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# Supporting Online Material for

## Species Loss and Aboveground Carbon Storage in a Tropical Forest

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**SUPPORTING ONLINE MATERIAL**

## Materials and methods

### *Study site*

The 50 ha forest census plot on BCI was established in 1982 and has been censused every five years since 1985 (*S1*, *S2*). BCI consists of 1500 ha of diverse, moist, lowland tropical forest. Detailed descriptions of the flora and fauna can be found in (*S3*, *S4*). The climate of BCI is warm all year, but rainfall is seasonal. Forty-eight ha in the plot are old growth (>600 years); the remaining two are 90 year-old forest. A detailed description of the census methods can be found in (*S2*).

### *Species traits*

We developed several extinction scenarios in which extinction probability is proportional to trait values (Table S1). Traits intrinsic to the BCI 50 ha census data included sapling and adult abundance, sapling and adult mortality rate, sapling and adult population growth rate, sapling and adult mean relative growth rate, maximum dbh, species basal area, and species total volume. Traits extrinsic to the plot data included wood specific gravity (*S5*, *S6*), geographic extent (*S7*), and precipitation habitat affinity (*S7*).

Sapling (1-10 cm dbh) and adult (>10 cm dbh) abundances were based on the 1995 census of the BCI plot (*S2*). We calculated population growth rate using a standard exponential model in which $r=\ln(n_{t2}/n_{t1})/t$, where $n_{t1}$ is number of individuals (>10 cm dbh) in 1982, $n_{t2}$ is abundance in 1995, and t=13 years. We calculated annual mortality (*S8*) for each species as $m=1-(n_{t2}/n_{t1})^{1/t}$, t=5, where $n_{t1}$ is initial number of individuals per species and $n_{t2}$ is the number of survivors. To increase sample size for mortality we pooled mortality rate from the 1985-90 and 1990-95 census intervals. For the five species with no saplings, we substituted mean mortality. We calculated individual relative growth rate for each species as $rgr=\ln(dbh_{t2}/dbh_{t1})/t$, again pooling results from both the 1985-90 and 1990-95 census intervals. In calculating rgr, we followed (*S9*) by excluding all individuals that shrank more than 5% per year in either the current or the prior census interval, all individuals whose stems broke off below 1.3 m yet survived and, all individuals that grew by more than 75mm per year. We quantified maximum dbh as the greatest value observed per species in any of the four censuses. Species basal area is simply the total observed basal area for each species, and species volume is total volume for each species (V=H*BA/3). We estimated height (H) for each individual as $H=c*(1-\exp(-a*D^b))$ following the allometric model of (*S6*), where D is diameter and c, a and b are species-specific fitted parameters. We had no allometric height model for 67 species, which accounted for 53% of species yet only 10% of basal area in the simulation. For these species we used a consensus model developed by (*S6*). We calculated geographic frequency as the proportion of sites occupied by canopy individuals across 42 permanent plots that span the isthmus of Panama (*S7*). Precipitation habitat affinity was derived from this same dataset and quantified as annual precipitation at the site where the species occurs at the highest stem density.

*Quantifying carbon sequestration*

We quantified carbon storage per ha as

$$C\,(\text{Kg ha}^{-1}) = A^{-1}\varphi\sum_i\sum_j \exp(-2.409 + 0.952\ln(\rho_i D_j^{\,2} H_j)) \qquad \text{(S1)}$$

where $D_i$, and $H_i$ are diameter and height of individual *i* and $\rho_i$ is wood specific gravity of species *i*, following the allometric model of (*S10*), *A* is area, and $\varphi$ is carbon as a proportion of biomass and estimated to be 0.5 (*S5*). We recognize the fact that allometric models may be the greatest source of variability in estimates of standing stocks of above-ground biomass (*S11*). We therefore chose the model of (*S10*), considered by (*S6*) to be the most reliable predictor so far developed.

*The simulation*

For the simulation, we used the 1995 BCI 50 ha census and included all individuals (>10 cm dbh) for which we had data for specific gravity (126 of 227 species). These species constitute 87% of basal area (>10 cm dbh), and 79% of above-ground biomass (>10 cm dbh). Note that because our measure of C storage is based on this reduced subset of species, our estimates of C per hectare are lower than those reported by (*S6*).

To simulate loss of species diversity from the 50 ha plot, we removed species either randomly or with probabilities proportional to their trait values. We log-transformed abundance, annual mortality, maximum dbh, total basal area, and total volume. We then normalized all traits such that species extinction probabilities spanned 0.01-0.99.

After species were removed from the plot, the remaining species were allowed to compensate fully for the lost basal area through a random draw, with replacement, of all remaining individuals. This approach allowed us to maintain basal area at a constant level, which is the most parsimonius assumption for compensation given limited empirical data for species interactions and is supported by both empirical observations, which show minimal variability in basal area per hectare throughout mature neotropical forests (*S12*), and by theoretical work, which argues that forested communities maximize resource capture by maximizing basal area (*S13*, *S14*). By compensating for lost basal area through a random draw of the remaining individuals, we utilize a null model approach in which the fully reconstituted community reflects both the size frequency distribution and the rank abundance of the remaining species.

*Analysis*

We quantified the overall effect of each extinction scenario on ecosystem function (above-ground carbon storage) as carbon storage evaluated at one species (estimated from a linear fit to the simulation results) as a percentage of carbon storage in the intact community (Carbon storage, Table S1). We quantified biological insurance (BI) as the slope of the relationship between the coefficient of variation of above-ground carbon and $\log_2$ of species richness (BI slope, Table S1), which is equivalent to the change in variability for each two-fold change in species richness. Because variability is zero for the full community and necessarily increases as species are lost, we also quantified biological insurance relative to BI under random extinction.

Table S1. Tropical forest carbon storage under different trait-based extinction scenarios. Carbon storage is change in above-ground carbon relative to the intact community evaluated at one species from a fitted linear model. BEF (Biodiversity-ecosystem function) slope is change in carbon (Mg C $ha^{-1}$) for each doubling of species richness. $r^2$ is proportion of variability explained by this linear fit. Biological insurance (BI) slope is change in CV for each doubling of species richness. Adults >10 cm diameter at breast height (dbh), Saplings 1-10 cm dbh.

| Extinction scenario | Trait | Carbon storage | Carbon storage relative to random extinction | BEF slope | $r^2$ | Biological insurance (BI) slope | BI relative to random extinction |
|---|---|---|---|---|---|---|---|
| Observed population trends | Sapling population growth rate | +16% | +20% | -2.74 | 0.04 | -0.07 | +17% |
| | Adult population growth rate | -6% | -2% | 1.19 | 0.02 | -0.03 | -43% |
| Adult mortality drives species extinctions | Adult mortality rate | -11% | -7% | 2.59 | 0.07 | -0.05 | -7% |
| Species with high sapling mortality lost first due to shift towards shade tolerant species | Sapling mortality rate | -33% | -30% | 5.64 | 0.20 | -0.07 | +21% |
| Low density species lost due to management for high density species | Inverse of wood density | +75% | +82% | -11.34 | 0.42 | -0.04 | -40% |
| High density species lost due to harvesting or management for low density wood pulp | Wood density | -70% | -69% | 11.24 | 0.85 | -0.04 | -29% |
| Species with smallest stature lost due to forest management | Inverse of maximum dbh | -13% | -10% | 2.34 | 0.31 | -0.02 | -71% |

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|---|---|---|---|---|---|---|---|
| Species with largest stature lost due to forest harvesting | Maximum dbh | -29% | -27% | 5.01 | 0.33 | -0.03 | -52% |
| Species with maximal basal area lost due to forest harvesting | Total basal area | -17% | -14% | 2.97 | 0.11 | -0.02 | -58% |
| Species with maximal wood volume lost due to forest harvesting | Total wood volume | -21% | -18% | 3.60 | 0.19 | -0.02 | -65% |
| Widespread species lost first, due to harvesting or disease outbreak | Geographic extent | -16% | -13% | 3.63 | 0.07 | -0.07 | +14% |
| Rare species lost due to demographic stochasticity | Adult abundance | -4% | -0% | 0.73 | 0.03 | -0.02 | -63% |
| Slow growing species lost first: fast growing species favored by CO2 fertilization or increased disturbance | Canopy relative growth rate | -9% | -6% | 1.26 | 0.02 | -0.03 | -42% |
| | Sapling relative growth rate | -34% | -32% | 6.69 | 0.31 | -0.05 | -17% |
| Endemics lost first due to climate change or demographic stochasticity | Inverse of geographic extent | -14% | -11% | 2.67 | 0.25 | -0.02 | -63% |
| Wet-forest species lost first due to increased drought frequency | Precipitation preference | +10% | +14% | -1.61 | 0.01 | -0.09 | +48% |
| Dry-forest species lost first due to increased precipitation | Inverse of precipitation preference | +2% | +6% | -0.90 | 0.02 | -0.02 | -59% |
| Random loss of species | | -4% | | 0.86 | 0.01 | -0.06 | |
| Mean | | -10% | -7% | 1.88 | 0.18 | -0.04 | -30% |
| Standard deviation | | 29% | 31% | 4.62 | 0.21 | 0.02 | 36% |

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|---|---|---|---|---|---|---|
| Maximum | +75% | +82% | 11.24 | 0.85 | -0.02 | +48% |
| Minimum | -70% | -69% | -11.34 | 0.01 | -0.09 | -71% |

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