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## ORIGINAL ARTICLE

In situ short-term responses of Amazonian understory plants to elevated CO<sub>2</sub>

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## Abstract

The response of plants to increasing atmospheric CO<sub>2</sub> depends on the ecological context where the plants are found. Several experiments with elevated CO<sub>2</sub> (eCO<sub>2</sub>) have been done worldwide, but the Amazonian forest understory has been neglected. As the central Amazon is limited by light and phosphorus, understanding how understory responds to eCO<sub>2</sub> is important for foreseeing how the forest will function in the future. In the understory of a natural forest in the Central Amazon, we installed four open-top chambers as control replicates and another four under eCO<sub>2</sub> (+250 ppm above

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ambient levels). Under  $eCO_2$ , we observed increases in carbon assimilation rate (67%), maximum electron transport rate (19%), quantum yield (56%), and water use efficiency (78%). We also detected an increase in leaf area (51%) and stem diameter increment (65%). Central Amazon understory responded positively to  $eCO_2$  by increasing their ability to capture and use light and the extra primary productivity was allocated to supporting more leaf and conducting tissues. The increment in leaf area while maintaining transpiration rates suggests that the understory will increase its contribution to evapotranspiration. Therefore, this forest might be less resistant in the future to extreme drought, as no reduction in transpiration rates were detected.

#### KEYWORDS

apparent photosynthetic quantum yield,  $CO_2$  enrichment, leaf area, open-top chambers, photosynthesis, tropical forest, water-use efficiency

## 1 | INTRODUCTION

The Amazon forests store around 100 petagrams of carbon (Pg C) in their aboveground live biomass (Feldpausch et al., 2012; Malhi et al., 2006), which represents c. 20% of the carbon (C) stored in the world's forest vegetation (Baccini et al., 2012; Houghton, 2007; Saatchi et al., 2011). Intact Amazonian forests have acted as a large C sink over the past decades (Brienen et al., 2015; Hubau et al., 2020), accounting for c. 25% of the terrestrial C sink (Pan et al., 2011; Phillips et al., 2009). However, the response of Amazon forests to increasing atmospheric carbon dioxide concentration ( $[CO_2]$ ) is highly uncertain (Cernusak et al., 2013) since the increase in  $[CO_2]$  does not necessarily translate directly into an increase in  $CO_2$  uptake by the forests (Terrer et al., 2019). Given that nutrient availability, rainfall variability and light environment constrain plant C assimilation, these factors impose limitations to the forests' responses to elevated  $CO_2$  ( $eCO_2$ ) (Chazdon, 1988; Ellsworth et al., 2017; Fleischer et al., 2019; McCarthy et al., 2010; Walker et al., 2021).

The Amazonian *terra-firme* (upland) forests are characterized by high species diversity (Fauser et al., 2015; ter Steege et al., 2013) that forms a dense and continuous canopy, resulting in vertical gradients of irradiance, decreasing from the top of the canopy to the forest understory (Chazdon, 1988; Wright & Van Schaik, 1994). The irradiance that reaches the lower layer of the Amazon Forest is usually less than 5% of that reaching the top canopy (Dos Santos et al., 2019), potentially making light the strongest limiting factor for understory plants (Baldocchi & Collineau, 1994; Chazdon, 1988). The vertical gradient in incident light in the Amazon is closely reflected in leaf  $CO_2$  assimilation rates throughout the vertical forest strata (Domingues et al., 2005), with plants inhabiting the understory being dependent on brief and unstable periods of high light density (*sunflecks*) to maintain a positive carbon balance in the long term (Chazdon, 1988; Chazdon & Pearcy, 1991; Neufeld & Young, 2003). Limiting light level conditions, close to the plant compensation point, is thought to trigger the largest responses of plants to  $eCO_2$  (Kimball, 1986;

Poorter and Pérez-Soba, 2001). Therefore, forest understories are a highly interesting component of  $eCO_2$  research.

The understory of tropical forests is inhabited not only by species that are restricted to completing their life cycles under shaded conditions (typical understory species), but also by juveniles of trees and lianas that will eventually reach the full sunlight environment at the top of the canopy (Valladares & Niinemets, 2008). Despite the relatively lower biomass stored in the midcanopy and understory compartments (30 vs. 70% from canopy trees for a Central Amazonia site), it is nonetheless a relevant component of the forest, contributing up to 32% of the wood productivity (Araujo et al., 2020). Moreover, it has been suggested that understory plants may be particularly responsive to  $eCO_2$  as they often operate near-neutral carbon balance due to limiting light availability, that is, close to their physiological light compensation point (LCP) (Curtis & Wang, 1998; Kubiske & Pregitzer, 1996; Lloyd & Farquhar, 2008; Würth et al., 1998). If understory plants are indeed particularly responsive to  $eCO_2$ , this may not only have consequences on C sequestration but may also result in changes in community structure and the future composition of tropical forests, as less responsive plants might be excluded from that community by competition (Hubau et al., 2019; Lapola et al., 2009). Therefore, there is an urgent need to better understand the response of the understory plant community to ongoing increase in  $[CO_2]$ .

As  $eCO_2$  increases photosynthetic efficiency, plants are expected to acclimate to the decreased demand for investments in ribulose 1,5-bisphosphate carboxylase/oxygenase (Rubisco), often represented by the leaf maximum carboxylation capacity ( $V_{cmax}$ ) (Rogers & Humphries, 2000). On the other hand,  $eCO_2$  can also increase the demand for cofactors produced by photosynthetic light reactions (ATP and NADPH), which can shift photosynthesis from being limited by Rubisco to being limited by the regeneration capacity of ribulose 1,5-bisphosphate (RUBP) (Drake et al., 1997), often represented by the leaf maximum electron transport rate ( $J_{max}$ ). This second possibility seems more likely in shaded conditions (Sharkey, 1985), but might be true also

for high-light environments. In addition, to offset the low light availability, understory plants tend to invest resources in strategies to optimize light capture, such as greater leaf area (Gommers et al., 2013; Valladares & Niinemets, 2008).

In that sense, an increase in understory leaf area could enhance the contribution of this forest stratum to the leaf-to-atmosphere moisture flux, offsetting a fraction of the possible decline in leaf transpiration ( $E$ ) due to reduced stomatal conductance ( $g_s$ ) under eCO<sub>2</sub> (Xu et al., 2016). The negative effect of eCO<sub>2</sub> on  $E$  has the potential to cascade into basin-wide changes in rainfall, which, particularly in the Amazon, is highly dependent on water vapour transferred back to the atmosphere via forest evapotranspiration (Sampaio et al., 2021; Zemp et al., 2017; but see Yang et al., 2016).

In situ field experiments are crucial for reducing uncertainties surrounding the response of tropical forests to eCO<sub>2</sub> and climate change. Through these experiments, it is possible to enhance the understanding of ecosystem processes to improve terrestrial biosphere models (Norby et al., 2016). While numerous experiments have been conducted with elevated CO<sub>2</sub> levels, in situ experiments, specifically in tropical forests, remain rare (for a review see Ainsworth & Long, 2004; Norby & Zak, 2011; Walker et al., 2021). As a result, the current knowledge about tropical rain forest plants response to eCO<sub>2</sub> is primarily based on experiments with seedlings growing in pots (e.g., Cernusak et al., 2011a; Reekie & Bazzaz, 1989; Slot et al., 2021; Ziska et al., 1991) and planted species (Arnone & Körner, 1995; Körner & Arnone, 1992; Würth et al., 1998).

Here we employed in situ open-top chambers (OTCs) to investigate the short-term (120–354 days) effect of eCO<sub>2</sub> on the photosynthetic parameters related to carbon assimilation and water use, and carbon allocation for the naturally occurring understory community of an old-growth forest in the Central Amazon. We tested the following hypotheses:

- (i) Plants in the tropical forest understory are responsive to eCO<sub>2</sub>, increasing their net CO<sub>2</sub> assimilation at saturating light ( $A_{sat}$ ), intrinsic water-use efficiency ( $iWUE$ ),  $J_{max}$ , apparent quantum yield ( $\Phi$ ), relative growth rate ( $RGR$ ) and leaf production ( $Lf_p$ ), while decreasing  $V_{cmax}$ ,  $g_s$ ,  $E$  and  $LCP$ .
- (ii) Due to their adaptation to low-light environments understory plants under eCO<sub>2</sub> prioritize allocation of carbon to leaf area ( $Lf_{area}$ ).

## 2 | MATERIALS AND METHODS

### 2.1 | Site description

The study site is located at the Experimental Station of Tropical Forestry (EEST/ZF-2), in Central Amazon (2°35'39"S, 60°12'29"W) at the experimental site of the AmazonFACE program (Free-Air CO<sub>2</sub> Enrichment—<https://amazonface.inpa.gov.br>). The site is situated on a low fertility and highly weathered deep soil, classified as geric Ferralsol, rich in clay (76%), well drained and with average nutrient

concentration of 0.1% nitrogen, 1.9% carbon and 0.01% phosphorus (101.8 mg kg<sup>-1</sup>) for the top 0–30 cm (Quesada et al., 2010). The vegetation of the site is classified as *terra firme* (upland) evergreen forest, characterized by high diversity of plant species, with an average canopy height of 30 m and canopy tree crowns close to each other (Pereira et al., 2019). On average, the irradiance reaching the understory of this site is less than 5% of that reaching the upper canopy, and over 75% of the understory daytime irradiance is below 25  $\mu\text{mol m}^{-2} \text{s}^{-1}$  (Dos Santos et al., 2019). The climate of the region is classified as rainy tropical, according to Köppen-Geiger (Peel et al., 2007). The local mean annual temperature is 26.7°C with low seasonal variation (24.5–27.5°C—min and max, respectively), and mean annual precipitation of 2400 mm, with a drier period between July and September when monthly precipitation can reach less than 100 mm (Ferreira et al., 2005; Tanaka et al., 2014).

### 2.2 | Experimental design

Eight steel-polypropylene OTCs, with 2.5 m diameter and 3 m height each, surrounded by soil trenching of 30 cm wide and 50 cm deep—to isolate them from the surrounding soil and plant roots—(Supporting information: Figure S1), were installed at the experimental site. The chambers were designed to increase the [CO<sub>2</sub>] inside them and were set up in pairs, with four control (ambient—aCO<sub>2</sub>) and four treatment (+250 ppmv—eCO<sub>2</sub>) chambers (Supporting information: Table S1). The distance between the OTC chambers varies between 14.7 and 219.4 m. The locations of the chambers were determined semi-randomly by using the Leaf Area Index (LAI) derived from hemispherical photos, aiming to homogenize the amount of light that reaches each area. Each pair of OTCs has a CO<sub>2</sub>/H<sub>2</sub>O nondispersive infrared (NDIR) gas analyser (LI-840A, Li-Cor® Biosciences) installed in a nearby central system that measures and records (Campbell Scientific CR1000 dataloggers) the CO<sub>2</sub> and water (H<sub>2</sub>O) concentrations inside the chambers every 1 min. This system was programmed to control the CO<sub>2</sub> injection in the eCO<sub>2</sub> replicates whenever the difference between the pair of OTCs falls below 200 ppmv. The CO<sub>2</sub> is injected inside the eCO<sub>2</sub> chambers through a gas line connected to a central cylinder system and spread by fans installed close to the injection hose. The CO<sub>2</sub> injection into the eCO<sub>2</sub> chambers started on 1 November 2019, and since then, CO<sub>2</sub> injectors have been switched on during daytime hours, that is, from 6 AM to 6 PM, each day. The mean ( $\pm$ SD) daytime [CO<sub>2</sub>] during 2020 was 466  $\pm$  21 and 732  $\pm$  24 ppmv among the control and treatment chambers, respectively.

In addition to [CO<sub>2</sub>] and [H<sub>2</sub>O] measurements inside the OTCs, we estimated the solar irradiance ( $\text{mol m}^{-2} \text{day}^{-1}$ ) from hemispherical photographs taken 1.5 m above the ground in the centre of each chamber using a Canon Rebel EOS T3 camera with Sigma fish-eye lens (8 mm) and further analysed using Gap Light Analyzer software (<https://www.caryinstitute.org/science/our-scientists/dr-charles-d-canham/gap-light-analyzer-gla>). For each OTC, the total solar radiation transmitted by the canopy (TSRT) was calculated as a function of the solar constant (1367 W m<sup>-2</sup>), geographical coordinates (latitude/longitude), cloudiness index ( $kt = 0.5$ ) and canopy

openness (percentage of open sky seen from beneath the forest canopy), and then transformed into photosynthetically active radiation (PAR) (Supporting information: Table S1).

Considering all OTCs, we identified 56 different plant species, belonging to 26 distinct families. Among the OTCs, the number of individual plants varied from  $n = 10$  to 18 (Supporting information: Table S1), with heights (considered here as the main stem length— $Ht$ ) between 0.28 and 3 m, diameter at the base (DB) ranging from 3.9 to 35 mm (Supporting information: Figure S2A and Table S2). Due to the high local biodiversity, there were no species that occurred in all OTCs (Supporting information: Table S2).

### 2.3 | Leaf level gas exchange measurements

Leaf level gas exchange parameters were determined through light-saturated  $\text{CO}_2$  assimilation versus intercellular  $\text{CO}_2$  concentration ( $A/C_i$ ) curves in up to three leaves from each of three individuals of different species per OTC ( $a\text{CO}_2 = 36$ ,  $e\text{CO}_2 = 34$ ), and light response curves in one leaf from each of the individuals selected for  $A/C_i$  curves per OTC ( $a\text{CO}_2 = 12$ ,  $e\text{CO}_2 = 12$ ), during March 2020, 120 days after  $\text{CO}_2$  enrichment started. These measurements were taken with a portable infrared gas analyser (IRGA-LI-6400XT; Li-Cor® Biosciences) on fully expanded leaves, between 8:00 AM and 3 PM, in individuals that either belonged to species that were more abundant or displayed a perceived larger contribution the LAI within a given OTC. Before the measurements, leaves were acclimated for at least 15 min by carefully monitoring assimilation rate and  $g_s$  values to ensure their stability. From each  $A/C_i$  response curve, the photosynthetic capacity parameters ( $V_{\text{cmax}}$  and  $J_{\text{max}}$ ,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) were calculated based on Farquhar et al. (1980) by a curve-fitting routine based on minimum least squares (Domingues et al., 2010) and adjusted to the standard temperature of 25°C (Bernacchi et al., 2001). From the light response curves, the  $A_{\text{sat}}$  ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ),  $g_s$  at  $A_{\text{sat}}$  ( $\text{mol m}^{-2} \text{s}^{-1}$ ),  $E$  at  $A_{\text{sat}}$  ( $\text{mmol m}^{-2} \text{s}^{-1}$ ) and  $iWUE$  ( $\mu\text{mol mol}^{-1}$ ) were quantified, and the  $LCP$  ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) and the  $\Phi$  ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) were calculated.

For all measurements, the standardized set conditions inside the IRGA chamber were airflow of  $400 \mu\text{mol s}^{-1}$ , relative humidity between 60% and 70%, and leaf temperature of 30°C. The  $A/C_i$  curves were performed at a saturating photosynthetic photon flux density (PPFD) of  $1000 \mu\text{mol m}^{-2} \text{s}^{-1}$ , and the reference  $[\text{CO}_2]$  were controlled as follows: 400, 300, 200, 75, 50, 400, 600, 800, 1000, 1200 and  $1500 \mu\text{mol mol}^{-1}$ . The light response curves were performed at  $[\text{CO}_2]$  of  $400 \mu\text{mol mol}^{-1}$  for  $a\text{CO}_2$  and  $600 \mu\text{mol mol}^{-1}$  for  $e\text{CO}_2$ , using a PPFD sequence of 250, 500, 750, 1000, 1500, 500, 250, 100, 75, 50, 25, 10, 5 and  $0 \mu\text{mol m}^{-2} \text{s}^{-1}$ . The  $A_{\text{sat}}$ ,  $g_s$ ,  $E$  and  $iWUE$  parameters were taken from these curves, under PPFD of  $1000 \mu\text{mol m}^{-2} \text{s}^{-1}$ , and according to the  $\text{CO}_2$  treatment, at  $400 \mu\text{mol mol}^{-1}$  for  $a\text{CO}_2$  and  $600 \mu\text{mol mol}^{-1}$  for  $e\text{CO}_2$ . The  $LCP$  was calculated by the equation:

$$LCP = \frac{R_d}{\alpha}, \quad (1)$$

where  $R_d$  is the dark respiration rate (PPFD = 0) and  $\alpha$  is the light response curve initial slope, between 0 and  $50 \mu\text{mol m}^{-2} \text{s}^{-1}$  PPFD. The  $\Phi$  was determined as the light response curve initial slope above  $LCP$ .

### 2.4 | Leaf production

We measured leaf production ( $Lf_p$ ) of 55 individuals in  $a\text{CO}_2$ , and 47 individuals in  $e\text{CO}_2$ , from January to October 2020, with  $Lf_p$  defined as the number of newly produced leaves divided by the number of individual plants within a given OTC. Leaf production monitoring followed the methodology by Menezes et al. (2022) where, at the beginning of the experiment, all leaves from each individual were included as initial stock, and the leaves from both ends (proximal and terminal) of each branch were tagged to follow changes in leaf demography. Thereafter, the new flushed leaves were included in the demographic censuses when their leaf blade was nearly expanded, while scars left from an abscised petiole were considered to be dead leaves. Leaf demographic censuses were performed in November 2019, January, March, July and October 2020. The cumulative  $Lf_p$  was calculated as the sum of total flushed leaves during the sampled period, that is, 354 days after the start of the experiment.

### 2.5 | Leaf area

We quantified changes in individual leaf area ( $Lf_{\text{area}}$ ) by measuring two fully expanded leaves from the same branch, one that flushed before ( $t_1$ ) and another that flushed after ( $t_2$ ) the onset of the experiment (November 2019), on all plants that flushed new leaves ( $a\text{CO}_2 = 42$ ,  $e\text{CO}_2 = 41$ ). Measurements of both leaves were taken in the same campaign (July 2020).  $Lf_{\text{area}}$  was determined from photographs taken from leaves overlaying graph paper and processed in the ImageJ software (<https://imagej.nih.gov/ij/>). The results are presented as the sum of the mean leaf area ( $\text{m}^2$ ) per treatment, and the percentage change in leaf area ( $Lf_{\text{area}}\%$ ) was calculated as the difference between the leaves that flushed before and after  $\text{CO}_2$  enrichment starts, in the same branch.

### 2.6 | Height, diameter and relative growth rate

We measured the individual plants main stem length (which is often their height) ( $Ht$ ;  $a\text{CO}_2 = 51$ ,  $e\text{CO}_2 = 44$ ) and the stem base diameter ( $BD$ ;  $a\text{CO}_2 = 56$ ,  $e\text{CO}_2 = 45$ ) in November 2019 and September 2020. The  $Ht$  was measured with a millimetre measuring tape, from the base of the stem to the apex of the main stem, even when the individual's growth pattern was not completely vertical (e.g., lianas). In each plant, two perpendicular measurements of the  $BD$  were taken using a digital calliper (Mitutoyo/Absolute). The  $BD$  measurement point was set in the first campaign, at 5 cm from the ground. Thereafter, subsequent measurements were taken at the same marked point. For subsequent analysis, we



divided the plants in three height classes:  $20 \leq 80$ ,  $80 < 140$  and  $\geq 140$  cm, and three diameter classes:  $3 \leq 9$ ,  $9 < 15$  and  $\geq 15$  mm.

Daily mean height (cm day<sup>-1</sup>) and base diameter (mm day<sup>-1</sup>) increment were calculated for each plant, as the difference between  $H_t$  and  $BD$ , respectively, measured in September 2020– $t_2$  and November 2019– $t_1$  (when CO<sub>2</sub> enrichment started). We also calculated the relative growth rate (RGR) for each plant, using  $BD^2 \times H_t$  as a non-destructive surrogate for plant dry mass (Bloomberg et al., 2008). RGR was calculated as

$$RGR = \left[ \ln(BD_{t_2}^2 \times H_{t_2}) - \ln(BD_{t_1}^2 \times H_{t_1}) \right] / (t_2 - t_1), \quad (2)$$

where  $BD_{t_1}$  and  $BD_{t_2}$  are initial and final base diameter (mm),  $H_{t_1}$  and  $H_{t_2}$  are initial and final total height (cm), and  $t_1$  and  $t_2$  are initial and final time (days).

## 2.7 | Statistical analyses

We analysed the effects of eCO<sub>2</sub> on leaf-level gas exchange ( $A_{sat}$ ,  $g_s$ ,  $E$ ,  $iWUE$ ,  $V_{cmax}$ ,  $J_{max}$ ,  $J_{max} \cdot V_{cmax}$ ,  $LCP$  and  $\Phi$ ),  $Lf_p$ ,  $Lf_{area}$  and plant growth ( $H_t$ ,  $BD$  and  $RGR$ ). Due to the high diversity of species and considering the fact that there were no species that occurred in every OTC, it was not feasible to consider species identity in our analyses. Instead, we evaluated parameters averages (Supporting Information: Table S3) from each OTCs as sampling units ( $n = 8$ ), establishing comparisons between the control (ambient–aCO<sub>2</sub>,  $n = 4$ ) and treatment (+250 ppmv–eCO<sub>2</sub>,  $n = 4$ ) OTCs. For the  $Lf_p$  data, we first averaged the rate of leaf production for each OTC (number of new leaves produced within the time interval divided by the number of individuals within a given OTC) and afterwards we calculated the mean and standard deviations among the four OTCs from each treatment. We also analysed the average absolute accumulation of new leaves as the sum of all leaves produced within each OTC (Section 2.4). In the case of  $H_t$  and  $BD$ , the analyses were conducted according to the previously mentioned size class division specified in Section 2.6.

Differences between the parameters measured under aCO<sub>2</sub> and eCO<sub>2</sub> were analysed by generalized linear mixed models, with the CO<sub>2</sub> treatment as categorical fixed effect with two levels. For all parameters, we found that models including species identity or ambient light levels as random effects were not significantly different from those that did not ( $p \leq 0.05$ ); therefore, these factors were not included in the final models. To account for the chambers' natural environmental variation, we included OTC pairs as a random effect in the mixed models, using the 'glmmTMB' package (Brooks et al., 2017). The leaf-level gas exchange parameters are presented as the mean  $\pm$  SD and reported as the mean percentage change of the response ratio  $[(r - 1) \times 100]$ , where  $r$  = response under eCO<sub>2</sub>/response under aCO<sub>2</sub>. Significant differences were regarded at  $p \leq 0.05$ . The statistical analyses were performed with R version 4.1.2 (R Core Team 2021).

## 3 | RESULTS

### 3.1 | CO<sub>2</sub> enrichment effects on leaf gas exchange

We evaluated the response of leaf gas exchange to eCO<sub>2</sub> 120 days after CO<sub>2</sub> enrichment started. Under eCO<sub>2</sub> the  $A_{sat}$  was 67% and the  $iWUE$  was 78% higher than aCO<sub>2</sub> ( $p \leq 0.001$  for both).  $J_{max}$  and the  $J_{max} \cdot V_{cmax}$  ratio were 19% higher under eCO<sub>2</sub> ( $p \leq 0.001$  for both). For  $V_{cmax}$ ,  $g_s$  and  $E$ , no significant changes were observed under eCO<sub>2</sub> ( $p = 0.7$ ,  $p = 0.5$  and  $p = 0.3$ , respectively). The  $\Phi$  was 56% higher ( $p \leq 0.001$ ), while  $LCP$  did not show significant difference between the treatments ( $p = 0.3$ ) (Figure 1 and Table 1). Regarding the quality of the  $A/C_i$  curve fitting, the average root mean squared error (RMSE) was 0.11 (ranging from 0.04 to 0.28).

### 3.2 | CO<sub>2</sub> enrichment effects on leaf production, leaf area and plant growth

Plants under aCO<sub>2</sub> produced more leaves between January and March 2020 (Figure 2). However, between March and June,  $Lf_p$  was more than two times higher under eCO<sub>2</sub> than aCO<sub>2</sub> (59 vs. 18 leaves, Figure 2). Despite this, the cumulative  $Lf_p$  was higher under aCO<sub>2</sub> than eCO<sub>2</sub> for that period. Between June and October,  $Lf_p$  was 85% higher under eCO<sub>2</sub>, although it was not statistically different from aCO<sub>2</sub> ( $p = 0.059$ ). At the end of our study, we observed that the absolute accumulated  $Lf_p$ , between January and October, was 23% higher under eCO<sub>2</sub>, although no significant difference was detected between treatments ( $p = 0.3$ ) (Figure 2).

The  $Lf_{area}$  that flushed after the onset of CO<sub>2</sub> enrichment, compared to those already present before the experiment started (November 2019), increased by 51% under eCO<sub>2</sub> and 19% under aCO<sub>2</sub> ( $p \leq 0.001$ ) (Figure 3).

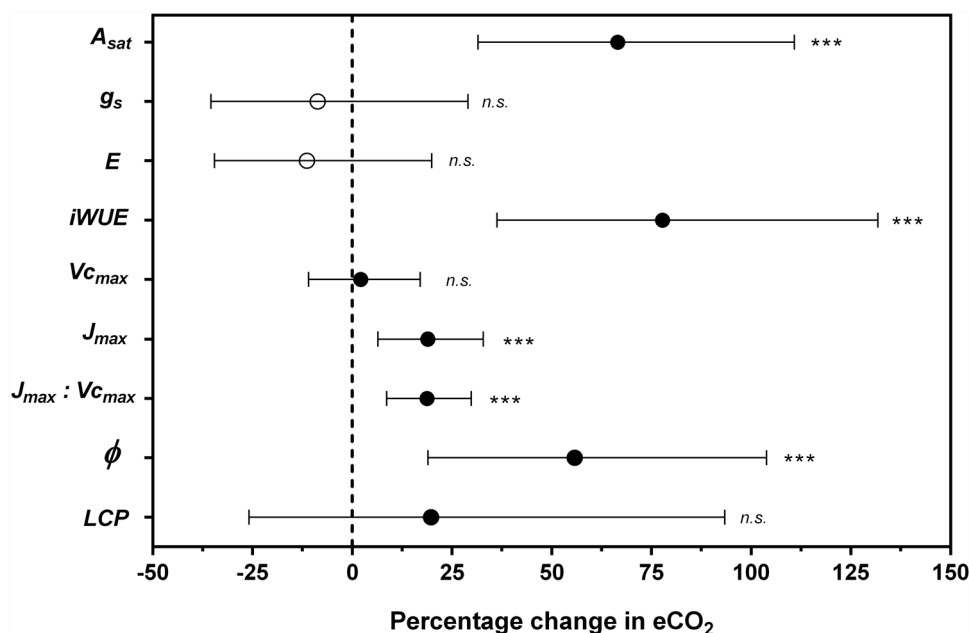
Although we observed a trend of higher total  $H_t$  of 23% under eCO<sub>2</sub>, this increase was not statistically significant (Figure 4), except for the larger size class ( $\geq 140$  cm) ( $p = 0.2$ ,  $p = 0.9$  and  $p \leq 0.001$ , respectively). When all  $BD$  classes were considered together, increment was significant ( $p \leq 0.001$ ) and 65% higher at eCO<sub>2</sub>. That was also true for the intermediary and largest size classes ( $9 < 15$  and  $\geq 15$  mm) ( $p \leq 0.001$  for both). For the smallest size classes ( $3 < 9$ ), no difference was detected ( $p = 0.02$ ) (Figure 5).

Concerning the  $RGR$ , we detected a 29% increment under eCO<sub>2</sub> ( $p = 0.01$ ) (Figure 6).

## 4 | DISCUSSION

### 4.1 | Carbon assimilation and growth responses to elevated CO<sub>2</sub>

This Amazonian understory community showed higher potential carbon assimilation rates ( $A_{sat}$ ) under eCO<sub>2</sub>, as previously observed in



**FIGURE 1** Mean response to  $eCO_2$  ( $n = 8$ ,  $\pm 95\%$  CI) of net  $CO_2$  assimilation at saturating light ( $A_{sat}$ ,  $\mu mol\ m^{-2}\ s^{-1}$ ), stomatal conductance ( $g_s$ ,  $mol\ m^{-2}\ s^{-1}$ ), transpiration ( $E$ ,  $mmol\ m^{-2}\ s^{-1}$ ), intrinsic water-use efficiency ( $iWUE$ ,  $\mu mol\ mol^{-1}$ ), apparent maximum carboxylation rate of Rubisco ( $V_{cmax}$ ,  $\mu mol\ m^{-2}\ s^{-1}$ ), apparent maximum electron transport rate for RuBP regeneration under saturating light ( $J_{max}$ ,  $\mu mol\ m^{-2}\ s^{-1}$ ),  $J_{max} : V_{cmax}$  ratio, apparent quantum yield ( $\Phi$ ,  $\mu mol\ m^{-2}\ s^{-1}$ ) and light compensation point ( $LCP$ ,  $\mu mol\ m^{-2}\ s^{-1}$ ). The dashed line represents no change, black circle (●) an increase and open circle (○) a decrease under  $eCO_2$ . The asterisks indicate significant treatment effect (\*\*\*)  $p \leq 0.001$  and n.s. = no significant,  $n = 8$  OTCs (4- $aCO_2$  and 4- $eCO_2$ ).

**TABLE 1** Gas exchange parameters of plants under ambient ( $aCO_2$ ) and elevated ( $eCO_2$ )  $CO_2$  concentration.

Variable	$aCO_2$	$eCO_2$	$p$
$A_{sat}$	$3.7 \pm 0.7$	$6.1 \pm 0.8$	$\leq 0.001$
$g_s$	$0.077 \pm 0.03$	$0.069 \pm 0.008$	0.5
$E$	$1.11 \pm 0.3$	$0.97 \pm 0.12$	0.3
$iWUE$	$54.1 \pm 9.9$	$96.2 \pm 19.2$	$\leq 0.001$
$V_{cmax}$	$18.4 \pm 1.3$	$18.8 \pm 2.3$	0.7
$J_{max}$	$26.1 \pm 0.7$	$31.1 \pm 3.4$	$\leq 0.001$
$J_{max} : V_{cmax}$	$1.45 \pm 0.10$	$1.72 \pm 0.10$	$\leq 0.001$
$\Phi$	$0.02 \pm 0.005$	$0.03 \pm 0.003$	$\leq 0.001$
$LCP$	$8.7 \pm 1.4$	$10.6 \pm 4.9$	0.3

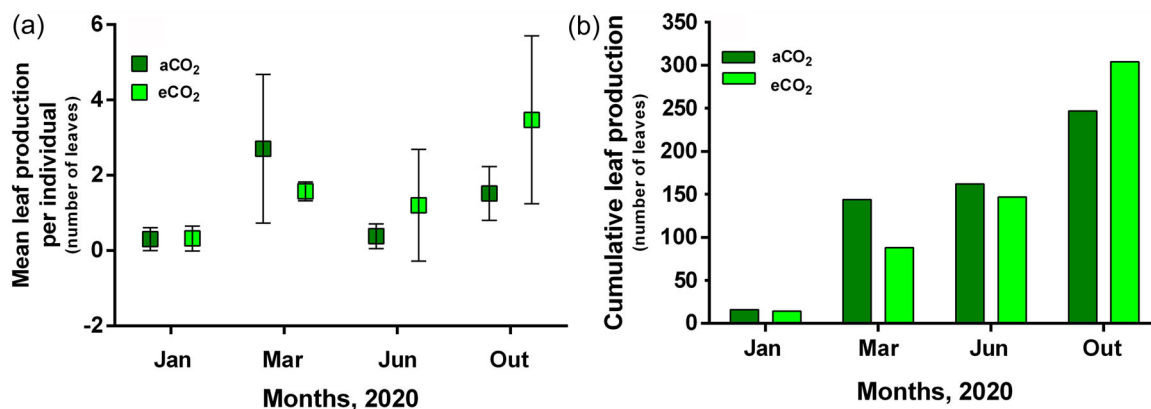
Note: Mean  $\pm$  SD and  $p$  value for each parameter analysed between treatments.

Net  $CO_2$  assimilation at saturating light ( $A_{sat}$ ,  $\mu mol\ m^{-2}\ s^{-1}$ ), stomatal conductance ( $g_s$ ,  $mol\ m^{-2}\ s^{-1}$ ), transpiration rate ( $E$ ,  $mmol\ m^{-2}\ s^{-1}$ ), intrinsic water-use efficiency ( $iWUE$ ,  $\mu mol\ mol^{-1}$ ), maximum carboxylation rate of Rubisco ( $V_{cmax}$ ,  $\mu mol\ m^{-2}\ s^{-1}$ ), maximum electron transport rate for RuBP regeneration under saturating light ( $J_{max}$ ,  $\mu mol\ m^{-2}\ s^{-1}$ ),  $J_{max} : V_{cmax}$  ratio, apparent quantum yield ( $\Phi$ ,  $\mu mol\ m^{-2}\ s^{-1}$ ) and light compensation point ( $LCP$ ,  $\mu mol\ m^{-2}\ s^{-1}$ ).

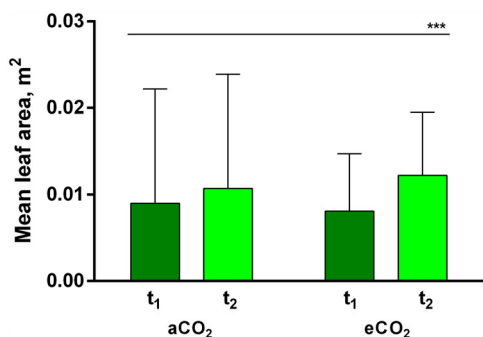
shade plants (DeLucia & Thomas, 2000; Hättenschwiler, 2001; Kubiske & Pregitzer, 1996). The increase in  $A_{sat}$  was sustained by an enhancement in  $J_{max}$ , indicating a high energy demand for RuBP regeneration, which suggests an enhancement in the capacity of

these plants to utilize sunflecks (DeLucia & Thomas, 2000; Pearcy, 1990). Thus,  $eCO_2$  may facilitate shaded plants in the understory to better exploit sunflecks which is the main, but erratic, light resource available. Despite previous  $eCO_2$  studies reporting a reduction in  $V_{cmax}$  under  $eCO_2$  (Ainsworth & Long, 2004; Leakey et al., 2002; Medlyn et al., 1999), we did not observe a downregulation of carboxylation capacity. This may be linked to the relatively short observation period of this study, implying insufficient time for the process of downregulation to occur in these plants (Ainsworth et al., 2004b; Moore et al., 1999; Sage, 1994). Alternatively, it might result from non-limiting nitrogen availability. Similar studies have previously demonstrated a reduction in  $LCP$  and an increase in  $\Phi$  under  $eCO_2$  and limited light (Hättenschwiler, 2001; Kubiske & Pregitzer, 1996). We hypothesized that under  $eCO_2$  and understory conditions, plants decrease their  $LCP$  and increase  $\Phi$  to optimize light use and carbon assimilation (Drake et al., 1997). Here, the  $eCO_2$  did not lead to a decrease in the  $LCP$ , a result also recorded by Norby et al. (2003) for understory shaded leaves. Instead, there was a high variability among plants in both treatments, which can be related to the diversity of species present within the community (Drake et al., 1997; Kubiske & Pregitzer, 1996) but not accounted for by our experimental design. However, the higher values of  $\Phi$  reiterate the increase in assimilation and consequent carbon gain observed in response to  $eCO_2$  (Kubiske & Pregitzer, 1996).

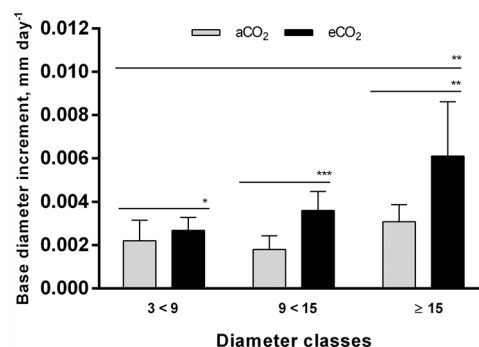
Such an increase in carbon assimilation ( $A_{sat}$ ,  $J_{max}$  and  $\Phi$ ) resulted in a higher  $Lf_{area}$ ,  $BD$  and  $RGR$  under  $eCO_2$ , which implies that these plants prioritize investments towards increasing light capture and processing into fixed carbon, perhaps boosting their performance in



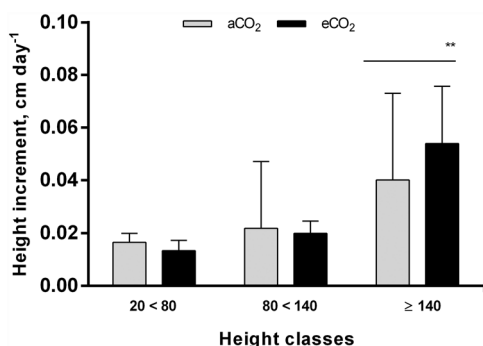
**FIGURE 2** (a) Mean  $\pm$  SD and (b) cumulative leaf production measured over four field campaigns (January, March, June and October 2020) across treatments: dark green is aCO<sub>2</sub> and light green is eCO<sub>2</sub>. Bars indicate the standard deviation of the means. [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



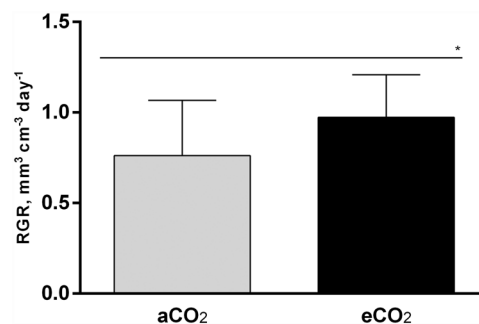
**FIGURE 3** Mean leaf area (m<sup>2</sup>) of the open-top chambers (OTC,  $n = 8$ ) of leaves that flushed before (dark green bars— $t_1$ ) and after (light green bars— $t_2$ ) the onset of CO<sub>2</sub> enrichment (November 2019). Bars indicate the standard deviation of the means. The asterisks indicate significant treatment effect (\*\* $p \leq 0.001$ ),  $n = 8$  OTCs (4— $aCO_2$  and 4— $eCO_2$ ). [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 5** Daily mean base diameter increment (mm day<sup>-1</sup>) of plants under aCO<sub>2</sub> (grey bars) and eCO<sub>2</sub> (black bars), divided into three diameter classes (3 < 9, 9 < 15 and  $\geq 15$  mm). Error bars indicate the standard deviation of the means. The asterisks indicate significant treatment effect (\* $p \leq 0.05$ ),  $n = 8$  OTCs (4— $aCO_2$  and 4— $eCO_2$ ).



**FIGURE 4** Daily mean height increment (cm day<sup>-1</sup>) of plants under aCO<sub>2</sub> (grey bars) and eCO<sub>2</sub> (black bars), divided into three height classes (20 < 80, 80 < 140 and  $\geq 140$  cm). Error bars indicate the standard deviation of the means. The asterisks indicate significant treatment effect (\*\* $p \leq 0.01$ ),  $n = 8$  OTCs (4— $aCO_2$  and 4— $eCO_2$ ).



**FIGURE 6** Mean daily relative growth rate (RGR, mm<sup>3</sup> cm<sup>-3</sup> day<sup>-1</sup>) of plants under aCO<sub>2</sub> (grey bars) and eCO<sub>2</sub> (black bars). Error bars indicate the standard deviation of the means. The asterisks indicate significant treatment effect (\* $p \leq 0.05$ ),  $n = 8$  OTCs (4— $aCO_2$  and 4— $eCO_2$ ).



the understory environment (Valladares & Niinemets, 2008). Higher *BD* and a weak *Ht* response of the individuals indicate that in this forest, the understory community may be more responsive to  $e\text{CO}_2$  in terms of growth to acquire resources (Givnish, 1988). Plants adapted to shade conditions may invest resources to optimize light capture (Gommers et al., 2013) at the expense of vertical growth (Valladares & Niinemets, 2008), in contrast to canopy species that survive by waiting for better conditions, such as canopy openings, to further develop (Swaine & Whitmore, 1988). Indeed, plants growing under shaded conditions are expected to benefit disproportionately from  $e\text{CO}_2$  as they live closer to their *LCP* and are known to be more responsive to  $e\text{CO}_2$  (Curtis & Wang, 1998; Lloyd & Farquhar, 2008), with our observations supporting the view that  $e\text{CO}_2$  can stimulate and change growth performance in the Amazonian understory. We observed wide variations occurring in *LCP*, as well as growth responses that could indicate very different overall  $e\text{CO}_2$  responses by different species in our plant community and suggest that some species may develop competitive advantages over others under  $e\text{CO}_2$  scenarios in the future. While our study did not focus on specific species, the results presented here reinforce the idea that, regardless of the species or habit, a tropical plant community can respond to environmental changes, such as  $e\text{CO}_2$ . Marvin et al. (2015), in an experiment with tropical liana and tree seedlings, showed that both life forms had significant responses to  $e\text{CO}_2$ , but no difference between them, which supports the effect of  $e\text{CO}_2$  on tropical plant communities. This goes against the idea that increasing atmospheric  $[\text{CO}_2]$  is causing an expansion of the lianas in tropical forests (Schnitzer and Bongers, 2011). However, the extent to which such changes could alter the whole forest species composition in the future remains speculative, and an in-depth evaluation of species or functional group responses to  $e\text{CO}_2$  is needed (Lapola et al., 2009; Marvin et al., 2015). If species respond differently to  $e\text{CO}_2$ , some species could show a disproportional change in performance compared to others. Perhaps species at the acquisitive end of the conservative-acquisitive spectrum will benefit more from the increasing atmospheric  $[\text{CO}_2]$ . Their increased performance might reflect on their population dynamics within the community (i.e., reproduction, recruitment and mortality rates), likely culminating in alterations in community structure (i.e., species composition and/or dominance and rarity patterns).

## 4.2 | Water-use efficiency under elevated $\text{CO}_2$

We found that the increase in *iWUE* was driven primarily by increased  $A_{\text{sat}}$  with little variation in  $g_s$  and *E*. Although it is widely known that  $e\text{CO}_2$  tends to reduce  $g_s$  (Ainsworth & Long, 2004; Ainsworth & Rogers, 2007; Medlyn et al., 2011), this is not true in all cases (Ellsworth, 1999). The smaller or nonsignificant changes in  $g_s$  under  $e\text{CO}_2$  are more commonly observed in plants with low rates of metabolism (Saxe et al., 1998), and the  $\text{CO}_2$ -induced reductions in  $g_s$  decrease from the top to the bottom of the canopy (Domingues et al., 2007; Gunderson et al., 2002; Wullschlegel et al., 2002), which was the case of this study. The no response of  $g_s$  to

$e\text{CO}_2$  in our study may also have been due to the limited variation of other environmental factors, such as humidity and temperature (and consequently the vapour pressure deficit—*VPD*), since the stomata are sensitive to environmental conditions (Grossiord et al., 2020; Gunderson et al., 2002) and these variables are, in general, reasonably constant in the understory of tropical forests (Mendes & Marengo, 2017). In these cases, when the increase in *iWUE* is due only to the increase in  $A_{\text{sat}}$ , there is no improvement in the water economy (Saxe et al., 1998). However, there could be changes in the understory water fluxes to the atmosphere since we observed a significant increase in  $Lf_{\text{area}}$  in our study. Even without significant changes in  $g_s$ , a higher transpirative foliar area may enhance the contribution of the understorey stratum to ecosystem evapotranspiration rates, which may in turn affect land-atmosphere fluxes.

Maximizing *E* rates is a possible mechanism for plants to ensure sufficient nutrient uptake when under competition, especially under low phosphorus availability (Cernusak et al., 2011b). There are experimental and modelling studies showing that the Central Amazon Forest is limited by phosphorus (Cunha et al., 2022; Fleischer et al., 2019). The lack of response in both  $g_s$  and *E* observed in our experiment might be the reflex of these variables being more strongly influenced by phosphorus competition at the forest understory. Such strategy might be facilitated by the fact that tropical forest understory plants tend to maintain high  $g_s$  to minimize the stomatal limitation of assimilation rates during brief sunflecks (Percy, 1990). It makes sense that at the humid tropics such acquisitive strategies are favoured, although drought events during El Niño years certainly favours the conservative species (Domingues et al., 2018). We still have very limited understanding of how variable are tropical plant species regarding their functional strategies, although species can be remarkably different (Thompson et al., 2019).

Ecosystem level manipulation experiments are scientifically challenging and financially demanding. Many ecosystem processes are dependent on relatively long timescales, especially for forests. Even more challenging is the particular way that each species contributes to ecosystem functioning. Considering the large diversity of species that are present in tropical forests, replication of experimental units is the limiting factor on extrapolations of single experiments to the whole tropical forest biome. That is certainly the case for our experimental design. A way forward is recognizing that groups of species converge are often redundant on their functional ecology, forming functional groups. In the past, species were simply grouped by anecdotal knowledge of their distribution along the successional changes that communities undergo after disturbances. Nowadays, the characterization of species based on their functional traits is an interesting possibility of forming truly functional groups that can simplify ecosystem studies and enable extrapolation of local studies to larger scales.

## 5 | CONCLUSION

The Amazon forest understory, despite growing in a light-limited environment, responded positively to  $\text{CO}_2$  enrichment. We showed that these understory plants improve their C gain, through higher  $A_{\text{sat}}$  and  $\Phi$ ,

and their growth, through higher  $BD$  increment and  $Lf_{area}$  under  $eCO_2$ . These results depict how this light and phosphorus-limited ecosystem can increase assimilation rates and modulate investments of resources to enhance the capture and efficient use of light and potentially have significant impacts on the structure and composition of the Amazon in the future. No decrease in  $g_s$  was observed and, together with the increase in  $Lf_{area}$ , this result suggests an enhancement in the contribution of understory to leaf-to-atmosphere moisture flux, predicted to decrease in upper canopy trees. These results, together with several studies that have already been carried out with  $eCO_2$ , demonstrate the flexibility of plant communities to adjust to the current scenario of increased atmospheric CO<sub>2</sub> and its impact on global climate change. Still, a better grasp of individual species abilities is a knowledge gap that needs addressing.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## REFERENCES

- Ainsworth, E.A. & Long, S.P. (2004) What have we learned from 15 years of free-air CO<sub>2</sub> enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO<sub>2</sub>. *New Phytologist*, 165(2), 351–372.
- Ainsworth, E.A. & Rogers, A. (2007) The response of photosynthesis and stomatal conductance to rising [CO<sub>2</sub>]: mechanisms and environmental interactions. *Plant, Cell & Environment*, 30(3), 258–270.
- Ainsworth, E.A., Rogers, A., Nelson, R. & Long, S.P. (2004b) Testing the "source-sink" hypothesis of down-regulation of photosynthesis in elevated [CO<sub>2</sub>] in the field with single gene substitutions in *Glycine max*. *Agricultural and Forest Meteorology*, 122(1–2), 85–94.
- Araujo, R.F., Chambers, J.Q., Celes, C.H.S., Muller-Landau, H.C., Santos, A.P.F., Emmert, F. et al. (2020) Integrating high resolution drone imagery and forest inventory to distinguish canopy and understory trees and quantify their contributions to forest structure and dynamics. *PLoS One*, 15(12), e0243079.
- Arnone, J.A. & Körner, C. (1995) Soil and biomass carbon pools in model communities of tropical plants under elevated CO<sub>2</sub>. *Oecologia*, 104(1), 61–71.
- Baccini, A., Goetz, S.J., Walker, W.S., Laporte, N.T., Sun, M., Sulla-Menashe, D. et al. (2012) Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nature Climate Change*, 2(3), 182–185.
- Baldocchi, D. & Collineau, S. (1994) The physical nature of solar radiation in heterogeneous canopies: spatial and temporal attributes. In: Cadwell, M.M., Ray, J. & Pearce, R.P. (Eds.) *Exploitation of environmental heterogeneity by plants. ecophysiological processes above-and belowground*. Academic Press, pp. 21–71.
- Bernacchi, C.J., Singaas, E.L., Pimentel, C., Portis Jr., A.R. & Long, S.P. (2001) Improved temperature response functions for models of Rubisco-limited photosynthesis. *Plant, Cell & Environment*, 24(2), 253–259.
- Bloomberg, M., Mason, E.G., Jarvis, P. & Sedcole, R. (2008) Predicting seedling biomass of radiata pine from allometric variables. *New Forests*, 36(1), 103–114.

- Brienen, R.J.W., Phillips, O.L., Feldpausch, T.R., Gloor, E., Baker, T.R., Lloyd, J. et al. (2015) Long-term decline of the Amazon carbon sink. *Nature*, 519(7543), 344–348.
- Brooks, E., Kristensen, K., Benthem, J., Magnusson, A., Berg, W., Nielsen, A. et al. (2017) glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *The R Journal*, 9(2), 378–400.
- Cernusak, L.A., Winter, K., Dalling, J.W., Holtum, J.A.M., Jaramillo, C., Körner, C. et al. (2013) Tropical forest responses to increasing atmospheric CO<sub>2</sub>: current knowledge and opportunities for future research. *Functional Plant Biology*, 40(6), 531–551.
- Cernusak, L.A., Winter, K., Martínez, C., Correa, E., Aranda, J., García, M. et al. (2011a) Responses of legume versus nonlegume tropical tree seedlings to elevated CO<sub>2</sub> concentration. *Plant Physiology*, 157(1), 372–385.
- Cernusak, L.A., Winter, K. & Turner, B.L. (2011b) Transpiration modulates phosphorus acquisition in tropical tree seedlings. *Tree Physiology*, 31(8), 878–885.
- Chazdon, R.L. (1988) Sunflecks and their importance to forest understorey plants. *Advances in ecological research*, 18, 1–63.
- Chazdon, R.L. & Pearcy, R.W. (1991) The importance of sunflecks for forest understorey plants. *Bioscience*, 41(11), 760–766.
- Cunha, H.F.V., Andersen, K.M., Lugli, L.F., Santana, F.D., Aleixo, I.F., Moraes, A.M. et al. (2022) Direct evidence for phosphorus limitation on Amazon forest productivity. *Nature*, 608, 558–562.
- Curtis, P.S. & Wang, X. (1998) A meta-analysis of elevated CO<sub>2</sub> effects on woody plant mass, form, and physiology. *Oecologia*, 113(3), 299–313.
- DeLucia, E.H. & Thomas, R.B. (2000) Photosynthetic responses to CO<sub>2</sub> enrichment of four hardwood species in a forest understorey. *Oecologia*, 122(1), 11–19.
- Domingues, T.F., Berry, J.A., Martinelli, L.A., Ometto, J.P.H.B. & Ehleringer, J.R. (2005) Parameterization of canopy structure and leaf-level gas exchange for an Eastern Amazonian tropical rain forest (Tapajós National Forest, Pará, Brazil). *Earth Interactions*, 9(17), 1–23.
- Domingues, T.F., Martinelli, L.A. & Ehleringer, J.R. (2007) Ecophysiological traits of plant functional groups in forest and pasture ecosystems from eastern Amazônia, Brazil. *Plant Ecology*, 193, 101–112.
- Domingues, T.F., Meir, P., Feldpausch, T.R., Saiz, G., Veenendaal, E.M., Schrod, F. et al. (2010) Co-limitation of photosynthetic capacity by nitrogen and phosphorus in West Africa woodlands. *Plant, Cell & Environment*, 33(6), 959–980.
- Domingues, T.F., Ometto, J.P.H.B., Nepstad, D.C., Brando, P.M., Martinelli, L.A. & Ehleringer, J.R. (2018) Ecophysiological plasticity of Amazonian trees to long-term drought. *Oecologia*, 187, 933–940.
- Drake, B.G., González-Meler, M.A. & Long, S.P. (1997) More efficient plants: a consequence of rising atmospheric CO<sub>2</sub>? *Annual Review of Plant Physiology and Plant Molecular Biology*, 48, 609–639.
- Ellsworth, D.S. (1999) CO<sub>2</sub> enrichment in a maturing pine forest: are CO<sub>2</sub> exchange and water status in the canopy affected? *Plant, Cell & Environment*, 22(5), 461–472.
- Ellsworth, D.S., Anderson, I.C., Crous, K.Y., Cooke, J., Drake, J.E., Gherlenda, A.N. et al. (2017) Elevated CO<sub>2</sub> does not increase eucalypt forest productivity on a low-phosphorus soil. *Nature Climate Change*, 7(4), 279–282.
- Farquhar, G.D., von Caemmerer, S. & Berry, J.A. (1980) A biochemical model of photosynthetic CO<sub>2</sub> assimilation in leaves of C3 species. *Planta*, 149(1), 78–90.
- Fauset, S., Johnson, M.O., Gloor, M., Baker, T.R., Monteagudo, M.A. & Brienen, R.J.W. et al. (2015) Hyperdominance in Amazonian forest carbon cycling. *Nature Communications*, 6(1), 6857.
- Feldpausch, T.R., Lloyd, J., Lewis, S.L., Brienen, R.J.W., Gloor, M., Monteagudo Mendoza, A. et al. (2012) Tree height integrated into pantropical forest biomass estimates. *Biogeosciences*, 9(8), 3381–3403.
- Ferreira, S.J.F., Luizão, F.J. & Dallarosa, R.L.G. (2005) Throughfall and rainfall interception by an upland forest submitted to selective logging in Central Amazonia. *Acta Amazonica*, 35, 55–62.
- Fleischer, K., Rammig, A., De Kauwe, M.G., Walker, A.P., Domingues, T.F., Fuchslueger, L. et al. (2019) Amazon forest response to CO<sub>2</sub> fertilization dependent on plant phosphorus acquisition. *Nature Geoscience*, 12(9), 736–741.
- Givnish, T. (1988) Adaptation to sun and shade: a whole-plant perspective. *Functional Plant Biology*, 15(2), 63–92.
- Gommers, C.M.M., Visser, E.J.W., Onge St, K.R.S., Voeseenek, L.A.C.J. & Pierik, R. (2013) Shade tolerance: when growing tall is not an option. *Trends in Plant Science*, 18(2), 65–71.
- Grossiord, C., Buckley, T.N., Cernusak, L.A., Novick, K.A., Poulter, B., Siegwolf, R.T.W. et al. (2020) Plant responses to rising vapor pressure deficit. *New Phytologist*, 226(6), 1550–1566.
- Gunderson, C.A., Sholtis, J.D., Wulschleger, S.D., Tissue, D.T., Hanson, P.J. & Norby, R.J. (2002) Environmental and stomatal control of photosynthetic enhancement in the canopy of a sweetgum (*Liquidambar styraciflua* L.) plantation during 3 years of CO<sub>2</sub> enrichment. *Plant, Cell & Environment*, 25(3), 379–393.
- Hättenschwiler, S. (2001) Tree seedling growth in natural deep shade: functional traits related to interspecific variation in response to elevated CO<sub>2</sub>. *Oecologia*, 129(1), 31–42.
- Houghton, R.A. (2007) Balancing the global carbon budget. *Annual Review of Earth and Planetary Sciences*, 35(1), 313–347.
- Hubau, W., Lewis, S.L., Phillips, O.L., Affum-Baffoe, K., Beeckman, H., Cuni-Sanchez, A. et al. (2020) Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, 579(7797), 80–87.
- Hubau, W., De Mil, T., Van den Bulcke, J., Phillips, O.L., Angoboy Ilondea, B., Van Acker, J. et al. (2019) The persistence of carbon in the African forest understorey. *Nature Plants*, 5(2), 133–140.
- Kimball, B.A. (1986) CO<sub>2</sub> stimulation of growth and yield under environmental restraints. In: Enoch, H.Z. & Kimball, B.A. (Eds.) *Carbon dioxide enrichment of greenhouse crops. Vol. II. Physiology, yield and economics*. Boca Raton: CRC Press, pp. 53–67.
- Körner, C. & Arnone III, J.A. (1992) Responses to elevated carbon dioxide in artificial tropical ecosystems. *Science*, 257(5077), 1672–1675.
- Kubiske, M.E. & Pregitzer, K.S. (1996) Effects of elevated CO<sub>2</sub> and light availability on the photosynthetic light response of trees of contrasting shade tolerance. *Tree Physiology*, 16(3), 351–358.
- Lapola, D.M., Oyama, M.D., & Nobre, C.A. (2009) Exploring the range of climate biome projections for tropical South America: The role of CO<sub>2</sub> fertilization and seasonality. *Global Biogeochemical Cycles*, 23(3). <https://doi.org/10.1029/2008gb003357>
- Leakey, A.D.B., Press, M.C., Scholes, J.D. & Watling, J.R. (2002) Relative enhancement of photosynthesis and growth at elevated CO<sub>2</sub> is greater under sunflecks than uniform irradiance in a tropical rain forest tree seedling. *Plant, Cell & Environment*, 25(12), 1701–1714.
- Lloyd, J. & Farquhar, G.D. (2008) Effects of rising temperatures and [CO<sub>2</sub>] on the physiology of tropical forest trees. *Philosophical Transactions of the Royal Society, B: Biological Sciences*, 363(1498), 1811–1817.
- Malhi, Y., Wood, D., Baker, T.R., Wright, J., Phillips, O.L., Cochrane, T. et al. (2006) The regional variation of aboveground live biomass in old-growth Amazonian forests. *Global Change Biology*, 12(7), 1107–1138.
- Marvin, D.C., Winter, K., Burnham, R.J. & Schnitzer, S.A. (2015) No evidence that elevated CO<sub>2</sub> gives tropical lianas an advantage over tropical trees. *Global Change Biology*, 21(5), 2055–2069.
- McCarthy, H.R., Oren, R., Johnsen, K.H., Gallet-Budynek, A., Pritchard, S.G., Cook, C.W. et al. (2010) Re-assessment of plant carbon dynamics at the Duke free-air CO<sub>2</sub> enrichment site: interactions of atmospheric [CO<sub>2</sub>] with nitrogen and water availability over stand development. *New Phytologist*, 185(2), 514–528.
- Medlyn, B.E., Badeck, F.W., de Pury, D.G.G., Barton, C.V.M., Broadmeadow, M., Ceulemans, R. et al. (1999) Effects of elevated

- [CO<sub>2</sub>] on photosynthesis in European forest species: a meta-analysis of model parameters. *Plant, Cell & Environment*, 22(12), 1475–1495.
- Medlyn, B.E., Duursma, R.A., Eamus, D., Ellsworth, D.S., Prentice, I.C., Barton, C.V.M. et al. (2011) Reconciling the optimal and empirical approaches to modelling stomatal conductance. *Global Change Biology*, 17(6), 2134–2144.
- Mendes, K.R. & Marengo, R.A. (2017) Stomatal opening in response to the simultaneous increase in vapor pressure deficit and temperature over a 24-h period under constant light in a tropical rainforest of the central Amazon. *Theoretical and Experimental Plant Physiology*, 29(4), 187–194.
- Menezes, J., Garcia, S., Grandis, A., Nascimento, H., Domingues, T.F., Guedes, A.V. et al. (2022) Changes in leaf functional traits with leaf age: when do leaves decrease their photosynthetic capacity in Amazonian trees? *Tree Physiology*, 42(5), 922–938.
- Moore, B.D., Cheng, S.H., Sims, D. & Seemann, J.R. (1999) The biochemical and molecular basis for photosynthetic acclimation to elevated atmospheric CO<sub>2</sub>. *Plant, Cell & Environment*, 22(6), 567–582.
- Neufeld, H.S. & Young, D.R. (2003) Ecophysiology of the herbaceous layer in temperate deciduous forests. In: Gilliam, F. (Ed.) *The herbaceous layer in forests of eastern North America*. Oxford: Oxford University Press, pp. 38–90.
- Norby, R.J., De Kauwe, M.G., Domingues, T.F., Duursma, R.A., Ellsworth, D.S., Goll, D.S. et al. (2016) Model-data synthesis for the next generation of forest free-air CO<sub>2</sub> enrichment (FACE) experiments. *New Phytologist*, 209(1), 17–28.
- Norby, R.J., Sholtis, J.D., Gunderson, C.A. & Jawdy, S.S. (2003) Leaf dynamics of a deciduous forest canopy: no response to elevated CO<sub>2</sub>. *Oecologia*, 136(4), 574–584.
- Norby, R.J. & Zak, D.R. (2011) Ecological lessons from free-air CO<sub>2</sub> enrichment (FACE) experiments. *Annual Review of Ecology, Evolution, and Systematics*, 42(1), 181–203.
- Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A. et al. (2011) A large and persistent carbon sink in the world's forests. *Science*, 333(6045), 988–993.
- Pearcy, R.W. (1990) Sunflecks and photosynthesis in plant canopies. *Annual Review of Plant Physiology and Plant Molecular Biology*, 41, 421–453.
- Peel, M.C., Finlayson, B.L. & McMahon, T.A. (2007) Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11(5), 1633–1644.
- Pereira, I., Mendonça do Nascimento, H., Boni Vicari, M., Disney, M., DeLucia, E., Domingues, T. et al. (2019) Performance of laser-based electronic devices for structural analysis of Amazonian terra-firme forests. *Remote Sensing*, 11(5), 510.
- Phillips, O.L., Aragão, L.E.O.C., Lewis, S.L., Fisher, J.B., Lloyd, J., López-González, G. et al. (2009) Drought sensitivity of the Amazon rainforest. *Science*, 323(5919), 1344–1347.
- Poorter, H. & Pérez-Soba, M. (2001) The growth response of plants to elevated CO<sub>2</sub> under non-optimal environmental conditions. *Oecologia*, 129, 1–20.
- Quesada, C.A., Lloyd, J., Schwarz, M., Patiño, S., Baker, T.R., Czimczik, C. et al. (2010) Variations in chemical and physical properties of Amazon forest soils in relation to their genesis. *Biogeosciences*, 7(5), 1515–1541.
- R Core Team. (2021) *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>
- Reekie, E.G. & Bazzaz, F.A. (1989) Competition and patterns of resource use among seedlings of five tropical trees grown at ambient and elevated CO<sub>2</sub>. *Oecologia*, 79(2), 212–222.
- Rogers, A. & Humphries, S.W. (2000) A mechanistic evaluation of photosynthetic acclimation at elevated CO<sub>2</sub>. *Global Change Biology*, 6(8), 1005–1011.
- Saatchi, S.S., Harris, N.L., Brown, S., Lefsky, M., Mitchard, E.T.A., Salas, W. et al. (2011) Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences*, 108(24), 9899–9904.
- Sage, R.F. (1994) Acclimation of photosynthesis to increasing atmospheric CO<sub>2</sub>: the gas exchange perspective. In: *Photosynthesis research*. Vol. 39. Kluwer Academic Publishers.
- Sampaio, G., Shimizu, M.H., Guimarães-Júnior, C.A., Alexandre, F., Guatura, M., Cardoso, M. et al. (2021) CO<sub>2</sub> physiological effect can cause rainfall decrease as strong as large-scale deforestation in the Amazon. *Biogeosciences*, 18(8), 2511–2525.
- Dos Santos, V.A.H.F., Nelson, B.W., Rodrigues, J.V.F.C., Garcia, M.N., Ceron, J.V.B. & Ferreira, M.J. (2019) Fluorescence parameters among leaf photosynthesis-related traits are the best proxies for CO<sub>2</sub> assimilation in Central Amazon trees. *Brazilian Journal of Botany*, 42(2), 239–247.
- Saxe, H., Ellsworth, D.S. & Heath, J. (1998) Tree and forest functioning in an enriched CO<sub>2</sub> atmosphere. *New Phytologist*, 139(3), 395–436.
- Schnitzer, S.A. & Bongers, F. (2011) Increasing liana abundance and biomass in tropical forests: emerging patterns and putative mechanisms. *Ecology Letters*, 14, 397–406.
- Sharkey, T.D. (1985) Photosynthesis in intact leaves of C3 plants: physics, physiology and rate limitations. *The Botanical Review*, 51(1), 53–105.
- Slot, M., Rifai, S.W. & Winter, K. (2021) Photosynthetic plasticity of a tropical tree species, *Tabebuia rosea*, in response to elevated temperature and [CO<sub>2</sub>]. *Plant, Cell & Environment*, 44(7), 2347–2364.
- ter Steege, H., Pitman, N.C.A., Sabatier, D., Baraloto, C., Salomão, R.P., Guevara, J.E. et al. (2013) Hyperdominance in the Amazonian tree flora. *Science*, 342(6156), 1243092.
- Swaine, M.D. & Whitmore, T.C. (1988) On the definition of ecological species groups in tropical rain forests. *Vegetatio*, 75(1), 81–86.
- Tanaka, L.M.S., Satyamurty, P. & Machado, L.A.T. (2014) Diurnal variation of precipitation in central Amazon Basin. *International Journal of Climatology*, 34(13), 3574–3584.
- Terrer, C., Jackson, R.B., Prentice, I.C., Keenan, T.F., Kaiser, C., Vicca, S. et al. (2019) Nitrogen and phosphorus constrain the CO<sub>2</sub> fertilization of global plant biomass. *Nature Climate Change*, 9(9), 684–689.
- Thompson, J.B., Slot, M., Dalling, J.W., Winter, K., Turner, B.L. & Zalamea, P.-C. (2019) Species-specific effects of phosphorus addition on tropical tree seedling response to elevated CO<sub>2</sub>. *Functional Ecology*, 33, 1871–1881.
- Valladares, F. & Niinemets, Ü. (2008) Shade tolerance, a key plant feature of complex nature and consequences. *Annual Review of Ecology, Evolution, and Systematics*, 39, 237–257.
- Walker, A.P., De Kauwe, M.G., Bastos, A., Belmecheri, S., Georgiou, K., Keeling, R.F. et al. (2021) Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO<sub>2</sub>. *New Phytologist*, 229(5), 2413–2445.
- Wright, S.J. & Van Schaik, C.P. (1994) Light and the phenology of tropical trees. *The American Naturalist*, 143(1), 192–199.
- Wullschlegel, S.D., Gunderson, C.A., Hanson, P.J., Wilson, K.B. & Norby, R.J. (2002) Sensitivity of stomatal and canopy conductance to elevated CO<sub>2</sub> concentration-interacting variables and perspectives of scale. *New Phytologist*, 153(3), 485–496.
- Würth, M.K.R., Winter, K. & Körner, C. (1998) In situ responses to elevated CO<sub>2</sub> in tropical forest understorey plants. *Functional Ecology*, 12(6), 886–895.
- Xu, Z., Jiang, Y., Jia, B. & Zhou, G. (2016) Elevated-CO<sub>2</sub> response of stomata and its dependence on environmental factors. *Frontiers in Plant Science*, 7, 657.
- Yang, Y., Donohue, R.J., McVicar, T.R., Roderick, M.L. & Beck, H.E. (2016) Long-term CO<sub>2</sub> fertilization increases vegetation productivity and has little effect on hydrological partitioning in tropical rainforests. *Journal of Geophysical Research: Biogeosciences*, 121(8), 2125–2140.
- Zemp, D.C., Schleussner, C.F., Barbosa, H.M.J. & Rammig, A. (2017) Deforestation effects on Amazon forest resilience. *Geophysical Research Letters*, 44(12), 6182–6190.



Ziska, L.H., Hogan, K.P., Smith, A.P. & Drake, B.G. (1991) Growth and photosynthetic response of nine tropical species with long-term exposure to elevated carbon dioxide. *Oecologia*, 86(3), 383–389.

## SUPPORTING INFORMATION

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