. We found only 3 Sapele trees greater than 2 m in diameter in 130 hectares. This suggests to us that even a sample of 130 hectares might not be enough to capture the complete picture of all large trees in a forest. On the other hand, it might be that Sapele grew larger in Nigeria than in the Sangha Trinational. We expect that Kennedy had a much larger effective sample size with all the trees being cut commercially or for research in 1929 in Southern Nigeria compared to what we had in our 130 ha of plots.

Despite being so important to the economies of so many countries for so long, it is notable how little published data is available on large Sapele trees (Table 4). The nearest level of sampling with comparable data we could find was Bia Tano Forest Reserve in Ghana with 106 ha of sample and a total of 67 Sapele trees greater than 87 cm dbh (Taylor, 1960). For the three forest reserves in Ghana with the highest levels of Sapele trees over 87 cm dbh, the densities were about half the densities from our study site.

**TABLE 4** Densities of Sapele greater than 87 cm in diameter from 3 forest reserves in Ghana using transformed data from Taylor (1960) p. 192 and comparable figures from our study

| | Numbers of Sapele above 87 cm | Hectares sampled | Density of Sapele above 87 cm, stems $ha^{-1}$ |
|---|---|---|---|
| Bobiri FR | 22 | 38 | 0.58 |
| Bonkoni FR | 47 | 69 | 0.68 |
| Bia Tano FR | 67 | 106 | 0.63 |
| Our study | 170 | 130 | 1.31 |

Other studies also report a "most abundant big tree species" for their sampled forest. We note that for La Selva in Costa Rica and Korup in Cameroon, like in our study, there is a clear winner amongst the big tree species. Clark et al., (2019) reported that *Pentaclethra macroloba* was by far the commonest big tree at La Selva. Similarly, Thomas et al., (2003) identified *Lecomtedoxa klaineana* as the commonest tree above 60 cm dbh in their 50-ha plot and reported that it was three times more common than the next most common big tree. However, without a standard plot size or definition of a big tree, these results are not easily comparable.

## 7.3 | Megabiota, big trees and big fungi

There is increasing recognition by the scientific community of big trees in discussions on the disproportionate importance of megabiota (the largest plants and animals) for biosphere function (Enquist et al., 2020; Schweiger & Svenning, 2020). In addition to the big trees documented in this study, the Congo Basin is also renowned for its large mammals including forest elephants, western lowland gorillas, forest buffalo, giant forest hogs and chimpanzees. The presence of big trees is important to the survival of these species. The megafauna rely on big trees, not only for shelter and protection, but also as sources of food.

Recent modelling across western Equatorial Africa, found gorillas and chimpanzees occur at higher densities in taller forests (Strindberg et al., 2018). Similarly, the physical structure of the forest also influences the abundance of elephants with higher densities occurring in more intact forests (Blake et al., 2009). Elephants maintain trails that criss-cross closed-canopy forests, leading to preferred fruit bearing trees (Blake et al., 2004). There is also evidence that mammals alter forest structure. For example, we observed trampling by elephants that appears to have hampered the establishment and persistence of woody plants in the understory below large individuals of *Duboscia macrocarpa* and *Chrysophyllum lacourtianum* in our plots.

Over their long evolutionary history, many of the big tree species and large mammals have become interdependent. In our study, we observed that 10% of the individual big trees and 20.7% of the species had large fruit which are eaten and the seeds dispersed by elephants. Compared to the Amazonian and Asian tropics, the Congo Basin forests are typified by low tree stem densities abundances

(Lewis et al., 2013)—a phenomenon possibly related to the influence of elephants (Terborgh et al., 2016). Recent research indicates the actions of forest elephants might result in fewer individual tree stems with higher wood densities (Berzaghi et al., 2018).

It is not just plants and animals that make up megabiota. For example, picture a family group of forest elephants led by the matriarch, moving slowly out of a swamp and into a patch of *G. dewevrei* during a mast fruiting year in one of our big tree plots. The elephants' aim is to consume the large seeds, but as well as these visible large mammals, the scene also includes the ectomycorrhiza hidden below ground that forms a symbiosis between big fungi and big trees, and which may cover many square metres. The yellow mushrooms *Cantharellus rufopunctatus* which are gathered and sold in markets, are one of the most of obvious and tasty of the several fungi that have an ectomycorrhizal relationship with *Gilbertiodendron*. Megafauna, megaflora and megafungi are tightly connected within ecological communities and play disproportionately important roles in maintaining forest health and the biosphere of our planet.

## 7.4 | Big trees and society

Almost half of the big tree species in our study are relied upon by people living in the Sangha Trinational. The trees provide foods ranging from oil-rich seeds and honey to edible caterpillars and symbiotic fungi. Most of these food species are actively gathered from the forest and sold, and two of them are regarded as famine food.

Linguistically, we recorded species-specific Bambenjele names for 66 of the 92 species of large trees. An additional 10 species had local names that were applied to more than one species in a genus. In the villages and hunting camps of the Sangha Trinational, Sapele is well known as a big tree. It has quasi-mythical status as being associated with power and virility. This was mentioned twice by male field assistants during informal interviews. Women and men both referred to gathering food from this big tree species, in the form of caterpillars which feed on Sapele leaves.

Sapele is also widely known in the region as the big tree that drives most of the economy. Roads, hospitals, schools and the cash economy are all linked to the use of big trees, and Sapele is recognised as the most important of these. At the national level, Sapele is important to the formal economies of the Central African Republic, Cameroon and Republic of Congo.

The most important societal impact of big trees will in the next few years be at the level of global society. We recommend that two things should happen as a result of our study and of others raising awareness of megabiota (Enquist et al., 2020; Schweiger & Svenning, 2020). The first will not be a surprise to this readership that there will be widespread recognition and financial support for the maintenance of big trees for carbon sequestration. Our second recommendation, perhaps more ambitious, is that large trees will become a focus for major conservation initiatives, such as those that have occurred with charismatic megafauna like whales, pandas and elephants. For both of these to happen, more data are required in relation to determining what species the big trees are, and where they grow. The sampling method that we describe here can be used to produce the required data.

## 7.5 | Big trees and conservation

The governments in the Congo Basin are interested in diversifying their economies while striving to meet the program goals of the United Nations Framework Convention on Climate Change from Deforestation and Degradation (REDD). Five of our big tree plots were established in the Djéké Triangle, an area located outside of the NNNP. The Djéké Triangle is being considered for increased protected status given its intact nature, immediate proximity to the NNNP, and the presence of Mondika, a long-term gorilla research and tourism site. Our study of the big trees provides a more comprehensive characterisation of the biodiversity in the Djéké Triangle than conventional botanical surveys that were previously conducted in the area. In terms of number of big tree species and individual stems, it rivals the results of the big tree plots inventoried inside the NNNP, which supports our assertion that this area is of high conservation value. In addition, Mondika was among the first sites where western lowland gorillas were habituated to human presence and the site has since become world-renowned, not only for the great ape research but also for the involvement of a large number of indigenous people in this long-term conservation project. Providing benefits to local people while protecting keystone structures, such as the big trees and megafauna, are necessary to combat the multiple threats facing the conservation of these forests.

At present, industrial logging is the major agent of change in the abundance of big trees in the northern part of the Republic of Congo and throughout the Congo Basin (Asner et al., 2010; Potapov et al., 2017). High selectivity of timber species and low stem extraction rates, estimated at <2.5 trees/ha (Congolaise Industrielle des Bois, 2006), are typical of this region and affect only 10%–20% of the forest canopy (Putz et al., 2000). While these impacts on the forest structure are low compared to those of conventional logging practices in other tropical regions (see the review by Putz et al., 2008), there is reason for concern over the future of the bigger timber trees. The current harvest of *Entandrophragma* spp. is unsustainable due to low recruitment post-logging (Hall et al., 2003). Furthermore, the continued demand for timber will likely lead to diversification of the marketable timber species and pressure to re-exploit areas already logged.

There is a concern that the tallest trees in tropical forests face a greater risk of death during extreme droughts due to hydraulic failure compared to smaller trees (Esquivel-Muelbert et al., 2019; Rowland et al., 2015; Ziegler et al., 2019). To quantify this risk, it is important that mortality rates of big trees are monitored during normal and abnormal drought periods. The establishment of permanent plots is a fundamental first step in measuring mortality rates for big trees. The number of species recorded as big trees in this study is important because it will be necessary to have a range of mortality

rates within and between species to improve the modelling of predicted change. For example, any predicted increase or decrease in the net carbon sink of the Congo Basin will have to take into account the species composition of the biggest trees because of the variation in wood density and mass of carbon between different species (Phillips et al., 2019), as well as any differences in mortality rates under different climate scenarios.

An important conservation message is contained in the species richness of the big tree class. Each one of the 92 species, which makes the 80-cm dbh class is likely to be an important resource for a wide variety of species or guilds of animals in this forest. For example, the two most common species of big trees, *E. cylindricum* and *P. macrocarpus* are the hosts for different species of edible caterpillars (pers. obs.). In addition, the top four species are home to stingless bees, the honey of which are consumed by indigenous peoples as well as harvested with complex tool kits by wild chimpanzees (Sanz & Morgan, 2013). Another example is that 17 species of big tree in the Sangha Trinational area produce specialised fruit with large seeds and fruit that are dispersed mostly by elephants (Table S1). We predict that more of the big tree species are likely to be keystone species or have outsized impacts on the local forest structure and composition once we gain a better understanding of the ecology and health of the forest.

The planet is facing the twin crises of biodiversity extinction and rising carbon dioxide levels. Enquist et al., (2020) have shown that, for tropical and temperate forests, the best predictor of forest biomass and above ground carbon is the size of the largest trees. Our results show that the largest trees in a tropical rain forest are more diverse than previously thought. By aligning biodiversity preservation and carbon sequestration, a more powerful argument can be made for conserving tropical forest compared to single benefits. Combining conservation strategies for biodiversity, carbon, food security and water security will be stronger than lobbying for any single issue.

## 7.6 | Big tree identification

Identification by logging company inventory teams in the Central African Republic, using both commercial and local names, was better for big trees (>30 cm dbh) than smaller trees (Réjou-Méchain et al., 2011). We encountered the same phenomenon, and think that the very big (>80 cm dbh) trees are even easier to identify than those above 30 cm diameter.

There are two reasons why identifying big trees might be easier than identifying smaller trees. First, the species pool is more restricted than the one for smaller trees. We found that the more speciose genera and those that are hard to identify in the Sangha Trinational (e.g. *Drypetes* with 18 spp., *Diospyros* with 9 spp., *Rinorea* with 7 spp., and *Beilschmeidia* with 4 spp.) occurred only as one species or were not sampled in the big tree plots. The only genus with more than three species greater than 80 cm in diameter was *Entandrophragma*, with four spp., all with local names and well known to us. Second, we found that certain trunk and bark characters at the base of the big trees are quite distinctive. These appear to take time to develop and are not present or as obvious on smaller and younger trees.

We think that many research sites in tropical forest will easily be able to assemble a similar team to survey big trees using comparable methods. In addition to making accurate identifications at the base of the trees, such a team will only require a few concentrated minutes collecting fallen material, to give a herbarium specimen, and taking photographs of the bark that should allow accurate identification later. The systematic recording of observations and tying photographs and specimens to individual trees is, of course, crucial, and requires a strict adherence to protocols. From our experience of travel restrictions due to an unforeseen global pandemic, we would encourage the making of the herbarium voucher at the time of the first survey.

## 7.7 | Methodological considerations

### 7.7.1 | What about 50-ha plots?

Fifty-hectare permanent plots are used across the tropics by the Forest Global Earth Observatory (ForestGEO), previously known as Center for Tropical Forest Science network, and these have been highly successful tools for understanding forest ecology and dynamics (Condit, 1995; and many subsequent references). Our question is: are data from 50-ha plots enough to compare the number of big tree species across the tropics? From our data, of 130 ha we took the first five 10-ha plots and found only 69 species in a forest that we estimate has 110 species of big trees. When we analysed the data from the first ten 10-ha plots (total 100 ha), we found 86 species occurring over 80 cm dbh and only 14 singleton species indicating a much better sampling compared to 50 ha. This suggests that a 50-ha plot is not a sufficiently large enough sample in a tropical forest to find out even the most basic question: How many species make the big tree category of >80 cm dbh? At our study site, a 50-ha plot would have told us which species of big tree was the most common, but it would have seriously underestimated the species richness in this size class.

### 7.7.2 | Why did we choose our plot size?

We chose big tree plots of 10 ha because we had used plots of 0.09, 0.1 and 1 ha and we were concerned about the amount of time taken to accurately delimit plots in the forest with a compass and tape measure. We found that establishing 10 ha plots and using the combination of GIS and GPS units saved an enormous amount of time. It would be possible, of course, to make big tree plots smaller than 10 ha, and depending on the questions being asked, it might be better to have smaller plots. Clark et al., (2019), for example used 0.5-ha plots. However, it will be much easier to make statistical comparisons if plots are the same size. Many recent global analyses (e.g. Bastin et al., 2015; Lewis et al., 2013) have used 1-ha plots for trees above 10 cm, so 10 ha is an approximately proportional

increase in size for bigger trees. The main disadvantage of plot sizes from 0.1 to 1 ha for large trees is that there would be so few trees in each plot that it would be harder to study the distribution of individual trees relative to others. So, for example it would be hard to answer the question: Do big trees of any species clump together? It will be much easier to make statistical comparison between sites if plots are the same size.

We suggest 10 ha as a plot size as it allows for more sample replication than a single larger plot at one site. If plots were any bigger –50 ha, for example, then in a heterogeneous forest it might be hard to restrict plots to one vegetation type, avoiding, for example riverine vegetation, or swamp forest. In our study with 10 ha, we still found we had to be careful to restrict the 10-ha plots to mixed species terra firma forest and we had to exclude 3 plots after measuring them for having more than 30% of *G. dewevrei*, which forms a different vegetation type.

### 7.7.3 | How big is a big tree in a tropical rain forest?

Clark et al., (2019) shy away from defining big trees. We agree with their point when they state that the "useful course is to acknowledge the biological diversity contained within any large tree classification." However, to rapidly inventory the large number of hectares (at least 100 ha) that our study suggests is necessary to sample big trees, we need a lower limit.

We choose 80 cm dbh that gave 2%–3% of all trees above 10 cm dbh at our study site. In other parts of the world, 70 cm dbh is emerging as a standard definition of large trees. It appears from our data that trees in the Sangha Trinational are bigger than in central or South America and that a higher diameter might be more appropriate in Africa. If we are to make global comparisons, however, it will be worth changing the lower limit of big trees to 70 cm dbh. We will be adding trees down to 70 cm in at least one of our permanent plots when we do our first re-census.

There are other ways of defining big trees. The definitions can be absolute or relative to other trees in a particular forest. In an extensive review of large old trees, Lindenmayer and Laurance (2017) suggested relying on diameter and height for species-specific characteristics. Lutz et al., (2018) used three metrics to define big trees, two of them relative to other trees in a forest and one fixed. The fixed metric was a diameter of greater than 60 cm. The relative metrics were the largest 1% of trees >1 cm diameter and the diameter above which the individuals with that diameter in a plot contributed to half of the above ground woody biomass of a plot.

An analysis of a global series of 1-ha plots (Bastin et al., 2015) showed that the largest 20 trees in those plots provided enough data to act as good predictors of a series of parameters required for estimating carbon in tropical forests. To measure the largest 20 trees per ha, in our study area, we would have to drop the minimum dbh to 60 cm and for other forests that minimum would have to be smaller still. For rapid assessments of different forests replicated sets of 1-ha plots of 60 cm dbh might be appropriate, however, for permanent plots that will be used in global analyses, we propose that 70 cm dbh is the best compromise as a definition of a big tree.

## 7.8 | Training data sets for remote sensing

The advances in remote sensing, from satellites, aeroplanes or drones over the past 20 years has been spectacular. The crowns of individual big trees can be distinguished in images from satellites, some species can be identified (Sánchez-Azofeifa et al., 2011) and numerous structural parameters of the forest from leaf size to tree height can be gathered remotely in ways which would have seemed almost incredible 20 years ago. Bush et al., (2020) show that we are almost at the tipping point of being able to monitor individual crowns of big trees from satellites even in cloudy tropical rain forests in Gabon, and Park et al.,(2019) used drones to measure leaf change in individual trees and species in Panama.

These advances bring forward exciting new data sets and questions such as the mortality of individual big tree species (Kellner & Hubbell, 2017). Most interesting, perhaps, is the combination of data collected on the ground in permanent plots and the use of high-performance computing on large volumes of remote sensing data that will allow us to scale up from individual trees or 10-ha plots to the region or continent. Establishing permanent plots of well-identified, precisely located trees and making the data available to other research communities as training sets for various remote sensing techniques will open several avenues of research. As the price of remote sensing continues to drop and the technology matures the need for accurately located and identified tree plots will increase. Marselis et al., (2020), for example, call for more coincident lidar and field data to improve models.

## 7.9 | Need for global data

There are continental differences in the proportion of contribution to biomass by different sized trees (Bastin et al., 2018). In Africa, the trees above 70 cm diameter contribute more to total biomass in a forest than the same class of trees in Asia and South America (Bastin et al., 2018). These trees above 70 cm dbh are more abundant in Africa (Lewis et al., 2013, and our data here). Overall, there is a consistent picture that in African forest plots (>10 cm dbh) there are fewer but larger diameter stems compared to the Americas and Asia (Bastin et al., 2018; Feldpausch et al., 2012; Lewis et al., 2013). These differences between continents emphasise the need for standard sampling protocols to allow global analyses, such as the 1-ha plot networks, but for bigger trees.

# 8 | CONCLUSION

There is a surge of interest in big trees due to their important global ecosystem functions in carbon, water and nutrient cycles. Especially

in tropical rain forests there are, however, a lack of basic data on big trees. In our limited sample, we were able to show unexpected richness in big tree species and to uncover patterns in big tree dominance that were not present in data from smaller plots. If we establish standard plot sizes for assessing big trees, we will be able to contribute to monitoring and mitigation of the two global challenges of climate change and species extinction. We suggest that plots of 10 ha are quick and accurate to set up and survey, using freely available GIS software and a hand held GPS unit. From our results, we recommend, sampling at least 10 separate plots to give 100 ha of sample in mixed species terra firma tropical rain forest. For global comparisons, we recommend the emerging consensus of a lower limit of 70 cm dbh as the definition of a big tree.

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## AUTHOR CONTRIBUTIONS

DH and DM planned and designed the research. SN, DH, MM and DM conducted the fieldwork, DH CS analysed the data, DH wrote the manuscript. All authors saw and commented on the manuscript.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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