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After more than a decade of soil moisture deficit, tropical rainforest trees maintain photosynthetic capacity, despite increased leaf respiration.

Running Head: Tropical forest drought and leaf physiology

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Abstract

Determining climate change feedbacks from tropical rainforests requires an understanding of how carbon gain through photosynthesis and loss through respiration will be altered. One of the key changes that tropical rainforests may experience under future climate change scenarios is reduced soil moisture availability. In this study we examine if and how both leaf photosynthesis and leaf dark respiration acclimate following more than 12 years of experimental soil moisture deficit, via a through-fall exclusion experiment (TFE) in an eastern Amazonian rainforest. We find that experimentally drought-stressed trees and taxa maintain the same maximum leaf photosynthetic capacity as trees in corresponding control forest, independent of their susceptibility to drought-induced mortality. We hypothesise that photosynthetic capacity is maintained across all treatments and taxa to take advantage of short-lived periods of high moisture availability, when stomatal conductance (g_s) and photosynthesis can increase rapidly, potentially compensating for reduced assimilate supply at other times. Average leaf dark respiration (R_d) was elevated in the TFE-treated forest trees relative to the control by $28.2 \pm 2.8\%$ (mean \pm one standard error). This mean R_d value was dominated by a $48.5 \pm 3.6\%$ increase in the R_d of drought-sensitive taxa, and likely reflects the need for additional metabolic support required for stress-related repair, and hydraulic or osmotic maintenance processes. Following soil moisture deficit that is maintained for several

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years, our data suggest that changes in respiration drive greater shifts in the canopy carbon balance, than changes in photosynthetic capacity.

Introduction

Tropical rainforests are the world's most productive and biodiverse terrestrial ecosystem (Beer *et al.*, 2010), harbouring a substantial store of carbon, particularly in Amazonia because of its area (Grace *et al.*, 2014). How long tropical rainforests will remain a store of carbon remains uncertain, and may depend upon the intensity and/or frequency of future drought events (Gatti *et al.*, 2014, Phillips *et al.*, 2009). Small shifts in photosynthetic and autotrophic respiratory process responses to seasonal reductions in moisture have previously been shown to shift the carbon balance of tropical rainforests (Bonal *et al.*, 2008, Meir *et al.*, 2008, Rowland *et al.*, 2014); however how photosynthesis and respiration interact and acclimate to multi-year drought in tropical rainforest remains poorly understood.

Evidence from studies of drought-induced changes in photosynthesis and leaf respiration suggest that the effects on photosynthesis are greater than on autotrophic respiration (Catoni & Gratani, 2014, Chastain *et al.*, 2014, Ciais *et al.*, 2005, Doughty *et al.*, 2015, Flexas *et al.*, 2006, Meir *et al.*, 2008). Drought-induced reductions in leaf-level photosynthesis have been found to occur through either reductions in stomatal conductance (g_s) and/or mesophyll conductance (Catoni & Gratani, 2014, Chastain *et al.*, 2014, Flexas *et al.*, 2006, Miranda *et al.*, 2005, Stahl *et al.*, 2013), or reductions in biochemical efficiency (Flexas & Medrano, 2002, Galmes *et al.*, 2013, Lawlor & Cornic, 2002, Reddy *et al.*, 2004). During short term or less severe drought events, down-regulation of metabolic processes as a result of low g_s is thought to be the main limitation on photosynthesis (Flexas *et al.*, 2006, Flexas & Medrano, 2002).

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Photosynthetic capacity represents the maximum rate at which leaves can photosynthesise in optimum conditions. Provided optimum conditions are realised reductions in photosynthetic capacity will restrict total photosynthesis; in turn increased photosynthetic capacity will only increase photosynthesis in the absence of other limitations such as stomatal conductance or light. If a canopy photosynthesis is optimised to maximise light use efficiency (Hirose *et al.*, 1988, Kull & Kruijt, 1999), photosynthetic capacity is likely to be maintained, or potentially increased during these less severe drought events in order to maximise photosynthetic output at a lower g_s . However, as the severity and length of drought increases, accumulation of reactive oxygen species (ROS) can occur if g_s drops below a threshold value; this will result in more permanent reductions in photosynthesis through biochemical changes causing cellular damage (Flexas *et al.*, 2006). Cellular damage occurring during severe drought stress can reduce leaf metabolic function by: decreasing ribulose1, 5-biphosphate (RuBP) regeneration capacity, ATP synthesis or ATP content in the leaf, and Rubisco activity; or, by increasing leaf photochemical reaction rates (chlorophyll fluorescence) or photoinhibition (Flexas *et al.*, 2006, Flexas & Medrano, 2002, Galmes *et al.*, 2013, Reddy *et al.*, 2004). Consequently, under severe drought-stressed conditions photosynthetic capacity (the maximum rates of carboxylation of Rubisco (V_{cmax}) and/or electron transport (J_{max})) may decline, driving changes in total leaf scale photosynthesis.

The processes involved in leaf respiration remain less well understood than for photosynthesis (Atkin *et al.*, 2015, Atkin & Macherel, 2009, Atkin *et al.*, 2013); particularly in tropical rainforests and in relation to drought (Meir *et al.*, 2008, Meir & Woodward, 2010, Rowland *et al.*, 2014). Short-term, acute water stress is generally found to inhibit R_d because of either reduced substrate supply from photosynthesis with respiratory substrates being diverted to form compounds for osmotic regulation, or through direct reductions in mitochondrial respiratory capacity (Atkin & Macherel, 2009, Ayub *et al.*, 2011, Catoni &

Gratani, 2014, Chastain *et al.*, 2014, O'Brien *et al.*, 2015). However it is also possible that R_d can increase during periods of drought if substrate demand for processes such as hydraulic maintenance and repair (Brodersen & McElrone, 2013), and phloem transport regulation (Mencuccini & Hölttä, 2010) increases, or if drought conditions lead to a greater need to oxidise ROS or other redox equivalents, elevating photorespiration (Atkin & Macherel, 2009). Evidence of increasing R_d during drought is limited but has been reported for both crop plants and forests (Atkin & Macherel, 2009, Miranda *et al.*, 2005, Varone & Gratani, 2015).

The responses to long-term drought stress are likely to differ from those of short-term drought because certain processes, which may be sustainable over short time periods, are unlikely to facilitate long-term drought survival. Over longer time periods structural or physiological acclimation may occur to facilitate adaptation to drought conditions at a whole tree scale. Acclimation to drought within trees has been reported to occur across various time-scales from seasonal to multi-annual. In response to seasonal drought trees have been reported to increase their leaf-scale water-use efficiency (WUE: unit photosynthesis per unit water loss; Bonal *et al.*, 2007), reduce the rate at which R_d increases with temperature to minimise leaf carbon loss (Crous *et al.*, 2011) as well as to increase leaf mass per area (Sperlich *et al.*, 2015). Over multi-year drought conditions the key acclimation processes may differ as whole tree-scale structural changes become possible and perhaps necessary to maintain a positive carbon balance. These structural changes may include altered root growth patterns (Metcalf *et al.*, 2007), changes in canopy leaf area (Brando *et al.*, 2008, Metcalf *et al.*, 2010a) or changes in carbon allocation and stem growth (Brando *et al.*, 2008, da Costa *et al.*, 2010, Metcalf *et al.*, 2010b). Such structural changes are likely to compensate for, or facilitate further, any changes in physiology. Increased leaf-level respiration was found after five years of experimental drought, on a mix of shaded and sunlit leaves of a tropical

rainforest (Metcalf *et al.*, 2010b). Maintaining elevated respiration would require enhanced substrate use, thus also requiring acclimation responses in either allocation to growth or from carbon storage. However whether elevated R_d is related to acclimation responses in photosynthetic capacity or WUE, or even if elevated R_d can be maintained during long-term soil moisture deficit (e.g. for more than a decade), has yet to be determined.

In tropical rainforest, where species diversity is high and drought-sensitivity has been shown to vary with taxonomic identity (da Costa *et al.*, 2010, Nepstad *et al.*, 2007), there is likely to be a range of photosynthetic and respiratory acclimation responses to drought in any forest stand (Stahl *et al.*, 2013). Understanding these processes and their possible acclimation in the context of long-term drought in tropical rainforests is key to constraining the variability which currently exists in model predictions of such processes in future climate change scenarios (Galbraith *et al.*, 2010, Huntingford *et al.*, 2013, Powell *et al.*, 2013, Rowland *et al.*, 2015), or in more conceptual models (Meir *et al.*, 2015a).

We present wet and dry season measurements of photosynthetic capacity (V_{cmax} and J_{max}), R_d , g_s , photosynthesis in saturating light and ambient atmospheric CO_2 concentration (A_{sat}), WUE and leaf nutrient content for tropical rainforest which has experienced 13 years of experimental soil moisture deficit imposed by a through-fall exclusion (TFE) treatment and corresponding, adjacent control forest. We also compare variables for tree taxa that have been previously determined as sensitive or resistant to drought in terms of their mortality response to experimental soil moisture deficit (da Costa *et al.*, 2010). The results are compared with earlier measurements of photosynthesis and respiration made during the first three years of the experiment. Using these data we test the following hypotheses: (1) V_{cmax} , J_{max} , and R_d , change following prolonged soil moisture deficit; (2) Drought sensitivity (specified as the drought-induced mortality risk of specific tree genera) constrains the physiological response (V_{cmax} , J_{max} , R_d , A_{sat} and WUE) of a tree to seasonal or experimental drought; and (3) the

relationships between R_d , photosynthetic capacity and nutrient content change following prolonged soil moisture deficit.

Materials and methods

Site

This study was performed at a long-term TFE experiment in tropical rainforest, located in the Caxiuanã National Forest Reserve in the eastern Amazon (1°43'S. 51°27'W), on *terra firme* forest, with yellow oxisol soils (Ruivo & Cunha, 2003). The site is 15 m above sea level, has a mean annual rainfall between 2000 and 2500 mm and a pronounced dry season between June and November when monthly rainfall is <100 mm.

The experiment comprises two 1 ha plots, a treatment (TFE) and a control. In the TFE plot plastic panels and gutters are supported at a height of 1-2 m and exclude 50 % of the incident rainfall (da Costa *et al.*, 2010). A corresponding control plot is sited <50 m from the TFE, where there has been no manipulation of incident through-fall. As with many large-scale ecosystem manipulations, this experiment was prohibitively large and expensive to permit replication. The potential insights derived from long-term monitoring at large scale were favoured over the use of smaller plots replicated over large geographical areas (Carpenter, 1996, Osmond *et al.*, 2004). In addition, the large horizontal extent of many tree roots in this forest ecosystem made a small-plot design inappropriate. As described in earlier publications from this experiment (da Costa *et al.*, 2010, Fisher *et al.*, 2007, Meir *et al.*, 2009, Meir *et al.*, 2015b), and as also performed in other un-replicated large scale experiments such as at Hubbard Brook, pre-treatment data were obtained before the start of the experiment, enabling comparison over time as well as by treatment (see also Nepstad *et al.*, 2002, Davidson *et al.*,

2004). Perimeter trenching to 1-2 m depth was used to avoid lateral in-flow of soil water, and the litter on each panel was transferred manually to the forest floor immediately below it every few days to maintain these biogeochemical inputs to the soil. For more experimental details see (Fisher *et al.*, 2007, Meir *et al.*, 2009, da Costa *et al.*, 2010). The TFE experiment has been maintained continuously since January 2002 until the present (2015), and thus, prior to this study, the trees had experienced a 50% reduction in through-fall for 12-13 years.

Species selection and measurement protocol

Campaigns during 2013-14

In October-November 2013 (peak dry season) and July 2014 (peak wet season) leaf photosynthesis and leaf dark respiration measurements were performed on 21 canopy-top trees from the control and TFE forest (42 samples in total; Table 1). The selected trees were from six genera, with 3-6 replicates per genus. We tested the criteria used by da Costa *et al.*, (2010; See Table S1) to identify how sensitive these genera were to drought stress. We found strong consistency with the da Costa *et al.* (2010) results using six additional years of data, from (i.e., from 2009 to 2014). Of the six genera employed, three were classed as sensitive, and three as resistant to drought in terms of their drought-induced mortality response (Table S1). Branches from the canopy-tops of 21 trees from the TFE plot and 20 trees from the control plot were cut between 10 am and 3 pm, over several days in each sampling season. The stems were then immediately immersed in water, and re-cut to reconstitute the water supply to leaves, as also performed elsewhere for the chosen gas exchange measurements (Domingues *et al.*, 2010). After re-cutting underwater, branches were left to stabilise in a canopy opening, in full ambient irradiance for a minimum of 30 minutes before leaf measurements were conducted. Gas exchange measurements were performed using three

LICOR 6400 portable photosynthesis systems (LI-COR, Nebraska, USA), which were regularly cross-calibrated through checking repeated measures on the same leaves to ensure consistency among measurements. Following careful field tests on-site, no significant effect of branch cutting was found on our measurements (See measurement protocol below, and Figure S1).

V_{cmax} and J_{max} were derived by measuring photosynthesis at different concentrations of CO_2 (50-2000 ppm) in the leaf chamber. $A\text{-}C_i$ curves (C_i , the CO_2 concentration of the leaf intercellular spaces) were performed using a saturating photosynthetically active radiation (PAR) intensity of $2000 \mu\text{mol m}^{-2} \text{s}^{-1}$, determined from light curves performed separately on each genus. V_{cmax} and J_{max} were calculated from the $A\text{-}C_i$ curves after temperature-correction to $25 \text{ }^\circ\text{C}$ using the equations from Sharkey et al. (2007). Model fitting was carried out using the `optim` function in R, which optimises the fit of an $A\text{-}C_i$ curve to the data (R.3.0.2; R Core Team). As we were unable to measure mesophyll conductance we assumed it to be infinite (i.e. there to be no mesophyll conductance limitation) in our fitting procedure, rather than fitting this parameter separately, to avoid introducing unknown biases in our comparisons of control with treatment. Saturating photosynthesis (A_{sat}) was measured separately to the $A\text{-}C_i$ curves at a CO_2 concentration of 400 ppm and a PAR intensity of $2000 \mu\text{mol m}^{-2} \text{s}^{-1}$. A_{sat} was corrected to $25 \text{ }^\circ\text{C}$ using standard temperature constants from Sharkey et al. (2007). To standardise for variations in A_{sat} caused by differences in the internal CO_2 concentration (C_i) when leaves are exposed to the same external CO_2 concentrations A_{sat} was corrected to a common C_i value; the median C_i of all A_{sat} measurements was used as the common C_i value. A_{sat} was only measured if photosynthesis and g_s had remained stable within the LI-COR chamber for a minimum period of 10 minutes. Intrinsic leaf water use efficiency (WUE) was calculated as A_{sat} divided by the g_s measured at A_{sat} . Since the branches were cut, measured WUE may not be identical to WUE of intact branches at the top of the canopy; however the

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effects of cutting on photosynthesis and maximum g_s were non-significant (Fig. S1), and sampling among tree taxa was balanced between the control and TFE (Table 1), thereby minimizing potential biases due to branch cutting. Leaf dark respiration (R_d) was measured after keeping the leaf in complete darkness inside tinfoil, for 30 minutes. R_d measurements were corrected to 25 °C using Equation 1, where R_{dt} is respiration at the leaf temperature inside the leaf chamber, T is the leaf temperature inside the leaf chamber and the Q_{10} factor 2.2 represents the factor by which respiration increases for a 10 °C increase in leaf temperature (Atkin & Tjoelker, 2003).

$$R_d = R_{dt} \cdot 2.2^{\frac{25-T}{10}}$$

Equation 1

Measurement campaigns during 2001-03

$A-C_i$ curves were also recorded on attached leaves from trees adjacent to two walk-up observation towers in each plot, in both the wet and dry seasons of 2001 (pre-TFE treatment), 2002 and 2003. Samples were taken from 11 trees of 10 different species in the control, and nine trees of nine different species in the TFE; the total number of samples taken per period are shown in Table S2. As some of the tree canopies were partially shaded on each plot (Table S2), saturating PAR intensity for these curves was set at 1000 $\mu\text{mol m}^{-2} \text{s}^{-1}$. To ensure comparability between the 2001-03 and the 2013-14 protocols, $A-C_i$ curves and leaf respiration were re-measured on these same trees in 2013 and 2014 (Table S2). However, only one $A-C_i$ curve and two R_d measurements could be determined in the TFE because of tree mortality and loss of the branches close to the tower since 2003. V_{cmax} and J_{max} were calculated from the $A-C_i$ data using the same method as above. During the 2001-2003 campaigns, light response curves were also performed on the same leaves employed for $A-C_i$

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curves in both control and TFE plots. Previously published data on R_d at Caxiuanã (Metcalfé *et al.*, 2010) were derived from these light response curves.

Additional measurement campaigns

Additional R_d data were obtained in 2007 on sunlit and shaded leaves from cut branches obtained from both the control and TFE plots (Metcalfé *et al.*, 2010a; Table S3). All these values of R_d were corrected to 25°C using Equation 1. The same trees sampled in 2007 by Metcalfé *et al.* (2010a) were re-sampled where possible in this study, in peak dry season 2013, and peak wet season 2014 (Table S3). In summary, we synthesised leaf measurements of V_{cmax} , J_{max} and R_d from the experiment over the full experimental period, 2001-2013, to test the hypotheses laid out above.

Nutrient and leaf mass analysis

All leaves used for gas exchange were collected, scanned to obtain leaf area, dried to constant mass and weighed. Leaf area was measured from the scanned images using the Image J software (<http://imagej.nih.gov/ij/>), which, together with the dry mass of the leaf was used to calculate leaf mass per area (LMA, g m^{-2}), and its reciprocal, specific leaf area (SLA $\text{m}^{-2} \text{kg}^{-1}$). Following removal of the petiole and the main vein, and grinding of the dry tissue, nitrogen (*N*) and phosphorus (*P*) content of all leaves were measured in the EMBRAPA laboratories in Belem, Para, Brazil. *N* concentrations of 0.1 g subsamples were determined by dry combustion using a LECO CNS-2000 analyser (LECO Corporation, Michigan) and tested against laboratory standards. *P* concentrations of 0.1 g subsamples were determined by the molybdate method (Murphy & Riley, 1962) after digestion using sulphuric acid and peroxide.

Statistics

All statistical analyses were done in R (Version 3.02, R Core Team). Mixed effects modelling was performed following standard methods (Zuur *et al.*, 2009), using the *lm4* package. Models were formulated to test for a drought treatment effect on V_{cmax} , J_{max} , R_d , N , P , LMA and SLA where plot, sensitivity status (whether a tree belonged to a taxon which was considered sensitive or resistant to drought-induced mortality based on the data from this experiment; Table S1) and season were considered as fixed effects, and individual tree, nested within genus was considered as a random effect. Models were also formulated to test if a single relationship was maintained between V_{cmax} , J_{max} , R_d and leaf nutrients plus the combination of SLA (or LMA), in both the control and TFE, independent of drought stress. In these models N , P , and either LMA or SLA were considered fixed effects and individual tree, nested within genus, was considered as a random effect. All tests were performed on both a leaf area and a leaf mass basis. To find the most appropriate model for a variable, a likelihood ratio test with one degree of freedom was used to compare models with and without the variable of interest. Models were tested both with and without variable interactions. All other tests for significance throughout the paper were done using the Wilcoxon rank-sum test statistic, and significant results were considered as those with a P value <0.05.

Results:

Campaigns during 2013-14

No significant differences were found for V_{cmax} and J_{max} between the control and the TFE plots, in either wet or dry seasons (Fig. 1a & b). The average values for V_{cmax} and J_{max} across both seasons were $29.1 \pm 1.8 \mu\text{mol m}^{-2} \text{s}^{-1}$ (one standard error) and $51.1 \pm 2.8 \mu\text{mol m}^{-2} \text{s}^{-1}$, respectively in the control plot, and $26.8 \pm 1.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ and $45.2 \pm 1.9 \mu\text{mol m}^{-2} \text{s}^{-1}$

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respectively, in the TFE. The average $J_{\max} : V_{\max}$ ratio was 1.8 ± 0.1 in both the control and the TFE plot. Leaf respiration (R_d) was significantly elevated ($P=0.03$) in the TFE ($0.9 \pm 0.1 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) relative to the control plot ($0.7 \pm 0.1 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) during the dry season, but no significant differences existed in the wet season (Fig. 1c). These results were very similar when expressed on a leaf mass basis (Fig. S2). The significant increase in R_d in the TFE during the dry season was driven by elevated respiration in the tree taxa vulnerable to drought-induced mortality, rather than by an overall increase across all trees and taxa (Fig. 2; Table S1). R_d in drought-vulnerable taxa increased $48.5 \pm 3.6 \%$ ($P=0.02$; Fig. 2) in the TFE, relative to the average R_d of the same taxa in control plot; in contrast no significant changes in the respiration rates of the drought-resistant taxa were observed. The relationships of R_d with V_{\max} and J_{\max} were stronger in the control plot than in the TFE (Fig. 3), particularly during the dry season when correlation coefficients were >0.5 in the control plot while no significant relationships were found for the TFE (Fig. 3).

Tree vulnerability status seemed to influence seasonal patterns of WUE, A_{sat} and g_s . Resistant taxa in the control plot experienced significantly increased WUE in the dry season ($P=0.03$; Fig. 4a) by delivering an elevated A_{sat} at a similar g_s to the wet season. This did not occur in either the vulnerable or resistant trees in the TFE because A_{sat} was not elevated and g_s was reduced in the dry season (Fig. 4b, c). The vulnerable trees in the TFE experienced a significant $34.0 \pm 5.1 \%$ ($P=0.02$) reduction in A_{sat} from the peak of the wet season to the peak of the dry season, which was related to a drop of $22.9 \pm 9.6 \%$ in peak g_s ($P=0.02$; Fig. 4b, c).

The mixed effect model analysis demonstrated that none of the treatment effect (plot), season, vulnerability status or any combination of these variables contributed significantly to predicting V_{\max} , J_{\max} , N , and P , on either a mass or area basis, and the same was also true for modelling LMA and SLA (Table 2). As no plot or seasonal difference was detectable in any of these variables, we found that across both plots and both seasons LMA was significant in

the modelling of V_{cmax} on an area basis and N was significant in the modelling of V_{cmax} and J_{max} on a mass basis (Table 2). In contrast the interaction of plot, vulnerability status and season was a highly significant component of the best model of R_d , on both a mass and area basis (Table 2). The importance of plot, season and drought sensitivity in explaining the variance in R_d prevented a more general model of R_d based on N , P , LMA or SLA, or any combination of these variables, from being significant (Table 2).

Comparison between the 2013-14 results and earlier campaigns

Over the 13 years of the TFE experiment, the ratio of TFE: control V_{cmax} remained close to 1.0, suggesting leaf photosynthetic capacity was not altered throughout the experiment (Fig. 5a). In contrast, measurements of TFE: control R_d over 13 years of drought were significantly greater than 1.0. This conclusion was robust to tests carried out to determine the potential influence of using leaf samples taken in different seasons from different species using fundamentally different measurement methods (i.e., cut and uncut branches from shaded and sunlit canopy positions). The magnitude of the difference in R_d between the control and TFE plots is likely to have been affected by the composition of tree taxa, where sampling of taxa differed, and canopy height in the samples, and also the seasonal conditions, but despite these sources of potential variation, the overall R_d signal was significant and remained elevated in the TFE plot (Fig. 5b).

Discussion

Although the TFE does not simulate the atmospheric effects of drought, it allows us to isolate the impacts of prolonged soil moisture deficit on leaf physiology, a process which is poorly simulated in ecosystem models, yet responsible for substantial uncertainty in modelled

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climate change predictions for Amazonia (Powell *et al.*, 2013; Rowland *et al.*, 2015). Following 13 years of soil moisture deficit in the TFE there has been no change in the photosynthetic capacity of the trees, but a $48.5 \pm 3.6\%$ increase in the leaf level R_d of drought-vulnerable trees in the TFE relative to the control (Fig. 1 & 5, Table 2). Our measured values of both V_{cmax} and J_{max} lie well within the ranges previously measured in tropical rainforests (Carswell *et al.*, 2000, Coste *et al.*, 2005, Domingues *et al.*, 2005, Meir *et al.*, 2007, van de Weg *et al.*, 2012) and we demonstrate that substantial long-term reductions in soil moisture availability in the TFE (Rowland *et al.*, submitted) have no impact on the values of these photosynthetic parameters. In addition, no significant difference was observed in A_{sat} between the control and TFE plots in either vulnerable or resistant trees (Fig. 4c); however seasonal differences in A_{sat} and g_s at A_{sat} were greater for the drought vulnerable trees in the TFE (Fig. 4b, c). These results suggest that, in the TFE, even the taxa which are vulnerable to drought-induced mortality can achieve the same maximum photosynthetic rates as the control trees. However, as photosynthetic capacity does not equate to realised photosynthesis, it is possible that the TFE trees may still suffer from lower photosynthesis for example caused by lower daily average g_s .

Interestingly the taxa which are resistant to drought-induced mortality in the TFE showed no obvious signs of acclimation of photosynthetic capacity, R_d or g_s at A_{sat} and this may suggest that these trees acclimate to the drought conditions in other ways, such as reducing individual canopy leaf area or by increasing root water uptake (Metcalf *et al.*, 2010a, Metcalf *et al.*, 2010b, Metcalf *et al.*, 2007). However maintenance of photosynthetic capacity in the droughted leaves may instead be an acclimation response itself; provided sufficient light and nutrients are available, investment in maintaining V_{cmax} and J_{max} , at the expense of other investments within the tree, would compensate for canopy-scale reductions in g_s and C_i , allowing maximization of photosynthetic output during wetter periods when g_s is elevated.

This would, in theory, optimise light-use efficiency in the canopy (Hirose *et al.*, 1988, Meir *et al.*, 2002, Niinemets *et al.*, 2015), provided no other long-term drought-related stress was occurring within the leaf. This potential for the droughted trees to maintain the same maximum photosynthetic output is consistent with the recent demonstration at this TFE experiment of no depletion of stored leaf, stem and branch non-structural carbohydrates (NSC), and no reduced investment into carbon-demanding processes such as growth following 13 years of experimental drought (Rowland *et al.*, submitted).

Previously, Metcalfe *et al.*, (2010a) found R_d to be elevated in the TFE but their sample was taken from a subset of mostly shaded leaves, from trees of widely differing species in the control and TFE, without replication by species or mortality-risk. Using a sample design that balances tree taxa between plots across vulnerability status we show here that increased R_d is a long-term acclimation response in the TFE, and is attributable to the higher respiration of certain taxa vulnerable to drought-induced mortality, during the driest parts of the year. Increased R_d in response to low soil moisture has been observed elsewhere in Amazonia (Miranda *et al.*, 2005) and has also been reported in Mediterranean species, as, albeit during shorter term drought conditions, elevations in R_d were associated with low resistance to water stress in three taxa that had higher plant maintenance costs during drought (Varone & Gratani, 2015). It is therefore possible that an enhanced respiration cost during drought is a trait which has not been selected against in the Amazon because of its adaptive advantage. Significant reductions in g_s and A_{sat} in the drought-vulnerable trees suggest they are more hydraulically vulnerable during the dry season (Fig. 4). Consequently, elevated R_d in these taxa may be explained by an increased necessity for hydraulic repair (Brodersen & McElrone, 2013), for processing of ROS (Atkin & Macherel, 2009, Ribas-Carbo *et al.*, 2005) and/or an increase in photorespiration (Atkin & Macherel, 2009), or, counter intuitively here, use of increased substrate supply, which may occur if processes involved in carbon use or

transport are more impaired by drought than photosynthesis (Körner, 2013). We thus hypothesise that the increased carbon use (this study) and high mortality (da Costa *et al.*, 2010; Table S1) in vulnerable trees in the TFE plot (Fig. 2) are caused by a reduced ability to cope with the physiological stress caused by prolonged reductions in soil water content, but that this physiological stress is not severe enough to decrease photosynthetic capacity.

The biochemistry of photosynthesis and R_d are related, such that a short-term down-regulation of photosynthesis has frequently been observed to lead to a down-regulation of R_d (Catoni & Gratani, 2014, Chastain *et al.*, 2014, Flexas *et al.*, 2006). Reductions in the ratio of photosynthesis to R_d during drought have been reported elsewhere in the literature (Atkin & Macherel, 2009, Catoni & Gratani, 2014, Chastain *et al.*, 2014, Miranda *et al.*, 2005); we find this result at the Caxiuanã TFE experiment, but unlike the cited studies we find this to be driven only by increased R_d rather than decreased photosynthetic capacity. Our results also demonstrate that the relationship between photosynthetic capacity (V_{cmax} and J_{max}) and R_d are much weaker in the TFE than in control forest (Fig. 3), and that the standard relationships expected between R_d and N , P , LMA or SLA (Atkin *et al.*, 2015) are not found because of a significant treatment effect on R_d , but not on N , P , LMA or SLA (Table 2). This may suggest that N and P do not substantially limit R_d , in these plots. These results also suggest that the normally tight coupling of leaf respiratory processes with photosynthetic processes, and their relationships with leaf nutrient content and LMA or SLA are disrupted during long-term drought stress in tropical trees, and new model formulations are needed to simulate this response to drought.

This study examines how photosynthetic capacity and leaf dark respiration (R_d) acclimate to long-term (>12 years) soil moisture deficit in a tropical rainforest. Using a sampling design with a balanced selection of tree taxa between control and treatment we demonstrate that, following 12-13 years of soil moisture deficit, photosynthetic capacity is unchanged even in

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taxa which are prone to drought-induced mortality. The rate of R_d in the dry season in the experimentally droughted forest was, however, significantly elevated because of a $48.5 \pm 3.6\%$ increase in the R_d of taxa which are prone to drought-induced mortality. We conclude that, even after a severe and prolonged reduction in soil moisture availability, trees are able to maintain the same photosynthetic capacity, despite increasing R_d . Such results suggest that better models of acclimation in R_d and overall gas exchange may be necessary to accurately simulate the responses of tropical rainforests to drought.

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References

- Atkin OK, Bloomfield KJ, Reich PB *et al.* (2015) Global variability in leaf respiration in relation to climate, plant functional types and leaf traits. *New Phytol*, **206**, 614-636.
- Atkin OK, Macherel D (2009) The crucial role of plant mitochondria in orchestrating drought tolerance. *Ann Bot*, **103**, 581-597.
- Atkin OK, Tjoelker MG (2003) Thermal acclimation and the dynamic response of plant respiration to temperature. *Trends in Plant Science*, **8**, 343-351.

- Atkin OK, Turnbull MH, Zaragoza-Castells J, Fyllas NM, Lloyd J, Meir P, Griffin KL (2013) Light inhibition of leaf respiration as soil fertility declines along a post-glacial chronosequence in New Zealand: an analysis using the Kok method. *Plant and Soil*, **367**, 163-182.
- Ayub G, Smith RA, Tissue DT, Atkin OK (2011) Impacts of drought on leaf respiration in darkness and light in *Eucalyptus saligna* exposed to industrial-age atmospheric CO₂ and growth temperature. *New Phytol*, **190**, 1003-1018.
- Beer C, Reichstein M, Tomelleri E *et al.* (2010) Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate. *Science*, **329**, 834-838.
- Bonal D, Born C, Brechet C, Coste S, Marcon E, Roggy JC, Guehl JM (2007) The successional status of tropical rainforest tree species is associated with differences in leaf carbon isotope discrimination and functional traits. *Annals of Forest Science*, **64**, 169-176.
- Bonal D, Bosc A, Ponton S *et al.* (2008) Impact of severe dry season on net ecosystem exchange in the Neotropical rainforest of French Guiana. *Glob Chang Biol*, **14**, 1917-1933.
- Brando PM, Nepstad DC, Davidson EA, Trumbore SE, Ray D, Camargo P (2008) Drought effects on litterfall, wood production and belowground carbon cycling in an Amazon forest: results of a throughfall reduction experiment. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **363**, 1839-1848.
- Brodersen CR, McElrone AJ (2013) Maintenance of xylem network transport capacity: a review of embolism repair in vascular plants. *Frontiers in Plant Science*, **4**.
- Carpenter SR (1996) Microcosm experiments have limited relevance for community and ecosystem ecology. *Ecology*, **77**, 677-680.

- Carswell FE, Meir P, Wandelli EV *et al.* (2000) Photosynthetic capacity in a central Amazonian rain forest. *Tree Physiology*, **20**, 179-186.
- Catoni R, Gratani L (2014) Variations in leaf respiration and photosynthesis ratio in response to air temperature and water availability among Mediterranean evergreen species. *Journal of Arid Environments*, **102**, 82-88.
- Chastain DR, Snider JL, Collins GD, Perry CD, Whitaker J, Byrd SA (2014) Water deficit in field-grown *Gossypium hirsutum* primarily limits net photosynthesis by decreasing stomatal conductance, increasing photorespiration, and increasing the ratio of dark respiration to gross photosynthesis. *J Plant Physiol*, **171**, 1576-1585.
- Ciais P, Reichstein M, Viovy N *et al.* (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, **437**, 529-533.
- Coste S, Roggy JC, Imbert P, Born C, Bonal D, Dreyer E (2005) Leaf photosynthetic traits of 14 tropical rain forest species in relation to leaf nitrogen concentration and shade tolerance. *Tree Physiology*, **25**, 1127-1137.
- Crous KY, Zaragoza-Castells J, Low M *et al.* (2011) Seasonal acclimation of leaf respiration in *Eucalyptus saligna* trees: impacts of elevated atmospheric CO₂ and summer drought. *Glob Chang Biol*, **17**, 1560-1576.
- Da Costa ACL, Galbraith D, Almeida S *et al.* (2010) Effect of 7 yr of experimental drought on vegetation dynamics and biomass storage of an eastern Amazonian rainforest. *New Phytologist*, **187**, 579-591.
- Davidson EA, Ishida FY, Nepstad DC (2004) Effects of an experimental drought on soil emissions of carbon dioxide, methane, nitrous oxide, and nitric oxide in a moist tropical forest. *Glob Chang Biol*, **10**, 718-730.
- Domingues TF, Berry JA, Martinelli LA, Ometto JPHB, Ehleringer JR (2005) Parameterization of canopy structure and leaf-level gas exchange for an eastern

- Amazonian tropical rain forest (Tapajos National Forest, Para, Brazil). *Earth Interactions*, **9**.
- Domingues TF, Meir P, Feldpausch TR *et al.* (2010) Co-limitation of photosynthetic capacity by nitrogen and phosphorus in West Africa woodlands. *Plant Cell and Environment*, **33**, 959-980.
- Doughty CE, Metcalfe DB, Girardin CaJ *et al.* (2015) Drought impact on forest carbon dynamics and fluxes in Amazonia. *Nature*, **519**, 78-U140.
- Fisher RA, Williams M, Da Costa AL, Malhi Y, Da Costa RF, Almeida S, Meir P (2007) The response of an Eastern Amazonian rain forest to drought stress: results and modelling analyses from a throughfall exclusion experiment. *Glob Chang Biol*, **13**, 2361-2378.
- Flexas J, Bota J, Galmes J, Medrano H, Ribas-Carbo M (2006) Keeping a positive carbon balance under adverse conditions: responses of photosynthesis and respiration to water stress. *Physiologia Plantarum*, **127**, 343-352.
- Flexas J, Medrano H (2002) Drought-inhibition of photosynthesis in C-3 plants: Stomatal and non-stomatal limitations revisited. *Ann Bot*, **89**, 183-189.
- Galbraith D, Levy PE, Sitch S, Huntingford C, Cox P, Williams M, Meir P (2010) Multiple mechanisms of Amazonian forest biomass losses in three dynamic global vegetation models under climate change. *New Phytologist*, **187**, 647-665.
- Galmes J, Aranjuelo I, Medrano H, Flexas J (2013) Variation in Rubisco content and activity under variable climatic factors. *Photosynth Res*, **117**, 73-90.
- Gatti LV, Gloor M, Miller JB *et al.* (2014) Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements. *Nature*, **506**, 76-+.
- Grace J, Mitchard E, Gloor E (2014) Perturbations in the carbon budget of the tropics. *Glob Chang Biol*, **20**, 3238-3255.

- Hirose T, Werger MJA, Pons TL, Vanrheenen JWA (1988) Canopy Structure and Leaf Nitrogen Distribution in a Stand of *Lysimachia-Vulgaris* L as Influenced by Stand Density. *Oecologia*, **77**, 145-150.
- Huntingford C, Zelazowski P, Galbraith D *et al.* (2013) Simulated resilience of tropical rainforests to CO₂-induced climate change. *Nature Geoscience*, **6**, 268-273.
- Körner C (2013) Growth Controls Photosynthesis – Mostly. *Nova Acta Leopoldina*, **391**, 273–283.
- Kull O, Kruijt B (1999) Acclimation of photosynthesis to light: a mechanistic approach. *Functional Ecology*, **13**, 24-36.
- Lawlor DW, Cornic G (2002) Photosynthetic carbon assimilation and associated metabolism in relation to water deficits in higher plants. *Plant Cell and Environment*, **25**, 275-294.
- Meir P, Brando PM, Nepstad D *et al.* (2009) The Effects of Drought on Amazonian Rain Forests. *Amazonia and Global Change*, **186**, 429-449.
- Meir P, Kruijt B, Broadmeadow M *et al.* (2002) Acclimation of photosynthetic capacity to irradiance in tree canopies in relation to leaf nitrogen concentration and leaf mass per unit area. *Plant Cell and Environment*, **25**, 343-357.
- Meir P, Levy PE, Grace J, Jarvis PG (2007) Photosynthetic parameters from two contrasting woody vegetation types in West Africa. *Plant Ecology*, **192**, 277-287.
- Meir P, Mencuccini M, Dewar RC (2015a) Drought-related tree mortality: addressing the gaps in understanding and prediction. *New Phytologist*, n/a-n/a.
- Meir P, Metcalfe DB, Costa ACL, Fisher RA (2008) The fate of assimilated carbon during drought: impacts on respiration in Amazon rainforests. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **363**, 1849-1855.

- Meir P, Wood TE, Galbraith DR, Brando PM, Da Costa ACL, L. R, V. FL (2015b) Threshold responses to soil moisture deficit by trees and soil in tropical rain forests: insights from field experiments. *Bioscience*.
- Meir P, Woodward FI (2010) Amazonian rain forests and drought: response and vulnerability. *New Phytologist*, **187**, 553-557.
- Mencuccini M, Hölttä T (2010) The significance of phloem transport for the speed with which canopy photosynthesis and belowground respiration are linked. *New Phytologist*, **185**, 189-203.
- Metcalf DB, Lobo-Do-Vale R, Chaves MM *et al.* (2010a) Impacts of experimentally imposed drought on leaf respiration and morphology in an Amazon rain forest. *Functional Ecology*, **24**, 524-533.
- Metcalf DB, Meir P, Aragao LEOC *et al.* (2010b) Shifts in plant respiration and carbon use efficiency at a large-scale drought experiment in the eastern Amazon. *New Phytologist*, **187**, 608-621.
- Metcalf DB, Meir P, Aragao LEOC *et al.* (2007) Factors controlling spatio-temporal variation in carbon dioxide efflux from surface litter, roots, and soil organic matter at four rain forest sites in the eastern Amazon. *Journal of Geophysical Research-Biogeosciences*, **112**.
- Miranda EJ, Vourlitis GL, Priante N *et al.* (2005) Seasonal variation in the leaf gas exchange of tropical forest trees in the rain forest-savanna transition of the southern Amazon Basin. *Journal of Tropical Ecology*, **21**, 451-460.
- Murphy J, Riley JP (1962) A Modified Single Solution Method for Determination of Phosphate in Natural Waters. *Analytica Chimica Acta*, **26**, 31-&.

- Nepstad DC, Moutinho P, Dias MB *et al.* (2002) The effects of partial throughfall exclusion on canopy processes, aboveground production, and biogeochemistry of an Amazon forest. *Journal of Geophysical Research-Atmospheres*, **107**.
- Nepstad DC, Tohver IM, Ray D, Moutinho P, Cardinot G (2007) Mortality of large trees and lianas following experimental drought in an amazon forest. *Ecology*, **88**, 2259-2269.
- Niinemets U, Keenan TF, Hallik L (2015) A worldwide analysis of within-canopy variations in leaf structural, chemical and physiological traits across plant functional types. *New Phytologist*, **205**, 973-993.
- O'brien MJ, Burslem DFRP, Caduff A, Tay J, Hector A (2015) Contrasting nonstructural carbohydrate dynamics of tropical tree seedlings under water deficit and variability. *New Phytologist*, **205**, 1083-1094.
- Osmond B, Ananyev G, Berry J *et al.* (2004) Changing the way we think about global change research: scaling up in experimental ecosystem science. *Glob Chang Biol*, **10**, 393-407.
- Phillips OL, Aragao LEOC, Lewis SL *et al.* (2009) Drought Sensitivity of the Amazon Rainforest. *Science*, **323**, 1344-1347.
- Powell TL, Galbraith DR, Christoffersen BO *et al.* (2013) Confronting model predictions of carbon fluxes with measurements of Amazon forests subjected to experimental drought. *New Phytologist*, **200**, 350-364.
- Reddy AR, Chaitanya KV, Vivekanandan M (2004) Drought-induced responses of photosynthesis and antioxidant metabolism in higher plants. *J Plant Physiol*, **161**, 1189-1202.
- Ribas-Carbo M, Taylor NL, Giles L *et al.* (2005) Effects of water stress on respiration in soybean leaves. *Plant Physiol*, **139**, 466-473.

- Rowland L, da costa ACL, Mencuccini M, et al. (Submitted) Long-term drought in tropical forest: death from hydraulic failure, not carbon starvation. *Nature*
- Rowland L, Harper A, Christoffersen BO *et al.* (2015) Modelling climate change responses in tropical forests: similar productivity estimates across five models, but different mechanisms and responses. *Geoscientific Model Development*, **8**, 1097-1110.
- Rowland L, Hill TC, Stahl C *et al.* (2014) Evidence for strong seasonality in the carbon storage and carbon use efficiency of an Amazonian forest. *Glob Chang Biol*, **20**, 979-991.
- Ruivo M, Cunha E (2003) Mineral and organic components in archaeological black earth and yellow latosol in Caxiuanã, Amazon, Brazil. In: *Ecosystems and sustainable development*. (ed Tiezzi E, Brebbia, C. A., Uso, J. L., (Eds)) pp Page. Southampton, UK, WIT Press.
- Sharkey TD, Bernacchi CJ, Farquhar GD, Singsaas EL (2007) Fitting photosynthetic carbon dioxide response curves for C(3) leaves. *Plant Cell Environ*, **30**, 1035-1040.
- Sperlich D, Chang CT, Peñuelas J, Gracia C, Sabaté S (2015) Seasonal variability of foliar photosynthetic and morphological traits and drought impacts in a Mediterranean mixed forest. *Tree Physiology*.
- Stahl C, Burban B, Wagner F, Goret JY, Bompy F, Bonal D (2013) Influence of Seasonal Variations in Soil Water Availability on Gas Exchange of Tropical Canopy Trees. *Biotropica*, **45**, 155-164.
- Van De Weg MJ, Meir P, Grace J, Ramos GD (2012) Photosynthetic parameters, dark respiration and leaf traits in the canopy of a Peruvian tropical montane cloud forest. *Oecologia*, **168**, 23-34.
- Varone L, Gratani L (2015) Leaf respiration responsiveness to induced water stress in Mediterranean species. *Environmental and Experimental Botany*, **109**, 141-150.

Zuur AF, Ieno EN, Walker NJ, Saveliev AA, Smith G (2009) *Mixed Effects Models and Extensions in Ecology with R.*, New York, Springer.

Figure Captions

Fig. 1: Average V_{cmax} (a), J_{max} (b) and R_{d} (c) expressed in $\mu\text{mol m}^{-2} \text{s}^{-1}$ in the control (C; white) and TFE (grey) plots, in peak dry season 2013 (November) and peak wet season 2014 (June). Error bars show the standard error.

Fig. 2: R_{d} for the resistant and vulnerable tree taxa in the control (white) and TFE (grey) plot in peak dry season of 2013. Columns with a * indicates significant difference with $P < 0.05$. Error bars show standard error.

Fig. 3: Relationships between V_{cmax} and R_{d} (a-d) and J_{max} and R_{d} (e-h) during the wet and dry season in the control and TFE plot. If the linear line is significant ($P < 0.05$), the linear relationship, correlation coefficient (r^2) and significance value (P) are shown.

Fig. 4: Box plots of water use efficiency (WUE; a), stomatal conductance (g_s ; b) and light-saturated photosynthesis at 400 ppm of CO_2 (A_{sat}) during peak dry season 2013 and peak wet season (2014) for vulnerable and resistant tree taxa in the control (white) and TFE (grey) plots. * indicates significant difference with $p < 0.05$.

Fig. 5: Ratio of TFE: control plot V_{cmax} (a) and R_{d} (b) values for various measurement campaigns made at the Caxiuanã TFE experiment from prior to the start of the experiment (2001) to 2013; see Methods for details. The symbols indicate the differences in the sample selection. 'Uncut tower trees' are data from leaves on attached branches accessed via a walk-up through-canopy tower. 'Metcalf sample' are from leaves on the same trees sampled by Metcalfe et al. (2010). This study used cut branches with fully sunlit leaves and the results from Fig. 2 are re-plotted here.

Tables

Table 1: Genus, species with genus and sensitivity to drought-induced mortality (see table S1) for the number of trees sampled in the control and TFE plots for the 2013 and 2014 analysis of R_d , V_{cmax} , J_{max} , A_{sat} , g_s , leaf nutrients and LMA.

Genus	Species sampled within Genus	Vulnerability	No° sampled on control plot	No° sampled on TFE plot
<i>Eschweilera</i>	<i>coriacea</i> , <i>grandiflora</i> , <i>pedicellata</i>	Vulnerable	5	6
<i>Licania</i>	<i>membranacea</i> , <i>octandra</i>	Resistant	3	3
<i>Manilkara</i>	<i>bidentata</i>	Vulnerable	3	3
<i>Pouteria</i>	<i>anomala</i>	Vulnerable	3	3
<i>Protium</i>	<i>tenuifolium</i> , <i>paniculatum</i>	Resistant	3	3
<i>Swartzia</i>	<i>racemosa</i>	Resistant	3	3

Table 2: Mixed effect model results on a leaf area and a leaf mass basis, to test for: a) the drought treatment effect on V_{cmax} , J_{max} , R_d , nitrogen (N), phosphorus (P), leaf mass per area (LMA), and specific leaf area (SLA), using the treatment effect (control versus TFE plot (PI)), tree vulnerable or resistant status (V), and season (S) as fixed variables and tree nested within genus as the random component of the model. b) the effect of nutrients and leaf area and mass on V_{cmax} , J_{max} and R_d , using N, P and either LMA or SLA as fixed variables and tree nested within genus as the random component of the model. The significance of the intercept (p) and valid fixed variables are shown as well as the proportion of the model variance accounted for by the random component of the model (R variance, %). * indicates variable interaction.

a. Models to test treatment effects				
Y variable	Fixed variables tested	Significant fixed variables	R	Variance, %
V_{cmax} area basis	Pl, V, S	None		64.41
J_{max} area basis	Pl, V, S	None		43.53
R_d area basis	Pl, V, S	Pl*V*S ($p=0.02$)		31.54
N area basis	Pl, V, S	None		78.34
P area basis	Pl, V, S	None		17.36
LMA	Pl, V, S	None		52.46
V_{cmax} mass basis	Pl, V, S	None		52.35
J_{max} mass basis	Pl, V, S	None		32.61
R_d mass basis	Pl, V, S	Pl*V*S ($p=0.02$)		43.60
N mass basis	Pl, V, S	None		71.21
P mass basis	Pl, V, S	None		30.78
SLA	Pl, V, S	None		60.30
b. Models to test Nutrient and Leaf mass/area effects				
Y variable	Fixed variables tested	Significant Fixed variables	R	Variance (%)
V_{cmax} area basis	N, P, LMA	LMA ($p<0.01$)		68.86
J_{max} area basis	N, P, LMA	None		45.01
R_d area basis	N, P, LMA	None		4.62
V_{cmax} mass basis	N, P, SLA	N ($p<0.01$)		44.98
J_{max} mass basis	N, P, SLA	N ($p<0.01$)		14.97
R_d mass basis	N, P, SLA	None		27.73





