

Supplementary Material

The combined impacts of experimental defaunation and logging on seedling traits and diversity

Alys Granados*, Henry Bernard & Jedediah F. Brodie

*Corresponding author: alysgranados@gmail.com

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Table S1.1 Body mass (kg) and diet of mammal species excluded from our treatment plots in logged and unlogged forest in Sabah, Malaysian Borneo.

| Latin name | Common name | Body mass (kg) | Diet | References |
|-----------------------------------|------------------------|----------------|------------------------------|------------|
| <i>Elephas maximum borneensis</i> | Borneo pygmy elephant | 2500 | browse, fruit | [1] |
| <i>Rusa unicolor</i> | Sambar deer | 200 | grass, browse, fruit | [1,2] |
| <i>Muntiacus atheroides</i> | Yellow muntjac | 16-20 | browse, fruit | [1] |
| <i>Muntiacus muntjak</i> | Red muntjac | 20-28 | browse, fruit | [1] |
| <i>Tragulid napu</i> | Greater chevrotain | 4.25 | fruit | [1,3] |
| <i>Tragulid javanicus</i> | Lesser chevrotain | 2.25 | fruit | [1] |
| <i>Sus barbatus</i> | Bearded pig | 75 - 200 | seeds, fruits, invertebrates | [1] |
| <i>Hystrix brachyura</i> | Malayan porcupine | 8 | seeds, fruits, bark | [4] |
| <i>Trichys fasciculata</i> | Long tailed porcupine | 1.75 | seeds, fruits, bark | [4] |
| <i>Hystrix crassispinis</i> | Thick-spined porcupine | 4.68 | seeds, fruits, bark | [4] |

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3. Heydon MJ. 1994 The ecology and management of rain forest ungulates in Sabah, Malaysia: implications of forest disturbance. Final report to ODA/NERC project F3CR26/G1/05. Institute of Tropical Biology, University of Aberdeen, Aberdeen, UK
4. Jones KE. et al. 2009 PanTHERIA: a species-level database of life history, ecology, and geography of extant and recently extinct mammals. *Ecology* **90**, 2648.

Table S1.2. Taxonomic information for the seedlings in our experimental exclusion plots and in control plots in logged (L) and unlogged (UL) forest in Sabah, Malaysian Borneo.

| Family | Genus | Forest type |
|------------------|-----------------------|-------------|
| Achariaceae | <i>Ryparosa</i> | L, UL |
| | <i>Hydnocarpus</i> | L |
| Cornaceae | <i>Alangium</i> | L, UL |
| Anacardiaceae | <i>Buchanania</i> | L |
| | <i>Polyalthia</i> | L, UL |
| Annonaceae | <i>Neouvaria</i> | |
| | <i>Popowia</i> | L, UL |
| | <i>Xylopia</i> | L |
| | <i>Gonionthalamus</i> | UL |
| Apocynaceae | <i>Kopsia</i> | L, UL |
| Bombaceae | <i>Durio</i> | L |
| Burseraceae | <i>Santiria</i> | L |
| | <i>Dacryodes</i> | L |
| | <i>Canarium</i> | L |
| Calophyllaceae | <i>Calophyllum</i> | L |
| Celastraceae | <i>Lophopetalum</i> | L |
| Clusiaceae | <i>Garcinia</i> | UL |
| Dilleniaceae | <i>Dillenia</i> | L |
| Dipterocarpaceae | <i>Dipterocarpus</i> | L |
| | <i>Dryobalanops</i> | L |
| Dipterocarpaceae | <i>Shorea</i> | L, UL |
| | <i>Parashorea</i> | L, UL |
| Ebenaceae | <i>Diospyros</i> | L, UL |
| Elaeocarpaceae | <i>Elaeocarpus</i> | L |
| Euphorbiaceae | <i>Mallotus</i> | L, UL |
| | <i>Croton</i> | UL |

| Family | Genus | Forest type |
|-----------------|---------------------------|-------------|
| Escalloniaceae | <i>Polyosma</i> | UL |
| | <i>Neoscortechinia</i> | UL |
| Fabaceae | <i>Dialium</i> | L, UL |
| | <i>Cynometra</i> | L |
| | <i>Saraca</i> | UL |
| | <i>Crudia</i> | UL |
| Fagaceae | <i>Castanopsis</i> | L, UL |
| | <i>Lithocarpus</i> | L, UL |
| Hypericaceae | <i>Cratoxylum</i> | L |
| Leguminosae | <i>Fordia</i> | L |
| Leguminosae | <i>Koompassia</i> | L, UL |
| Lauraceae | <i>Litsea</i> | L, UL |
| | <i>Beilschmiedia</i> | L, UL |
| | <i>Dehaasia</i> | UL |
| | <i>Eusideroxylon</i> | UL |
| Leeaceae | <i>Leea</i> | L |
| Malvaceae | <i>Brownlowia</i> | L |
| Malvaceae | <i>Microcos</i> | L, UL |
| | <i>Pentace</i> | L, UL |
| | <i>Pterospermum</i> | L |
| Melastomataceae | <i>Pternandra</i> | L |
| Meliaceae | <i>Reinwardtiodendron</i> | UL |
| | <i>Dysoxylum</i> | L |
| | <i>Chisocheton</i> | L, UL |
| | <i>Aglaia</i> | L, UL |
| | <i>Lansium</i> | L |
| Moraceae | <i>Ficus</i> | L |
| Myristicaceae | <i>Knema</i> | L, UL |
| Myrsinaceae | <i>Ardisia</i> | L |

| Family | Genus | Forest type |
|------------------|----------------------|-------------|
| Myrtaceae | <i>Syzygium</i> | L, UL |
| Olacaceae | <i>Ochanostachys</i> | L |
| | <i>Chionanthus</i> | UL |
| Pentaphylacaceae | <i>Adrinandra</i> | L |
| Phyllanthaceae | <i>Glochidion</i> | L, UL |
| | <i>Antidesma</i> | L |
| | <i>Baccaurea</i> | L, UL |
| | <i>Aporusa</i> | L, UL |
| | <i>Cleistanthus</i> | L |
| Polygalaceae | <i>Xanthophyllum</i> | L, UL |
| Putranjivaceae | <i>Drypetes</i> | L, UL |
| Rhamnaceae | <i>Ziziphus</i> | UL |
| Rhizophoraceae | <i>Carallia</i> | L |
| Rubiaceae | <i>Urophyllum</i> | UL |
| | <i>Praravinia</i> | L |
| Rutaceae | <i>Glycosmis</i> | L, UL |
| | <i>Diplospora</i> | L, UL |
| | <i>Clausena</i> | L, UL |
| Sapindaceae | <i>Lepisanthes</i> | L |
| | <i>Paranephelium</i> | L |
| Sapindaceae | <i>Dimocarpus</i> | L, UL |
| | <i>Pometia</i> | L |
| | <i>Nephelium</i> | UL |
| Stemonuraceae | <i>Stemonurus</i> | L, UL |
| Symplocaceae | <i>Symplocos</i> | L |
| Urticaceae | <i>Pipturus</i> | L |

Table S1.3. Mean fruit length (cm) and standard deviation (SD) for seedling genera tagged in animal exclusion and control plots based on data from published and unpublished sources (Supplementary Material S2). Data were unavailable for *Brownlowia* spp.

| Genus | Mean fruit size (cm) | SD |
|----------------------|----------------------|------|
| <i>Adinandra</i> | 1.1 | 0 |
| <i>Aglaia</i> | 1.46 | 0.62 |
| <i>Alangium</i> | 1.53 | 0.07 |
| <i>Antidesma</i> | 1.08 | 0.75 |
| <i>Aporusa</i> | 1.15 | 1.16 |
| <i>Ardisia</i> | 0.82 | 0.01 |
| <i>Baccaurea</i> | 1.14 | 0.81 |
| <i>Beilschmiedia</i> | 1.72 | 0.54 |
| <i>Buchanania</i> | 1.52 | 0.02 |
| <i>Calophyllum</i> | 3.5 | 0.01 |
| <i>Canarium</i> | 3.09 | 0.8 |
| <i>Carallia</i> | 0.07 | 0.01 |
| <i>Castanopsis</i> | 0.87 | 1.16 |
| <i>Chionanthus</i> | 2.38 | 1.23 |
| <i>Chisocheton</i> | 1.32 | 0 |
| <i>Clausena</i> | 1.8 | 0 |
| <i>Cleistanthus</i> | 1.32 | 0 |
| <i>Cratoxylum</i> | 0.03 | 0 |
| <i>Croton</i> | 1.55 | 0.43 |
| <i>Crudia</i> | 7.25 | 0.53 |
| <i>Cynometra</i> | 2.98 | 0.86 |
| <i>Dacryodes</i> | 1.91 | 0.86 |

| Genus | Mean fruit size (cm) | SD |
|----------------------|----------------------|------|
| <i>Dehaasia</i> | 2.87 | 0.66 |
| <i>Dialium</i> | 2.77 | 1.09 |
| <i>Dillenia</i> | 2.49 | 4.61 |
| <i>Dimocarpus</i> | 1.55 | 0.39 |
| <i>Diospyros</i> | 1.58 | 0.59 |
| <i>Diplospora</i> | 1.6 | 0.98 |
| <i>Dipterocarpus</i> | 1.58 | 1.04 |
| <i>Dryobalanops</i> | 1.91 | 2.28 |
| <i>Drypetes</i> | 1.95 | 0.3 |
| <i>Durio</i> | 0.61 | 0.06 |
| <i>Dysoxylum</i> | 1.07 | 1.18 |
| <i>Elaeocarpus</i> | 1.25 | 0.21 |
| <i>Eusideroxylon</i> | 8.4 | 1.06 |
| <i>Ficus</i> | 1.78 | 1.76 |
| <i>Fordia</i> | 2.83 | 1.1 |
| <i>Garcinia</i> | 3.24 | 0.72 |
| <i>Glochidion</i> | 0.55 | 0.58 |
| <i>Glycosmis</i> | 2.2 | 0.15 |
| <i>Goniothalamus</i> | 2.5 | 0.13 |
| <i>Hydnocarpus</i> | 3 | 1.41 |
| <i>Knema</i> | 0.02 | 1.57 |
| <i>Koompassia</i> | 10.8 | 0.85 |
| <i>Kopsia</i> | 1.99 | 0.41 |
| <i>Lansium</i> | 4 | 2.52 |
| <i>Leea</i> | 0.03 | 0.91 |
| <i>Lepisanthes</i> | 0.03 | 0.01 |

| Genus | Mean fruit size (cm) | SD |
|---------------------------|----------------------|------|
| <i>Lithocarpus</i> | 1.91 | 0.51 |
| <i>Litsea</i> | 1.3 | 4.56 |
| <i>Lophopetalum</i> | 12 | 0 |
| <i>Mallotus</i> | 1.07 | 0.69 |
| <i>Microcos</i> | 1.34 | 0.8 |
| <i>Neoscortechinia</i> | 1.85 | 1.53 |
| <i>Neouvaria</i> | 1.2 | 0.25 |
| <i>Nephelium</i> | 2.75 | 3.89 |
| <i>Ochanostachys</i> | 2.1 | 0.01 |
| <i>Paranephelium</i> | 1.12 | 1.4 |
| <i>Parashorea</i> | 2.08 | 1.57 |
| <i>Pentace</i> | 1.4 | 0.68 |
| <i>Pipturus</i> | 0.06 | 0.03 |
| <i>Polyalthia</i> | 0.77 | 0.82 |
| <i>Polyosma</i> | 0.07 | 0 |
| <i>Pometia</i> | 2.58 | 3.3 |
| <i>Popowia</i> | 1.38 | 0.25 |
| <i>Praravinia</i> | 1.92 | 0.01 |
| <i>Pternandra</i> | 0.6 | 0.26 |
| <i>Pterospermum</i> | 10.4 | 0.09 |
| <i>Reinwardtiodendron</i> | 0.88 | 1.17 |
| <i>Ryparosa</i> | 0.03 | 0.45 |
| <i>Santiria</i> | 1.59 | 0.23 |
| <i>Saraca</i> | 4.8 | 5.47 |
| <i>Shorea</i> | 2.01 | 0.52 |
| <i>Stemonurus</i> | 2.25 | 0.18 |

| Genus | Mean fruit size (cm) | SD |
|----------------------|----------------------|------|
| <i>Symplocos</i> | 2 | 0.71 |
| <i>Syzygium</i> | 1.25 | 0.36 |
| <i>Urophyllum</i> | 1.56 | 0.63 |
| <i>Xanthophyllum</i> | 1.9 | 0.71 |
| <i>Xylopia</i> | 2.5 | 0 |
| <i>Ziziphus</i> | 2.75 | 0.61 |

S2. Trait information

We obtained trait values for wood density, specific leaf area, and fruit size for each seedling genus represented in our treatment plots. These values were then used to calculate community weighted means of each trait in each treatment at each survey period. Trait values were obtained from the TRY plant trait database (<https://www.try-db.org>), the Dryad Digital Repository (<http://www.datadryad.org>), and additional unpublished sources (see below).

Wood density

Chave J, Coomes D, Jansen S, Lewis SL, Swenson NG, Zanne, AE. 2009 Towards a worldwide wood economics spectrum *Ecol. Lett.* **12**, 351-366.

Zanne AE, Lopez-Gonzalez G, Coomes DA, Ilic J, Jansen S, Lewis SL, Miller RB, Swenson NG, Wiemann MC, Chave J. 2009 Data from: Towards a worldwide wood economics spectrum. Dryad Digital Repository. <http://dx.doi.org/10.5061/dryad.234>.

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Peñuelas J, Sardans J, Llusia J, Silva J, Owen SM, Bala-Ola B, Linatoc AC, Dalimin MN, Niinemets Ü. 2013 Foliar chemistry and standing folivory of early and late-successional

species in a Bornean rainforest. *Plant Ecol. Divers.* **6**, 245–256.

(doi:10.1080/17550874.2013.768713)

Prentice IC, Meng T, Wang H, Harrison SP, Ni J, Wang G. 2011 Evidence of a universal scaling relationship for leaf CO₂ drawdown along an aridity gradient. *New Phytol.* **190**, 169–180.

(doi:10.1111/j.1469-8137.2010.03579.x)

Shipley B. 2002 Trade-offs between net assimilation rate and specific leaf area in determining relative growth rate: relationship with daily irradiance. *Funct. Ecol.* **16**, 682–689.

(doi:10.1046/j.1365-2435.2002.00672.x)

Wright IJ. *et al.* 2004 The worldwide leaf economics spectrum. *Nature* **428**, 821–827.

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Wright J. Pasoh Leaf Data. Unpublished Data.

Fruit Length

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Spermatophyta **11/3**, 419–768.

Birkinshaw C. 2001 Fruit characteristics of species dispersed by the Black Lemur (*Eulemur macaco*) in the Lokobe Forest, Madagascar. *Biotropica* **33**, 478–486.

Brown KA, Flynn DF, Abram NK, Ingram JC, Johnson SE, Wright P. 2011 Assessing natural resource use by forest-reliant communities in Madagascar using functional diversity and functional redundancy metrics. *PloS One* **6**, e24107.

Granados A, Brodie JF. Unpublished Data.

Jacobs M. 1976 The study of lianas. *Flora Malesiana Bull.* **29**, 2610–2618.

Leenhouts PW, Kalkman C, Lam, HJ. 1955 Burseraceae. *Flora Malesiana - Ser. 1*,

Spermatophyta **5**, 209–296.

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S3. Supplementary Methods and Results

We used general linear mixed effects models (GLMM) to determine the impacts of *exclusion treatment* (a factor with 4 levels) and *forest type* (a factor with 2 levels; logged and unlogged) on overall seedling mortality and on average yearly growth (cm/year). All models included a random effect for *experimental block* nested in *forest* (a random term with six levels).

Overall seedling mortality was modeled as a binary response with two levels (dead or alive). Aside from testing the effects of *forest type* and *treatment*, we also tested for a significant *forest* \times *treatment* interaction. Estimates are presented on a logit scale and errors are assumed to be binomially distributed.

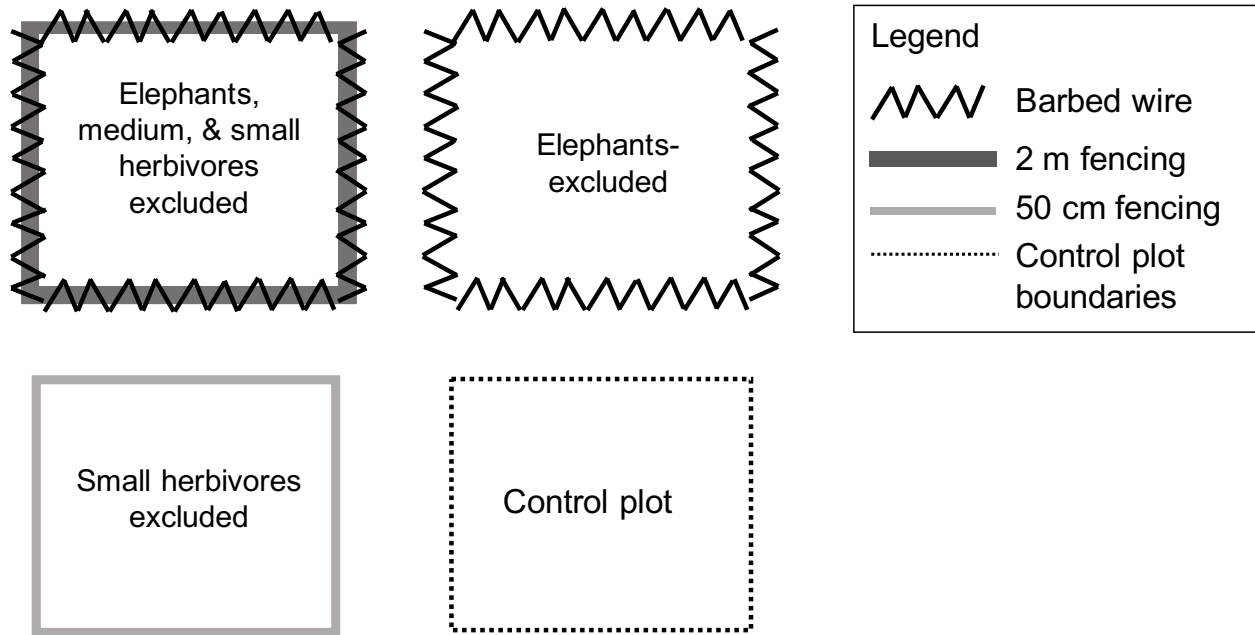
We evaluated seedling height (cm) at the onset of our study as a function of forest type (logged and unlogged) to test for differences prior to treatment effects. We then used data from all survey periods to determine the average annual change in height for each seedling and modeled this growth response as a function of *forest type*, *exclusion treatment*, and a *forest* \times *treatment* interaction.

Seedling mortality was lower where all herbivores were excluded than in control plots (difference between treatments = -1.30; 95% CI: -2.09 to -0.50). Fewer seedlings also died where only small herbivores were excluded than in control plots (difference between treatments = -1.22; 95% CI: -1.90 to -0.54). Within unlogged forest, mortality was higher where only small herbivores were excluded (parameter estimate for *forest* \times *treatment* interaction = 0.94; 95% CI: 0.13 to 1.75). Where only elephants were excluded, mortality was higher in logged than in unlogged forest (parameter estimate for *forest* \times *treatment* interaction = -1.03 95% CI: 1.94 to -0.13) (figure S4.1).

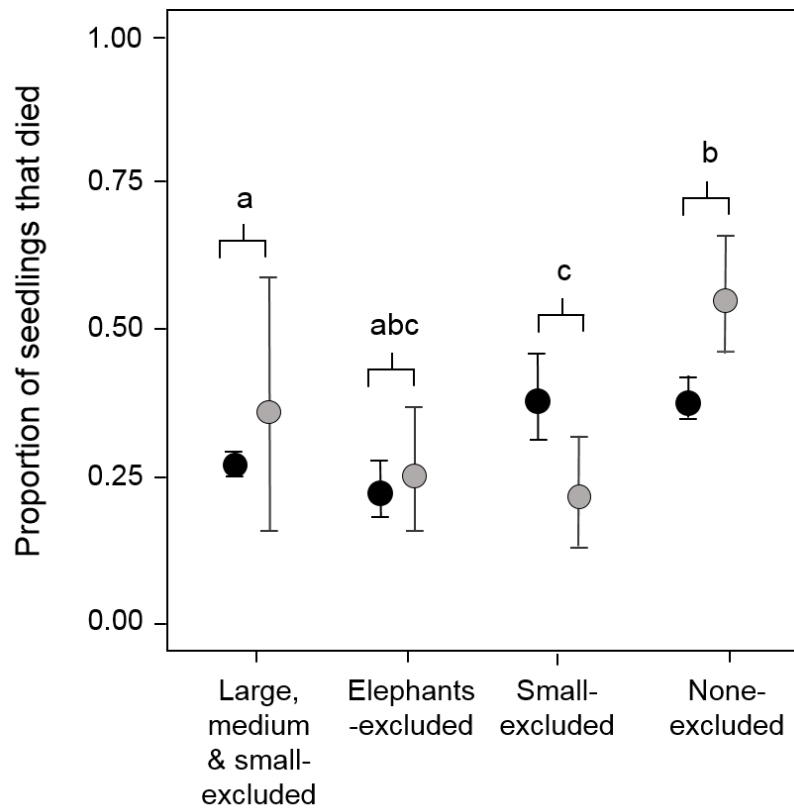
Shorter seedlings were more likely to die, suggesting they were more vulnerable to herbivory (parameter estimate = -3.01; 95% CI: -3.59 to -2.07) whereas taller seedlings were more likely to die in control plots (parameter estimate for *treatment* × *height* interaction: 0.38; 95% CI: 0.03 to 0.74).

Mean seedling height did not differ between logged and unlogged forest in 2013 nor did mean height differ between areas in 2016. Seedlings with smaller changes in growth exhibited greater mortality than seedlings with larger changes in growth (parameter estimate = -0.60; 95% CI: -0.75 to -0.44). Average annual changes in growth were higher where all herbivores were excluded than in control plots (difference between treatments = 0.85; 95% CI: 0.04 to 1.66; figure S4.2). Growth was significantly lower in control plots than in treatments excluding only elephants (difference between treatments = -1.19; 95% CI: -1.98 to -0.40). There was a significant *forest* × *treatment* interaction as seedlings grew more with the exclusion of all herbivores in logged forest than in unlogged forest (difference between forests = 1.44; 95% CI: 0.04 to 2.85).

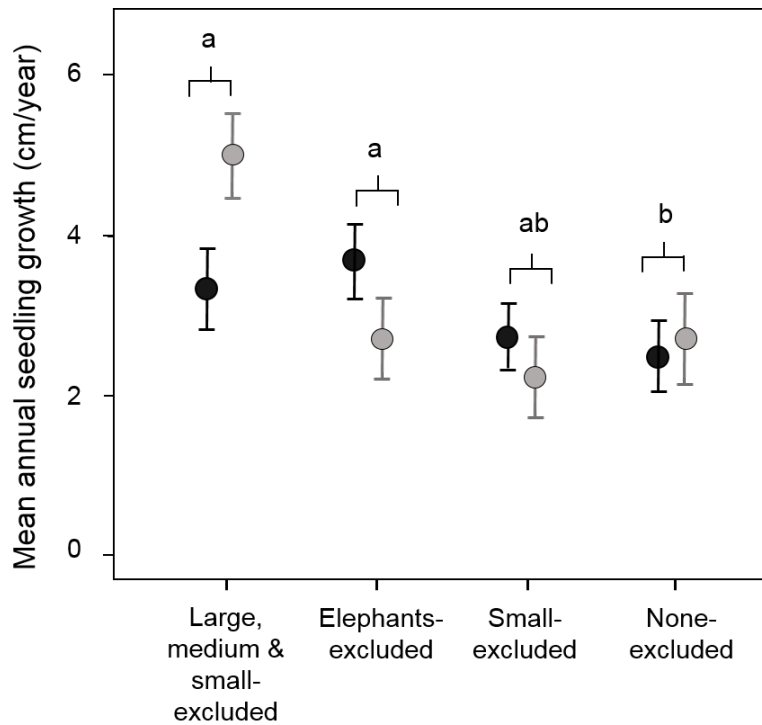
S4. Supplementary Figures



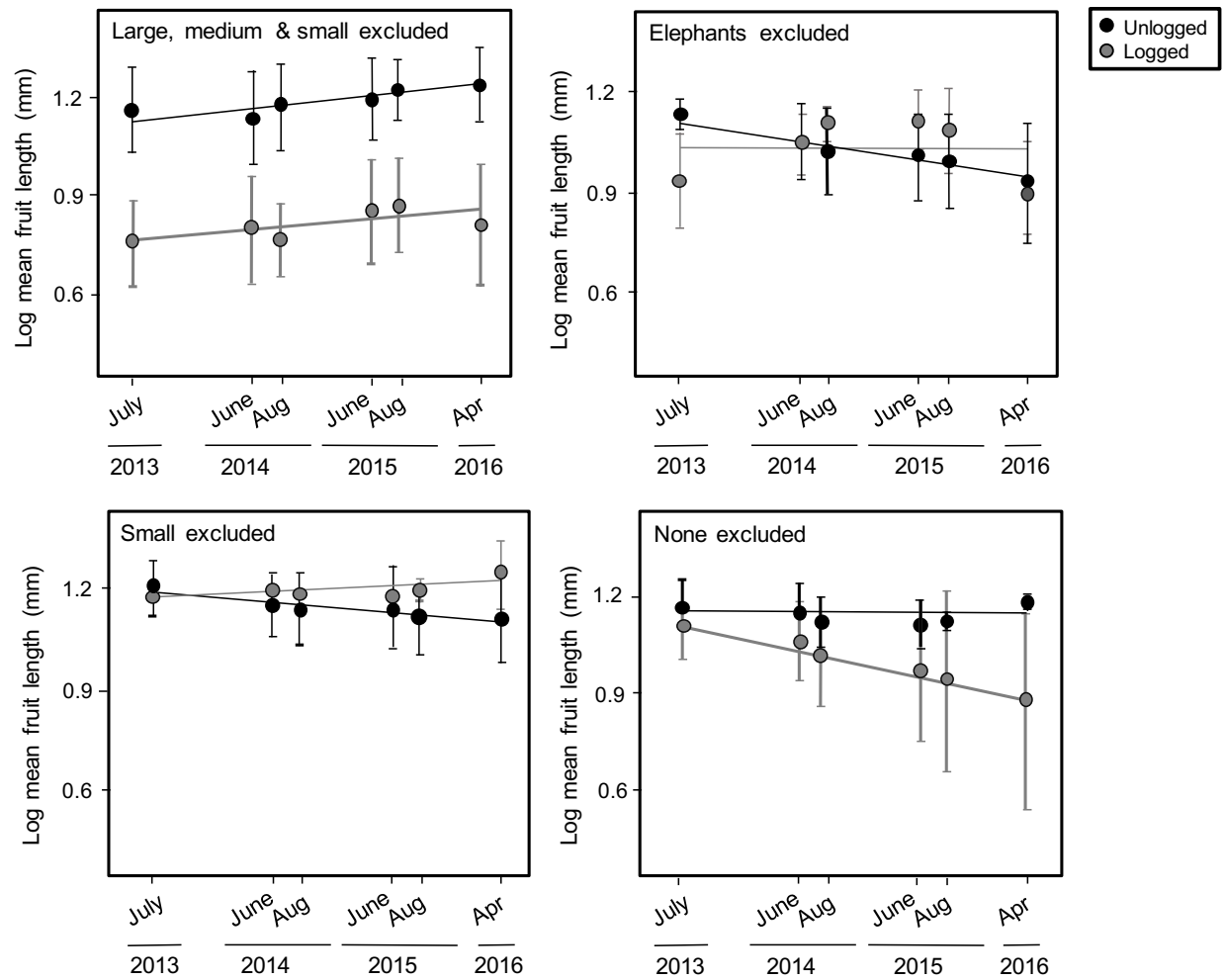
S4.1. Diagram of one enclosure block the materials used to construct each of the four treatments used in our study. Six enclosures were constructed in all: three in logged forest (Sabah Biodiversity Experiment) and three in unlogged forest (Danum Valley Conservation Area). Seedling survival inside each plot was monitored over four years (2013-2016).



S4.2. Seedling mortality across exclusion treatments in unlogged (black) and logged (grey) forest. Standard error bars are shown. Letters denote significant differences in mortality between enclosure treatments based on non-overlapping 95% confidence intervals.



S4.3. Mean seedling growth across exclusion treatments in unlogged (black) and logged (grey) forest. Standard error bars are shown. Letters denote significant differences in growth between enclosure treatments based on non-overlapping 95% confidence intervals.



S4.4. Change in \log_{10} -transformed community fruit length (mm) for non-dipterocarp seedling genera in exclusion treatments in unlogged and logged forest. Standard error bars are shown. Exclusion plots were visited six times over the course of our study (July 2013, June 2014, August 2014, June 2015, June 2015, and April 2016) during which individual seedlings were recorded as alive, dead, or missing.