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Supplement of

Potassium limitation of forest productivity – Part 1: A mechanistic model simulating the effects of potassium availability on canopy carbon and water fluxes in tropical eucalypt stands

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6 Supplementary material

6.1 CASTANEA-MAESPA schematic

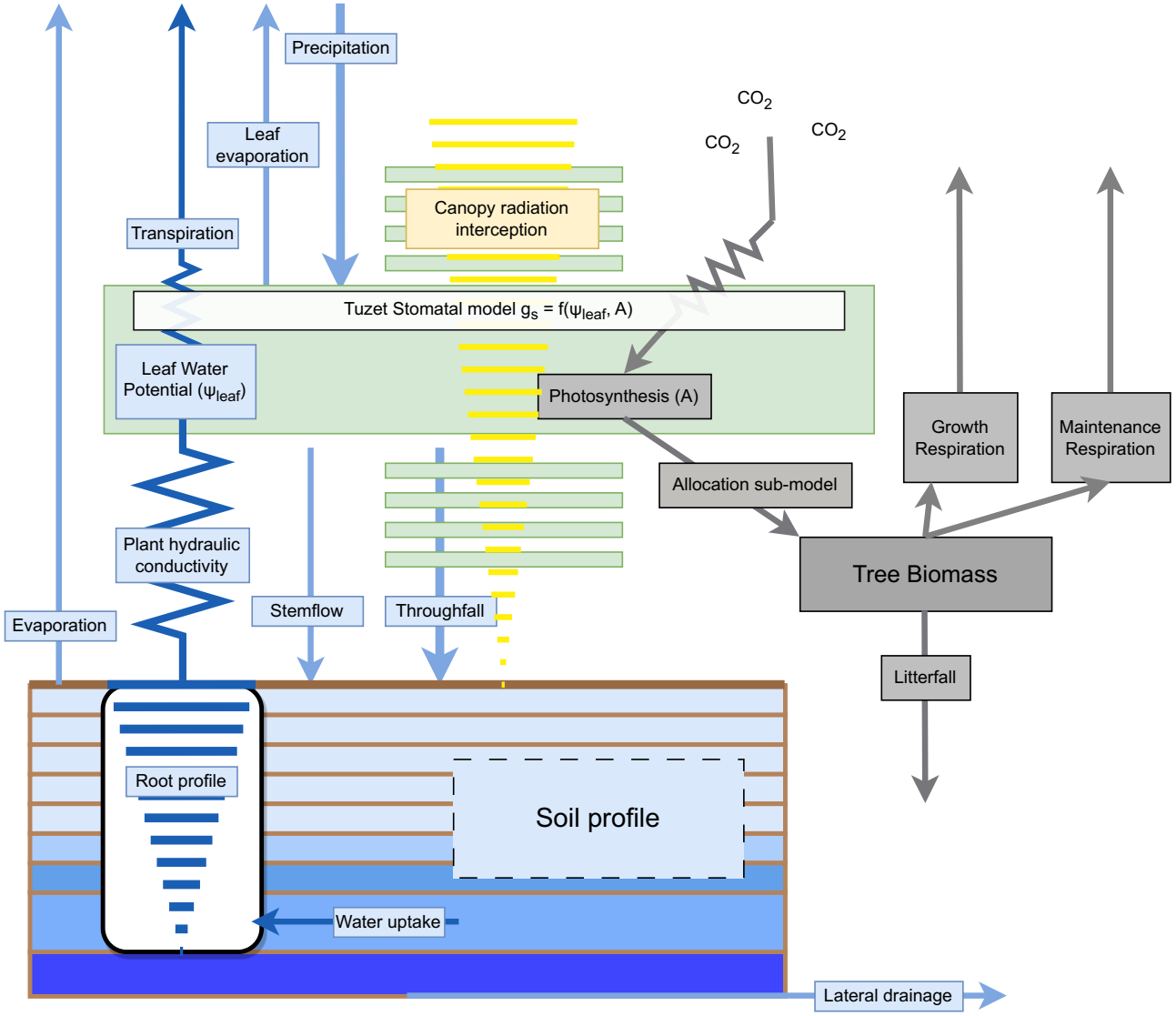

Figure S1: Synthetic representation of the structure of the CASTANEA-MAESPA model. Blue boxes represent processes of the water balance model. Grey boxes represent pools and processes of the carbon balance model. Green boxes are canopy layers. The K balance model was purposefully omitted here.

6.2 Parameters

Parameter	Symbol	Value	Units	Source
Atmospheric deposition	$K_{atmosphere \rightarrow soil}$	0.5	$gK.m^{-2}.yr^{-1}$	Measured in Laclau et al. (2010)
Initial K contained in litter	K_{litter}^{ini}	1.92	$gK.m^{-2}$	Measured in Laclau et al. (2010)
Initial K contained in soil	K_{soil}^{ini}	0.507	$gK.m^{-2}$	Calculated from Maquère (2008)
Litter K leaching response to rainfall	σ	0.002005	mm^{-1}	Calculated from average rainfall and K litter dynamics measured by Maquère (2008)
Resistance to uptake from the soil	$R_{soil \rightarrow xylem}$	30	days	Assumed
Optimal K concentration of phloem sap	$[K]_{phloem}^{opti}$	0.33	$g.L^{-1}$	Maximum measured value in phloem sap (Battie-Laclau et al., 2014b)
Minimum K concentration of phloem sap	$[K]_{phloem}^{min}$	0.07	$g.L^{-1}$	Minimum measured value in phloem sap (Battie-Laclau et al., 2014b)

Table S1: Parameters related to the circulation of K in the system

Parameter	Symbol	Value	Units	Source
Curvature parameter	θ	0.5	unitless	Found in Grassi et al. (2002)
Quantum efficiency	α	0.24	$mol.mol^{-1}$	Found in Grassi et al. (2002)
Empirical coefficient in two-slope Tuzet model	G_{11}	8	unitless	Calibrated on EUCFLUX flux data
Empirical coefficient in two-slope Tuzet model	G_{12}	25	unitless	Calibrated on EUCFLUX flux data

Table S2: Photosynthetic parameters that were modified from Christina et al. (2017). The values of the other parameters related to the MAESPA model can be found in Table S1 of Christina et al. (2017).

6.2.1 Multiple normalised RMSE

Multiple normalised RMSE was defined as:

$$MNRMSE = \sum_{u=0}^{m} \left[\frac{\sqrt{\frac{\sum_{i=0}^{n}(y_{u,i} - \hat{y}_{u,i})^2}{n}}}{\bar{y}_u} \right] \times \frac{1}{m} \tag{S1}$$

where m was the number of variables to fit, n was the number of occurrences of each m^{th} variable, $y_{u,i}$ was the the u,i^{th} observation of y, $\hat{y}_{u,i}$ was the u,i^{th} modelled value of y, $\bar{y}_u$ was the mean of the observed values of y_u.

Parameter	Symbol	Value	Units	Source
Target K concentration in leaf water	$[K]_{leaf}^{max}$	5.85	$g.L^{-1}$	(Battie-Laclau et al., 2013)
Leaf K leaching coefficient	λ	0.000090	mm^{-1}	Calculated from average rainfall, leaf K concentration in the +K stand and Laclau et al. (2010)
Resistance to leaf to phloem K flux	$R_{leaf \rightarrow phloem}$	130	days	Assumed from leaf lifespan in oK stand (Battie-Laclau et al., 2013)
Flattening factor	f_p	4	unitless	Calibrated using leaf production on the fully fertilised EUCFLUX stand
Number of leaves produced by height increment	κ	380	$nb_{leaves}.m^{-2}.m_{tree}^{-1}$	Calibrated using leaf production on the fully fertilised EUCFLUX stand
Leaf Lifespan	LLS	380	days	Calibrated using leaf production, biomass and fall measurements on the fully fertilised EUCFLUX stand
Minimum K concentration in leaf water	$[K]_{min}$	0.78	$g.L^{-1}$	Minimum measured K concentration in leaf water (Battie-Laclau et al., 2013)
Target leaf area	LA_{max}	3500	mm^2	measured in scans (Fig.S5)
Maximum leaf area reduction due to K	r	0.8	mm^2	Measured in scans from Itatinga and Battie-Laclau et al. (2013)
Half time of leaf expansion	$t50_{LA}$	30	days	Calibrated on leaf expansion data (Battie-Laclau et al., 2013)
Rate of leaf expansion	k_{LA}	0.1	$.days^{-1}$	Calibrated on leaf expansion data (Battie-Laclau et al., 2013)
Half time of leaf mass increase	$t50_{BF}$	45	days	Calibrated on leaf expansion data (Battie-Laclau et al., 2013) and SLA (Battie-Laclau et al., 2014a)
Rate of leaf mass increase	k_{BF}	0.1	$.days^{-1}$	Calibrated on leaf expansion data (Battie-Laclau et al., 2013) SLA (Battie-Laclau et al., 2014a)
Maximal mass of a leaf during the rotation	$BF_{max}^{rotation}$	0.5	gDM	Calibrated using leaf scans and SLA measurements
Slope parameter of the tree height leaf mass relationship	s_{BF}	0.3	unitless	Calibrated using leaf mass and tree height measurements
Power parameter of the tree height leaf mass relationship	P	0.3	unitless	Calibrated using leaf mass and tree height measurements
Carbon content of a leaf	TC	0.5	$gC.gDM^{-1}$	Assumed
Resorption rate	k_r	0.2	$.days^{-1}$	Assumed from Battie-Laclau et al. (2013)
Water expulsion rate	α	0.1	$mL.day^{-1}$	Calibrated using measurements in Laclau et al. (2009)
Conversion factor from deficit days to symptoms	Θ	0.44	unitless	Calibrated using measurements in Battie-Laclau et al. (2013)
Maximum leaf symptom proportion	SP_{max}	0.44	$m^2_{symptoms}.m^2_{leaf}$	Calculated using max symptom area proportion in Battie-Laclau et al. (2013)

Table S3: Parameters related to the leaf cohort sub-model

6.3 Cumulated GPP

6.4 Leaf lifespan

The lifespan of leaves was measured in a Eucalypt stand planted in 2018 in place of the EUCFLUX experiment described above. Leaf lifespan was measured on 4 trees that were chosen due to their proximity with the flux tower, thus allowing for easy access to branches. Leaf lifespan and production were followed by tagging axes. Every 50 cm along the trunk (primary axis) a secondary axis was tagged and all subsequent n^{th} order axes on the secondary axis were tagged (Fig.S3). If an axis exceeded 10 leaves tags were placed every 10 leaves from the base. Every two weeks, the number of leaves for each tag was counted and tags were added as needed.

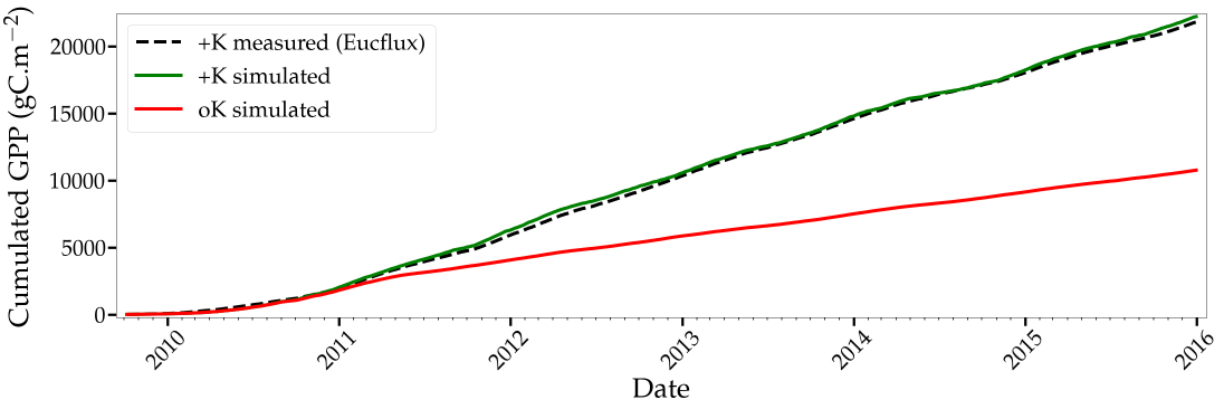

Figure S2: Measured and simulated GPP over the course of a rotation.

This methodology hinged upon the hypothesis that on a series of 10 leaves of the same axis, there could not be leaf production and leaf fall at the same time. It was possible to make this assumption since new leaf production was very fast.

The experiment lasted 15 months to be able to guarantee a good measurement of seasonal leaf production and leaf lifespan dynamics. Overall, 5597 leaves were followed from production to senescence. The biological material (i.e. clone) that was used for these measurements is different from that of the EUCFLUX experiment described in the main text.

While leaf lifespans followed a seasonal pattern (Fig.S4a-e) there was no link between the horizontal position of leaves on the axis and their lifespan (Fig.S4f). This suggests that leaf lifespan was not related to shading-induced C sink-source dynamics at the leaf level.

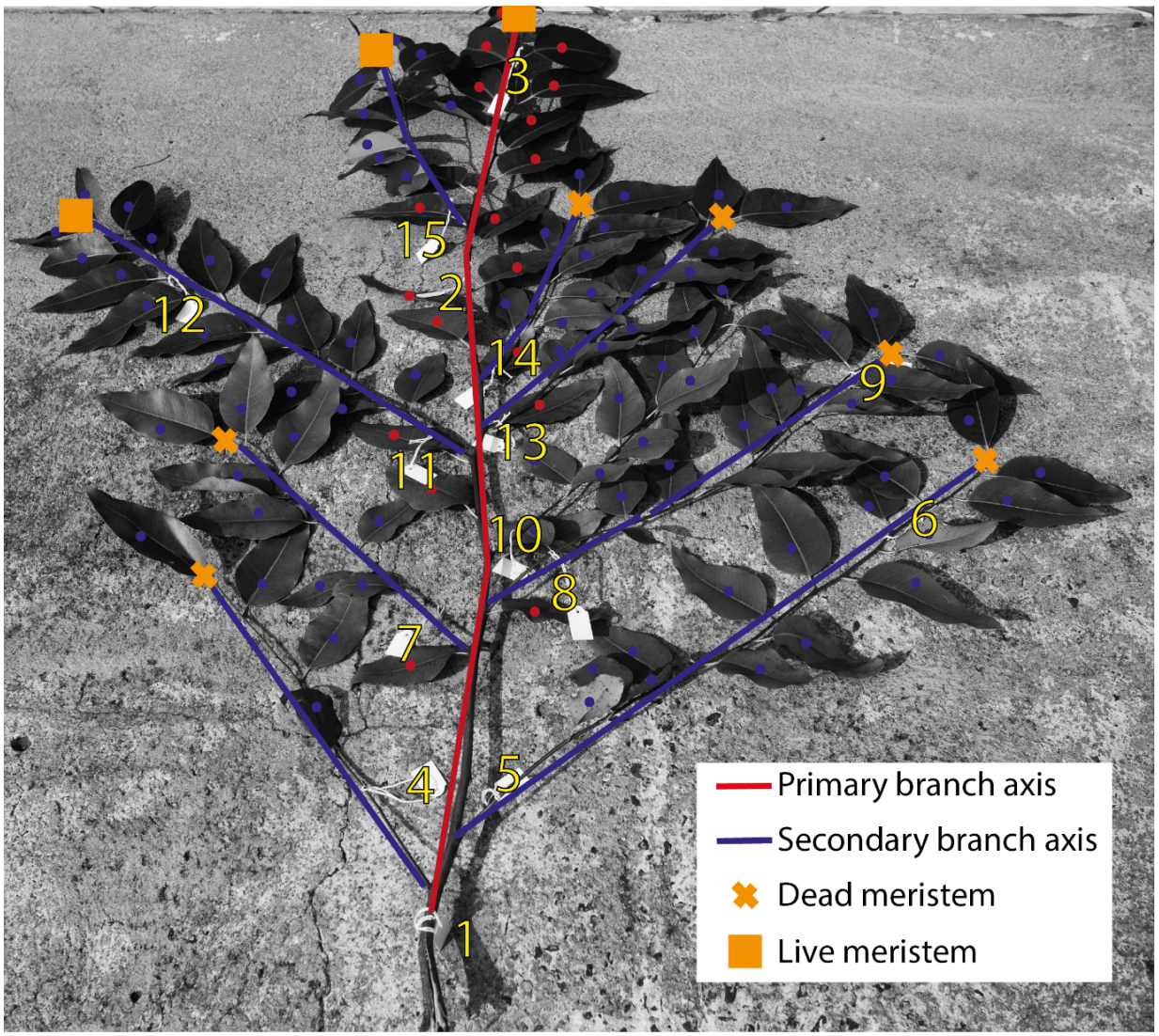

Figure S3: An example of the leaf tagging protocol on a cut branch. The numbers correspond to the number of the individual tags.

6.5 Leaf area and mass

While there was variation of mean area of individual leaves during the EUCFLUX rotation, no temporal trend was found after 15 months (Fig.S5). The difference between two locations of EUCFLUX stand, one close to the flux-tower (soil more sandy) and the other further to the flux-tower, on a more clayey soil, was also small. The lower mean leaf area at 12 months of age in the Clay site could be a consequence of high leaf production and low total leaf area (meaning that expanding leaves represent a higher proportion of leaves).

As a rule SLA decreased with tree height. This decrease of SLA with tree age (strongly related to height in these fast growing eucalypt plantations) has been observed at other sites (Fig.2 in le Maire et al., 2011). A two-slope relationship was apparent (Fig.S6a) but could not be mechanistically explained. It could be related to the shift in leaf morphology that happens

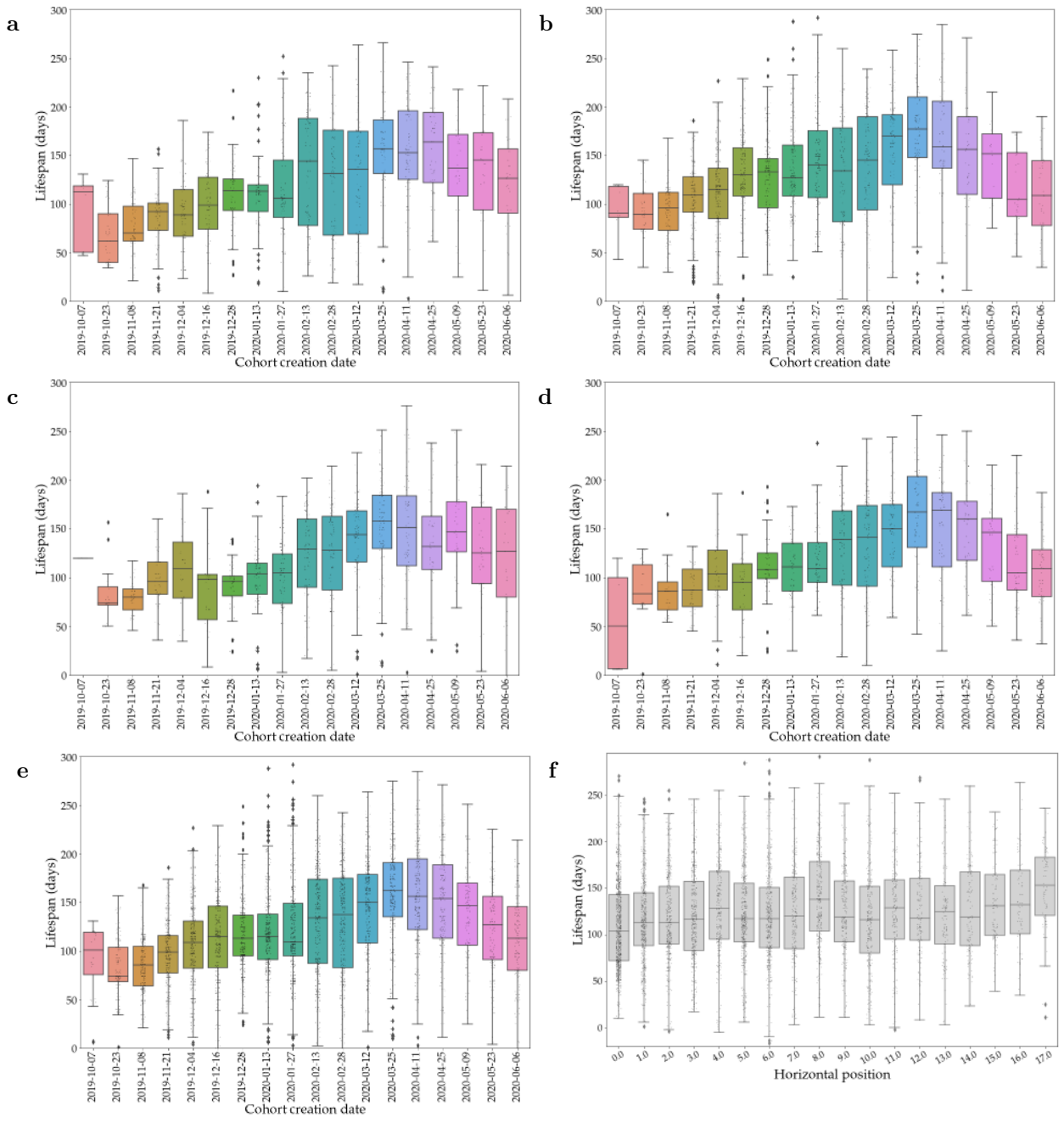

Figure S4: a,b,c,d boxplot of the lifespans of individual leaves of different cohorts from trees 1, 2, 3, and 4 respectively. e) The lifespans of the leaves from all trees when the datasets are joined together. f) Leaf lifespan in function of the leaves' position on the horizontal axis (number of the tertiary axis where the leaf is found: 1 is close to the trunk and 16 is far).

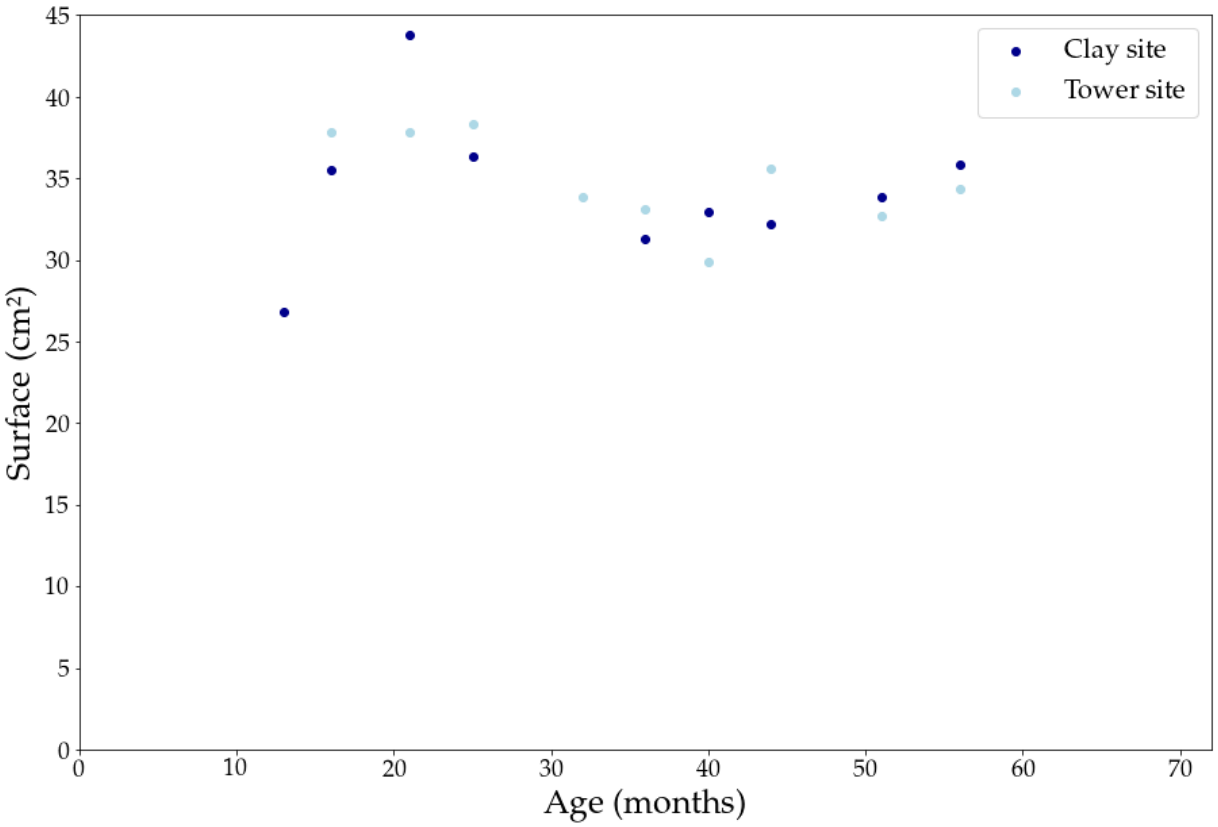

Figure S5: Upscaled mean leaf areas at two locations of EUCFLUX stand: The tower site (mainly sandy soil) in close proximity to the flux tower measurement and the Clay site (more clayey soil) further away from the tower but still on the EUCFLUX stand

at the beginning of the rotation (Fig.S6b).

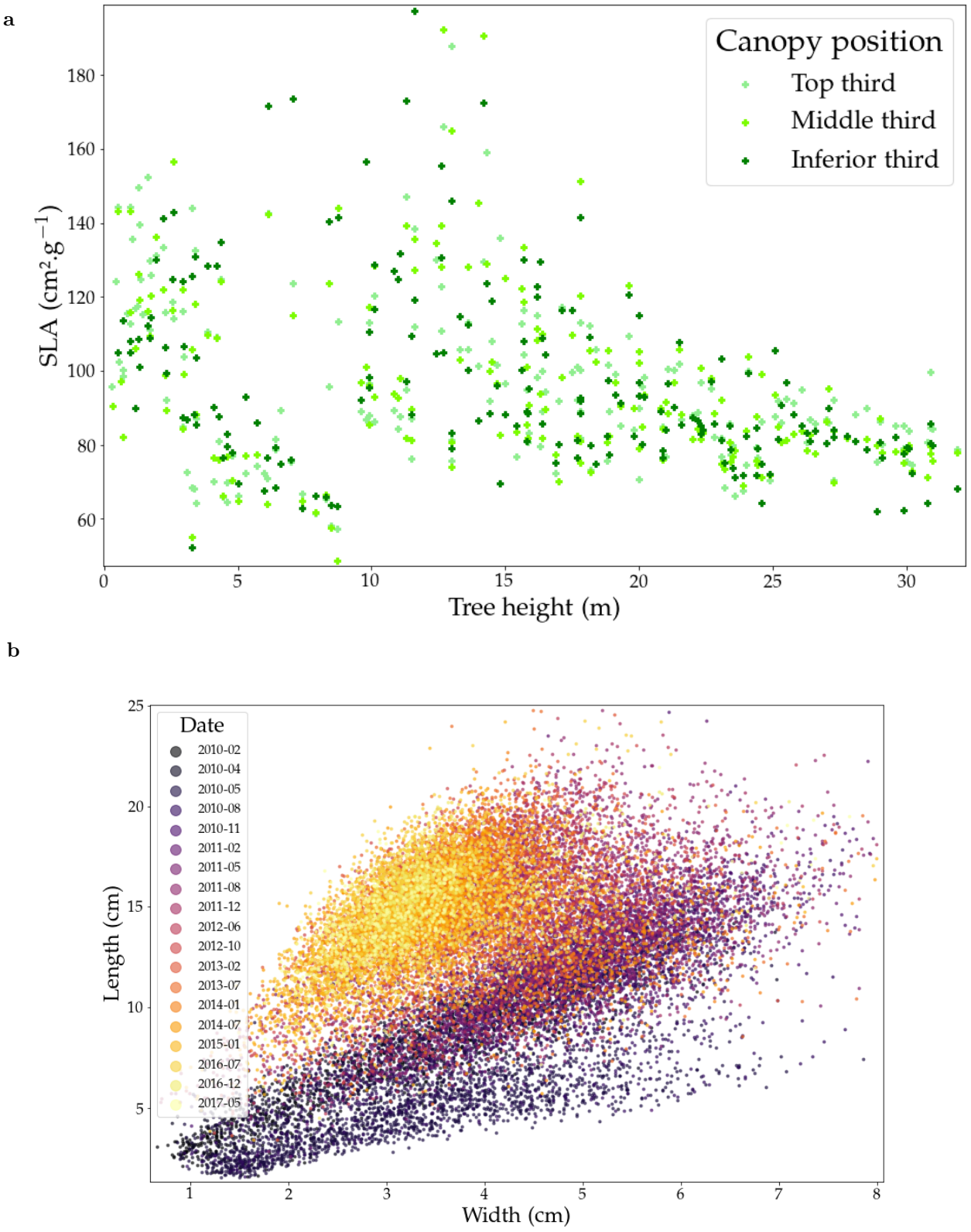

Figure S6: (a) Specific leaf areas of leaves at the EUCFLUX site in function of tree height. The canopy was cut into 3 thirds that show no difference in the response of SLA to tree height. (b) The leaf width in function of leaf length shows that there is a strong shift in leaf morphology over the course of the rotation. The colors represent the date at which the leaves were sampled. Each dot is an individual leaf that was scanned.

6.6 Leaf symptoms

Leaf symptoms were measured on the Itatinga experiment using leaf scans by using a classification algorithm based on the purple colour of the anthocyans.

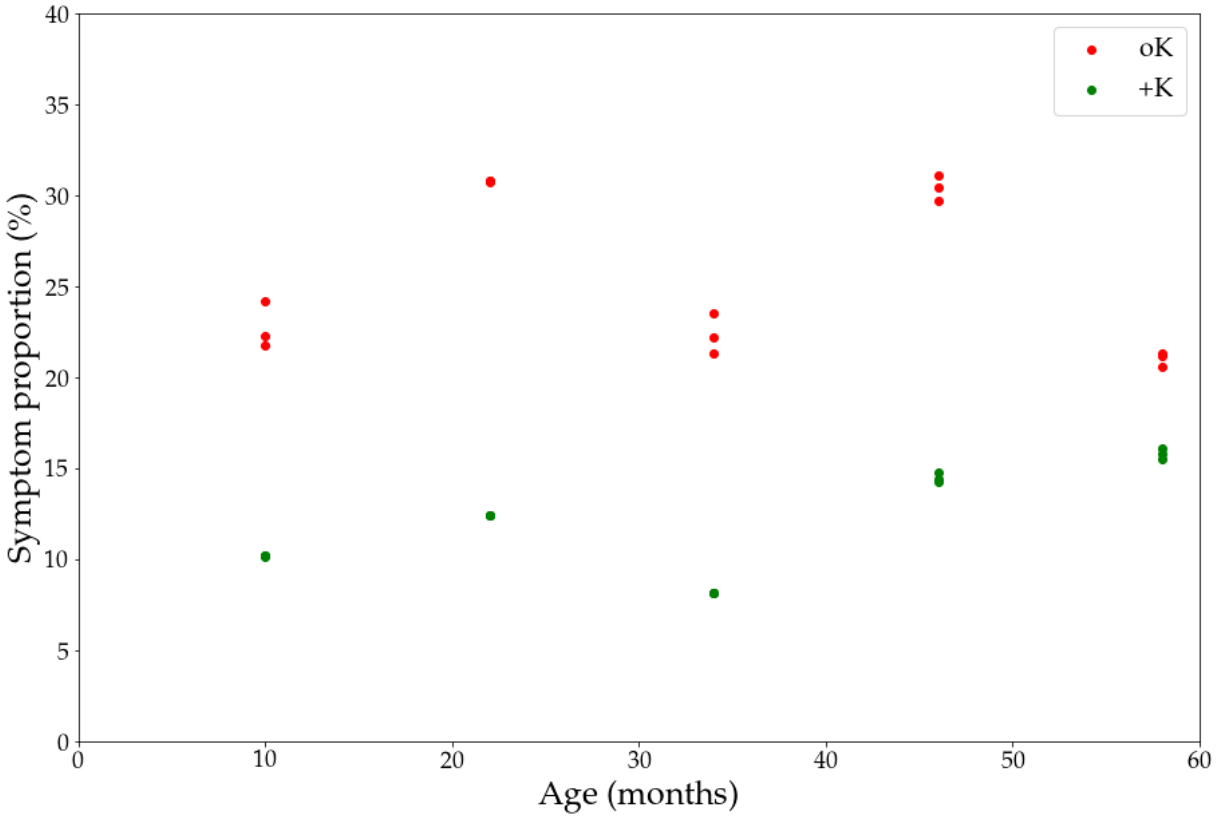

Figure S7: Upscaled mean leaf symptom proportion at the Itatinga experiment

6.7 Leaf Photosynthesis and nutrient content

In an attempt to understand the link between the K content of leaves and their photosynthetic capacity in planted eucalypts, a measurement campaign was set up. The site was an eucalypt plantation with a fully fertilised and K omission stands.

Eight trees in total were selected: 5 in the oK stand and 3 in the fully fertilised stand. These trees were cut in the field. On every tree, 4 branches were selected. One at the top of the canopy, one at the middle exterior of the canopy, one at the middle interior of the canopy and one at the bottom of the canopy. These branches were cut under water to prevent cavitation (Verryckt et al., 2020) and were brought back to the lab. There, on each branch 3 fully expanded leaves were selected. One close to the tip, one at the middle and one close to the base of the branch.

For each of the leaves a rapid A-Ci response curve (RACiR) was performed. The RACiR allows the phenotyping of more leaves than the traditional A-Ci curves (Stinziano et al., 2017). For each measurement series, an empty chamber calibration was performed (Fig.S8a-c, to measure the response of the CO_2 measurement to the CO_2 concentration ramp). This accounts for the offset and delay between the two IRGA cells that measure CO_2 concentrations (Stinziano et al., 2017). Then the reference CO_2 in the camber was continuously decreased from 620 to 50 ppm and increased in a second ramp from 1100 to 530 ppm. This protocol had previously been developed and tested on different eucalypt plantations and compared to classical A-Ci curves (personal communication, SUZANO). Photosynthetic traits *Vcmax* and *Jmax* were fitted on RACiR data collected for each leaf using the plantecophys R package (Duursma, 2015).

Each leaf was then scanned, weighed (both wet and dry weight) and the concentration in N, P and K were measured. Using the dry weight and leaf area determined by the scans, we calculated the leaf mass per area (LMA, g m^{-2}). This was needed to calculate the surfacic concentration of N, P and K (g of element m_{leaf}^{-2}). We then related the surfacic nutrient content of leaves with their photosynthetic traits (Fig.S8a-b). We observed no significant relationship between the leave's K surfacic concentration and photosynthetic traits in our dataset (Fig.S8b). This could be the consequence of the restricted, and overall high range of K surfacic concentrations measured here. Indeed, values of surfacic K concentrations in this oK experiment (1.0-2.0 gK m_{leaf}^{-2}, Fig.S8b) were higher than the observed values of the +K stand at Itatinga (i.e. the range at the Itatinga experimental site was 0.28 (oK) to 0.85 (+K) gK m_{leaf}^{-2}, data not shown).

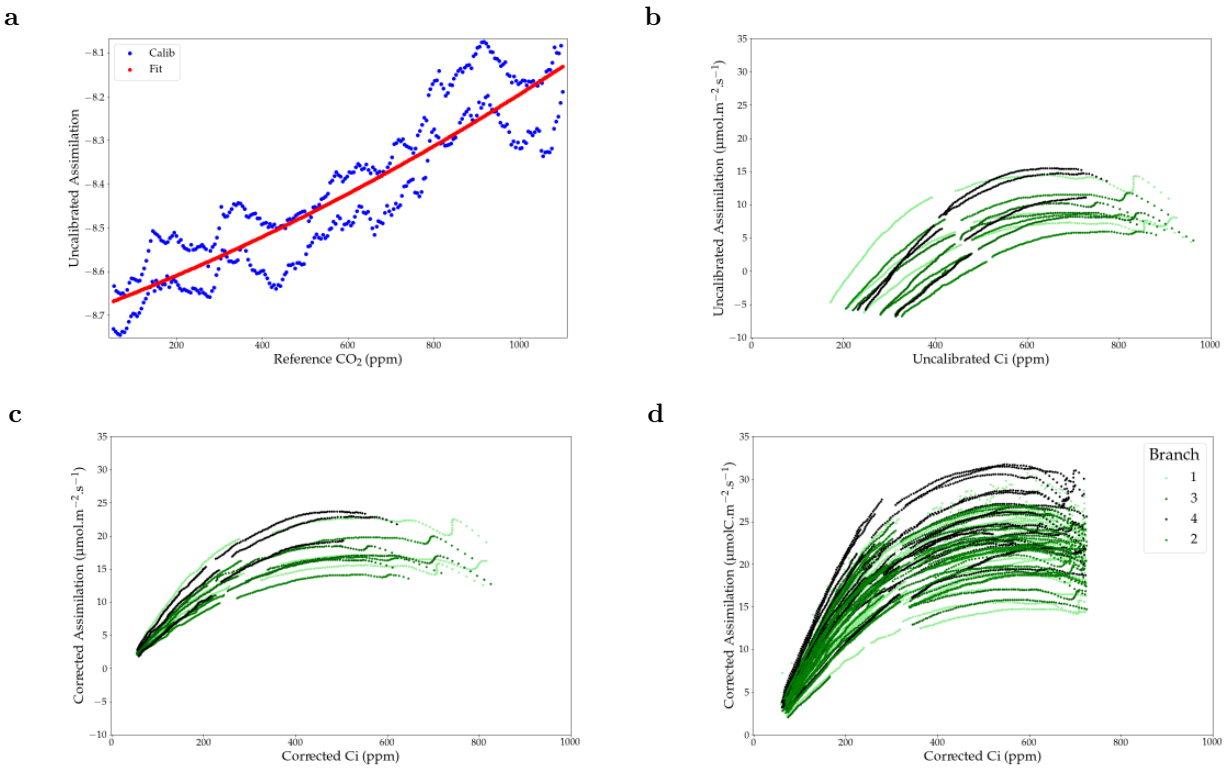

Figure S8: (a) The empty chamber calibration that is used in the RACiR method. (b) The uncorrected RACiR curves. (c) The same curves after correction by the calibration performed in a. (d) The RACiR curves of all the leaves that were used in this experiment. The number of measured leaves (62) was lower than the theoretical number of leaves that we planned to measure (96) due to technical difficulties.

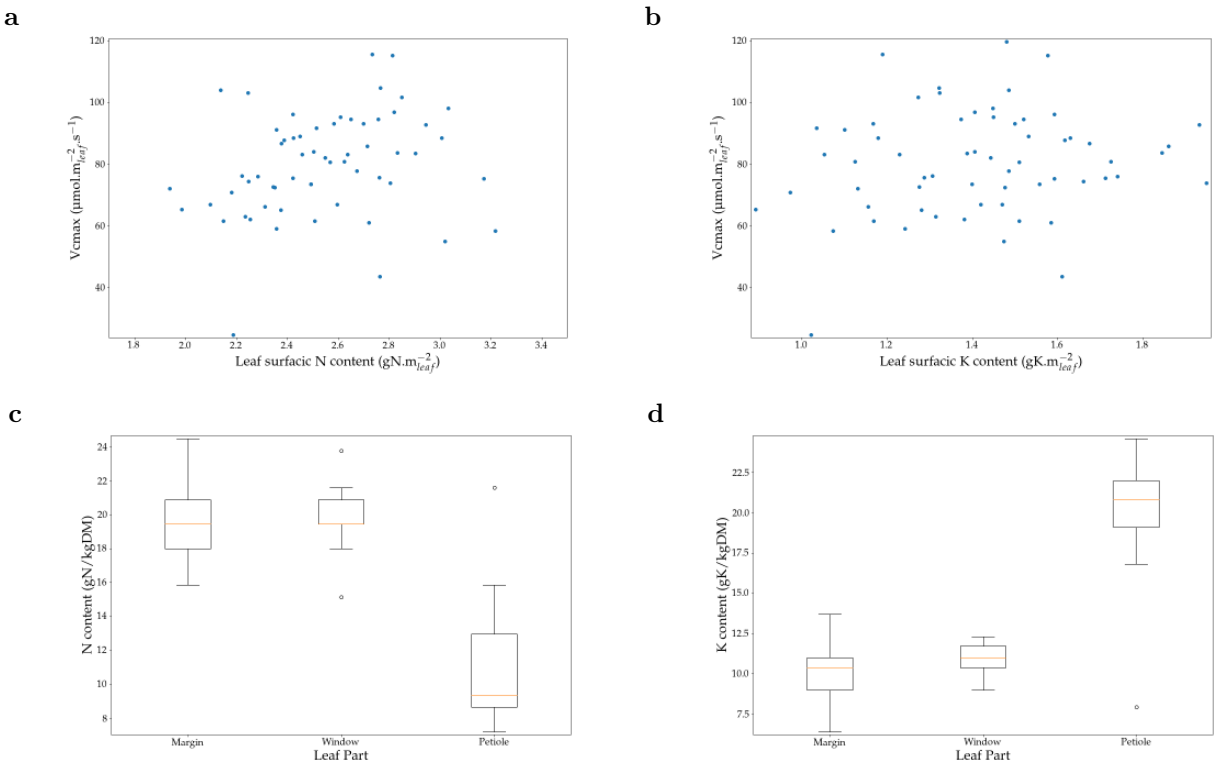

Figure S9: (a) The response of the maximum carboxylation rate *Vcmax* to the leaf N surfacic concentration (b) The response of the leaves' *Vcmax* to the K surfacic concentration. (c) The N mass concentration of each leaf part that was cut (d) The K mass concentration of each leaf part that was cut. Differences in the organ pattern of concentrations can be seen between N and K.