



# Age-dependent leaf physiology and consequences for crown-scale carbon uptake during the dry season in an Amazon evergreen forest

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## Summary

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- Satellite and tower-based metrics of forest-scale photosynthesis generally increase with dry season progression across central Amazônia, but the underlying mechanisms lack consensus.
- We conducted demographic surveys of leaf age composition, and measured the age dependence of leaf physiology in broadleaf canopy trees of abundant species at a central eastern Amazon site. Using a novel leaf-to-branch scaling approach, we used these data to independently test the much-debated hypothesis – arising from satellite and tower-based observations – that leaf phenology could explain the forest-scale pattern of dry season photosynthesis.
- Stomatal conductance and biochemical parameters of photosynthesis were higher for recently mature leaves than for old leaves. Most branches had multiple leaf age categories simultaneously present, and the number of recently mature leaves increased as the dry season progressed because old leaves were exchanged for new leaves.
- These findings provide the first direct field evidence that branch-scale photosynthetic capacity increases during the dry season, with a magnitude consistent with increases in ecosystem-scale photosynthetic capacity derived from flux towers. Interactions between leaf age-dependent physiology and shifting leaf age-demographic composition are sufficient to explain the dry season photosynthetic capacity pattern at this site, and should be considered in vegetation models of tropical evergreen forests.

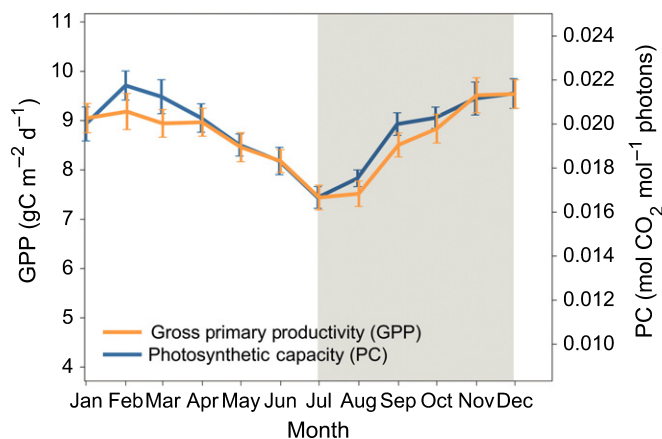
## Introduction

Seasonality is a major source of natural variation in climatic variables, and is known to drive cycles of plant productivity in many ecosystems (Keeling *et al.*, 1995; Penuelas *et al.*, 2009; Richardson *et al.*, 2012). Much of the Amazon rainforest – the largest tropical forest in the world – experiences seasonality of rainfall as a result of convection associated with the migration of the Intertropical Convergence Zone, coastal squall lines and other

meteorological systems (Horel *et al.*, 1989; Santos *et al.*, 2014; Batista da Silva Ferreira *et al.*, 2015). Evergreen forests of central Amazônia that experience wet and dry seasons show a curious pattern of dry season increase in gross primary productivity (GPP) derived from eddy covariance (EC) (Fig. 1; Saleska *et al.*, 2003; Hutryra *et al.*, 2007; Restrepo-Coupe *et al.*, 2013; Wu *et al.*, 2016), in contrast with many current land surface models (LSMs) that simulate decreasing GPP with seasonal declines in precipitation and soil water availability (Verbeeck *et al.*, 2011;

Restrepo-Coupe *et al.*, 2017). Landscape-scale remote sensing studies complement site-specific EC studies and show increases in vegetation indices ('green-up') during dry seasons over much of the central Amazon basin (Huete *et al.*, 2006; Bi *et al.*, 2015). Although the magnitude of the satellite-observed dry season green-up has been questioned (Morton *et al.*, 2014), it is statistically significant (Saleska *et al.*, 2016), and it suggests dry season changes in photosynthetic processes. Identifying the mechanism(s) driving the dry season GPP pattern, and developing LSMs accordingly, is important for attribution of seasonal changes to appropriate causes (Wu *et al.*, 2016) and, ultimately, for predictions of forest response to global climate change (Restrepo-Coupe *et al.*, 2017), as Amazônia is predicted to experience more severe dry periods in the future (Marengo *et al.*, 2012).

Hypothesized mechanisms for the late dry season GPP increase include: (1) increases in photosynthesis as a result of environmental changes (e.g. increased light availability; Tian *et al.*, 2000; Goulden *et al.*, 2004; Ichii *et al.*, 2005); (2) increases in the quantity of leaves (leaf area index, LAI) throughout the dry season (Goulden *et al.*, 2004; Myneni *et al.*, 2007); and (3) an increase in average leaf-level photosynthetic capacity (Goulden *et al.*, 2004; Doughty & Goulden, 2008; De Weirdt *et al.*, 2012; Kim *et al.*, 2012; Wu *et al.*, 2016). Although these hypotheses (Fig. 2) are not mutually exclusive, they have implications for the corrective features required to re-structure LSMs and the type of data required for large-scale parameterization. Seasonal changes in the environment demand greater understanding of the microclimate of complex canopies through time; shifts in LAI demand an understanding of when and where leaf birth or death dynamics are altering structure; and changes in leaf-level photosynthesis require an understanding of how the seasonality of this physiological process relates to plant strategy and the environment.



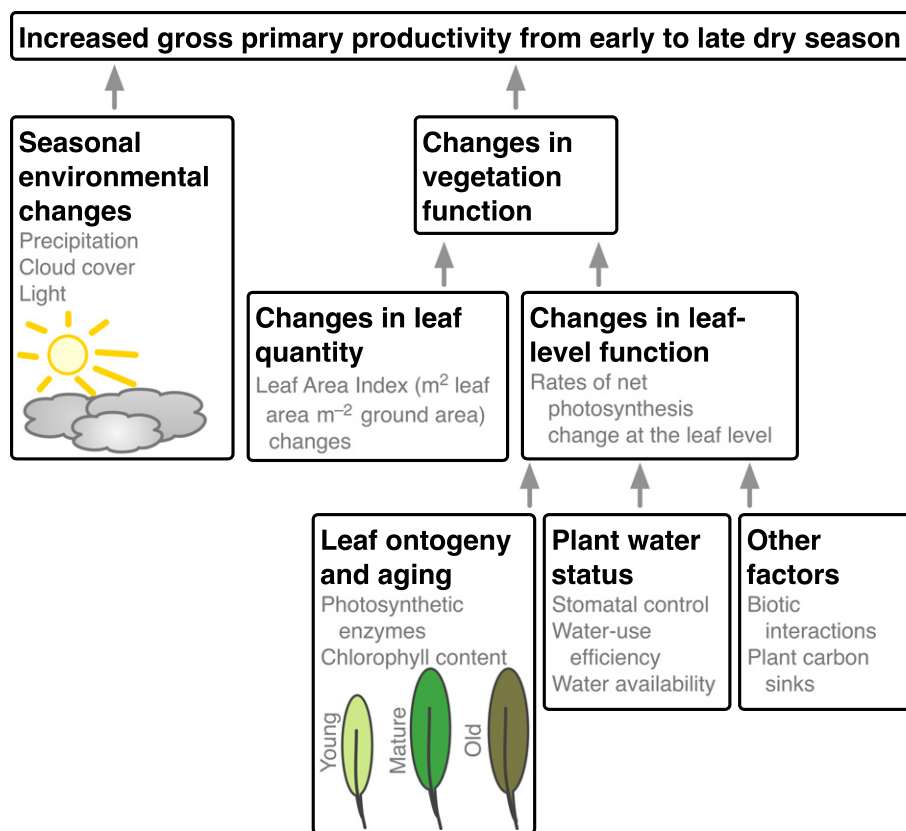
**Fig. 1** Annual cycle of eddy covariance-derived gross primary productivity (GPP) and canopy-scale photosynthetic capacity (PC), averaged over years (2002–2005 and 2009–2011) at K67 in the Tapajós National Forest, Brazil. The shaded gray region indicates the dry season. GPP is derived from the net ecosystem exchange (NEE) by assuming that nighttime NEE is representative of daytime ecosystem respiration. PC, the canopy-scale rate of carbon fixation per unit of light under reference environmental conditions, is derived from averaging the measured GPP : photosynthetically active radiation (PAR) ratio when PAR, vapor pressure deficit, air temperature and cloudiness all fall within fixed narrow ranges (replotted from Wu *et al.*, 2016). Error bars are  $\pm 1$  SE.

Previous studies comparing the hypothesized drivers of GPP seasonality have provided evidence that seasonal changes in environment or leaf quantity are insufficient to explain the observed dry season increases in EC-derived GPP (Doughty & Goulden, 2008; Wu *et al.*, 2016, 2017b). Ecosystem scale photosynthetic capacity (PC), a metric of ecosystem carbon uptake per unit incident light that is derived from GPP under fixed environmental conditions (photosynthetically active radiation, vapor pressure deficit, air temperature and cloudiness; Restrepo-Coupe *et al.*, 2013; Wu *et al.*, 2016), also increases as the dry season progresses (Fig. 1), suggesting that dry season increases in photosynthesis are not simply a result of environmental factors, but of biotic factors, such as leaf quantity (Wu *et al.*, 2016). However, changes in leaf quantity alone are also insufficient to account for GPP or PC seasonality according to modeling assessments and ground-based estimates of LAI, which show only modest seasonal variation (Doughty & Goulden, 2008; Brando *et al.*, 2010; Wu *et al.*, 2016).

A growing number of studies support the third hypothesis: seasonal increases in leaf-level photosynthetic capacity, with leaf phenology (the timing of leaf production and abscission) mediating the leaf-level increase (Doughty & Goulden, 2008; Restrepo-Coupe *et al.*, 2013; Wu *et al.*, 2016). Leaves undergo structural and biochemical changes during development, aging and senescence (Niinemets *et al.*, 2012; Pantin *et al.*, 2012). Any degree of synchronization of leaf phenology across crowns during the dry season would produce canopy-scale shifts in mean leaf age, which could explain the observed seasonal changes in both EC-derived GPP (Doughty & Goulden, 2008; Wu *et al.*, 2016) and reflectance (Chavana-Bryant *et al.*, 2017; Wu *et al.*, 2017a) during the dry season.

However, the hypothesis that leaf phenology increases mean leaf-level photosynthetic capacity, and thus explains dry season GPP increases in central Amazon forests (the 'leaf demography-ontogeny hypothesis') lacks consensus, in part because of the uncertainties and limitations inherent in large-scale estimations of photosynthesis. Remote sensing of humid equatorial forests with dense canopies is challenging because of cloudiness (Asner, 2001; Samanta *et al.*, 2010), signal saturation (Myneni *et al.*, 2007) and sun-sensor geometry artifacts (Morton *et al.*, 2014; Saleska *et al.*, 2016). Partitioning EC-measured net ecosystem exchange into GPP and respiratory components assumes that unobserved daytime ecosystem respiration behaves the same as nighttime respiration (Reichstein *et al.*, 2005; Lasslop *et al.*, 2009), an assumption that does not always hold (Wehr *et al.*, 2016; Oikawa *et al.*, 2017). As the main support for the leaf demography-ontogeny hypothesis relies on estimates of PC that are themselves derived from EC-GPP (Wu *et al.*, 2016), independent tests are needed.

To date, there have been no studies that have directly tested the leaf demography-ontogeny hypothesis across individual trees with both leaf-level photosynthesis and leaf demography data from canopy species in an Amazon forest where EC-derived GPP and PC are also observed. Most studies of photosynthesis in tropical forests have focused on fully expanded leaves that were neither immature nor showing signs of senescence (e.g. Domingues



**Fig. 2** Hypothesized causes for increases in gross primary productivity (GPP) with dry season progression in Amazonian tropical evergreen forests divided into two general categories: changes caused by seasonal shifts in environmental drivers (far left panel), and/or changes caused by vegetation structure and function (remaining panels). The latter are additionally divided between changes caused by leaf quantity (e.g. leaf area index) and/or by leaf-level physiological function. Leaf-level function may change as a result of ontogeny, plant water status and/or biotic interactions.

*et al.*, 2014), but the rare studies of age-specific leaf traits (e.g. Chavana-Bryant *et al.*, 2017) or photosynthesis (Sobrado, 1994; Ishida *et al.*, 1999; Kitajima *et al.*, 2002; Alves *et al.*, 2014) have shown that the effects of leaf age on physiology are significant. In evergreen forests of central Amazônia, direct observations of tree crowns (Brando *et al.*, 2010; Lopes *et al.*, 2016) and litterfall (Doughty & Goulden, 2008) have suggested dry season changes in leaf demography. Missing are studies that integrate field-based leaf demographic surveys with photosynthesis measurements in the same individual trees, where such coupled measurements have the power to show whether the timing and magnitude of changes in tree photosynthetic capacity agree with EC-derived PC. Furthermore, there are multiple limitations on photosynthesis, including biophysical limitations (e.g. stomatal conductance) and biochemical limitations (e.g.  $V_{\text{cmax}}$ , the maximum carboxylation rate of ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco), and  $J_{\text{max}}$ , the maximum rate of ribulose bisphosphate (RUBP) regeneration; Sharkey *et al.*, 2007), and so it is important to examine multiple constraints across leaves of different ages.

Here, we test the hypotheses that (1) leaf physiology, particularly photosynthetic capacity, is affected by leaf age; and (2) the leaf age composition (leaf demography) of individual tree crowns varies during the dry season in a moist tropical forest of the Amazon. Then we examine the combined effects of leaf age-dependent physiology and leaf demography on branch-level photosynthetic capacity. We compare the magnitude and direction of dry season changes in aggregate branch-level PC with previously reported EC-derived estimates of the canopy-level PC

(Wu *et al.*, 2016; Restrepo-Coupe *et al.*, 2017) to evaluate the consistency of 'bottom-up' leaf-to-branch estimates with 'top-down' EC-derived estimates of photosynthetic capacity.

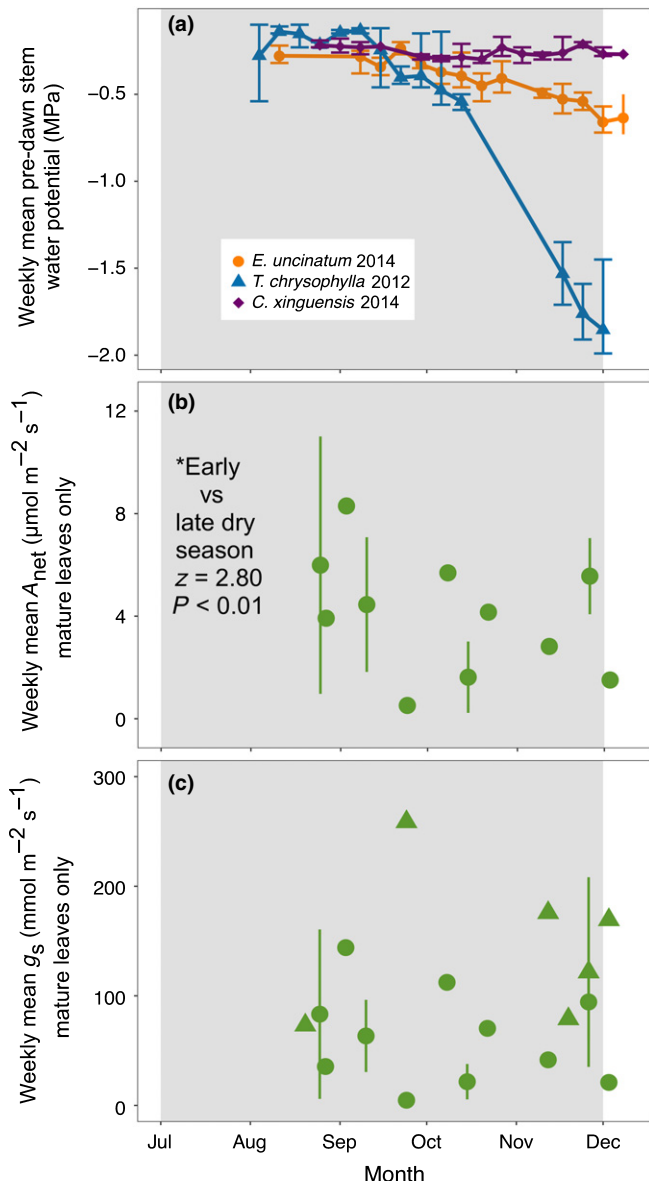
## Materials and Methods

### Site

All trees studied were within the footprint of the LBA-ECO EC tower located in the Tapajós National Forest (TNF; 54°58'W, 2°51'S, Pará, Brazil) near kilometer 67 (K67) of BR-163 (Hutyra *et al.*, 2007). The forest is classified as moist evergreen tropical forest, receiving an average of 2022 mm yr<sup>-1</sup> of precipitation, and typically experiencing a 5-month dry season (months with < 100 mm precipitation) from *c.* 15 July to *c.* 15 December each year (Rice *et al.*, 2004; Hutyra *et al.*, 2007). The forest is on flat terrain with a mean canopy height of *c.* 40–45 m (Hutyra *et al.*, 2007). During a typical dry season, canopy trees at this site generally maintain pre-dawn stem water potential above 2 MPa (Fig. 3a; Supporting Information Methods S1). For details on forest composition and structure, see Rice *et al.* (2004) and Vieira *et al.* (2004), and for information on the soil and water table, see Nepstad *et al.* (2002).

### Tree selection and canopy access

Five canopy trees (25–44 m tall) were selected for both leaf physiology measurements and leaf demographic surveys: *Erisma*



**Fig. 3** Time series during the dry season (gray) showing progression of (a) weekly mean pre-dawn (05:30 h) stem water potential for three trees (*Erisma uncinatum*, *Tachigali cf chrysophylla* and *Chamaecrista xinguensis*) using available data from 2012 to 2014, (b) weekly mean net assimilation rate ( $A_{net}$ ) of mature leaves only using within-tree means, and (c) weekly mean stomatal conductance ( $g_s$ ) of mature leaves only using within-tree means (Supporting Information Table S9; Figs S2, S3). Within-tree means in (b, c) are for seven trees (*Erisma uncinatum*, *Tachigali cf chrysophylla*, *Chamaecrista xinguensis*, *Mezilaurus itauba*, *Coussarea paniculata* and two *Manilkara elata*). Reference cell  $[CO_2]$  was  $350 \mu\text{mol mol}^{-1}$  for  $A_{net}$  and  $g_s$  from Li-Cor 6400. For  $g_s$ , circles show conductance from a Li-Cor 6400, and triangles show conductance from a porometer. Net assimilation in (b) shows a decrease from early (before October 15) to late (after October 15) in the dry season when mature leaves – the age conventionally chosen for ecophysiology studies – are examined (Table S2), a contrast with canopy-scale gross primary productivity (GPP) (Fig. 1). Error bars show data range in (c), and  $\pm 1$  SD of tree means in (b, c).

*uncinatum* Warm., *Manilkara elata* (Allemão ex Miq.) Monach., *Mezilaurus itauba* (Meisn.) Taub. ex Mez, *Tachigali cf chrysophylla* (Poepp.) Zarucchi & Herend. and *Chamaecrista*

*xinguensis* (Ducke) H.S. Irwin & Barneby. Their selection was based on the criteria that they represented abundant species (Table S1), they were within the footprint of the K67 EC tower and they could be accessed using arborist tree-climbing techniques. In addition, one mid-canopy tree *Coussarea paniculata* (Vahl) Standl., a second *Manilkara elata* accessible from a walk-up tower and a *Lecythis lurida* (Miers) S.A. Mori tree were opportunistically sampled. According to a biomass and species survey at the site (Vieira *et al.*, 2004; Pyle *et al.*, 2008) with resolved species names (Boyle *et al.*, 2013), these canopy trees belong to species accounting for *c.* 33% of the basal area at the K67 site. The crowns of the canopy trees included sun and shade microenvironments, with the exception of *T. cf chrysophylla*, which had an umbrella-shaped crown with few shaded branches, and *C. paniculata*, the mid-canopy tree with all branches shaded. The *T. cf chrysophylla* and *C. xinguensis* trees had compound leaves, and all other trees had simple leaves. Leaflets from compound leaves were used for all physiological measurements and counted as leaves for the leaf demographic surveys because we observed that individual leaflets on the same compound leaf showed variation in color and degree of expansion, suggesting that individual leaflets can reach maturity at different times. For the sampling of leaves and branches for physiological measurements and leaf demography (see sections below), single rope access techniques were used to climb into individual crowns of canopy trees. Leaving climbing ropes in trees can compromise rope integrity, and so trees were rigged and de-rigged with climbing ropes on each day of sampling. Tree climbing required the setting up of two rope systems, one for access into the canopy and one for movement within the canopy (branch-walking methods with a tie-in point high in the tree in combination with a lanyard). These arborist techniques allowed us to access branches that experienced sun and shade microenvironments at heights in excess of 35 m. The mid-canopy *C. paniculata* tree was accessed from above using a tie-in point from a larger canopy tree nearby or sampled with pole-pruners.

### Leaf-level gas exchange measurements

Leaf-level gas exchange at the K67 site was measured with a portable infrared gas exchange measurement system (LI-6400; Li-Cor Biosciences, Lincoln, NE, USA) during dry season field-work campaigns: August through December 2012, August 2013 and (for *C. paniculata* only) July 2015. Branch samples from the selected trees (Table S1) were collected via tree climbing, and included branches from both sunny and shady microenvironments if both were present. Before gas exchange measurements, branches were cut, gently lowered to the ground with ropes and recut under water within 15 min.

For each branch, leaves were then classified into age categories based on Chavana-Bryant *et al.* (2017), and further informed by *in situ* leaf tagging and photodocumentation carried out in these focal species to demonstrate leaf development (see Fig. S1 in Wu *et al.*, 2017a). Briefly, independently for each species, leaves were assigned age categories (young, mature, old) through visual assessment of leaf color, size, rigidity and position in relation to



other leaves and/or bud scars (for examples, see Fig. S1). ‘Young’ described immature leaves (<2 months old, not fully expanded and/or not fully green). ‘Mature’ described leaves that had recently reached maturity (fully expanded, green and 2–5 months old). ‘Old’ described leaves basal of young and mature leaves that were not yet senescent (fully expanded, attached below bud scars when bud scars were present and >5 months old).

Gas exchange was typically measured for each age category present on the sampled branch. Measurements of net CO<sub>2</sub> assimilation rate vs calculated substomatal CO<sub>2</sub> concentration ( $A/C_i$  curves) were conducted with an LI-6400 under a standardized set of conditions: block temperature was  $31 \pm 2^\circ\text{C}$ , photosynthetically active radiation was saturating ( $999\text{--}2001 \mu\text{mol m}^{-2} \text{s}^{-1}$ , estimated from a previous test for each tree) and relative humidity was controlled between 20% and 67%. Previous temperature response curves at this site showed an optimal photosynthesis temperature of  $c. 31^\circ\text{C}$  (Tribuzy, 2005). For all samples, the leaf area for gas exchange was  $6 \text{ cm}^2$  and the stomatal ratio was assumed to be 1. Oxygen concentration was not manipulated, and was assumed to be 21%. For  $A/C_i$  curves, the reference CO<sub>2</sub> concentrations were controlled as follows: 400, 100, 50, 100, 150, 250, 350, 550,  $750 \mu\text{mol mol}^{-1}$ , and then increased by increments of between 200 and  $500 \mu\text{mol mol}^{-1}$  to reach saturation at around  $2000 \mu\text{mol mol}^{-1}$ . We show the net assimilation ( $A_{\text{net}}$ ) at  $350 \mu\text{mol mol}^{-1}$  over the dry season (Fig. 3b). Before curve fitting (see the ‘Analysis’ section below), quality control for gas exchange measurements was applied to exclude values associated with instrument error and other likely outliers. It should be noted that, if initial gas exchange measurements from a candidate tree showed signs that recutting under water did not re-establish the water column, the tree was excluded from future gas exchange measurements (this was the case for the *L. lurida* tree). After quality control, a total of 97  $A/C_i$  curves were available for analysis. A subset of the  $V_{\text{cmax}}$  parameters from these curves was reported in Wu *et al.* (2016). (Gas exchange data are available from the Dryad Digital Repository: <https://doi.org/10.5061/dryad.h83t0>.)

### *In situ* stomatal conductance measurements

The stomatal conductance ( $g_s$ ) of the abaxial surface of the leaves was measured *in situ* in the canopy using a steady-state leaf porometer (Decagon Devices, Pullman, WA, USA) in automatic mode for five trees early in the dry season, before 15 October (Fig. S2), and nine trees late in the dry season, from 15 October to the end of the dry season (Fig. S3). From one to 29 leaves were selected for  $g_s$  measurement from each leaf age category present on branches at one to two locations within the crown that were accessible via climbing (see Table S9). When the same trees were measured both early and late in the dry season, the same leaves were measured at both time periods (if a leaf was missing, it was replaced with a nearby leaf of the original age category). Whenever possible, leaves were measured sequentially and repeatedly, such that each leaf was measured one to six times between the hours of 08:20 h and 16:55 h over 1–2 d. Multiple measurements for each leaf were averaged before meta-analysis (see the ‘Analysis’ section below).

(Porometer  $g_s$  data are available from the Dryad Digital Repository: <https://doi.org/10.5061/dryad.h83t0>.)

### Chlorophyll concentration

One to seven leaves from five trees (Table S1) were collected using arborist canopy access techniques on 13–15 November 2012, wrapped individually in aluminum foil, frozen in liquid nitrogen and kept frozen until chlorophyll was extracted (23 November, UFOPA campus). To determine Chl*a*, Chl*b* and total (Chl*a*+Chl*b*) content of leaves,  $c. 0.5 \text{ g}$  (FW) of each leaf was macerated in 7 ml of 80% acetone and then filtered. The filtrate volume was increased to a total of 20 ml. The supernatant was removed and the absorbance was measured at 663 nm and 647 nm for Chl*a* and Chl*b*, respectively, using a spectrophotometer (3300 UV; Nova Instruments, Ahmedabad, India), and the absorbance was used to estimate the chlorophyll content following Lichtenthaler (1987) (see Methods S2 for equations). (Chlorophyll concentration data are available from the Dryad Digital Repository: <https://doi.org/10.5061/dryad.h83t0>.)

### Leaf chemistry

A subsample of 6–95 leaves per leaf age category per tree from branch demography surveys, including almost all leaves used for gas exchange, were also analyzed for leaf chemistry (percentage nitrogen and carbon-to-nitrogen ratio). Leaves were placed into labeled envelopes and dried for at least 72 h at  $c. 60^\circ\text{C}$  in a drying oven. Leaf carbon and nitrogen composition were determined in a combustion analyzer coupled to a mass spectrometer for carbon isotopic analysis at the Centro de Energia Nuclear na Agricultura (CENA-USP), Piracicaba, Brazil. A standard of known isotopic content was run every 11 samples. (Leaf chemistry data are available from the Dryad Digital Repository: <https://doi.org/10.5061/dryad.h83t0>.)

### Assessing leaf demography of branches

We coupled the above measurements of leaf physiology with branch-level leaf demography surveys of co-occurring leaves on the same focal trees (Table S1). Field-based surveys of the number of leaves of different ages on individual branches (leaf demography of branches) can be a useful way to estimate leaf demography of crowns (Chavana-Bryant *et al.*, 2017). Leaf demography was assessed for each tree during the dry season in 2012 (August–December), 2013 (November) and 2014 (March for all trees, and again in July–August for three trees). To survey leaf demography for each tree,  $c. 1\text{-m}$ -long branches were collected from sun and shade microenvironments within the crown, depending on the microenvironments present as a result of crown structure (i.e. only sun branches for *Tachigali cf chrysophylla*). For each branch, leaves were then classified into age categories and counted. Leaves were categorized by age as described in the ‘Photosynthetic gas exchange’ section. Sometimes multiple (one to five) 1-m branches from similar microenvironments were surveyed on the same date, and averaged by combination of light

environment (sun or shade) and sample date for each tree before analysis. (Leaf demography data are available from the Dryad Digital Repository: <https://doi.org/10.5061/dryad.h83t0>.)

## Analysis

We fitted the photosynthesis model developed by Farquhar *et al.* (1980), with triose phosphate use (TPU) limitation (Harley *et al.*, 1992), to the  $A/C_i$  response curve data using a curve-fitting routine in the R computing environment (R Core Team, 2016) based on minimum least-squares (Domingues *et al.*, 2010). We report the following parameter estimates normalized to 25°C using the temperature dependences summarized in Sharkey *et al.* (2007):  $V_{\text{cmax}}$  (maximum carboxylation capacity),  $J_{\text{max}}$  (maximum rate of photosynthetic electron transport) and TPU.

Because not all trees exhibited leaves of all age categories during our sampling periods, and because the timing of sampling was constrained by conditions safe for tree-climbing, datasets had unequal sample sizes and/or did not include all possible combinations of time, tree and leaf age category. Meta-analysis, often used for pooling results from multiple independent datasets (Hedges *et al.*, 1999), therefore provided a useful method of summarizing the effect size of leaf age across multiple trees in our study. For each tree, we calculated the mean and variance of each physiological variable for each leaf age category (Tables S2–S13), and then used log-transformed response ratios ( $L$ ) and associated variance ( $v$ ) of photosynthetic characteristics to contrast mature leaves – the default for measurement in most ecophysiological studies – with young leaves and with old leaves for each tree (see Methods S3 for equations). We calculated  $L$  and  $v$  for the parameters from  $A/C_i$  curves, stomatal conductance and physiological trait data (total chlorophyll,  $\text{Chla}:\text{b}$  ratio, percentage nitrogen and carbon-to-nitrogen ratio), and then used fixed effect models fitted by weighted least-squares with the METAFOR package (Viechtbauer, 2010) in R (v.3.3.1). We evaluated the robustness of each meta-analysis by removing individual trees one at a time from the overall analysis to examine changes in statistical significance. We report the tree sample size ( $n$ ), unlogged response ratio (RR),  $z$ -score ( $z$ ) and  $P$  value.

Meta-analysis of the log response ratios was also used to contrast the number of leaves in different age categories early in the dry season compared with late in the dry season. Demographic survey data (the number of leaves in each age category and the total number of leaves) for all branches (sun and shade together) before 15 October (day of year, DOY = 288) for each tree were binned together as ‘early’ dry season, and leaf demographic surveys after 15 October were binned together as ‘late’ dry season. The wet season demographic surveys from 2014 were not included in this analysis as there was only one wet season survey date for each tree.

## Upscaling to estimate branch-level $V_{\text{cmax}}$

To examine how leaf-level changes in carboxylation capacity could affect ecosystem PC, we examined the combined effect of

leaf aging and leaf demography. We estimated  $V_{\text{cmax}}$  weighted by leaf demography (referred to as ‘branch-level  $V_{\text{cmax}}$ ’ in this study) for sun-exposed branches, shaded branches and all branches (sun and shade pooled) for each tree and sampling date (Methods S4). To estimate the magnitude of the change in branch-level  $V_{\text{cmax}}$  for sun and shade branches of each tree during the dry season, we fitted linear regressions of branch-level  $V_{\text{cmax}}$  vs DOY for the dry season period well constrained by data (DOY 200–350, see later Fig. 7a,b). To estimate the magnitude of the dry season shift in branch-level  $V_{\text{cmax}}$  across our focal trees, we calculated the mean slope and intercept for sun, shade and all branches, and tested whether the mean slope was significantly different from zero using two-sided  $t$ -tests (Methods S4).

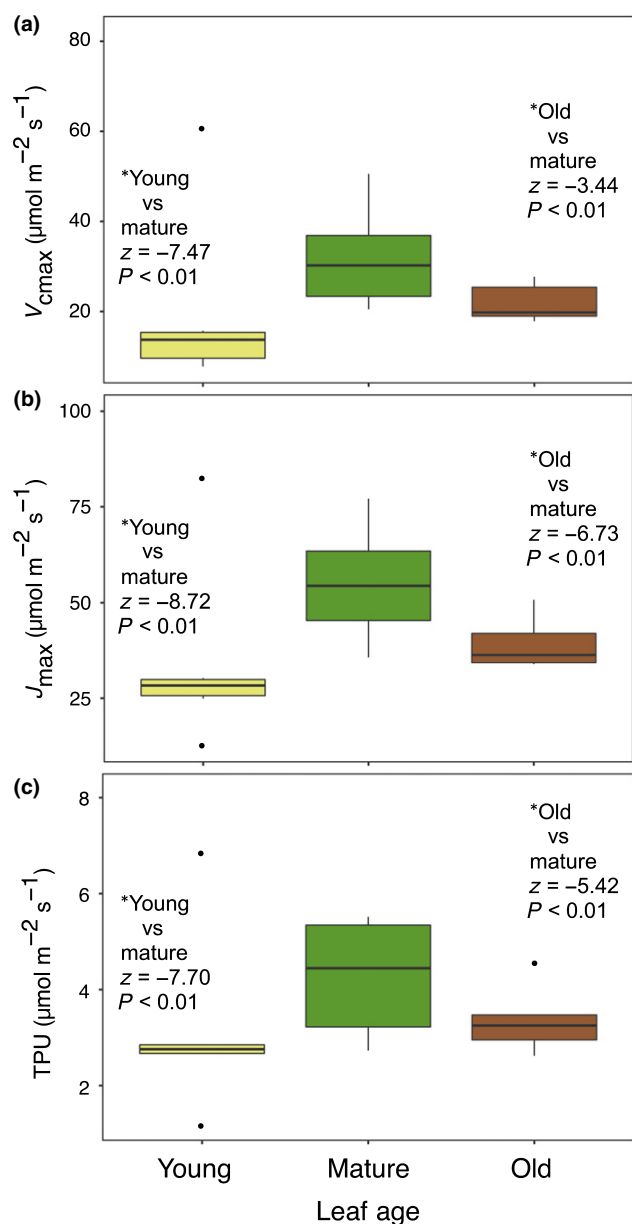
## Results

### Leaf-level gas exchange

Mature leaves showed a *c.* 14% average  $A_{\text{net}}$  decrease from early to late in the dry season (Fig. 3b;  $n = 4$  trees, RR = 1.32,  $z = 2.80$ ,  $P < 0.01$ ; although the significance is driven by one tree: Table S2). However, contrasting  $A/C_i$  parameters from gas exchange for leaves of different ages revealed an age dependence (Fig. 4). Sun and shade leaf  $A/C_i$  parameters showed a similar age dependence, and so were pooled for the analysis of leaf age means. Of the three age classes, mature leaves had the highest value for all  $A/C_i$  parameters. The average  $V_{\text{cmax}}$  of mature leaves was *c.* 60% greater than that of young leaves ( $n = 6$  trees, RR = 0.51,  $z = -7.47$ ,  $P < 0.01$ ; Fig. 4a) and *c.* 46% greater than that of old leaves ( $n = 6$  trees, RR = 0.80,  $z = -3.44$ ,  $P < 0.01$ ).  $J_{\text{max}}$  of mature leaves was, on average, *c.* 60% greater than that of young leaves ( $n = 6$  trees, RR = 0.53,  $z = -8.72$ ,  $P < 0.01$ ; Fig. 4b) and *c.* 40% greater than that of old leaves ( $n = 6$  trees, RR = 0.73,  $z = -6.73$ ,  $P < 0.01$ ). TPU of mature leaves was, on average, *c.* 34% greater than that of young leaves ( $n = 6$  trees, RR = 0.61,  $z = -7.70$ ,  $P < 0.01$ ; Fig. 4c) and *c.* 27% greater than that of old leaves ( $n = 6$  trees, RR = 0.76,  $z = -5.42$ ,  $P < 0.01$ ).

### *In situ* stomatal conductance

Examination of weekly mean stomatal conductance ( $g_s$ ) using tree-level means for mature leaves for seven trees qualitatively showed no clear trend with dry season progression (Fig. 3c). Yet, contrasts between  $g_s$  for mature vs old leaves revealed that  $g_s$  depends on leaf age (Fig. 5a; Table S9). Late in the dry season, after 15 October, mature leaves had 34% greater  $g_s$  than old leaves ( $n = 7$ , RR = 0.77,  $z = -5.50$ ,  $P < 0.01$ ). Although there were insufficient contrasts of young and mature leaves within the same tree to perform a meta-analysis, qualitative examination of partial diurnal cycles for trees that had young and mature leaf ages present suggested that  $g_s$  was higher in mature leaves than in young leaves in *M. itauba* and *E. uncinatum* (Figs S2, S3). Thus, conductance may follow a similar pattern with respect to age as the biochemical limitations, with mature leaves exhibiting higher conductance than old or young leaves.



**Fig. 4** Age dependence of photosynthetic parameters: (a) maximum rate of carboxylation ( $V_{cmax}$ ), (b) maximum rate of electron transport ( $J_{max}$ ) and (c) triose phosphate use (TPU) derived from  $A/C_i$  curves measured for leaves from six trees (sun leaves and shade leaves combined) at the K67 site. Leaf age categories are: young (yellow), mature (green) and old (brown) leaves (where age is defined as described in the text). Boxplots represent the distribution of individual tree means, with the bold horizontal line indicating the median, the top and bottom of each box indicating the first and third quartiles, the whiskers extending to the highest and lowest values that are within  $1.5 \times$  the interquartile range (IQR) of the upper and lower quartiles, respectively, and the circular dots indicating outliers. Individual tree means come from *Erisma uncinatum*, *Tachigali cf chrysophylla*, *Chamaecrista xinguensis*, *Mezilaurus itauba*, *Coussarea paniculata* and *Manilkara elata* trees (see Tables S3–S8 for means of all available data by tree).

### Chlorophyll concentration

The  $\text{Chl}a : b$  ratio and total chlorophyll content were dependent on leaf age. The  $\text{Chl}a : b$  ratio was 29% higher in young leaves

than in mature leaves ( $n = 3$  trees,  $\text{RR} = 1.20$ ,  $z = 3.73$ ,  $P < 0.01$ ; Fig. 5b) and 37% greater in mature leaves than in old leaves ( $n = 3$  trees,  $\text{RR} = 0.75$ ,  $z = -3.80$ ,  $P < 0.01$ ). Total chlorophyll was 90% greater in mature leaves than in young leaves ( $n = 3$  trees,  $\text{RR} = 0.55$ ,  $z = -6.00$ ,  $P < 0.01$ ; Fig. 5c), but 15% greater in old leaves than in mature leaves ( $n = 3$  trees,  $\text{RR} = 1.33$ ,  $z = 3.01$ ,  $P < 0.01$ ).

### Leaf chemistry

Leaf chemistry showed differences between mature and old, but not mature and young, categories. The percentage nitrogen in leaves was similar between mature and young leaves ( $n = 5$ ,  $\text{RR} = 1.00$ ,  $z = 0.09$ ,  $P = 0.92$ ; Fig. 5d), but, on average, 8% higher in mature leaves than in old leaves ( $n = 6$ ,  $\text{RR} = 0.93$ ,  $z = -7.75$ ,  $P < 0.01$ ). The ratio of leaf carbon to nitrogen was also similar between mature and young leaves ( $n = 5$ ,  $\text{RR} = 1.02$ ,  $z = -0.94$ ,  $P = 0.35$ ; Fig. 5e), but C:N of old leaves was, on average, 9% higher than that in mature leaves ( $n = 6$ ,  $\text{RR} = 1.09$ ,  $z = 8.66$ ,  $P < 0.01$ ).

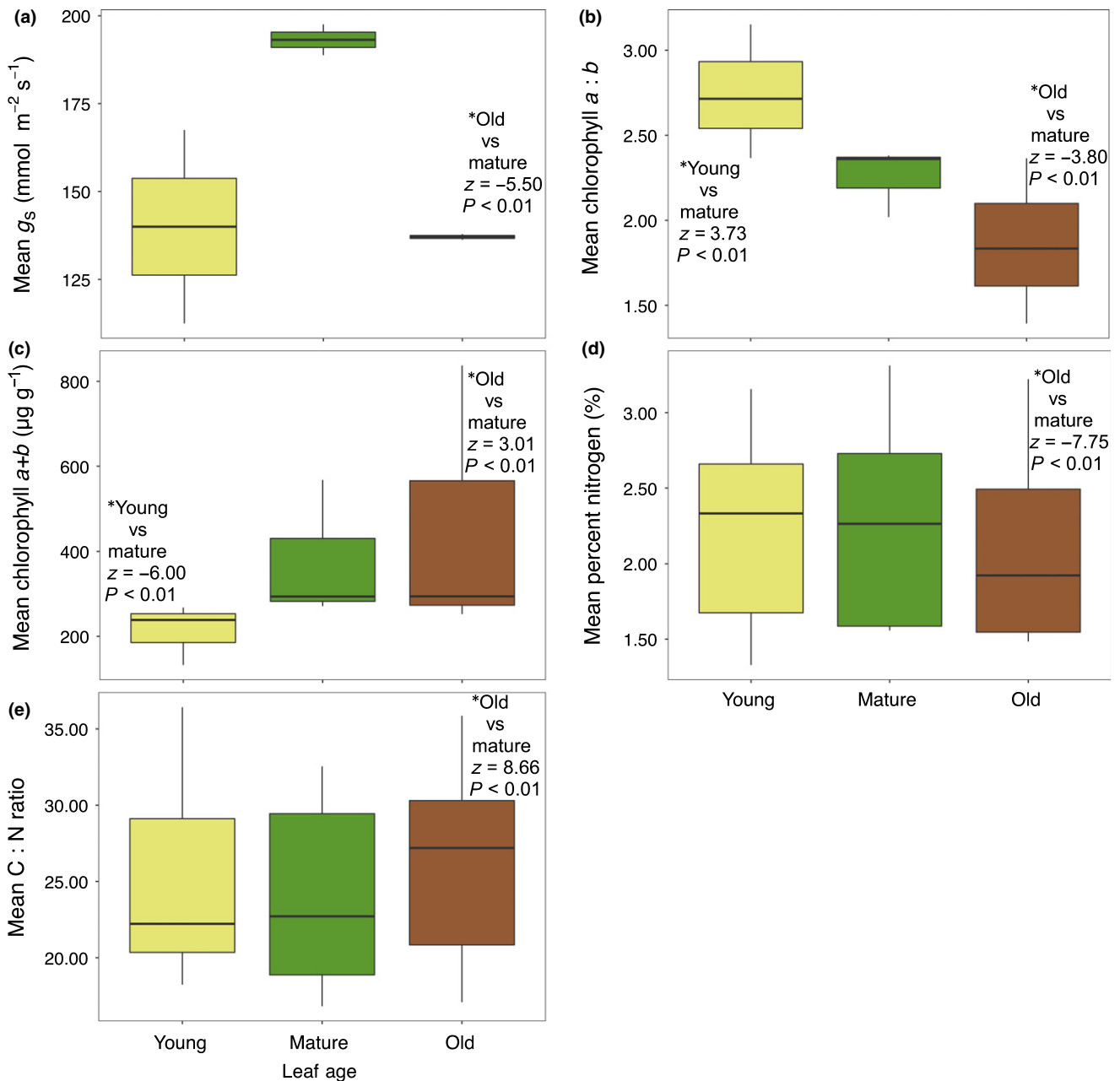
### Leaf demography

Dry season leaf demography on 1-m branches showed that leaf age composition varied across the dry season as young leaves became mature leaves and old leaves senesced and abscised (Fig. 6; Tables S18–S20). The difference between ‘early’ (23 July–15 October) and ‘late’ (15 October–5 December) dry season leaf number was significant for all leaf age categories. On average, the number of young leaves decreased by 78% from early to late dry season ( $n = 5$  trees,  $\text{RR} = 3.05$ ,  $z = 2.50$ ,  $P = 0.01$ ), mature leaves increased by 65% from early to late dry season ( $n = 5$  trees,  $\text{RR} = 0.58$ ,  $z = -2.97$ ,  $P < 0.01$ ) and old leaves decreased by 68% from early to late dry season ( $n = 5$  trees,  $\text{RR} = 2.01$ ,  $z = 4.79$ ,  $P < 0.01$ ). These changes in composition occurred despite relatively constant total leaf number on 1-m branches. The total number of leaves showed a subtle and insignificant 6% increase from early to late dry season ( $n = 5$  trees,  $\text{RR} = 0.85$ ,  $z = -1.21$ ,  $P = 0.23$ ).

### Branch-level $V_{cmax}$

Linear regression slopes for branch-level  $V_{cmax}$  for individual trees were significantly positive or near zero during the dry season (Table S21). Aggregate branch-level  $V_{cmax}$  increased significantly during the dry season for all leaves sampled (slope = 0.056, slope SE = 0.0113,  $t$  statistic = 4.88,  $n = 5$ ,  $P < 0.01$ ) and for sun branches (Fig. 7a, slope = 0.071, SE = 0.0101,  $t$  statistic = 7.05,  $n = 5$ ,  $P < 0.01$ ), but not for shade branches (Fig. 7b), as the shade mean slope was high (0.051), but not detectably different from zero (SE = 0.0371,  $t$  statistic = 1.38,  $n = 4$ ,  $P = 0.26$ ).

Using the aggregate slope and intercept to calculate the percentage increase in monthly average branch-level  $V_{cmax}$  between August and November yielded an increase of 24.1% for sun branches (significant) and 18.5% for shade branches (not significant). We compared branch-level  $V_{cmax}$  for sun and shade leaves



**Fig. 5** Age dependence of leaf physiological traits: (a) stomatal conductance from porometer measurements, (b) Chl  $a : b$  ratio, (c) total chlorophyll, (d) percentage nitrogen, (e) C : N ratio. Leaf age categories are: young (yellow), mature (green) and old (brown) leaves (where age is defined as described in the text). Shown are the leaf age by tree means from trees that had all leaf age categories sampled: in (a–c) six trees for leaf chemistry (*Erismia uncinatum*, *Tachigali cf chrysophylla*, *Chamaecrista xinguensis*, *Mezilaurus itauba*, *Coussarea paniculata* and *Manilkara elata*); in (d) two trees for  $g_s$  (*Erismia uncinatum* and *M. elata*); and in (e, f) two trees for chlorophyll (*Erismia uncinatum* and *C. xinguensis*). Boxplots represent the distribution of individual tree means (see Tables S9–S17 for all available data by tree), with the bold horizontal line indicating the median, the top and bottom of each box indicating the first and third quartiles, the whiskers extending to the highest and lowest values that are within  $1.5 \times$  the interquartile range (IQR) of the upper and lower quartiles, respectively, and the circular dots indicating outliers.

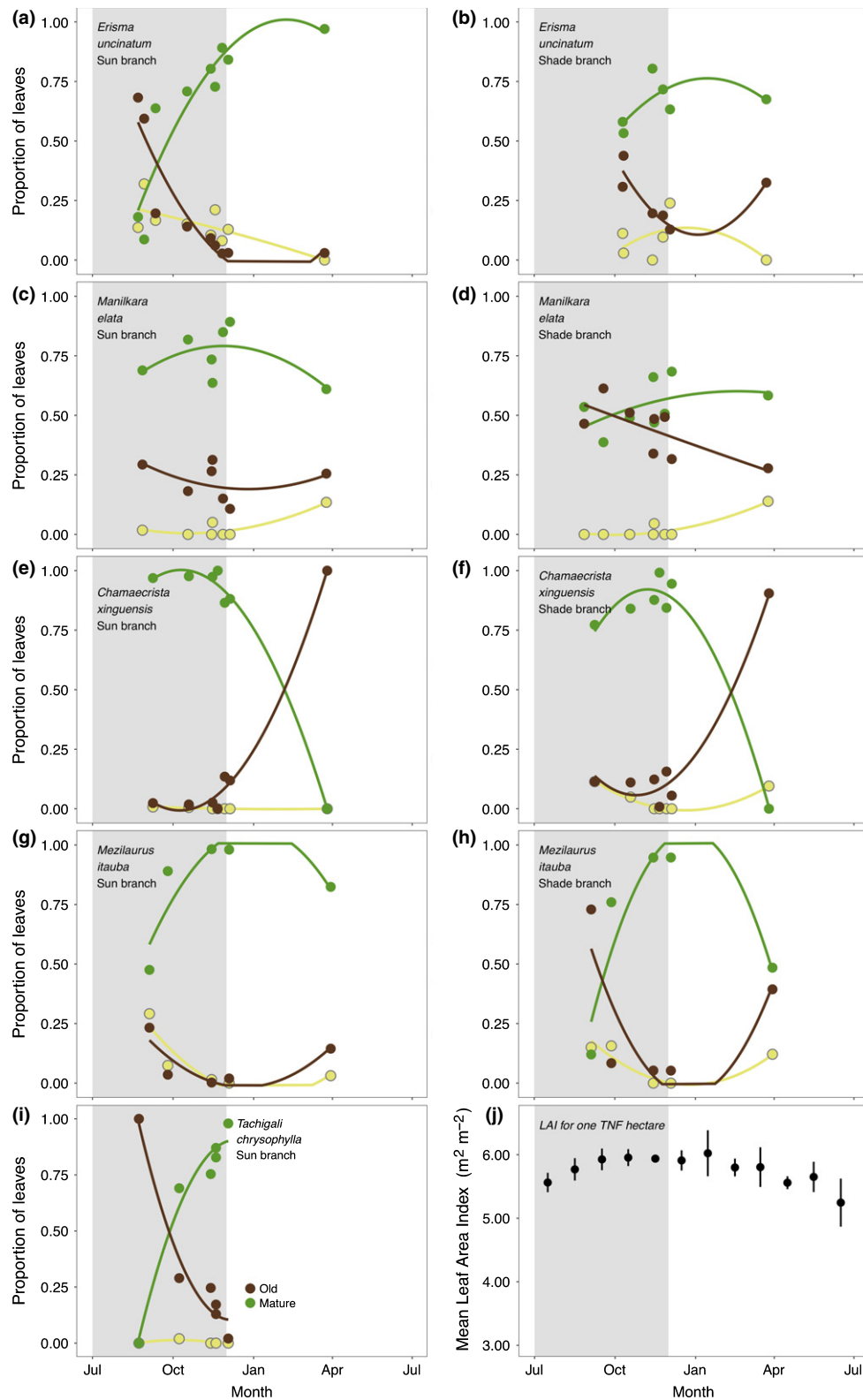
with the ecosystem PC reported in Fig. 1 (from Wu *et al.*, 2016) and found a similar rate of increase as the dry season progressed (Fig. 7c).

## Discussion

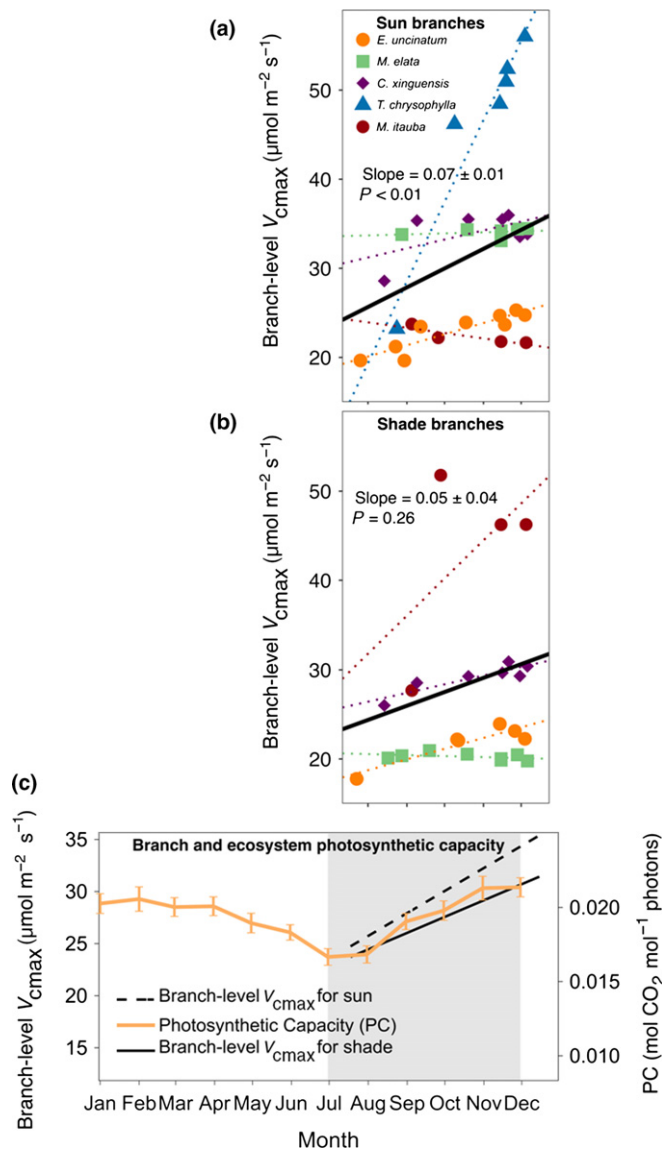
We investigated whether leaf physiology varies with leaf age in tropical trees, and whether leaf demography (the proportion of

young, mature and old leaves) varies during the dry season at a moist tropical site. Then, we coupled field-based measurements of leaf  $V_{\text{cmax}}$  and leaf demography for the first ‘bottom-up’ test of the hypothesis – which arises primarily from remote observations – that the combination of leaf age-dependent physiology and leaf demography drives the dry season increase in GPP and PC in central Amazonian forests (the leaf demography–ontogeny hypothesis; Wu *et al.*, 2016). We found evidence that leaf physiology





**Fig. 6** Leaf demography time series focusing on the dry season (gray) in the Tapajós National Forest (TNF) for five trees surveyed in 2012, 2013 and 2014. Sun branches are shown for five trees and shade branches are shown for four of the trees (*Mezilaurus itauba* had few shade branches because of the shape of its crown). The proportions of young (yellow circles), mature (green circles) and old (brown circles) leaves are shown for 1-m branches from *Erisma uncinatum* sun (a) and shade (b), *Manilkara elata* sun (c) and shade (d), *Chamaecrista xinguensis* sun (e) and shade (f), *Mezilaurus itauba* sun (g) and shade (h), and *Tachigali cf. chrysophylla* shade (i). Colored lines are polynomials fitted to the demography proportion data for the purpose of visualization. The lower right-hand panel (j) shows a time series of leaf area index (LAI) for this forest from Brando *et al.* (2010) with error bars showing  $\pm 1$  SE.



**Fig. 7** Branch-level  $V_{\text{cmax}}$  (estimated by weighting  $V_{\text{cmax}}$  by leaf age proportion) for (a) branches with sun leaves, (b) branches with shade leaves and (c) compared with canopy photosynthetic capacity (PC) derived from eddy covariance (as in Fig. 1). In (a, b), dotted lines show linear regressions for individual trees, and solid lines show the mean of all other lines, with  $\pm$  SE and statistical significance of the slope of composite black lines indicated. The full species names abbreviated in (a) are *Erismia uncinatum*, *Manilkara elata*, *Chamaecrista xinguensis*, *Tachigali cf chrysophylla* and *Mezilaurus itauba*. In (c), the eddy covariance-derived canopy PC (orange line) is compared with the mean branch-level  $V_{\text{cmax}}$  for sun (dashed black line) and shade (solid black line), with the vertical axes for PC (right) and branch-level  $V_{\text{cmax}}$  (left) each scaled to range from 50% to 150% of their respective minimum values; the dry season is indicated by the grey box. Month ticks are at the first of each month.

depends on leaf age, such that recently mature leaves have a higher capacity for photosynthesis than either young or old leaves (Figs 4, 5). On average, the total number of leaves on sampled branches did not vary significantly across the dry season, consistent with observations of only minor variations in canopy-scale LAI (Fig. 6j), but the age composition of these leaves did vary, giving direct evidence to support previous inferences from simple models

(Wu *et al.*, 2016, 2017c) that trees exchange old leaves for young leaves via leaf turnover during the dry season (Fig. 6). Combining the age dependence of leaf physiology results with the leaf demography results, we found that branch-level  $V_{\text{cmax}}$  of branches with sun-exposed leaves increased by 24.1% between August and November means, consistent with the 26.5% average increase independently observed over the same period in ecosystem-level PC estimated from EC (Fig. 7c). Shade leaf dynamics may also cause an increase in shade branch-level  $V_{\text{cmax}}$  (average increases were *c.* 18.5%), but high variation in shade branch-level  $V_{\text{cmax}}$  prevented us from statistically resolving the signal. We emphasize that measuring mature leaves only – the convention in most ecophysiological studies – neglects leaf demography and could lead to the conclusion that canopy photosynthesis does not increase with dry season progression (e.g.  $A_{\text{net}}$  time series of mature leaves only; Fig. 3b).

Although the five trees sampled represent a small fraction of the taxonomic diversity in this tropical evergreen forest, our samples represented five species accounting for a substantial portion (*c.* 33%) of tree basal area (Table S1). Our results suggest that leaf phenology impacts ecosystem-level carbon exchange in this evergreen forest. This implies that: (1) LAI alone should not be used as an indicator of leaf phenology in tropical evergreen forests (Fig. 6j); (2) LSMs seeking to incorporate leaf phenology in tropical evergreen forests should include the age dependence of limitations on photosynthesis that they represent, such as  $V_{\text{cmax}}$ ,  $J_{\text{max}}$ , TPU and  $g_s$ ; and (3) the replacement of old leaves with new leaves early in the dry season by tropical evergreen trees could represent a strategy to optimize carbon gain by aligning peak photosynthetic capacity of crowns with the period of high light during the dry season, a hypothesis warranting future investigation.

### Leaf physiology depends on leaf age

Our finding of the age-dependent development of leaves in tropical trees is consistent with the general paradigm of leaf ontogeny from temperate zone studies (Reich & Walters, 1991; Wilson *et al.*, 2001; Niinemets *et al.*, 2012; Pantin *et al.*, 2012), and also with the limited studies from trees of the Amazon basin on how leaf age affects photosynthesis (Doughty & Goulden, 2008; Alves *et al.*, 2014) and functional traits (Chavana-Bryant *et al.*, 2017; Wu *et al.*, 2017a). In this paradigm, carbon assimilation in young, developing leaves ‘ramps up’ with time as leaves reach maturity as a result of ontogenetic processes involving the light reaction machinery (Welsch *et al.*, 2000; Niinemets *et al.*, 2012), the Calvin–Benson cycle (Wilson *et al.*, 2001; Eichelmann *et al.*, 2004) and stomatal conductance (Willmer & Fricker, 1996; Pantin *et al.*, 2012). Mature leaves have the highest capacity for photosynthesis (Wilson *et al.*, 2001), which remains at a high level for a certain amount of time (depending on the total leaf lifespan and other factors) before declining as leaves approach senescence. In this study, support for the hypothesis that leaf photosynthetic capacity peaks in recently mature leaves before declining in old leaves was found in the  $A/C_i$  parameters ( $V_{\text{cmax}}$ ,  $J_{\text{max}}$  and TPU; Fig. 4) and also in total chlorophyll content (Fig. 5c). Percentage nitrogen was higher in mature leaves than in

old leaves (Fig. 5d), perhaps because trees were beginning to resorb nitrogen for use in new leaf buds and developing leaves (Hikosaka, 2004). Old leaves in this study also showed physiological changes that may be specific to tropical forests. In general, the  $\text{Chl}a:b$  ratio is lower in shade leaves, enabling them to absorb more light in the wavelengths less absorbed by sun leaves above (Boardman, 1977). Thus, the shift in  $\text{Chl}a:b$  ratio with leaf age (Fig. 5b) could represent a strategy to harvest more light in older leaves as they become increasingly self-shaded by younger (and more apical) leaves in tropical evergreen trees. Epiphyll colonization, common in tropical forests, also increases in old leaves (Coley *et al.*, 1993; Roberts *et al.* 1998). Epiphylls probably influence photosynthesis via light absorption, nitrogen fixation and perhaps even hormones (Coley & Kursar, 1996; Anthony *et al.*, 2002). Although we observed less epiphyll cover on the canopy leaves we studied compared with longer lived understory leaves in the TNF, more studies of epiphyll effects on photosynthesis are needed in Amazônia.

Importantly, leaf photosynthetic capacity, as indicated by metrics of efficiency related to the light reactions and the Calvin–Benson cycle (e.g. chlorophyll concentration,  $J_{\text{max}}$  and  $V_{\text{cmax}}$ ), does not solely determine apparent photosynthesis. Stomata may influence the intercellular concentration of  $\text{CO}_2$  by opening or closing. Our data suggest that mature leaves have higher stomatal conductance than old leaves co-occurring on the same tree (Figs 5a, S2, S3), and therefore higher photosynthetic capacity should indeed manifest as higher apparent photosynthesis. We speculate that, during drought, stomatal closure might limit photosynthesis and outweigh the leaf age effect.

### Leaf demography reveals dry season leaf turnover

This study found evidence of leaf turnover, the exchange of old leaves for new leaves, during the dry season within evergreen crowns at K67 (Fig. 6). As old leaves senesced and abscised, the average number of old leaves on 1-m branches decreased from 101 to 32, from early in the dry season (pre-15 October) to late in the dry season (post-15 October). Meanwhile, the average number of mature leaves across trees increased from 191 to 315, a 65% increase, as newly produced leaves reached maturity. This leaf turnover occurred even though the total quantity of leaves on 1-m branches did not change significantly from early in the dry season to late in the dry season ( $z = -1.21$ ,  $P = 0.23$ ). This finding is consistent with the leaf demography–ontogeny hypothesis that many evergreen trees exchange old leaves (with low photosynthetic capacity) for recently mature leaves (with high photosynthetic capacity) during the dry season whilst maintaining high LAI (Doughty & Goulden, 2008; Wu *et al.*, 2016). Our findings for this evergreen Amazon forest are in stark contrast with broadleaf deciduous forests, where LAI tracks changes in canopy photosynthetic capacity (e.g. Wilson *et al.*, 2001). Instead, the branch photosynthetic capacity in this forest tracks leaf age demographics rather than total leaf area, a finding that agrees with ecosystem-scale analyses at this site (Wu *et al.*, 2016).

The finding of leaf turnover within evergreen crowns does not indicate that *all* species or individuals behave similarly. As a result of the intensive effort required to survey leaf demography in tall evergreen trees, our study was limited to a small percentage of trees in one diverse tropical forest, and thus needs to be interpreted as a subsample of phenological behaviors present in evergreen tropical forests. Although all of the trees studied were evergreen (new leaves were produced before old leaves dropped), multiple phenological patterns co-occur in many tropical forests (Rivera *et al.*, 2002; Lopes *et al.*, 2016; Chavana-Bryant *et al.*, 2017). Furthermore, the *Manilkara elata* tree we examined showed signs of more constant leaf production than other trees examined in this study, suggesting that some tree species have more constant leaf age distribution than others (Fig. 6c,d). Another likely source of variation in leaf phenological behavior is the range of leaf lifespans found in tropical forests (Reich *et al.*, 2004). The present study focused on canopy trees, but understory plants account for *c.* 50% of LAI in this forest (Stark *et al.*, 2012) and generally have longer leaf lifespans (Reich *et al.*, 2004); therefore, leaf turnover in understory plants may affect a small fraction of understory leaves.

In addition to species diversity within a site, there is environmental variation across sites that could impact leaf phenology. The Amazon basin includes a gradient in precipitation seasonality from the northwestern Amazon, which is consistently wet, to the south and east, which experience dry seasons up to 5 months long (Sombroek, 2001; Restrepo-Coupe *et al.*, 2013). Satellite-based remote sensing studies suggest that there is a threshold amount of precipitation below which productivity in tropical forests is driven by moisture seasonality (Guan *et al.*, 2015). Average precipitation at the K67 site slightly exceeds this 2000 mm  $\text{yr}^{-1}$  precipitation threshold, and so productivity may not be limited by water availability during non-drought years. Field studies of leaf demography and photosynthesis should be conducted at more tropical forest sites with various rainfall regimes to further describe the relationship between wet/dry seasonality, leaf phenology and productivity across tropical forests.

### Implications of evergreen leaf phenology for LSMs

Our findings suggest that recent incorporations of leaf demography and leaf age dependence of physiology into LSMs represent progress towards the accurate representation of evergreen tropical forests. Studies with ORCHIDEE, a global process-based vegetation model (Krinner *et al.*, 2005), have shown that, when  $V_{\text{cmax}}$  is parameterized as a function of leaf age (four age classes), and LAI is more or less constant, the model produces seasonality in litterfall, leaf age and  $V_{\text{cmax}}$  (De Weirdt *et al.*, 2012). In the Ecosystem Demography model v.2 (ED2; Medvigy *et al.*, 2009), a phenology module that linearly related leaf turnover to incoming shortwave radiation, and then related leaf lifespan to photosynthetic capacity using the empirically based relationship from the leaf economic spectrum (Wright *et al.*, 2004; Kim *et al.*, 2012), created seasonality in LAI and litterfall, and generally improved the ability of ED2 to simulate the carbon fluxes at the K67 site.

Here, we attribute the observed seasonal GPP patterns to phenological mechanisms, and the next step is to resolve and model the eco-evolutionary constraints that give rise to these patterns. One such constraint could be carbon acquisition. A recent model that optimizes carbon acquisition as a function of leaf lifespan, when used to analyze 49 species across tropical and temperate forests (including data from this study), successfully predicted leaf lifespan and the rate of decline in PC with age in many tropical species, offering an approach useful for LSMs (Xu *et al.*, 2017). The current study reinforces the argument that providing more mechanistic detail relating tropical vegetation responses to climate variability, including seasonal variation, could help to improve earth system model projections of Amazon forests under climate change scenarios (Malhi *et al.*, 2009; Good *et al.*, 2011; Huntingford *et al.*, 2013; Restrepo-Coupe *et al.*, 2017; Wu *et al.*, 2017c), a long-standing modeling challenge (White *et al.*, 1999; Cox *et al.*, 2000).

### Dry season leaf turnover as adaptation to seasonal light variation

The leaf demography results suggest that leaf production of many canopy tropical trees at the K67 site is synchronized with the dry season. This timing of leaf turnover may represent a strategy for reducing leaf herbivory (Lowman, 1985; Aide, 1988; Coley & Barone, 1996) and also for enhancing carbon gain. Tropical evergreen trees with sufficient water supply that experience wet–dry seasonality may align their period of maximum photosynthetic capacity (when they have many recently mature leaves) with the dry season period of high light availability. Experimental manipulations of light quantity show that high light induces leaf production in tropical trees (Graham *et al.*, 2003) and, across tropical latitudes, observations of leaf production are linked to seasonal increases in daily light quantity (Borchert *et al.*, 2014), showing that high light can be a cue or proximate control over leaf production. The degree to which wet–dry seasonality has ultimately shaped temporal strategies of acquisition and allocation in tropical evergreen trees through natural selection still requires more investigation, but the current study suggests that dry season leaf turnover contributes to optimal light use across the year.

### Conclusions

This field-based study shows that the combination of age-dependent leaf physiology and canopy leaf demography increases branch-level estimates of  $V_{\text{cmax}}$  as the dry season progresses, consistent with independent estimates of ecosystem-level PC (Fig. 7c). These findings provide the first evidence from coupled leaf and branch-level measurements supporting the leaf demography–ontogeny hypothesis for dry season GPP increases in central Amazonian forests (Wu *et al.*, 2016), and emphasize the active role of leaf phenology in controlling carbon and water exchange in central Amazon broadleaf evergreen forests. Thus, phenological rhythms of tropical evergreen forests, although subtle compared with those of temperate deciduous forests, may modulate

similar vegetation feedbacks to the climate system (Richardson *et al.*, 2013), including not only seasonality of carbon uptake, but transpiration (Wright *et al.*, 2017) and canopy reflectance (Chavana-Bryant *et al.*, 2017; Wu *et al.*, 2017a).

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### Author contributions

L.P.A., S.R.S., T.E.H. and J.W. planned and designed the research. J.W., L.P.A. and N.P. surveyed leaf demography, and J.W. curated these surveys. L.P.A., M.N.S. and N.P. performed gas exchange. J.W., N.P., E.S.T. and L.P.A. extracted chlorophyll. P.B.d.C. contributed leaf chemistry. N.R.C., R.C.O.J., S.R.S. and R.d.S. obtained EC measurements. V.Y.I. and R.S.O. installed stem psychrometers. L.P.A. performed analyses on gas exchange and leaf demography. J.W. calculated PC. L.P.A. prepared the figures with contributions from S.G., and M.N.S. S.R.S., T.E.H., G.A.M., D.V.P., S.C.S., E.S.T. and L.P.A. interpreted the analyses. L.P.A. wrote the first draft and all authors contributed to editing the manuscript.

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### References

- Aide TM. 1988. Herbivory as a selective agent on the timing of leaf production in a tropical understory community. *Nature* **336**: 574–575.
- Alves EG, Harley P, Goncalves JF de C, da Silva Moura CE, Jardine K. 2014. Effects of light and temperature on isoprene emission at different leaf developmental stages of *Eschweilera coriacea* in central Amazon. *Acta Amazonica* **44**: 9–18.
- Anthony PA, Holtum JAM, Jackes BR. 2002. Shade acclimation of rainforest leaves to colonization by lichens. *Functional Ecology* **16**: 808–816.
- Asner GP. 2001. Cloud cover in Landsat observations of the Brazilian Amazon. *International Journal of Remote Sensing* **22**: 3855–3862.



- Batista da Silva Ferreira D, Barreiros de Souza E, Cavalcanti de Moraes B, Meira Filho LG. 2015. Spatial and temporal variability of rainfall in eastern Amazon during the rainy season. *The Scientific World Journal* 2015: 209783.
- Bi J, Knyazikhin Y, Choi S, Park T, Barichivich J, Ciais P, Fu R, Ganguly S, Hall F, Hilker T *et al.* 2015. Sunlight mediated seasonality in canopy structure and photosynthetic activity of Amazonian rainforests. *Environmental Research Letters* 10: 064014.
- Boardman NK. 1977. Comparative photosynthesis of sun and shade plants. *Annual Review of Plant Physiology* 28: 355–377.
- Borchert R, Calle Z, Strahler AH, Baertschi A, Magill RE, Broadhead JS, Kamau J, Njoroge J, Muthuri C. 2014. Insolation and photoperiodic control of tree development near the equator. *New Phytologist* 205: 7–13.
- Boyle B, Hopkins N, Lu Z, Garay JAR, Mozzherin D, Rees T, Matasci N, Narro ML, Piel WH, Mckay SJ *et al.* 2013. The taxonomic name resolution service: an online tool for automated standardization of plant names. *BMC Bioinformatics* 14: 16.
- Brando PM, Goetz SJ, Baccini A, Nepstad DC, Beck PSA, Christman MC. 2010. Seasonal and interannual variability of climate and vegetation indices across the Amazon. *Proceedings of the National Academy of Sciences, USA* 107: 14685–14690.
- Chavana-Bryant C, Malhi Y, Wu J, Asner GP, Anastasiou A, Enquist BJ, Cosio Caravasi EG, Doughty CE, Saleska SR, Martin RE *et al.* 2017. Leaf aging of Amazonian canopy trees as revealed by spectral and physiochemical measurements. *New Phytologist* 214: 1049–1063.
- Coley PD, Barone JA. 1996. Herbivory and plant defenses in tropical forests. *Annual Review of Ecology and Systematics* 27: 305–335.
- Coley PD, Kursar T. 1996. Causes and consequences of epiphyll colonization. In: Mulkey SS, Chazdon RL, Smith AP, eds. *Tropical forest plant ecophysiology*. New York, NY, USA: Chapman & Hall, 337–362.
- Coley PD, Kursar T, Machado J-L. 1993. Colonization of tropical rain forest leaves by epiphylls: effects of site and host plant leaf lifetime. *Ecology* 74: 619–623.
- Cox PM, Betts RA, Jones CD, Spall SA, Totterdell IJ. 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* 408: 184–187.
- De Weirdt M, Verbeeck H, Maignan F, Peylin P, Poulter B, Bonal D, Ciais P, Steppe K. 2012. Seasonal leaf dynamics for tropical evergreen forests in a process-based global ecosystem model. *Geoscientific Model Development* 5: 1091–1108.
- Domingues TF, Martinelli LA, Ehleringer JR. 2014. Seasonal patterns of leaf-level photosynthetic gas exchange in an eastern Amazonian rain forest. *Plant Ecology & Diversity* 7: 189–203.
- Domingues TF, Meir P, Feldpausch TR, Saiz G, Veenendaal EM, Schrodt F, Bird M, Djagbletey G, Hien F, Compaore H *et al.* 2010. Co-limitation of photosynthetic capacity by nitrogen and phosphorus in West Africa woodlands. *Plant, Cell & Environment* 33: 959–980.
- Doughty CE, Goulden ML. 2008. Seasonal patterns of tropical forest leaf area index and CO<sub>2</sub> exchange. *Journal of Geophysical Research* 113: G00B06.
- Eichelmann H, Oja V, Rasulov B, Padu E, Bichele I, Pettai H, Niinemets U, Laisk A. 2004. Development of leaf photosynthetic parameters in *Betula pendula* Roth leaves: correlations with photosystem I density. *Plant Biology* 6: 307–318.
- Farquhar GD, von Caemmerer S, Berry JA. 1980. A biochemical model of photosynthetic CO<sub>2</sub> assimilation in leaves of C<sub>3</sub> species. *Planta* 149: 78–90.
- Good P, Caesar J, Bernie D, Lowe JA, van der Linden P, Gosling SN, Warren R, Arnell NW, Smith S, Bamber J *et al.* 2011. A review of recent developments in climate change science. Part I: understanding of future change in the large-scale climate system. *Progress in Physical Geography* 35: 281–296.
- Goulden ML, Miller SD, da Rocha HR, Menton MC, de Freitas HC, Silva Figueira AME, De Sousa CAD. 2004. Diel and seasonal patterns of tropical forest CO<sub>2</sub> exchange. *Ecological Applications* 14: 42–54.
- Graham EA, Mulkey SS, Kitajima K, Phillips NG, Wright SJ. 2003. Cloud cover limits net CO<sub>2</sub> uptake and growth of a rainforest tree during tropical rainy seasons. *Proceedings of the National Academy of Sciences, USA* 100: 572–576.
- Guan K, Pan M, Li H, Wolf A, Wu J, Medvigy D, Caylor KK, Sheffield J, Wood EF, Malhi Y *et al.* 2015. Photosynthetic seasonality of global tropical forests constrained by hydroclimate. *Nature Geoscience* 8: 284–289.
- Harley PC, Thomas RB, Reynolds JF, Strain BR. 1992. Modelling photosynthesis of cotton grown in elevated CO<sub>2</sub>. *Plant, Cell & Environment* 15: 271–282.
- Hedges LV, Gurevitch J, Curtis PS. 1999. The meta-analysis of response ratios in experimental ecology. *Ecology* 80: 1150–1156.
- Hikosaka K. 2004. Leaf canopy as a dynamic system: ecophysiology and optimality in leaf turnover. *Annals of Botany* 95: 521–533.
- Horel JD, Hahmann AN, Geisler JE. 1989. An investigation of the annual cycle of convective activity over the tropical Americas. *Journal of Climate* 2: 1388–1403.
- Huete AR, Didan K, Shimabukuro YE, Ratana P, Saleska SR, Hutyra LR, Yang W, Nemani RR, Myneni R. 2006. Amazon rainforests green-up with sunlight in dry season. *Geophysical Research Letters* 33: L06405.
- Huntingford C, Zelazowski P, Galbraith D, Mercado LM, Sitch S, Fisher R, Lomas M, Walker AP, Jones CD, Booth BBB *et al.* 2013. Simulated resilience of tropical rainforests to CO<sub>2</sub>-induced climate change. *Nature Geoscience* 6: 268–273.
- Hutyra LR, Munger JW, Saleska SR, Gottlieb E, Daube BC, Dunn AL, Amaral DF, de Camargo PB, Wofsy SC. 2007. Seasonal controls on the exchange of carbon and water in an Amazonian rain forest. *Journal of Geophysical Research* 112: G03008.
- Ichii K, Hashimoto H, Nemani R, White M. 2005. Modeling the interannual variability and trends in gross and net primary productivity of tropical forests from 1982 to 1999. *Global and Planetary Change* 48: 274–286.
- Ishida A, Uemura A, Koike N, Matsumoto Y, Hoe AL. 1999. Interactive effects of leaf age and self-shading on leaf structure, photosynthetic capacity and chlorophyll fluorescence in the rain forest tree, *Dryobalanops aromatica*. *Tree Physiology* 19: 741–747.
- Keeling CD, Whorf TP, Wahlen M, Van der Plicht J. 1995. Interannual extremes in the rate of rise of atmospheric carbon-dioxide since 1980. *Nature* 375: 666–670.
- Kim Y, Knox RG, Longo M, Medvigy D, Hutyra LR, Pyle EH, Wofsy SC, Bras RL, Moorcroft PR. 2012. Seasonal carbon dynamics and water fluxes in an Amazon rainforest. *Global Change Biology* 18: 1322–1334.
- Kitajima K, Mulkey SS, Samaniego M, Joseph Wright S. 2002. Decline of photosynthetic capacity with leaf age and position in two tropical pioneer tree species. *American Journal of Botany* 89: 1925–1932.
- Krinner G, Viovy N, de Noblet-Ducoudré N, Ogée J, Polcher J, Friedlingstein P, Ciais P, Sitch S, Prentice IC. 2005. A dynamic global vegetation model for studies of the coupled atmosphere–biosphere system. *Global Biogeochemical Cycles* 19: GB1015.
- Lasslop G, Reichstein M, Papale D, Richardson AD, Arneeth A, Barr A, Stoy P, Wohlfahrt G. 2009. Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: critical issues and global evaluation. *Global Change Biology* 16: 187–208.
- Lichtenthaler HK. 1987. Chlorophylls and carotenoids: pigments of photosynthetic biomembranes. *Methods in Enzymology* 148: 350–382.
- Lopes AP, Nelson BW, Wu J, de Alencastro Graça PML, Tavares JV, Prohaska N, Martins GA, Saleska SR. 2016. Leaf flush drives dry season green-up of the Central Amazon. *Remote Sensing of Environment* 182: 90–98.
- Lowman MD. 1985. Temporal and spatial variability in insect grazing of the canopies of five Australian rainforest tree species. *Austral Ecology* 10: 7–24.
- Malhi Y, Aragão LEOC, Galbraith D, Huntingford C, Fisher R, Zelazowski P, Sitch S, McSweeney C, Meir P. 2009. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences, USA* 106: 20610–20615.
- Marengo JA, Chou SC, Kay G, Alves LM, Pesquero JF, Soares WR, Santos DC, Lyra AA, Sueiro G, Betts R *et al.* 2012. Development of regional future climate change scenarios in South America using the Eta CPTec/HadCM3 climate change projections: climatology and regional analyses for the Amazon, São Francisco and the Paraná River basins. *Climate Dynamics* 38: 1829–1848.
- Medvigy D, Wofsy SC, Munger JW, Hollinger DY, Moorcroft PR. 2009. Mechanistic scaling of ecosystem function and dynamics in space and time: ecosystem demography model version 2. *Journal of Geophysical Research* 114: G01002.

- Morton DC, Nagol J, Carabjal CC, Rosette J, Palace M, Cook BD, Vermote EF, Harding DJ, North PRJ. 2014. Amazon forests maintain consistent canopy structure and greenness during the dry season. *Nature* 506: 221–224.
- Myneni RB, Yang W, Nemani RR, Huete AR, Dickinson RE, Knyazikhin Y, Didan K, Fu R, Negrón Juárez RI, Saatchi SS *et al.* 2007. Large seasonal swings in leaf area of Amazon rainforests. *Proceedings of the National Academy of Sciences, USA* 104: 4820–4823.
- Nepstad DC, Moutinho P, Dias Filho MB, Davidson E, Cardinot G, Markewitz D, Figueiredo R, Vianna N, Chambers J, Ray D. 2002. The effects of partial throughfall exclusion on canopy processes, aboveground production, and biogeochemistry of an Amazon forest. *Journal of Geophysical Research* 107: 8085.
- Niinemets U, Garcia-Plazaola I, Tosens T. 2012. Photosynthesis during leaf development and ageing. In: Flexas J, Loreto F, Medrano H, eds. *Terrestrial photosynthesis in a changing environment*. Cambridge, UK: Cambridge University Press, 353–372.
- Oikawa PY, Sturtevant C, Knox SH, Verfaillie J, Huang YW, Baldocchi DD. 2017. Revisiting the partitioning of net ecosystem exchange of CO<sub>2</sub> into photosynthesis and respiration with simultaneous flux measurements of <sup>13</sup>CO<sub>2</sub> and CO<sub>2</sub>, soil respiration and a biophysical model, CANVEG. *Agricultural and Forest Meteorology* 234–235: 149–163.
- Pantin F, Simonneau T, Muller B. 2012. Coming of leaf age: control of growth by hydraulics and metabolics during leaf ontogeny. *New Phytologist* 196: 349–366.
- Penuelas J, Rutishauser T, Filella I. 2009. Phenology feedbacks on climate change. *Science* 324: 887.
- Pyle EH, Santoni GW, Nascimento HEM, Hutrya LR, Vieira S, Curran DJ, van Haren J, Saleska SR, Chow VY, Carmago PB *et al.* 2008. Dynamics of carbon, biomass, and structure in two Amazonian forests. *Journal of Geophysical Research* 113: 1–20.
- R Core Team (2016). *R: a language and environment for statistical computing*. Version 3.3.1. Vienna, Austria: R Foundation for Statistical Computing. [WWW document] URL <https://www.R-project.org/>
- Reich PB, Uhl C, Walters MB, Prugh L, Ellsworth DS. 2004. Leaf demography and phenology in Amazonian rain forest: a census of 40 000 leaves of 23 tree species. *Ecological Monographs* 74: 3–23.
- Reich PB, Walters MB. 1991. Leaf age and season influence the relationships between leaf nitrogen, leaf mass per area and photosynthesis in maple and oak trees. *Plant, Cell & Environment* 14: 251–259.
- Reichstein M, Falge E, Baldocchi D, Papale D, Aubinet M, Berbigier P, Bernhofer C, Buchmann N, Gilmanov T, Granier A *et al.* 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. *Global Change Biology* 11: 1424–1439.
- Restrepo-Coupe N, da Rocha HR, Hutrya LR, da Araujo AC, Borma LS, Christoffersen B, Cabral OMR, de Camargo PB, Cardoso FL, da Costa ACL *et al.* 2013. What drives the seasonality of photosynthesis across the Amazon basin? A cross-site analysis of eddy flux tower measurements from the Brasil flux network. *Agricultural and Forest Meteorology* 182–183: 128–144.
- Restrepo-Coupe N, Levine NM, Christoffersen BO, Albert LP, Wu J, Costa MH, Galbraith D, Imbuzeiro H, Martins G, da Araujo AC *et al.* 2017. Do dynamic global vegetation models capture the seasonality of carbon fluxes in the Amazon basin? A data–model intercomparison. *Global Change Biology* 23: 191–208.
- Rice AH, Pyle EH, Saleska SR, Hutrya L. 2004. Carbon balance and vegetation dynamics in an old-growth Amazonian forest. *Ecological Applications* 14: S55–S71.
- Richardson AD, Anderson RS, Arain MA, Barr AG, Bohrer G, Chen G, Chen JM, Ciais P, Davis KJ, Desai AR *et al.* 2012. Terrestrial biosphere models need better representation of vegetation phenology: results from the North American Carbon Program Site Synthesis. *Global Change Biology* 18: 566–584.
- Richardson AD, Keenan TF, Migliavacca M, Ryu Y, Sonnentag O, Toomey M. 2013. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agricultural and Forest Meteorology* 169: 156–173.
- Rivera G, Elliott S, Caldas LS, Nicolossi G, Coradin VTR, Borchert R. 2002. Increasing day-length induces spring flushing of tropical dry forest trees in the absence of rain. *Trees* 16: 445–456.
- Roberts DA, Nelson BW, Adams JB, Palmer F. 1998. Spectral changes with leaf aging in Amazon caatinga. *Trees* 12: 315–325.
- Saleska SR, Miller SD, Matross DM, Goulden ML, Wofsy SC, da Rocha HR, de Camargo PB, Crill P, Daube BC, de Freitas HC *et al.* 2003. Carbon in Amazon forests: unexpected seasonal fluxes and disturbance-induced losses. *Science* 302: 1554–1557.
- Saleska SR, Wu J, Guan K, Araújo AC, Huete A, Nobre AD, Restrepo-Coupe N. 2016. Dry-season greening of Amazon forests. *Nature* 531: E4–E5.
- Samanta A, Ganguly S, Hashimoto H, Devadiga S, Vermote E, Knyazikhin Y, Nemani RR, Myneni RB. 2010. Amazon forests did not green-up during the 2005 drought. *Geophysical Research Letters* 37: L05401.
- Santos EB, Lucio PS, Silva CMSE. 2014. Precipitation regionalization of the Brazilian Amazon. *Atmospheric Science Letters* 16: 185–192.
- Sharkey TD, Bernacchi CJ, Farquhar GD, Singaas EL. 2007. Fitting photosynthetic carbon dioxide response curves for C<sub>3</sub> leaves. *Plant, Cell & Environment* 30: 1035–1040.
- Sobrado MA. 1994. Leaf age effects on photosynthetic rate, transpiration rate and nitrogen-content in a tropical dry forest. *Physiologia Plantarum* 90: 210–215.
- Sombroek W. 2001. Spatial and temporal patterns of Amazon rainfall. *AMBIO: A Journal of the Human Environment* 30: 388–396.
- Stark SC, Leitold V, Wu JL, Hunter MO, de Castilho CV, Costa FRC, McMahon SM, Parker GG, Shimabukuro MT, Lefsky MA *et al.* 2012. Amazon forest carbon dynamics predicted by profiles of canopy leaf area and light environment. *Ecology Letters* 15: 1406–1414.
- Tian H, Melillo JM, Kicklighter DW, McGuire AD, Helfrich Iii J, Moore Iii B, Vörösmarty CJ. 2000. Climatic and biotic controls on annual carbon storage in Amazonian ecosystems. *Global Ecology and Biogeography* 9: 315–335.
- Tribuzy ES. 2005. *Variações da Temperatura Foliar do Dossel e o Seu Efeito Na Taxa Assimilatória de CO<sub>2</sub> Na Amazônia Central*. PhD Thesis, Universidade de São Paulo, Piracaba, Brazil.
- Verbeeck H, Peylin P, Bacour C, Bonal D, Steppe K, Ciais P. 2011. Seasonal patterns of CO<sub>2</sub> fluxes in Amazon forests: fusion of eddy covariance data and the ORCHIDEE model. *Journal of Geophysical Research* 116: G02018.
- Viechtbauer W. 2010. Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software* 36: 1–48.
- Vieira S, de Camargo PB, Selhorst D, da Silva R, Hutrya L, Chambers JQ, Brown IF, Higuichi N, Santos dos J, Wofsy SC *et al.* 2004. Forest structure and carbon dynamics in Amazonian tropical rain forests. *Oecologia* 140: 468–479.
- Wehr R, Munger JW, McManus JB, Nelson DD, Zahniser MS, Davidson EA, Wofsy SC, Saleska SR. 2016. Seasonality of temperate forest photosynthesis and daytime respiration. *Nature* 534: 680–683.
- Welsch R, Beyer P, Huguency P, Kleinig H, von Lintig J. 2000. Regulation and activation of phytoene synthase, a key enzyme in carotenoid biosynthesis, during photomorphogenesis. *Planta* 211: 846–854.
- White A, Cannell M, Friend AD. 1999. Climate change impacts on ecosystems and the terrestrial carbon sink: a new assessment. *Global Environmental Change* 9: S21–S30.
- Willmer C, Fricker M. 1996. *Stomata*. Dordrecht, the Netherlands: Springer Netherlands.
- Wilson KB, Baldocchi DD, Hanson PJ. 2001. Leaf age affects the seasonal pattern of photosynthetic capacity and net ecosystem exchange of carbon in a deciduous forest. *Plant, Cell & Environment* 24: 571–583.
- Wright IJ, Reich PB, Westoby M, Ackerly DD, Baruch Z, Bongers F, Cavender-Bares J, Chapin T, Cornelissen JHC, Diemer M *et al.* 2004. The worldwide leaf economics spectrum. *Nature* 428: 821–827.
- Wright JS, Fu R, Worden JR, Chakraborty S, Clinton NE, Risi C, Sun Y, Yin L. 2017. Rainforest-initiated wet season onset over the southern Amazon. *Proceedings of the National Academy of Sciences, USA* 114: 8481–8486.
- Wu J, Albert LP, Lopes AP, Restrepo-Coupe N, Hayek M, Wiedemann KT, Guan K, Stark SC, Christoffersen B, Prohaska N *et al.* 2016. Leaf development and demography explain photosynthetic seasonality in Amazon evergreen forests. *Science* 351: 972–976.
- Wu J, Chavana-Bryant C, Prohaska N, Serbin SP, Guan K, Albert LP, Yang X, van Leeuwen WJD, Garnello AJ, Martins G *et al.* 2017a. Convergence in relationships between leaf traits, spectra and age across diverse canopy

environments and two contrasting tropical forests. *New Phytologist* 214: 1033–1048.

- Wu J, Guan K, Hayek M, Restrepo-Coupe N, Wiedemann KT, Xu X, Wehr R, Christoffersen BO, Miao G, da Silva R *et al.* 2017b. Partitioning controls on Amazon forest photosynthesis between environmental and biotic factors at hourly to interannual timescales. *Global Change Biology* 23: 1240–1257.
- Wu J, Serbin SP, Xu X, Albert LP, Chen M, Meng R, Saleska SR, Rogers A. 2017c. The phenology of leaf quality and its within-canopy variation is essential for accurate modeling of photosynthesis in tropical evergreen forests. *Global Change Biology* 9: 4814–4827.
- Xu X, Medvigy D, Joseph Wright S, Kitajima K, Wu J, Albert LP, Martins GA, Saleska SR, Pacala SW. 2017. Variations of leaf longevity in tropical moist forests predicted by a trait-driven carbon optimality model. *Ecology Letters* 20: 1097–1106.

## Supporting Information

Additional Supporting Information may be found online in the Supporting Information tab for this article:

**Fig. S1** Examples of leaves from each age category for trees used in leaf demography surveys.

**Fig. S2** Stomatal conductance by leaf age and time of day for trees early in the dry season.

**Fig. S3** Stomatal conductance by leaf age and time of day for trees late in the dry season.

**Table S1** Focal tree information

**Table S2** Early vs late dry season  $A_{\text{net}}$  information by tree

**Table S3** Young and mature leaf  $V_{\text{cmax}}$  information by tree

**Table S4** Mature and old leaf  $V_{\text{cmax}}$  information by tree

**Table S5** Young and mature leaf  $J_{\text{max}}$  information by tree

**Table S6** Mature and old leaf  $J_{\text{max}}$  information by tree

**Table S7** Young and mature leaf triose phosphate use (TPU) information by tree

**Table S8** Mature and old leaf triose phosphate use (TPU) information by tree

**Table S9** Mature and old leaf stomatal conductance information by tree

**Table S10** Young and mature leaf Chl *a*: *b* ratio information by tree

**Table S11** Mature and old leaf Chl *a*: *b* ratio information by tree

**Table S12** Young and mature leaf total chlorophyll information by tree

**Table S13** Mature and old leaf total chlorophyll information by tree

**Table S14** Young and mature leaf percentage nitrogen information by tree

**Table S15** Mature and old leaf percentage nitrogen information by tree

**Table S16** Young and mature leaf carbon-to-nitrogen ratio information by tree

**Table S17** Mature and old leaf carbon-to-nitrogen ratio information by tree

**Table S18** Early vs late dry season number of young leaves on *c.* 1-m branches

**Table S19** Early vs late dry season number of mature leaves on *c.* 1-m branches

**Table S20** Early vs late dry season number of old leaves on *c.* 1-m branches

**Table S21** Linear regressions of branch-level  $V_{\text{cmax}}$  vs day of year

**Methods S1** Stem water potential.

**Methods S2** Chlorophyll concentration calculations.

**Methods S3** Meta-analysis equations.

**Methods S4** Branch-level  $V_{\text{cmax}}$  calculations.

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