nature geoscience

SUPPLEMENTARY INFORMATION
https://doi.org/10.1038/s41561-019-0395-6

In the format provided by the authors and unedited.

Carbon stocks in central African forests enhanced by elephant disturbance

Fabio Berzaghi[1,2,3*], Marcos Longo[4,5], Philippe Ciais[2], Stephen Blake[6,7], François Bretagnolle[3], Simone Vieira[8], Marcos Scaranello[4], Giuseppe Scarascia-Mugnozza[1] and Christopher E. Doughty[9]

[1]Dipartimento per la Innovazione nei sistemi Biologici, Agroalimentari e Forestali, University of Tuscia, Viterbo, Italy. [2]Laboratoire des Sciences du Climat et de l'Environnement, IPSL-LSCE CEA/CNRS/UVSQ, Gif-sur-Yvette, France. [3]Biogéosciences, UMR 6282 CNRS, Université Bourgogne Franche-Comté, Dijon, France. [4]Embrapa Agricultural Informatics, Campinas, Brazil. [5]NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA. [6]Department of Biology, Saint Louis University, St. Louis, MO, USA. [7]Wildlife Conservation Society, New York, NY, USA. [8]Núcleo de Estudos e Pesquisas Ambientais, Universidade Estadual de Campinas, Campinas, Brazil. [9]School of Informatics, Computing, and Cyber Systems, Northern Arizona University, Flagstaff, AZ, USA. *e-mail: fabio.berzaghi@lsce.ipsl.fr

Nature Geoscience

Supplementary Materials for

Biomass reduction following collapse of elephant populations in central African forests

Fabio Berzaghi*, Marcos Longo, Philippe Ciais, Stephen Blake, Francois Bretagnolle, Simone Vieira, Marcos Scaranello, Giuseppe Scarascia-Mugnozza, Christopher E. Doughty

* Correspondence to: fabio.berzaghi@lsce.ipsl.fr

This PDF file includes:

Supplementary considerations and results (Sections A and B)

Figs. 1 to 7

Tables 1 to 3

Section A

Further results and considerations regarding the S_{st} parameter

We present a consideration regarding the S_{st} parameter and the elephant-induced mortality of small trees. Forest elephants annual consumption at a density of 0.75 individuals km^{-2} is roughly 47 Mg km^{-2} yr^{-1} (i.e., 0.47 Mg ha^{-1} yr^{-1}) for the entire population, calculated with a gross assimilation efficiency of 22%[1] and estimates of biomass droppings[2]. Elephants consume the majority of leaf biomass outside closed-canopy forests, so only a fraction of 0.47 Mg ha^{-1} yr^{-1} would be consumed within the forest. In the control simulation (without elephants), the aboveground biomass and leaf biomass of small trees are approximately 9 Mg ha^{-1} and 3 Mg ha^{-1}, respectively. A survivorship of 90% roughly corresponds to 0.17 Mg ha^{-1} yr^{-1} lost due to elephant disturbance, in the model this biomass is returned to the soil. Thus, 0.17 Mg ha^{-1} of biomass lost due to elephant is a reasonable amount since it might include some biomass lost from consumption and some from direct elephant-induced tree mortality. A lower survivorship of small trees implies that the intensity of the disturbance is higher with more plant biomass lost. Further, in the model we use prescribed elephant densities which are introduced instantaneously and have no population dynamics. Thus, we assume a zero-sum game between plant biomass and elephant biomass. Mathematically, as the elephant density increases above 1 elephant km^{-2}, the disturbed area fraction (*Ae*) also increases, and the differences in the effects of S_{st} between different densities become smaller, as be observed in the increasingly similar trajectories as density increases. At elephant densities (0.25 and 0.5, 2, 3, and 4 elephants km^{-2}) the effect on AGB is mostly on the path taken and the time to reach steady-state, but not on the steady-state AGB (Supplementary Fig. 7). At densities of 0.75, 1, and 5 elephants km^{-2}, the difference between high survivorship and low/medium survivorship is between

8% and 15%, with some exceptions at 1 (medium) and 5 (low) elephants km^{-2}. The trend is however comparable in all simulations (Supplementary Fig. 7).

Section B

Central African sites with no elephants and intact forests

The African Tropical Rainforest Observatory Network (AfriTRON) is the largest rainforest monitoring data sets for central African forests, also used by Lewis et al. (2013) in their analysis. AfriTRON contains roughly 200 plots across central Africa. Following the 2016 IUCN African Elephant Status Report[3], we determined that forest elephants are absent in only one site in the entire AfriTRON network: Yangambi in the Democratic Republic of Congo, and possibly in Kisangani which is marked as “doubtful” in the report. This is not surprising because AfriTRON plots are often in protected areas where a higher probability of law enforcement reduces poaching probability[4]. We could not include Yangambi and Kisangani because we did not find any literature reporting the timing of elephant disappearance in these sites. However, comparing published data from the two sites to the Ndoki plots (disturbed and undisturbed) having similar soil and environmental conditions, shows that in Yangambi AGB and wood density are lower while stem density is higher[5] than Ndoki. In Kisangani AGB and wood density are also lower compared to the Ndoki disturbed plots, and stem density is higher than all Ndoki plots. However, without more information on elephant disturbance history at these two sites, we cannot draw any conclusions if these differences are partly due to absence of elephants.

References

1. Rees, P. A. Gross assimilation efficiency and food passage time in the African elephant. *Afr. J. Ecol.* **20**, 193–198 (1982).

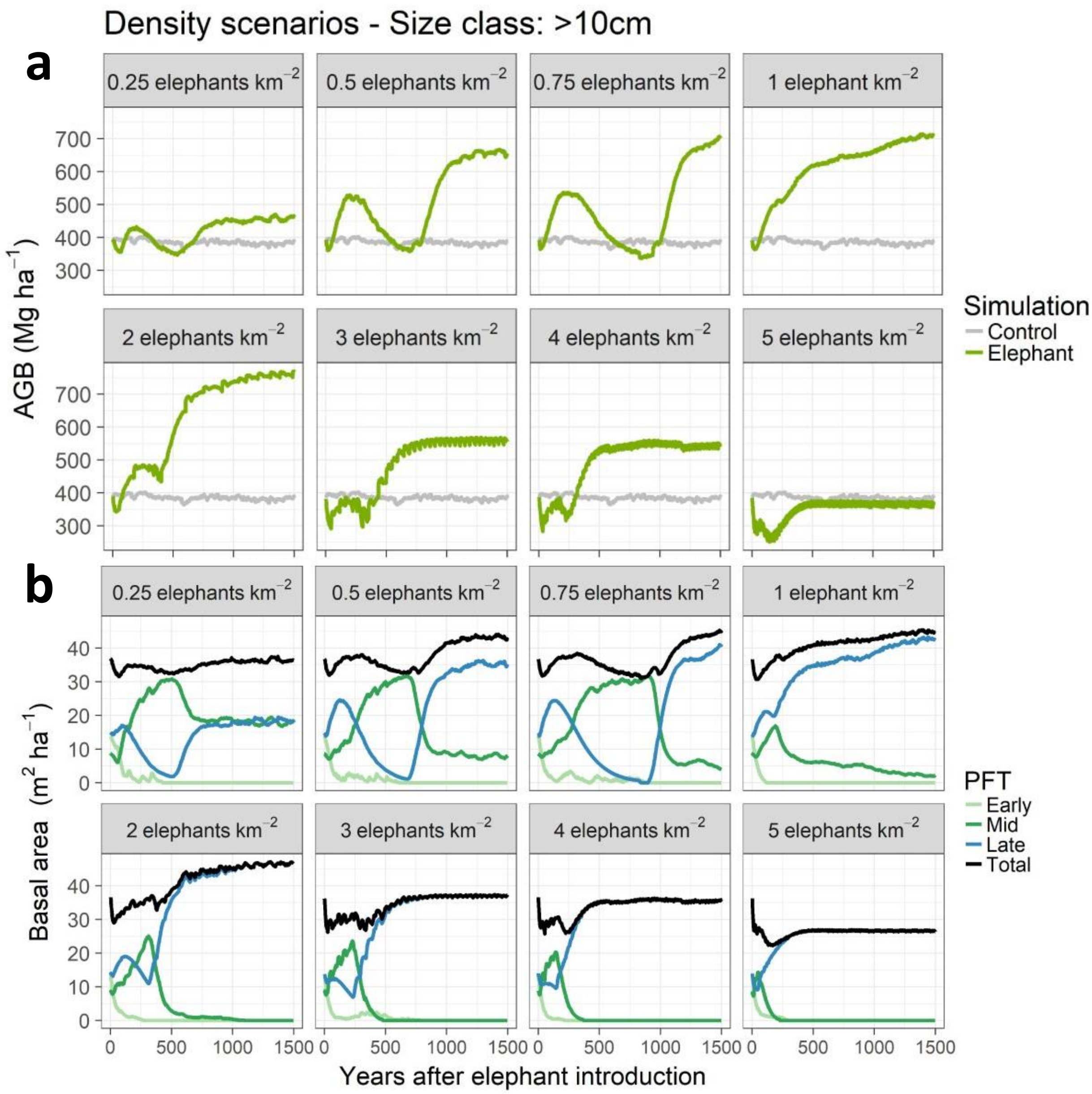
2. Wing, L. D. & Buss, I. O. Elephants and Forests. *Wildl. Monogr.* 3–92 (1970).

3. *African elephant status report 2016 : an update from the African Elephant Database*. (2016).

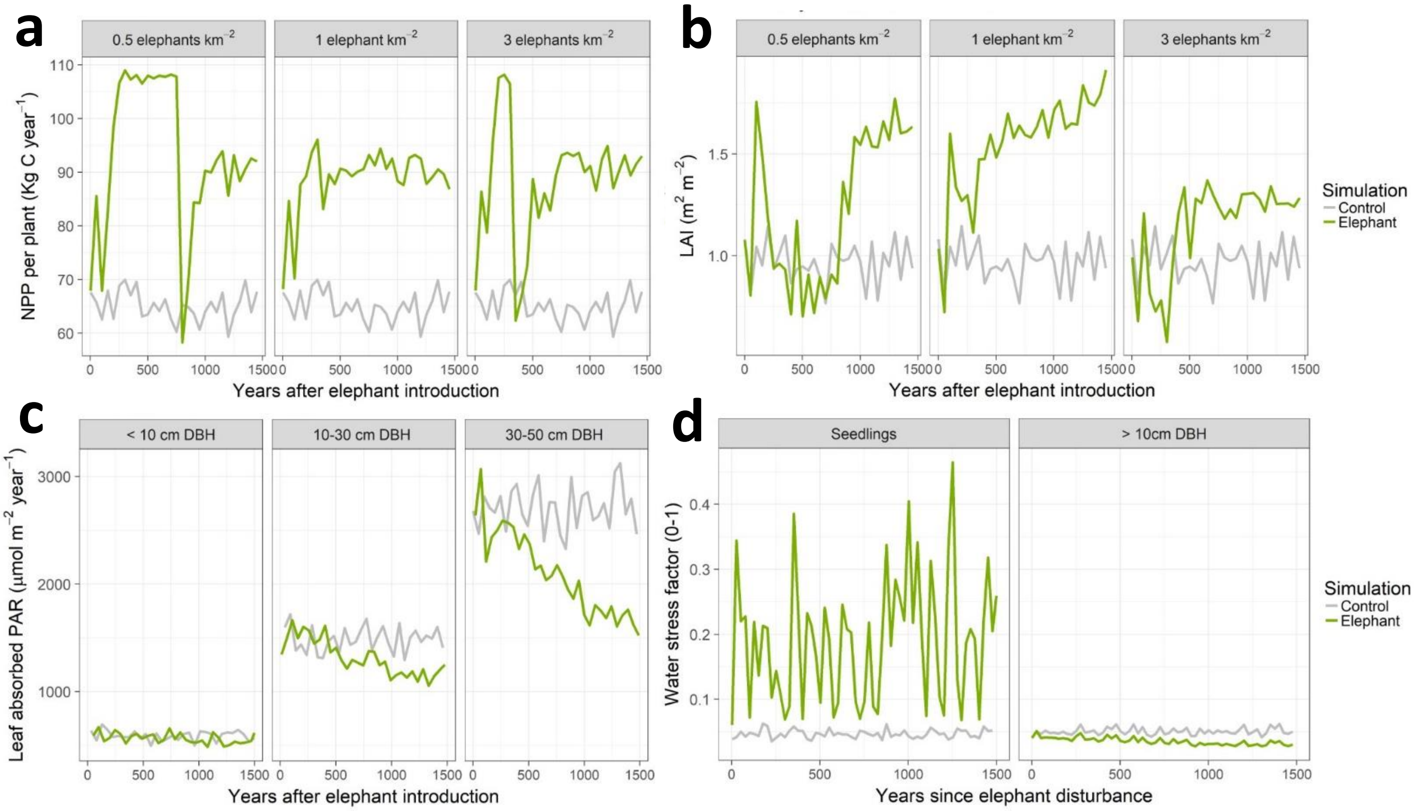
4. Maisels, F. *et al.* Devastating decline of forest elephants in Central Africa. *PLoS ONE* **8**, e59469 (2013).

5. Kearsley, E. *et al.* Conventional tree height–diameter relationships significantly overestimate aboveground carbon stocks in the Central Congo Basin. *Nat. Commun.* **4**, ncomms3269 (2013).

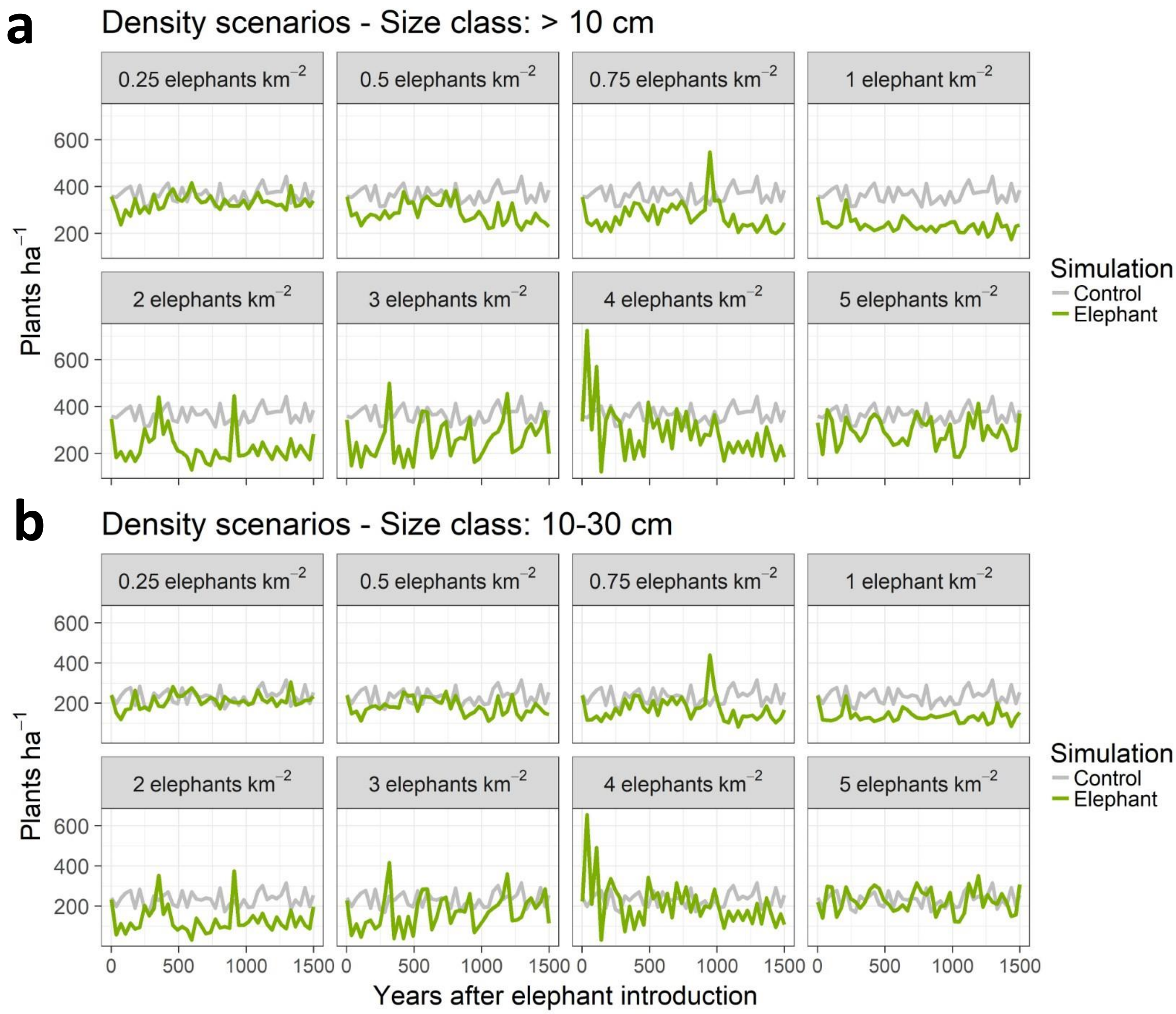
Figures



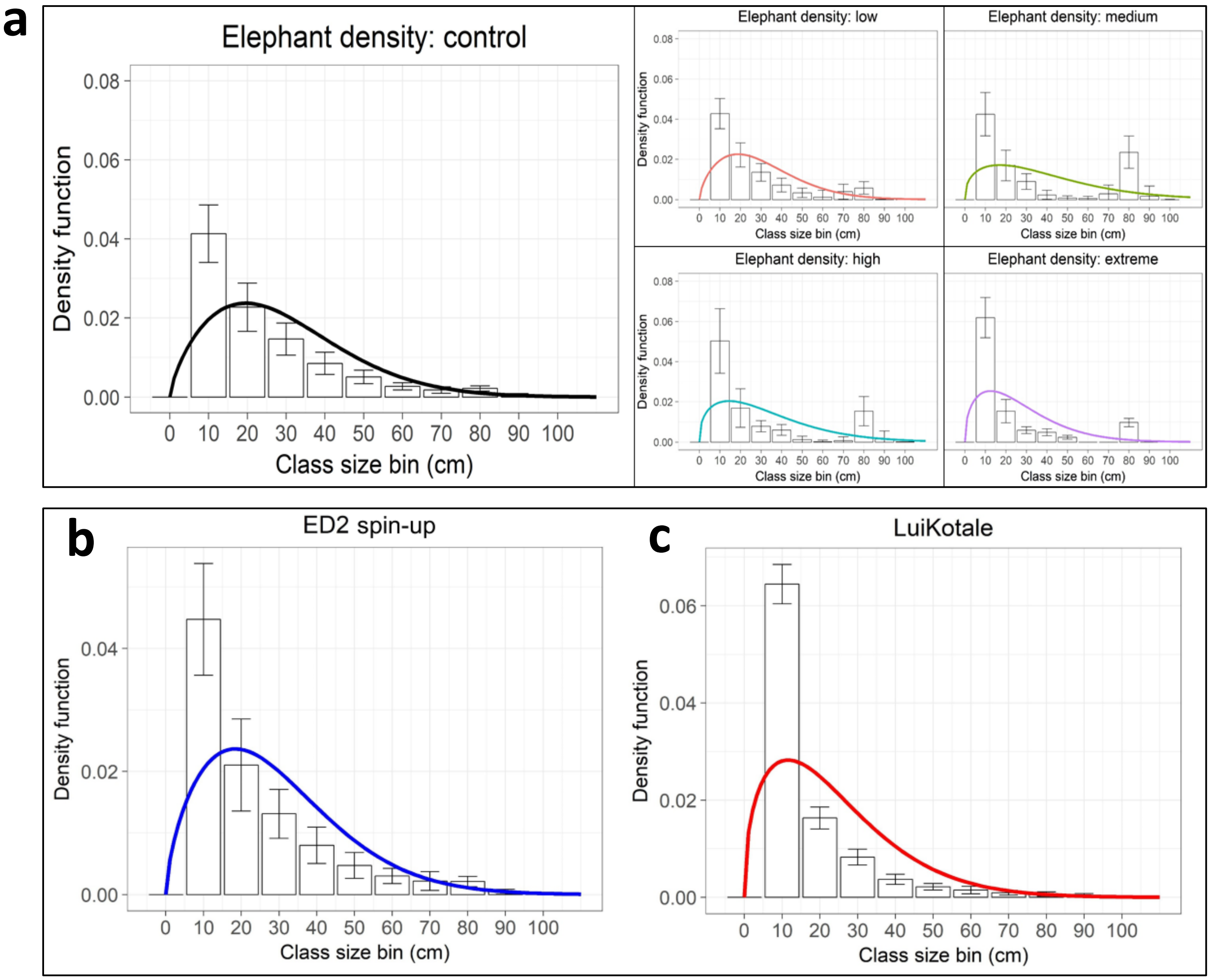
Supplementary Fig. 1 | Aboveground biomass and basal area of trees >10 cm DBH in elephant-disturbed forests. Modelled (**a**) above ground biomass (AGB) and (**b**) basal area at all prescribed elephant densities and in control forest (no elephant) until 1500 years after elephant were introduced.



Supplementary Fig. 2 | Plant primary productivity, leaf area, absorbed light, and water stress in elephant-disturbed forests. **a**, Net primary productivity (NPP) per plant for late-successional trees > 50 cm DBH; **b**, Average leaf area index for trees > 50 cm DBH; **c**, average absorbed photosynthetically active radiation (PAR) in different plant-size classes; **d**, average soil moisture stress factor at all elephant densities and for two plant-size classes. Seedlings are plants shorter than 0.5 m. Soil moisture stress factor goes from 0 to 1 (unitless). Higher values indicate higher stress, 0 means photosynthesis is not limited by water. Control forest (no elephant) until 1500 years after elephants were introduced. Data points are plotted every 25 or 50 years. Jittering is due to the division in size classes and the plotting interval.

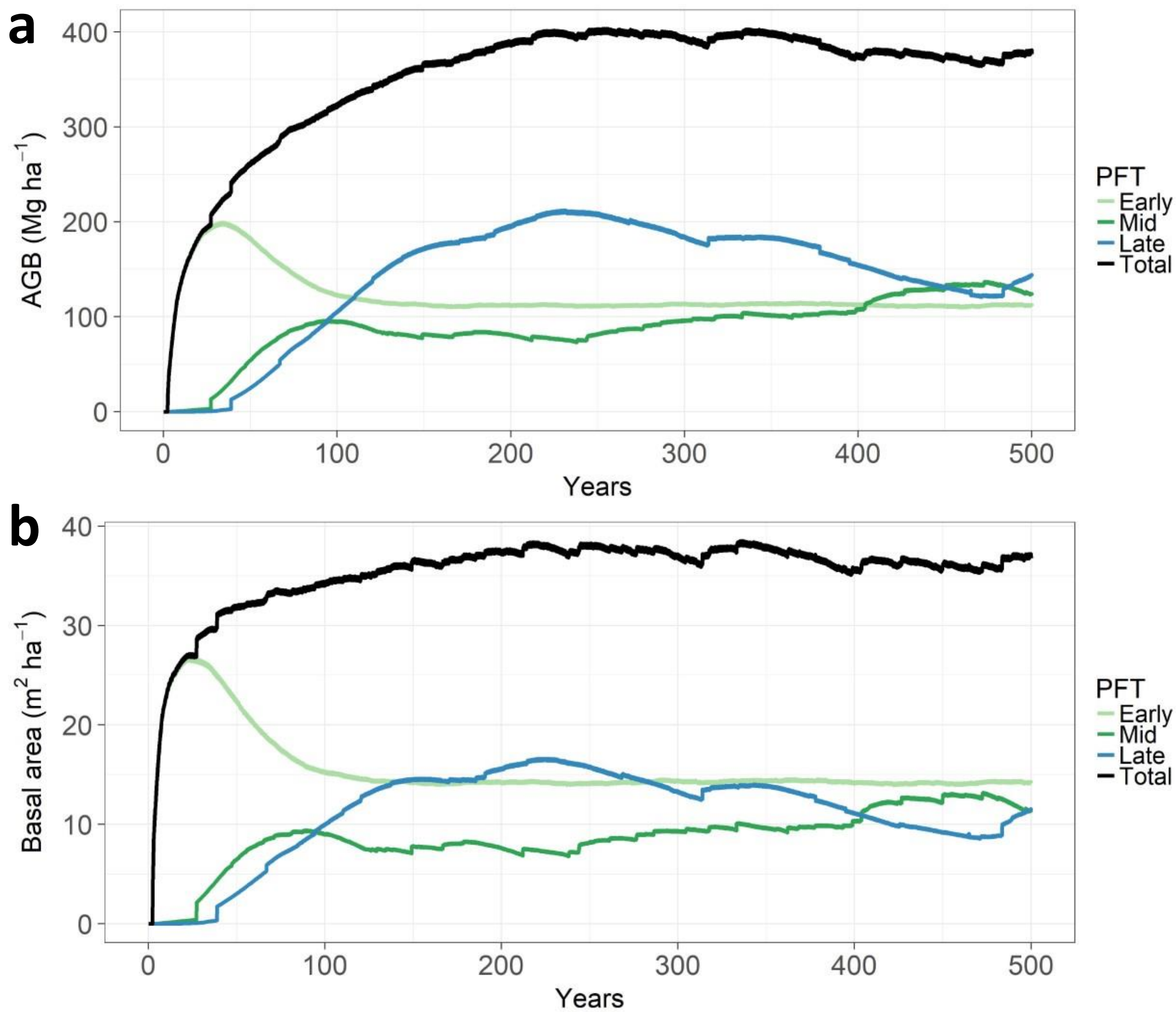


Supplementary Fig. 3 | Effect of elephant disturbance on tree density. Number of trees ha^{-1} with (**a**) DBH >10 cm and (**b**) DBH 10-30 cm in elephant-disturbed forests and in control forest (no elephant) until 1500 years after elephants were introduced. Data points are plotted every 75 years. Jittering in the plots is due to the division in size classes.

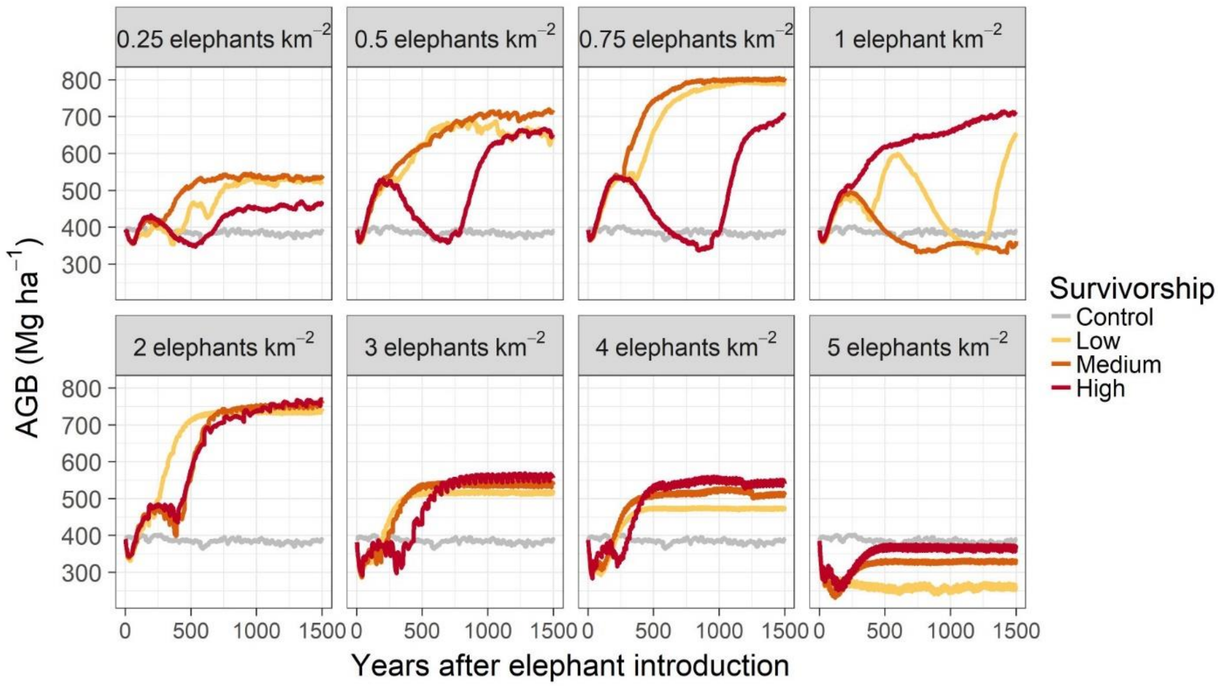


Supplementary Fig. 4 | Relative frequency of trees by size-class and weibull density function fitted to modelled and observed forest inventory data. a, ED2 modelled forests at equilibrium after elephant introduction, control is the forest without elephants; **b**, ED2 modelled forest after the 500 years spin-up period; **c**, LuiKotale forest data (15 1-ha plots). Error bars indicate standard deviation across years (**a**,**b**) or across plots (**c**). Each bin designates a size class of 10 cm, with the lower bound as the displayed size.

Supplementary Fig. 5 | Effect of elephant disturbance on tree size. Mean size (e.g., tree basal area) of trees with (**a**) DBH >10 cm and (**b**) DBH 10-30 cm in elephant-disturbed forests and in control forest (no elephant) until 1500 years after elephants were introduced. Data plotted every 75 years. Jittering in the plots is due to the division in size classes.



Supplementary Fig. 6 | Modelled forest properties during the 500-year spin-up period at LuiKotale. Above ground biomass (**a**) and basal area (**b**) for trees with DBH > 10 cm. Plant functional types are: early successional (pioneers) in light green, mid-successional in dark green, and late-successional (slow-growing) in blue. Total is the sum of the three plant functional types.



Supplementary Fig. 7 | Sensitivity analysis of small tree survivorship. AGB of trees with DBH >10 cm for all density scenarios, until 1500 years after elephant were introduced. Survivorship values are: 90% for high, 80% for medium, and 70% for low.

Supplementary Table 1 | Summary of the main parameters of the three tropical Plant Functional Types (PFT)

PFT Parameter	**early**	**mid**	**late**
Wood density (Kg m^{-3})	0.53	0.71	0.9
Mortality due to age (%)	5	2.8	0*
Leaf and root turnover rate (% lost per year)	100	50	33
Specific leaf area (m² leaf per kg C)	16	11.6	9.6
Maximum photosynthetic capacity (µmol m^{-2} s^{-1})	18.75	12.5	6.25
DBH-leaf or stem dead biomass allometry (higher value= higher leaf/dead biomass given the same diameter)	0.42/0.17	0.56/0.22	0.71/0.28

*Late-successional trees have no age dependent mortality but are still subject to other types of mortality (i.e., carbon starvation and treefall).

Supplementary Table 2 | Measured and modelled forest properties

Data source	AGB ($Mg\ ha^{-1}$)	Stem density ($Ind.\ ha^{-1}$)	Tree size (m^2) mean	Basal area ($m^2\ ha^{-1}$)
Diameter class (cm)	**All**	**All**	**All**	**All**
ED2 model (no elephants)	382 (377-387)	372 (329-415)	0.095 (0.087-0.103)	34.8 (34.3-35.3)
LuiKotale observations (no elephants)	582 (476-660)	436 (384-488)	0.076 (0.062-0.080)	33 (26-40)
ED2 model (with elephants at density 0.5-1.0 individual km^{-2})	424 (408-442)	353 (345-360)	0.107 (0.101-0.113)	35.8 (35.3-36.3)
Central African plots	429 (N/A)	425 (414-436)	0.074 (N/A)	31.5 (N/A)

Above ground biomass (AGB), stems per hectare, mean tree size, and basal area from different data sources. Confidence interval is given in parentheses. ED2 model statistics without elephants are calculated from the average of the 1500 years after the spin-up simulation. LuiKotale statistics are calculated across 15 1-ha plots. ED2 model with elephants is calculated from the average of the last 300 years after elephants were introduced and considering the spatial heterogeneity of elephant disturbance using eq. 3 (see Methods). Lewis et al. (2013) do not report confidence intervals for 196 central African plots.

Supplementary Table 3 | Comparison between sites disturbed and undisturbed by elephants

Data source	**Stem density (Ind. ha^{-1})**	**Tree size (m^2)**
Diameter class (cm)	**> 70 cm**	**10-30 cm**
LuiKotale (15 ha) no elephants	16.1^{ns} (11.1-21.1)	0.022* (0.015)
Ndoki (4.6 ha) disturbed	22.6^{ns} (17.6-27.4)	0.024* (0.018)
Ndoki (23 ha) undisturbed	17.5^{ns} (16.8-19.2)	NA

The total areas inventoried at each site are shown in parentheses. Significance level for statistical comparison: ns (non-significant) and * p = 0 .001.