Supporting Information

Article title: Tree crown damage and its effect on carbon cycling in a tropical forest

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Table S1. Additional model configurations.

Methods S1 Recovery algorithm

Recovery is calculated during daily allocation. It occurs after cohorts have used NPP to replace maintenance turnover of leaves and fine roots, and once all carbon pools are at their allometric targets. At this point cohorts can either use excess carbon to grow all pools including DBH along the current, damaged, allometric trajectories, or they can use excess carbon to increase carbon pools to the allometric targets of a lesser damaged class, at the expense of DBH growth. The recovery scalar parameter, f_r, determines the fraction of the cohort that recovers when carbon is available to do so. If $0 < f_r < 1$, then the cohort is split and some fraction remains in the current damage class d, while some fraction moves to damage class d_{-1}. Available carbon at the start of recovery is given by C_b.

The carbon pools for a cohort in damage class d are given by :
$C_{l,d}$ = leaf carbon
$C_{fr,d}$ = fine root carbon
$C_{sw,d}$ = sapwood carbon
$C_{str,d}$ = structural carbon
$C_{sto,d}$ = storage carbon

The allometric target carbon pools in damage class d_{-1} are given by :

$C_{l,d-1}$ = target leaf carbon d_{-1}
$C_{fr,d-1}$ = target fine root carbon d_{-1}
$C_{sw,d-1}$ = target sapwood carbon d_{-1}
$C_{str,d-1}$ = target structural carbon d_{-1}
$C_{sto,d-1}$ = target storage carbon d_{-1}

Total carbon of cohort in damage class d, C_d , is given by

$$C_d = C_{l,d} + C_{fr,d} + C_{sw,d} + C_{str,d} + C_{sto,d} \quad \text{eq. 1}$$

Total carbon of cohort in damage class d_{-1}, C_{d-1} , is given by

$$C_{d-1} = C_{l,d-1} + C_{fr,d-1} + C_{sw,d-1} + C_{str,d-1} + C_{sto,d-1} \quad \text{eq. 2}$$

Carbon demand for recovery, C_r, is thus

$$C_r = C_{d-1} - C_d \quad \text{eq. 3}$$

The maximum number of plants that can recover, n_{max}, is given by

$$n_{max} = C_b * n_d / C_r \quad \text{eq. 4}$$

where n_d is the number density of the cohort in damage class d and C_b is the carbon balance for the cohort, i.e. the amount of carbon available for growth or recovery.

The number of plants that recover, n_r , is given by:

$$n_r = n_{max} * f_r \quad \text{eq. 5}$$

where f_r is the recovery scalar parameter.

The per capita carbon of the newly recovered cohort is C_{d-1}, since all carbon pools are now at the allometric target for damage class *d-1*. The total carbon for the newly recovered cohort is $C_{d-1} * n_r$.

eq. 6

The per capita carbon of the fraction of the cohort that does not recover, $C_{d,t+1}$, is now

$C_{d,t+1} = (C_d * n_d - (C_{d-1} * n_r)) / (n_d - n_r)$ eq. 7

And total carbon in the cohort is $C_{d,t+1} * (n_d - n_r)$. eq. 8

Methods S2 Additional Sensitivity Analyses

Carbon storage parameter Carbon starvation mortality occurs in FATES when storage carbon is depleted. To test the effect of carbon storage on carbon starvation mortality in damaged trees, we ran a sensitivity analysis to the parameter which determines the allocation to storage carbon, relative to leaf carbon (s9). In this experiment we changed the allocation to storage parameter from 1.0 to 2.0 in increments of 0.1.

An increase in the allocation to storage parameter from 1.0 to 2.0 caused a decrease in carbon starvation mortality from 21 % yr^{-1} to 8 % yr^{-1} in trees < 20 cm DBH with 80% crown loss. In trees > 40 cm DBH, which have much higher storage carbon, changes to the allocation to storage parameter had no effect on carbon starvation mortality, regardless of crown damage (Fig. S8).

Root respiration parameter We tested how changes to root nitrogen (N) stoichiometry alter the ratio of leaf to root respiration, and carbon starvation mortality across damage classes. In these simulations (s10) we increased the root N stoichiometry from its default value of 0.02900 to 0.03300, 0.04125, 0.04950, 0.05775, and 0.06600 gN/gC, corresponding to 1.0, 1.25, 1.50, 1.75 and 2.00 times the leaf N stoichiometry. Observations from Amazonian forest plots reported in Malhi et al. (2009) and Doughty et al. (2014) suggest the ratio of leaf to root and stem respiration is between 0.48 and 1.02 (Fig. S9). A root N stoichiometry of 0.66 gN/gC gives a leaf to root respiration ratio of 0.86 for an undamaged tree. In the trees with 80% crown loss, carbon starvation mortality increased sharply from3% yr^{-1} to 34% yr^{-1} as root N stoichiometry increased from 0.058 gN/gC to 0.066 gN/gC (Fig. S3). Carbon starvation mortality in FATES is triggered when the ratio of storage carbon to leaf carbon falls below 1. Our results suggest that this threshold is reached when root nitrogen stoichiometry reaches a critical value between 0.058 gN/gC

to 0.066 gN/gC. At this level of root N stoichiometry root respiration can't be met by photosynthetic capacity, leading to a depletion of storage carbon and carbon starvation mortality.

Damage and recovery parameters To better understand how damage and recovery influence carbon cycling dynamics we ran an ensemble of simulations (s11) in which we tested all combinations of five annual damage rates (0.5% yr^{-1} to 5.0% yr^{-1}), and five values of the parameter for the fraction of NPP used for recovery (f_r) (0.0 to 1.0).

Decreases in AGB and carbon residence time are sensitive to the rate of damage and, to a lesser extent, recovery (Fig S10). With no recovery, an increase in the annual damage rate from 0.5% yr^{-1} to 5% yr^{-1} nearly halves carbon residence time from 28 years to 15 years, and decreases AGB from 11.6 kg C m^{-2} to 5.2 kg C m^{-2}. When the annual damage rate is 5% yr^{-1}, an increase in the recovery scalar, which sets the fraction of available carbon used for recovery versus growth within the current damage class, from 0 to 1 increases carbon residence time from 15 to 17 years, and AGB from 5.2 kg C m^{-2} to 6.6 kg C m^{-2}.

The rate of damage also alters the canopy area disturbed each year (Fig. S11). With no recovery, an increase in damage rate from 0.5% yr^{-1} to 5% yr^{-1} causes the loss of crown area from damage to increase from 23.8 to 233.4 $m^2\,yr^{-1}$, going from 15% to 56% of total canopy disturbance. Canopy disturbance area is mostly insensitive to recovery; with a damage rate of 5% yr^{-1}, an increase in the recovery scalar from 0 to 1 causes the loss of crown area from damage to increase from 233.4 $m^2\,yr^{-1}$ to 235.4 $m^2\,yr^{-1}$.

Table S1. Crown damage bins in damage class sensitivity analysis

Number of crown damage classes	Crown loss in each crown damage class
1	0%
2	0%, 80%
3	0, 60%, 80%
4	0%, 40%, 60%, 80%
5	0%, 20%, 40%, 60%, 80%

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154 **Table S2. Additional model configurations.**

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Simulation number	**s8**	**s9**	**s10**	**s11**
Name	Number of crown damage classes sensitivity	Carbon allocation to storage sensitivity	Root N sensitivity	Damage and recovery rate sensitivity
Crown damage classes (% crown loss)	See table S1	0, 20, 40, 60, 80	0, 20, 40, 60, 80	0, 20, 40, 60, 80
Root N stoichiometry	0.029	0.029	0.033, 0.04125, 0.0495, 0.05775, 0.066	0.066
Damage	Yes	Yes	Yes	Yes
Carbon storage decrease with damage	No	No	No	Yes
m_d term (additional damage-driven mortality)	No	No	No	No
Damage rate (% yr^{-1})	1	1	1	0.5, 1.625, 2.75, 3.875, 5
Recovery	0	0	0	0,0.25,0.50,0.75,1.0
PFTs	1	1	1	1
Allocation to storage	1.2	1.0,1.1,1.2,1.3,1.4,1.5,1.6,1.7,1.8,1.9,2.0	1.2	1.2

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Methods S3 Estimates of damage class from field data

The relative height of the living length *r* is calculated as *l/h*, where *h* is target allometric height calculated from DBH. Here we use equation 7 from (Martinez Cano et al. 2018).

$$h = \frac{58.0 * DBH^{0.73}}{21.8 + DBH^{0.73}} \quad \text{eq. 9}$$

The relative height of the base of the crown C_{rh} is calculated as C_h/h where C_h is the height of the base of the crown, here assumed to be 1.3 m. Although this is too low in large trees, it is inconsequential as the model assumes almost no biomass in branches at that height. If $r < C_{rh}$ then the fraction of biomass remaining is calculated as:

$$AGB_f = (1 - b_f) * (1 - (1-r)^a) \quad \text{eq. 10}$$

Where b_f is the fraction of biomass in branches, here 0.33 based on values from (Chambers et al. 2001) of 288 trees in the Central Amazon, and unpublished data from Duque et al of 296 trees in the Colombian Amazon. *a* and *b* (below) are parameters controlling tapering, with higher values giving more abrupt tapering. We set a = 2.631000 and b = 9.761049, to create smooth transitions from trunk to crown. The biomass of the damaged tree is then AGB_f * target biomass.

If $r \geq C_{rh}$ then the proportion of remaining biomass is calculated as:

$$AGB_f = bole_0 + \beta * (1 - (1 - (r - C_{rh}))^b) \quad \text{eq. 11}$$

Where $bole_0$ is calculated as

$$bole_0 = (1 - b_f) * (1 - (1 - C_{rh})^a) \quad \text{eq. 12}$$

And β is

$$\beta = \frac{(1 - bole_0)}{(1 - C_{rh}^b)} \quad \text{eq. 13}$$

The proportion of biomass remaining in the crown, AGB_c, is AGB_f - $bole_0$ and the biomass of the damaged trees is simply AGB_f * target biomass + AGB_c * target biomass * b_l.

To estimate target biomass we use equation 4 from (Chave et al. 2014):

$$AGB_{est} = 0.0673 * (\rho DBH^2 * h)^{0.976} \quad \text{eq. 14}$$

Where ρ is wood density, taken from (Zanne et al. 2009), see (Chave et al. 2009).

Because the damage protocol only records new damage each year, we use the cumulative product of damage loss to estimate b_l and note that this may be an underestimate of total damage in the tree.

Figures S1-S12

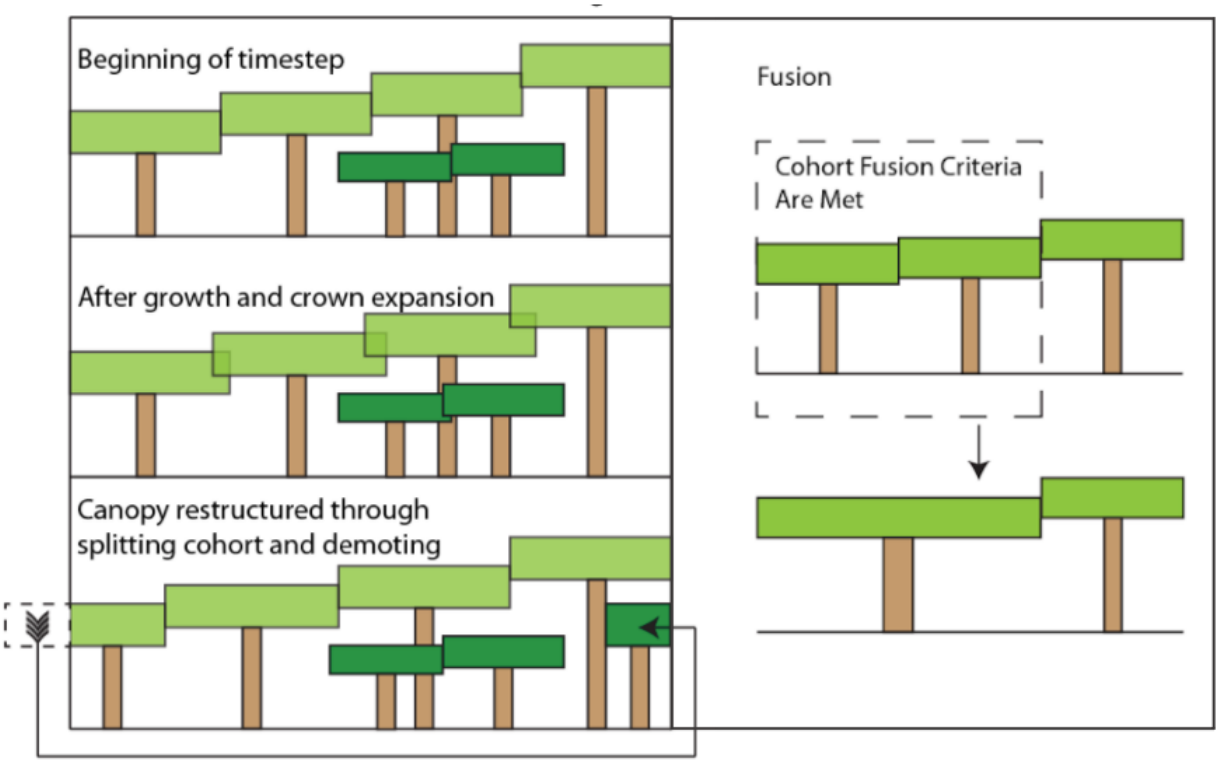

Figure S1. Cohort splitting and fusion schematic. The left hand panel shows cohort splitting following growth. The top panel is a patch at the beginning of the timestep. In the middle panel cohorts grow and their crowns expand. To keep total canopy area constant, in the bottom panel a fraction of the smallest cohort is demoted to the understory. This version represents the pure PPA configuration of FATES where canopy sorting is entirely deterministic. In the stochastic canopy organization configuration a fraction of all cohorts is demoted. In the right hand panel two cohorts that are within a specified dbh size threshold of one another are fused together.

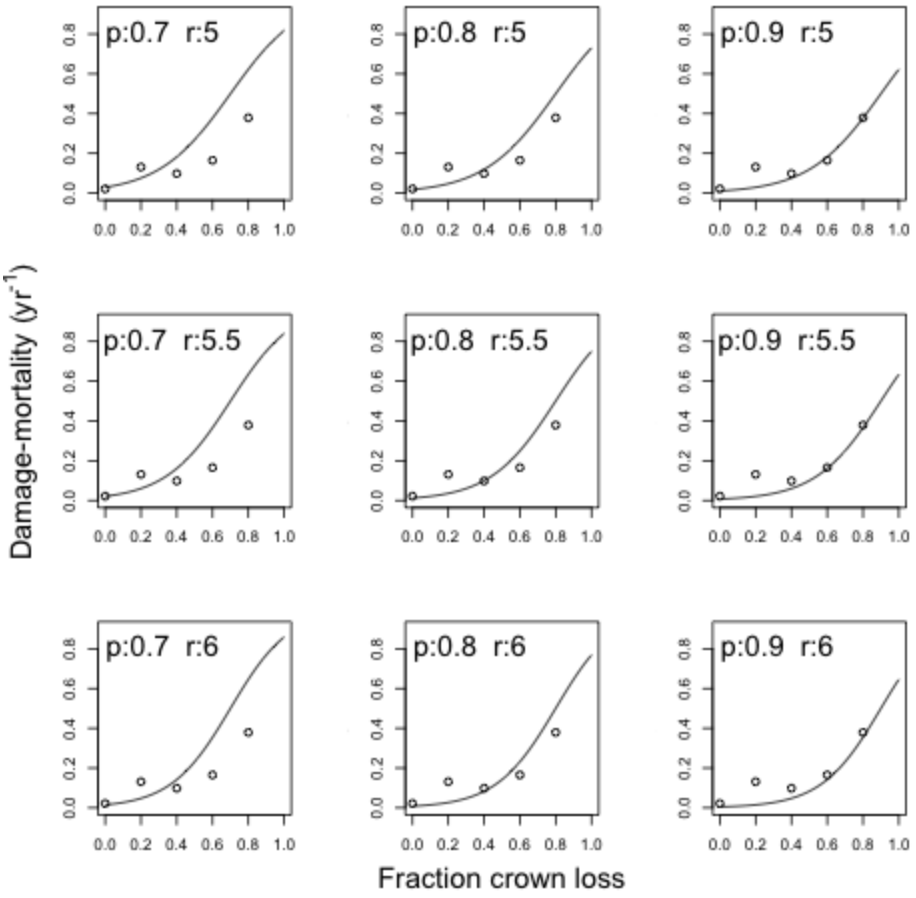

Figure S2. Damage-dependent mortality as a function of the *r* and *p* parameters. Left to right shows the effect of increasing the inflection point (*p*) while top to bottom show the effect of increasing the r parameter (*r*) on damage-dependent mortality. Circles show observations from damage and mortality surveys at BCI. In simulations in which this damage-dependent mortality was on, we set *p* = 0.9 and *r* = 5.5 (middle row, far right).

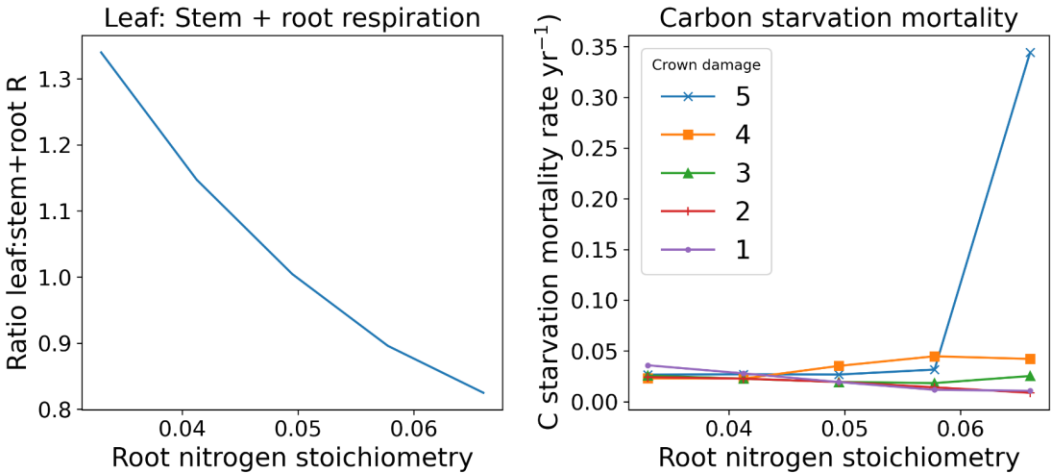

Figure S3. Effects of root nitrogen stoichiometry on the simulated ratio of leaf to stem + root respiration (left) and rates of carbon starvation mortality by damage class. The left hand panel shows the simulated ratio of total leaf to total stem + root growth and maintenance respiration as a function of root N stoichiometry in the control model (s1). The right hand panel shows carbon starvation mortality in each damage class as root N stoichiometry is increased. A decrease in the ratio of leaf to stem + root respiration causes a large increase in carbon starvation mortality in damaged trees.

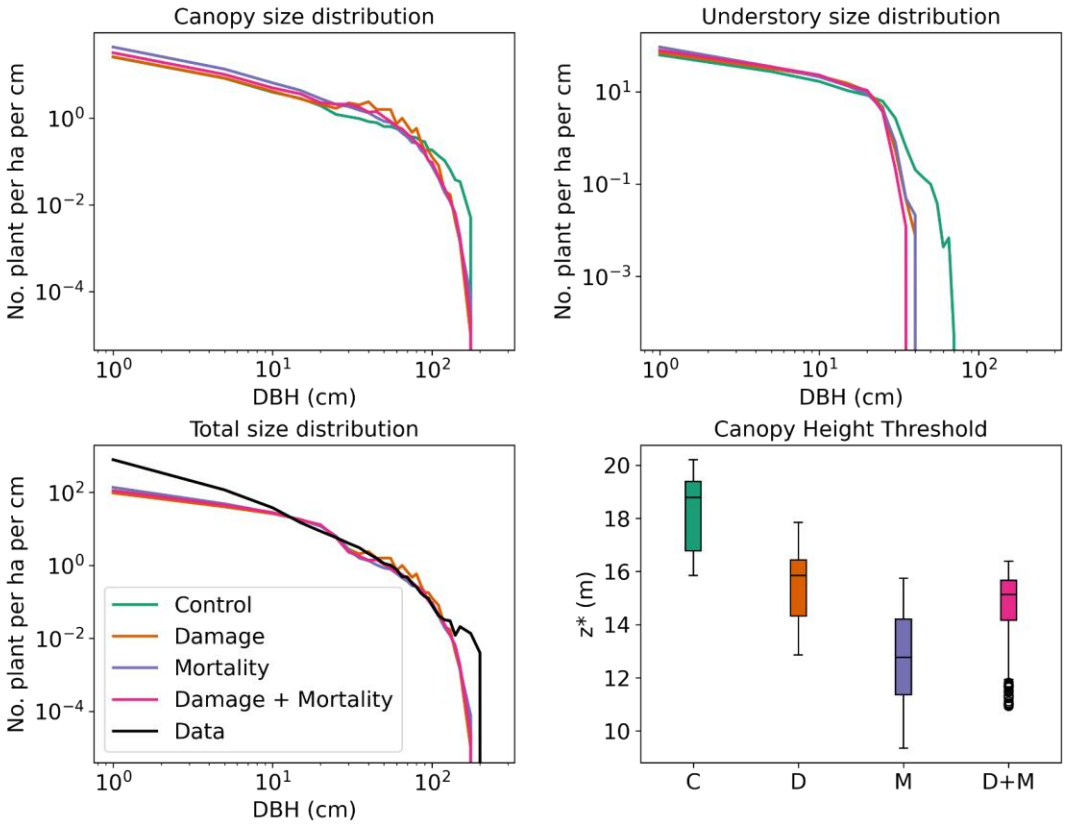

Figure S4. Simulated size distributions under four damage scenarios. The size distributions here are the mean number of individuals per ha over the last 50 years of the simulation, accounting for size bin width. The control simulation (C) (s1) has the damage module turned off. The damage simulation (D) (s2) has crown damage turned on - i.e. cohorts lose crown area and canopy biomass. In the mortality simulation (M) (s3) cohorts are split into damage classes and are subjected to damage related mortality but do not have any reduction in crown area or canopy biomass. In the damage + mortality simulation (D+M) (s4) cohorts have both crown damage and damage related mortality. Simulations with damage or damage mortality have fewer large trees in the understory since these cohorts are being promoted to the canopy due to either increases in mortality creating canopy gaps, and/or smaller crowns in the canopy allowing for a higher density of canopy cohorts. The bottom right panel shows the height threshold for a cohort being in the canopy in patches over 50 years, over the last 100 years of the simulation.

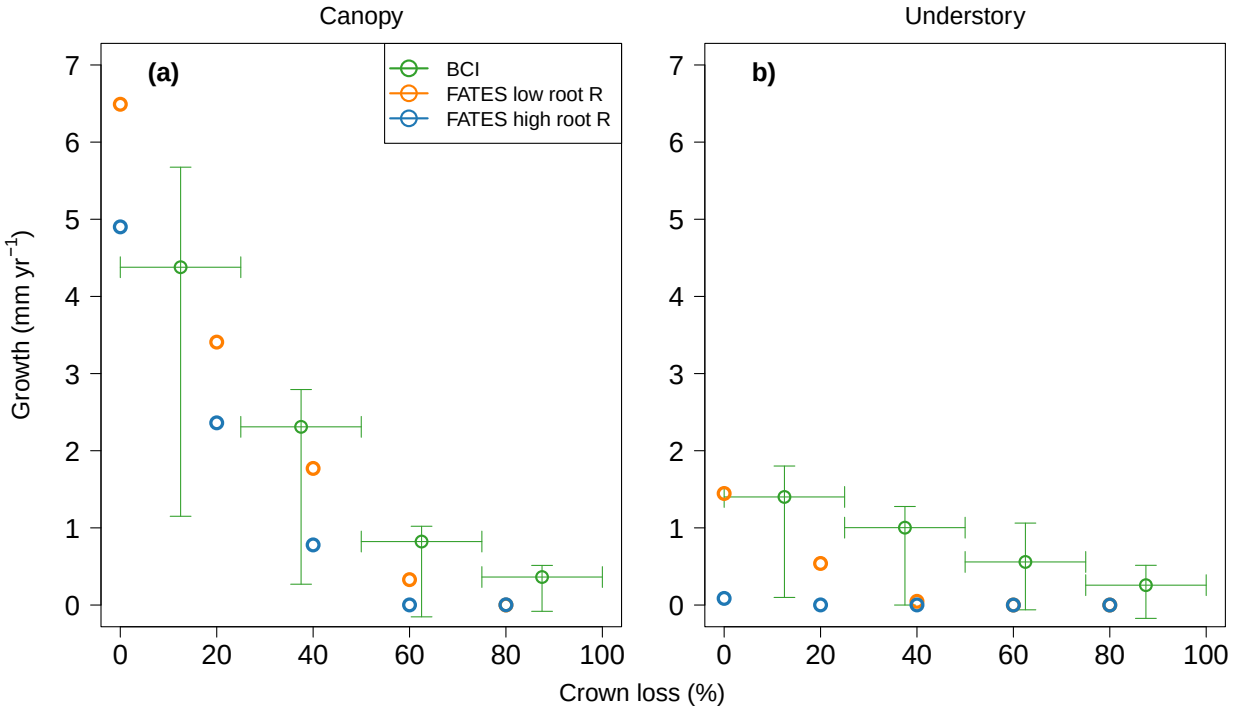

Figure S5. Annual growth rate by damage class and canopy layer in FATES simulations and observations from BCI. Orange circles show the low root N configuration of FATES (s4) and blue circles show the high root N configuration of FATES (s10). Green lines show growth rates from dendrometer band data at BCI, divided into canopy and understory. Error bars show the 50th percentile of growth rates across five census intervals. Note that damage classes in the observations are different than in FATES simulations, and hence points are offset. Damage classes in the observations include trees with a range of crown loss shown with horizontal lines, whereas in FATES damage classes correspond to a fixed percentage of crown loss. In the observational data from BCI trees with > 50% liana cover are excluded. See Fig. 5 for a version of this figure in which trees with high liana load are included.

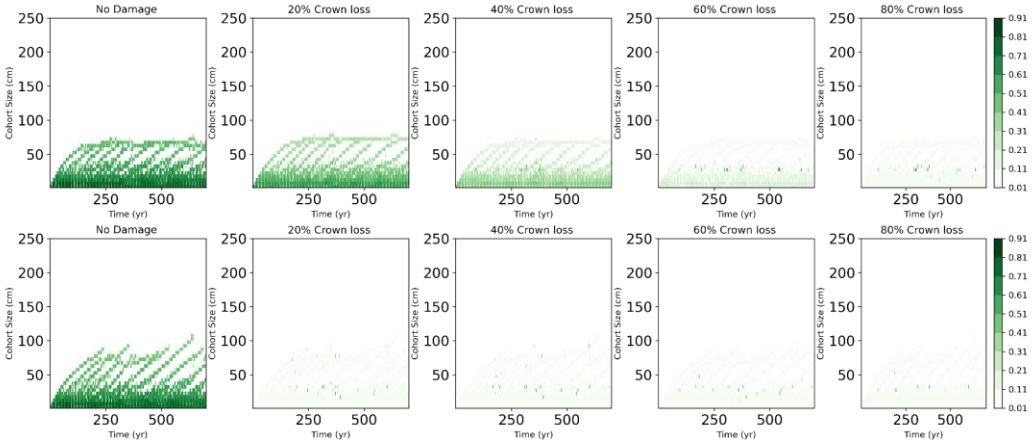

Figure S6. Size-dependent growth rates by damage class in a two PFT simulation (s5) with low and high recovery. When recovery is 1 (bottom row) NPP is used to re-grow canopy tissues at the expense of DBH growth. When recovery is 0 (top row) DBH growth is higher, but still declines with increasing crown loss.

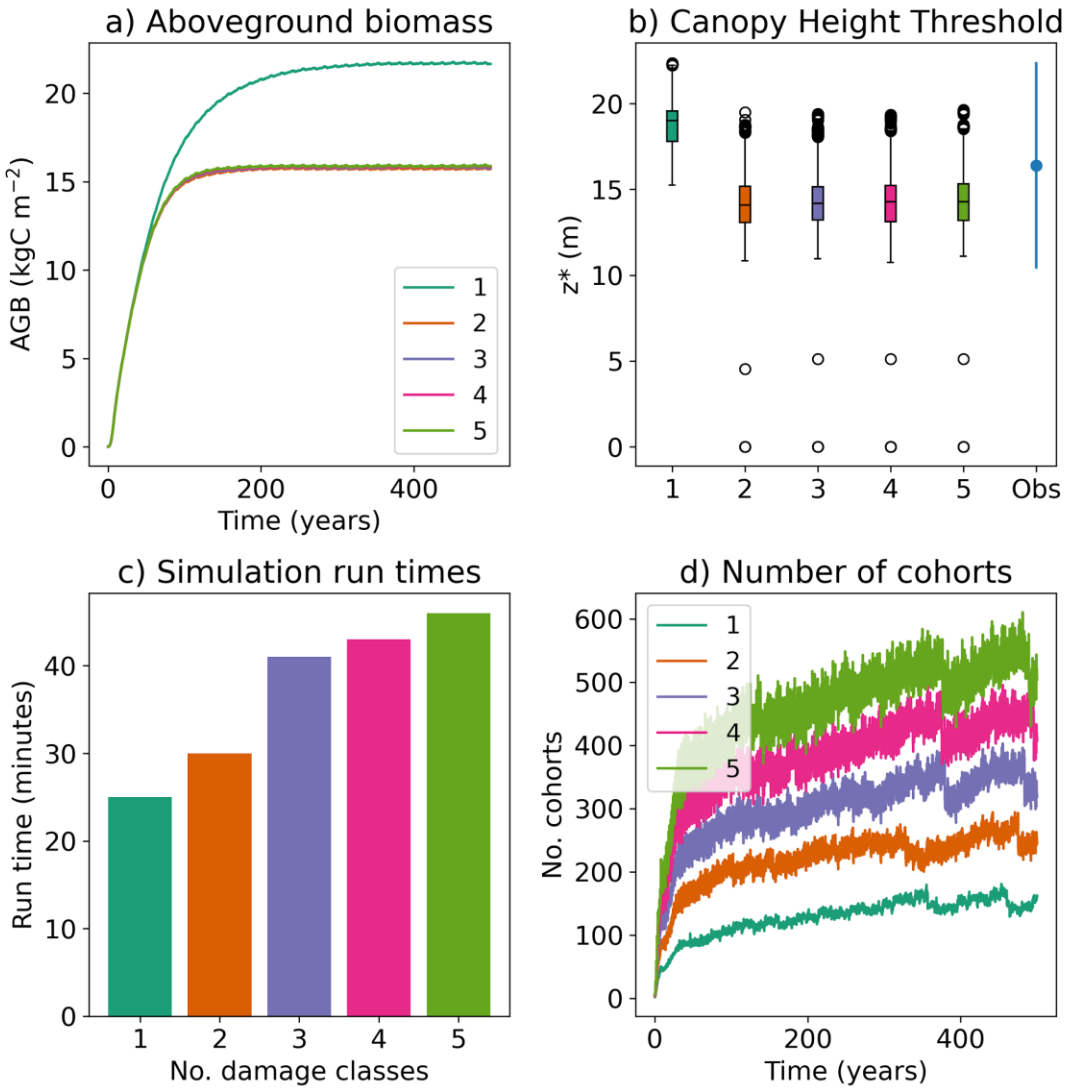

Figure S7. Sensitivity to the number of crown damage classes (s8). One damage class corresponds to only healthy trees (damage module off). Simulations with damage on always include an 80% crown loss class, with additional crown damage classes corresponding to lower levels of crown loss (see table S1). Aboveground biomass (a) and canopy height threshold (b) are lower in simulations with crown damage than in the control, but are unaffected by the number of crown damage classes. Simulation run times, here the time in minutes for the last 25 years of the simulation to run, increase with increasing numbers of damage classes (c), due to an increase in the number of cohorts to be tracked (d).

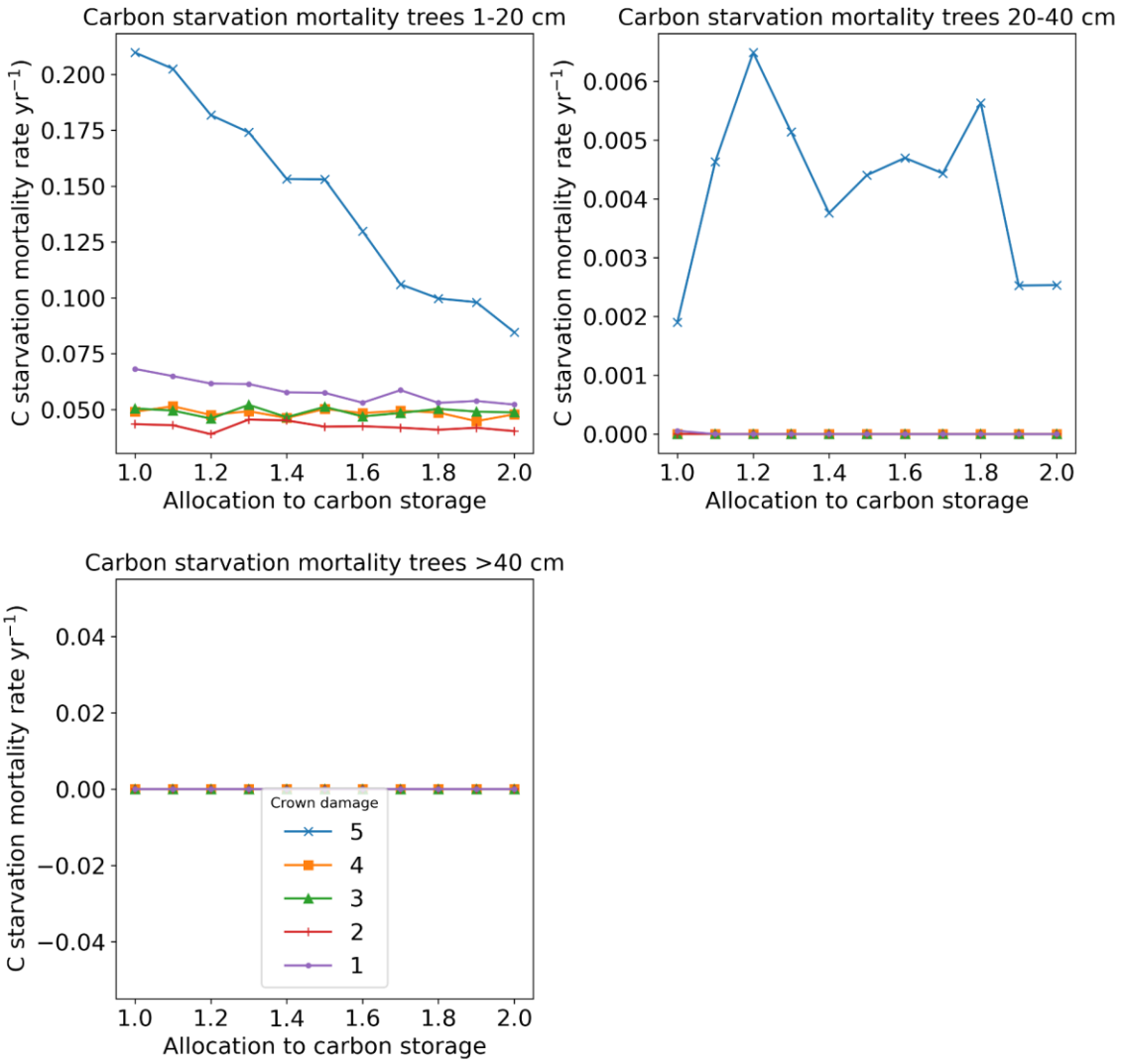

Figure S8. Carbon starvation mortality as a function of allocation to storage carbon (s7). In large trees (>40 cm) carbon starvation mortality was independent of allocation to storage carbon or the degree of damage. In small trees (between 1 and 40 cm DBH) with 80% crown loss increased allocation of carbon to storage led to decreased carbon starvation mortality.

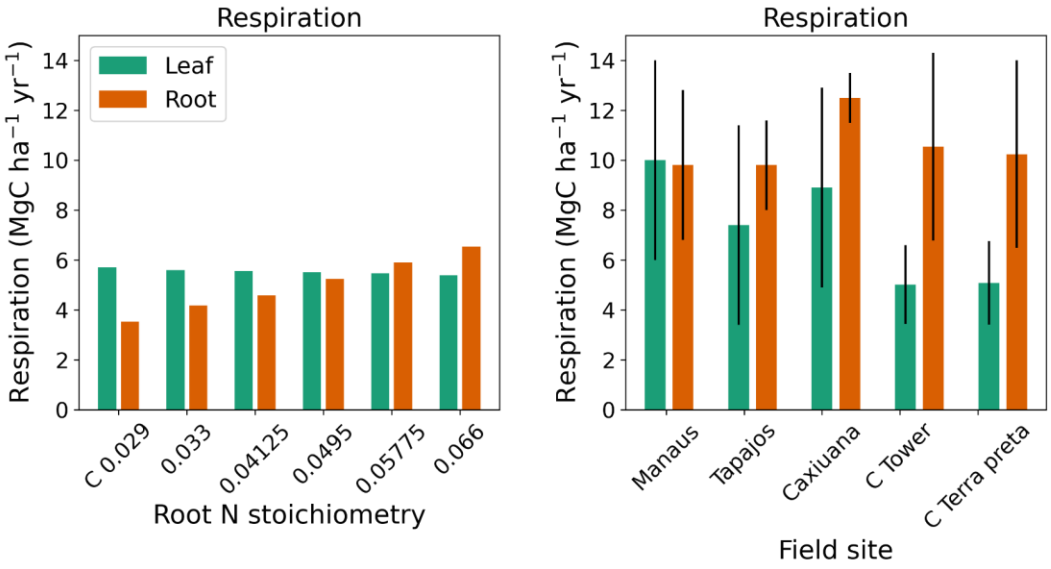

Figure S9. Leaf and stem + root respiration in FATES ensemble and observations. The left hand panel shows growth and maintenance respiration from an ensemble (s10) in which root N stoichiometry was increased from 0.033 to 0.066. The two left bars show a control (C) with the default parameterisation in FATES. The right hand panel shows values from Malhi et al. (2009) and Doughty et al. (2014). FATES underestimates stem and root respiration in all ensemble members although the ratio of leaf to stem and root respiration in the final ensemble member (with root N stoichiometry of 0.066) is within the range of the data.

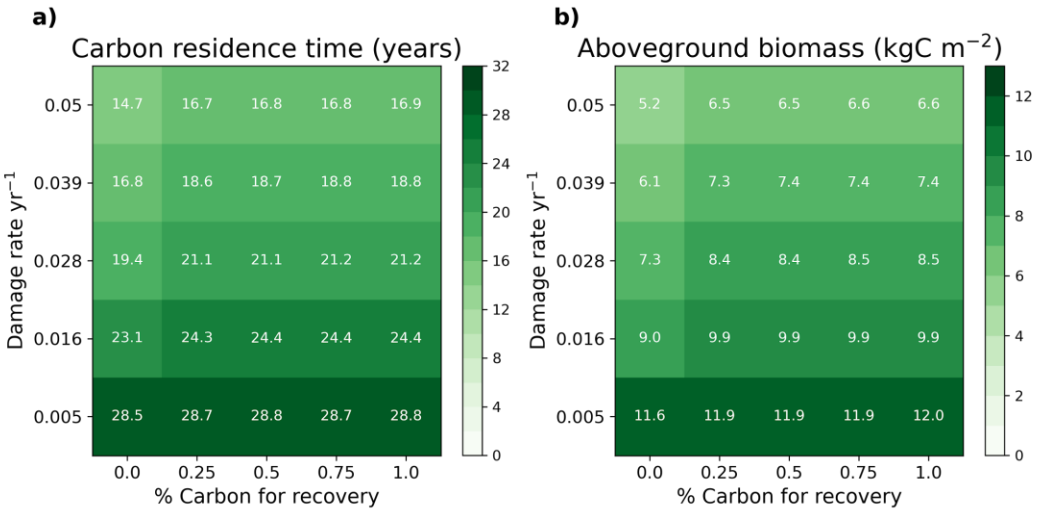

Figure S10. Sensitivity of AGB and carbon residence time to damage and recovery rates (s11). The recovery scalar determines the fraction of available carbon that goes towards recovery versus growth within the current damage class. The damage rate determines the fraction of

each cohort that is damaged each year. As the damage rate increases both carbon residence time a) and AGB b) decrease. In contrast, as the recovery scalar increases, and more cohorts recover, both carbon residence time and AGB increase.

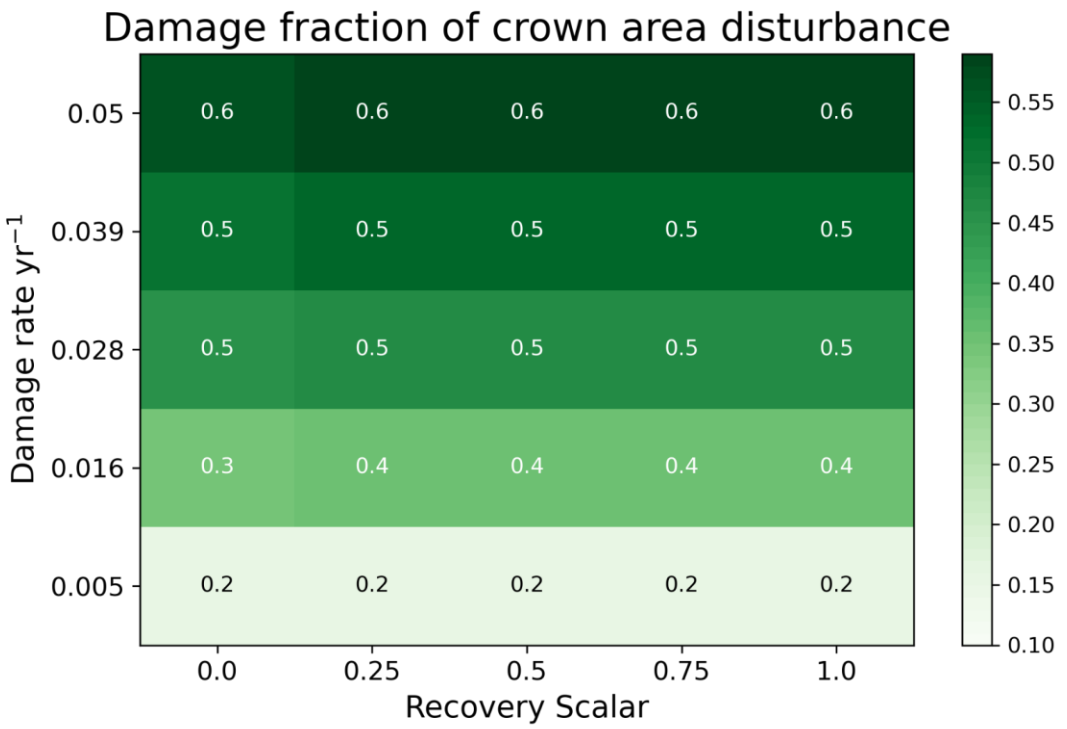

Figure S11. Fraction of canopy turnover from damage as a function of damage and recovery rate (s11). The proportion of canopy turnover from damage versus mortality increases as damage fraction and recovery scalar parameters increase. The fraction of canopy turnover from damage is most similar to observations at BCI when damage rate is 0.005 yr^{-1} and recovery scalar is 1.

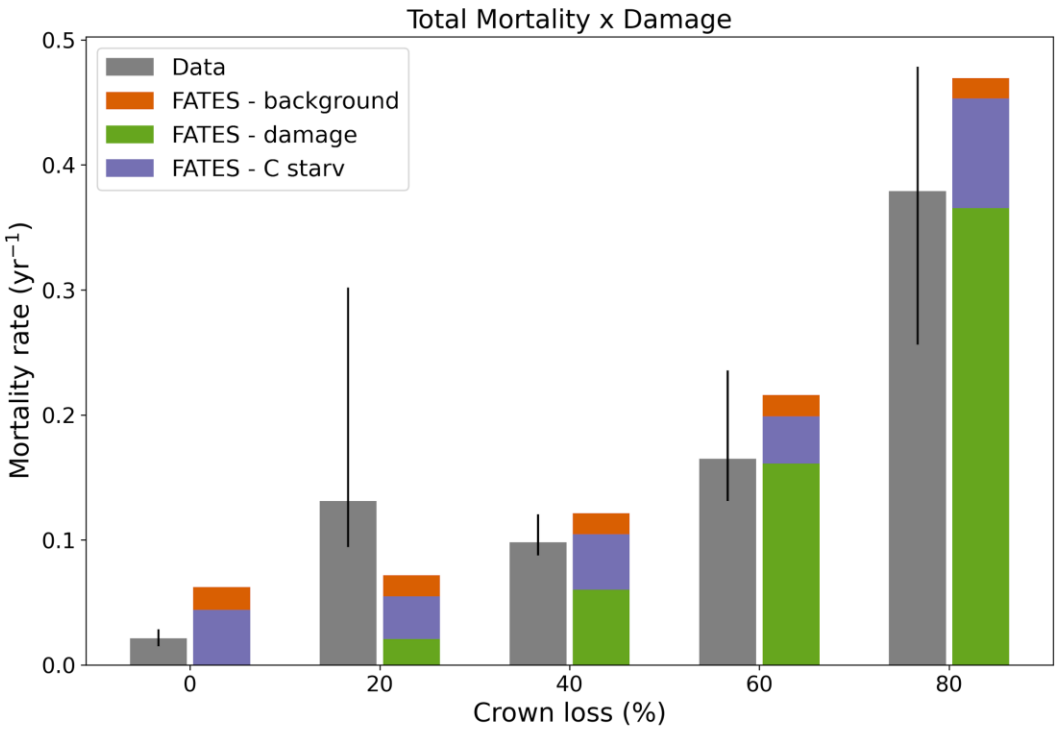

Figure S12. Mortality by crown damage class in empirical data and in the damage and mortality simulation (s4). Annual mortality from observations at BCI are shown with grey bars. Error bars show the range of mean mortality across three censuses. Background mortality from FATES simulations is shown with orange bars, damage dependent mortality is shown with green bars, and carbon starvation mortality with purple bars.