Supplementary materials for Parsing long-term tree recruitment, growth, and mortality to identify hurricane effects on structural and compositional change in a tropical forest

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S1: Diameter-Filling Algorithm for Missing Data

Long-term permanent forest plot data, including species and diameter of individual stems, allows for the study of post-disturbance successional changes [15,17,56,76–78]. Long-term records may occasionally have missing values or interrupted data collection, either from accidentally omitting stems or field work under hazardous conditions (e.g., steep areas or on landslides). Working with data sets that have missing values may lead to incomplete analyses or erroneous conclusions if the missing values are not recognized and addressed appropriately [79]. Data-processing algorithms contribute to fill data gaps and are needed to fully document published data and meet the needs of specific synthetic data products and models [79,80]. A data set that has been appropriately adjusted for missing diameter observations allows for the examination of error of diameter measurement, the calculation of diameter growth of individual stems and mortality, which could not be done using data with missing diameter measurement values. Hierarchical Bayesian models have been successfully used to estimate diameters, and in some cases even diameter growth, based on sparse observations [81,82]. In our case, the missing data are diameter values that can be estimated when "the missing stem" appears in a following census. When, as in our case, data sets have abundant observations that identify each stem using the tag and plot information of the stem through time, it is possible to develop a simple algorithm to estimate missing diameters in the long-term census data.

Due to accidental omission of stems or hazardous conditions in the seven consecutive censuses of this 25-year dataset, 4.7% of stem diameter entries had a missing value [83]. Previous studies that have used parts of this dataset had to assume that stems without diameter information were missing or dead [14,29,39,40]. Therefore, those studies were unable to calculate long-term stem diameter growth, recruitment, and mortality rates. To address the issue of missing diameters, we developed an algorithm to estimate and fill

the missing information for individual stem diameter values in the dataset. This way, the data could be used for individual stems through time with the adjusted version (algorithm-filled) or for standing stocks with the un-adjusted version (with field-missing diameters), with both data sets part of the same data package [83]. We report procedures used to address missing values and explicitly document them to maintain the integrity of the data and adequately interpret information content.

We defined two situations where we identify a stem as having a missing diameter measurement. In the first situation, a stem was identified as missing in a given census if it was present in the censuses before and after. In the second situation, a stem was identified as missing in prior censuses if its diameter when first identified and measured was greater than 20 cm, a criterion which is based on observations of the diameter size of recruited stems in our long-term data set (Figure S1).

To manage these two types of missing stems, we divided all the stems in all plots into two groups, one with no missing diameters in any of the censuses (template set) and the other with missing diameter values in some censuses. For each missing-diameter stem, we selected a reference stem from the template set such that the reference stem and the missing-diameter stem were the same species and had the closest diameters. In the rare case when there were no stems of the same species in the template set, we then selected another species that had the closest diameters to the target stem as a reference stem. The missing diameter(s) were then filled using the growth rate of the reference stem from the template set with no missing diameters if we knew nothing about the growth of the target stem (in the case of only having one census diameter available). Otherwise, the missing diameter(s) were filled using a rescaled growth rate of the reference stem. The scaling parameter was the growth rate ratio of the target stem to the reference stem (from the template set with no missing diameters) in a census interval where the growth of the target stem was known (see decision-making flowchart, equations, and examples in Figure S2a). Note that the diameter growth depends not only on the size and taxonomic identity of a stem, but also on environmental conditions [84], but we did not consider the latter in the filling algorithm. We present stem density, basal area, and aboveground biomass with both the unadjusted and the adjusted data set in Figure S3 for comparison, and then all other analyses presented in this study are based on the adjusted dataset, unless otherwise stated.

S2. Diameter Measurement Error

Understanding measurement error is important as stem diameters are sampled to calculate diameter growth. Diameter shrinkage is normally attributed to the loss of water in the stem and is associated with diurnal and seasonal cycles [85] or when the surrounding environment and soil are uncommonly dry [86,87]. Studies have recorded decreasing stem diameters in consecutive census data [88], however, diameter shrinkage is normally of the magnitude of around 0.05 cm [85–87], which is smaller than the precision (0.1 cm) of the diameter measurements using tapes at our study site. Hence, in our study, decreases in diameter were most likely measurement errors that are random or due to variability in placement of the tapes, for example, measurements taken at a different height due to irregularities in the main

stem, changes in the stem shape or bark surface, shifts in the ground, erosion, emergence of adventitious roots, steepness of the terrain, etc. [33,89].

The diameter measurement error is, hence, estimated as the recorded reductions in diameter between any two consecutive five-year-interval censuses. In most instances, growth is likely to be positive. Therefore, the measurement error we estimated is a minimum of the negative part of the distribution of the true measurement error. The positive part of the measurement error cannot be detected, but in theory it should have the same magnitude as that of the negative part according to random error assumption. The variability of positive errors should be the mirror image of the negative errors, but we cannot identify where those errors occurred and hence cannot make those corrections.

To estimate growth rates, any calculated negative diameter growth in this study (see Figure S1b) triggers a correction on the measured diameter. The correction involves designating the data point that led to the negative growth as missing and filling the missing diameters using the algorithm described in S1. Once designated as missing, the diameter was re-estimated using the algorithm described in S1 (Figure S2).

When analyzing measurement of diameter values (2,919 entries) from seven censuses spanning 25 years, the measurement error ranged from 0.1 cm (the highest precision of the diameter measurement) to 7.4 cm, with mean value of 0.48 cm. The samples fit an exponential distribution with 95% confidence interval of the estimated mean of the measurement error being between 0.44 and 0.53 (Figure S4a). Ninety-nine percent of the probability density were errors less than or equal to 2 cm, and hence we divided the measurement error into two classes—those errors that were less than 2 cm (routine errors) and greater than 2 cm (processing errors). Processing errors happened at any diameter size and were independent of diameter (Spearman's correlation coefficient r=0.01 and the p-value p=0.9749) (Figure S4b). Routine errors were clustered around diameters less than 20 cm (Figure S4b). Routine errors had a very weak (r=0.14) but significant (p=0.0014) positive correlation with diameter. However, when we analyzed the routine errors with diameters per species, we found that the correlation was insignificant for all individual species, except for *S. berteriana* a species that forms high buttresses (Figure S5).
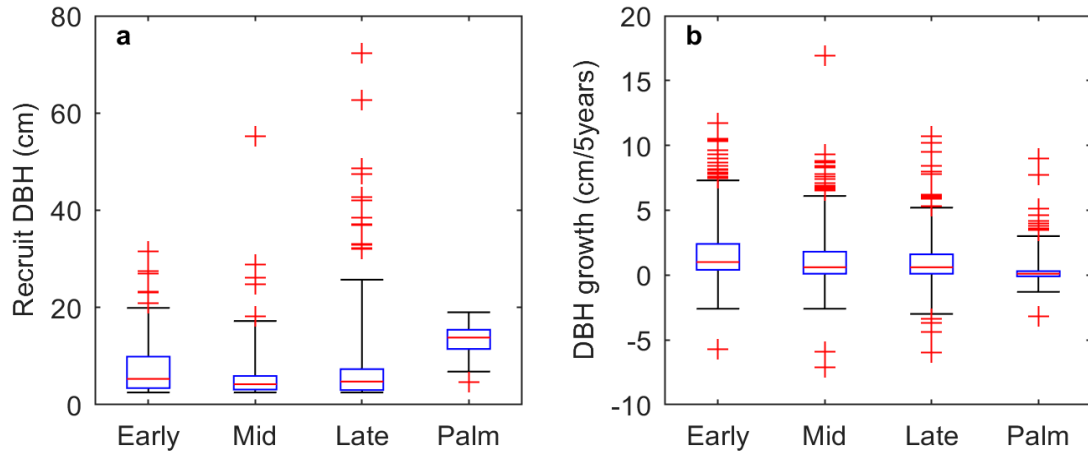
Figure S1. Boxplot of diameter (DBH) of recruited stems (**a**) and diameter growth rates (cm 5years^{-1}) of standing stems (**b**) for the four plant functional types (PFT; *Early*, *Mid*, *Late*, and *Palm*) using the Bisley Experimental Watersheds data set with unadjusted data negative growth rates. The boxplots show outliers (three standard deviations from the mean), and 0th, 25th, 50th, 75th, 100th quantiles of the data without outliers.
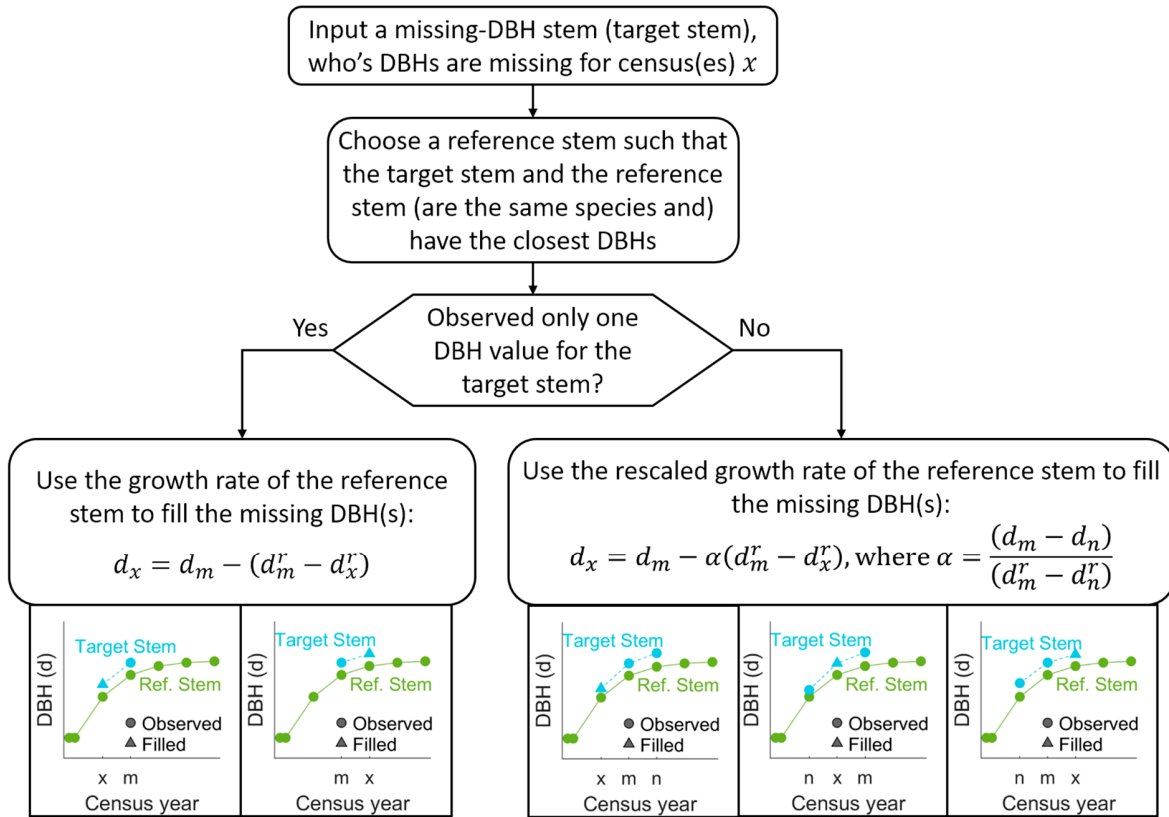
Figure S2. Flow chart decision diagram of the algorithm for filling missing diameter (DBH) of individual stems. Reference stems are from a template set, where DBH data of individual stems has no missing values in all census years (1989 to 2014). d_i represents DBH at i^{th} census year, and x represents missing-DBH census year(s), and m and n represent two none-missing-DBH census years that are closest to year x.
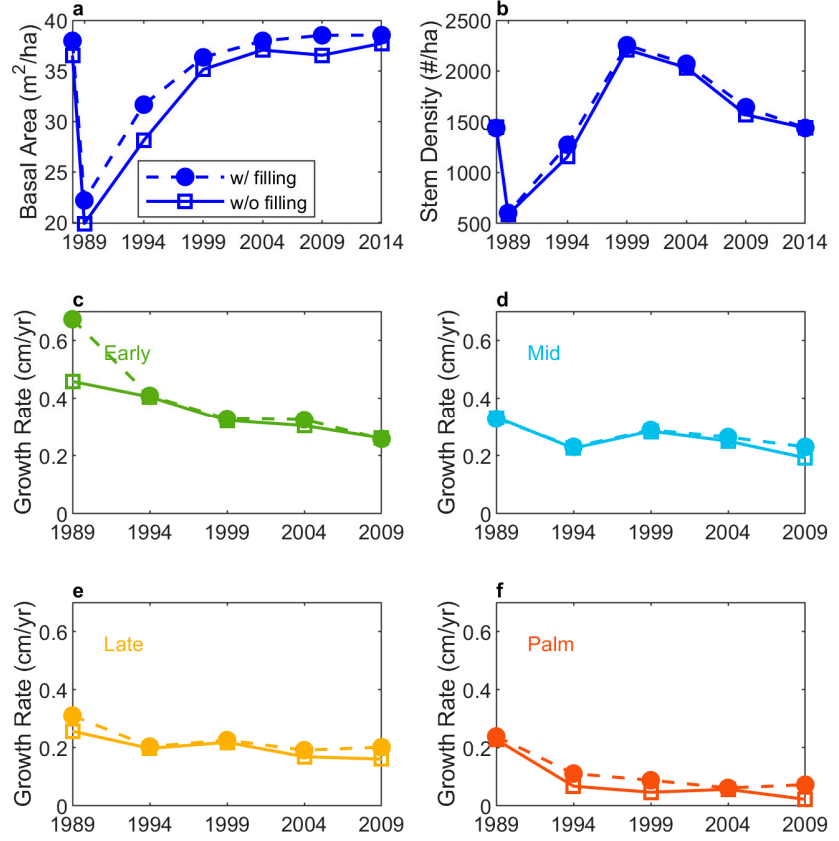

Figure S3. Time series of Basal Area (m² ha⁻¹), Stem Density (# ha⁻¹), and Growth Rate (cm yr⁻¹) per each Plant Functional Type (PFT). Adjusted/filled data set in circle symbols with hatched lines and the unadjusted/with missing values data set in square symbols and solid line. The X-axis shows the census years. For growth rates, the year in the x-axis indicates the first census used to calculate five-year-interval growth rate (converted to cm yr⁻¹ by dividing 5). For example, 1989 means the growth rate (cm yr⁻¹) between 1989 and 1994, averaged for all trees in the same PFT
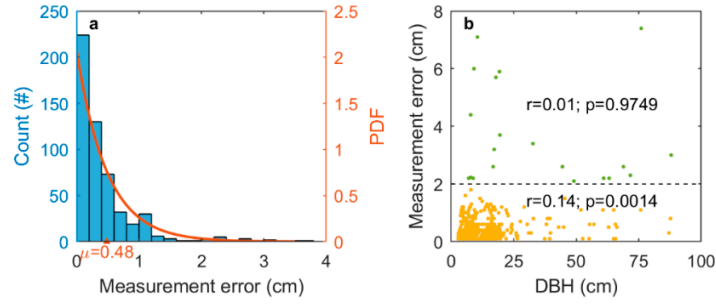
Figure S4. Measurement error (cm) of diameter. (a) Histogram of errors and the mean value of the measurement error. (b) Scatter plot of errors and the corresponding diameter (DBH) values. The Spearman's correlation coefficient (*r*) between the measurement error and DBH and the corresponding *p*-value (*p*) are shown for routine error (<2 cm) and processing error (≥2 cm).
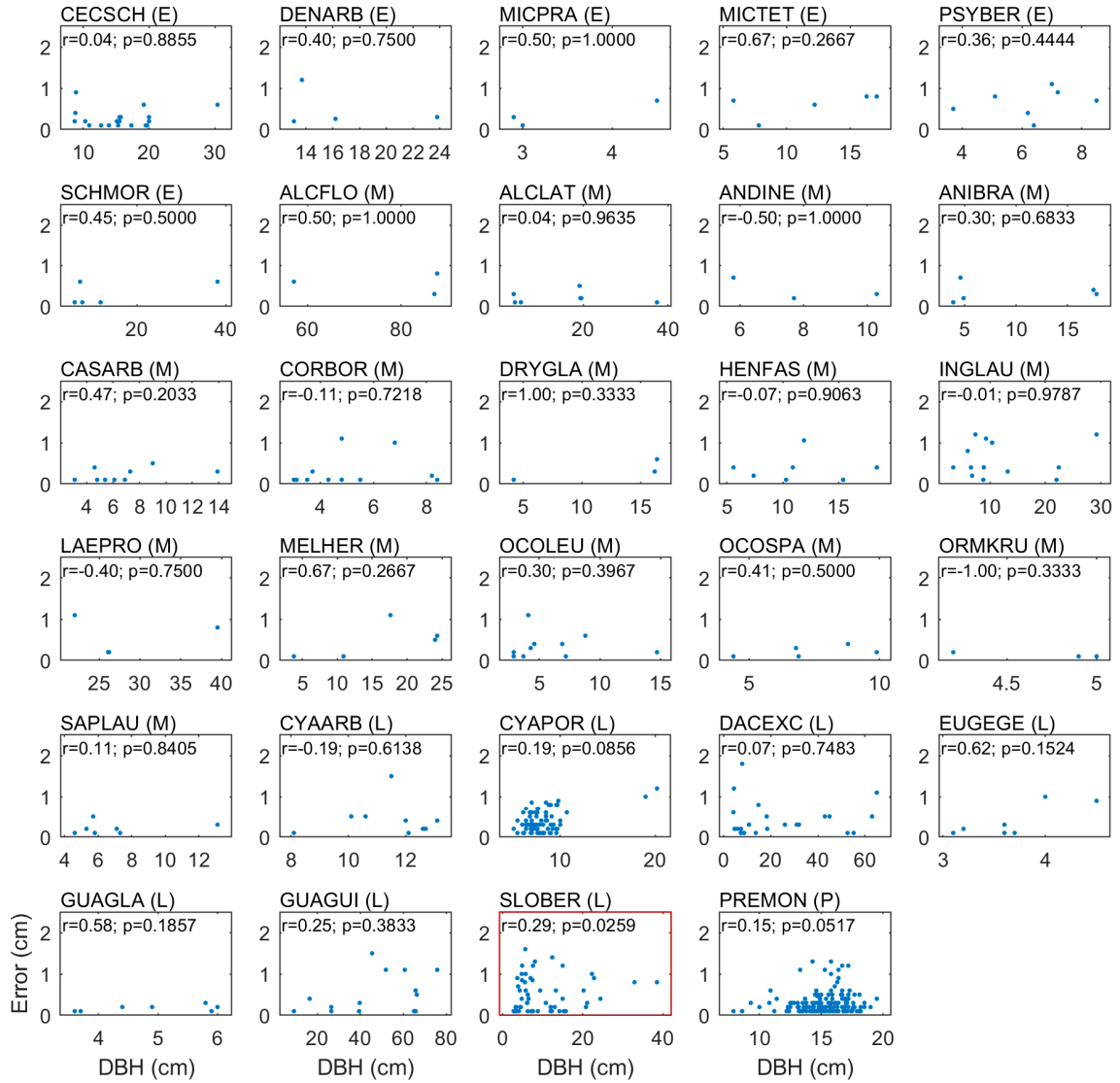
Figure S5. The scatter plots of distribution of measurement error and diameter (DBH) for 29 out of 65 species. Species shown are only those that had more than three samples of measurement error. The Spearman's correlation coefficient (r) between measurement error and DBH and the corresponding p-value (p) are calculated for each species. The species that has a significant correlation SLOBER ($p<0.05$) is boxed in red.
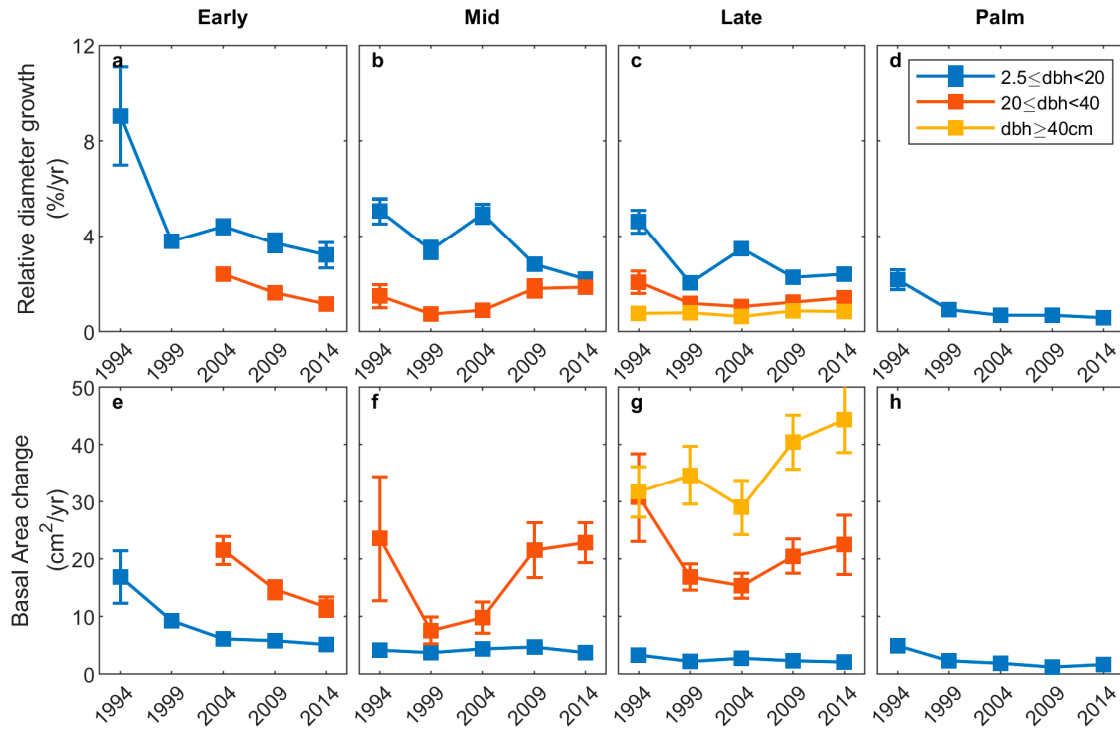

Figure S6. Relative diameter growth rate (**a-d**) and basal area (**e-h**), in five censuses for each diameter (DBH) size of (**a**) *Early*, (**b**) *Mid*, (**c**) *Late*, and (**d**) *Palm* PFTs. The markers and the bars indicate the mean and standard error, respectively; only values with more than 10 samples are shown. Lines in between square symbols are used for ease of visual connection of sample points and do not represent data.

Table S1. Code, Genus and species, Family, and Plant Function Type (PFT) of each species, listed in the order of descending abundance in the forest for each PFT. The scientific name of species follows the Integrated Taxonomic Information System (https://www.itis.gov/).

Code	Genus and species	Family	PFT
PREMON	*Prestoea montana*	Arecaceae	Palm
CECSCH	*Cecropia schreberiana*	Moraceae	Early
PSYBER	*Psychotria berteriana*	Rubiaceae	Early
SCHMOR	*Schefflera morototoni*	Araliaceae	Early
HENFAS	*Henriettea fascicularis*	Melastomataceae	Early
MICTET	*Miconia tetrandra*	Melastomataceae	Early
MICPRA	*Miconia prasina*	Melastomataceae	Early
DENARB	*Dendropanax arboreus*	Araliaceae	Early
UREBAC	*Urera baccifera*	Urticaceae	Early

PALRIP	*Palicourea riparia*	Rubiaceae	Early
PSYBRA	*Psychotria brachiata*	Rubiaceae	Early
CONHOT	*Conostegia hotteana*	Melastomataceae	Early
MICSER	*Miconia serrulata*	Melastomataceae	Early
HETCYM	*Clidemia cymosa*	Melastomataceae	Early
MICRAC	*Miconia racemosa*	Melastomataceae	Early
MICFOE	*Miconia foveolata*	Melastomataceae	Early
TETURB	*Tetrazygia urbanii*	Melastomataceae	Early
MICMIR	*Miconia mirabilis*	Melastomataceae	Early
CASARB	*Casearia arborea*	Flacourtiaceae	Mid
OCOLEU	*Ocotea leucoxylon*	Lauraceae	Mid
INGLAU	*Inga laurina*	Fabaceae	Mid
SAPLAU	*Sapium laurocerasus*	Euphorbiaceae	Mid
CORBOR	*Cordia borinquensis*	Boraginaceae	Mid
ALCLAT	*Alchornea latifolia*	Euphorbiaceae	Mid
ALCPOR	*Alchorneopsis portoricensis*	Euphorbiaceae	Mid
MELHER	*Meliosma herbertii*	Sabiaceae	Mid
ORMKRU	*Ormosia krugii*	Fabaceae	Mid
ANIBRA	*Aniba bracteata*	Lauraceae	Mid
MYRDEF	*Myrcia deflexa*	Myrtaceae	Mid
INGVER	*Inga vera*	Fabaceae	Mid
LAEPRO	*Laetia procera*	Flacourtiaceae	Mid
OCOSPA	*Ocotea spathulata*	Lauraceae	Mid
ANDINE	*Andira inermis*	Fabaceae	Mid
DRYGLA	*Drypetes glauca*	Euphorbiaceae	Mid
ANTOBT	*Antirhea obtusifolia*	Rubiaceae	Mid
CALSQU	*Calycogonium squamulosum*	Melastomataceae	Mid
ALCFLO	*Alchorneopsis floribunda*	Euphorbiaceae	Mid
MYRSPL	*Myrcia splendens*	Myrtaceae	Mid
MYRFAL	*Myrcia fallax*	Myrtaceae	Mid
BYRSPI	*Byrsonima spicata*	Malpighiaceae	Mid
HOMRAC	*Homalium racemosum*	Flacourtiaceae	Mid
SYZJAM	*Syzygium jambos*	Myrtaceae	Mid
QUATUR	*Quararibea turbinata*	Bombacaceae	Mid
TABHET	*Tabebuia heterophylla*	Bignoniaceae	Mid
MYRLEP	*Myrcia leptoclada*	Myrtaceae	Mid
OCOSIN	*Ocotea sintensis*	Lauraceae	Mid
SLOBER	*Sloanea berteriana*	Elaeocarpaceae	Late
DACEXC	*Dacryodes excelsa*	Burseraceae	Late
CYAPOR	*Cyathea portoricensis*	Cyatheaceae	Late
GUAGUI	*Guarea guidonia*	Meliaceae	Late
GUAGLA	*Guarea glabra*	Meliaceae	Late
MANBID	*Manilkara bidentata*	Sapotaceae	Late
CYAARB	*Cyathea arborea*	Cyatheaceae	Late
EUGEGE	*Eugenia eggersii*	Myrtaceae	Late
BUCCAP	*Buchenavia tetraphylla*	Combretaceae	Late
SWIMAC	*Swietenia macrophylla*	Meliaceae	Late
HIRRUG	*Hirtella rugosa*	Chrysobalanaceae	Late
ILESIN	*Ilex obcordata*	Aquifoliaceae	Late
EUGSTA	*Eugenia stahlii*	Myrtaceae	Late
TETBAL	*Tetragastris balsamifera*	Burseraceae	Late

TRIPAL	*Trichilia pallida*	Meliaceae	Late
KHANYA	*Khaya anthotheca*	Meliaceae	Late
CASGUI	*Cassipourea guianensis*	Rhizophoraceae	Late
LAPPOR	*Laplacea portoricensis*	Theaceae	Late
MAGSPL	*Magnolia splendens*	Magnoliaceae	Late

Table S2. Growth rates (mean and standard error; cm yr^{-1}) of each PFT in each topographic settings: valley, slope, and ridge. If the difference between two settings for a PFT is significant at 99% confidence level ($p<0.01$), then the growth rate is marked with a letter: "v" means significantly different from **v**alley plots, "s" means significantly different from **s**lope plots, and "r" means significantly different from the **r**idge.

	Valley	Slope	Ridge
Early	0.30±0.03	0.37±0.01	0.31±0.03
Mid	0.22±0.03	0.29±0.01 [r]	0.18±0.02 [s]
Late	0.16±0.03 [r]	0.21±0.009	0.25±0.01 [v]
Palm	0.16±0.04 [s]	0.082±0.008 [v]	0.077±0.01

Table S3. Same as Table S2, but for the mortality rate (%).

	Valley	Slope	Ridge
1989	58.06	61.52 [r]	46 [s]
1994	3.85	2.97	0.93
1999	13.75	13.59	9.8
2004	38.71 [r]	34.57 [r]	19.93 [v,s]
2009	39.39 [r]	29.47	23.66 [v]
2014	27.94	22.16	23.19

Table S4. Same as Table S2, but for the recruitment rate (%).

	Valley	Slope	Ridge
1994	211.54 [s,r]	132.71 [v,r]	42.59 [v,s]
1999	68.75 [s,r]	92.39 [v]	90.2 [v]
2004	18.55 [r]	22.08 [r]	34.78 [v,s]
2009	8.08	8.79	6.62
2014	22.06 [s, r]	10.69 [v]	6.08 [v]

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