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The fate of Amazon rain forests under soil drought: collapse or stabilization?

Pablo Sanchez-Martinez, LR Martius, P Bittencourt, M Silva, O Binks, V Negrão-Rodrigues, J Athaydes Silva Junior, AC Da Costa, RJ Selman, S Rifai, L Rowland, M Mencuccini, P Meir

The importance of the Amazon forest

The importance of the Amazon forest

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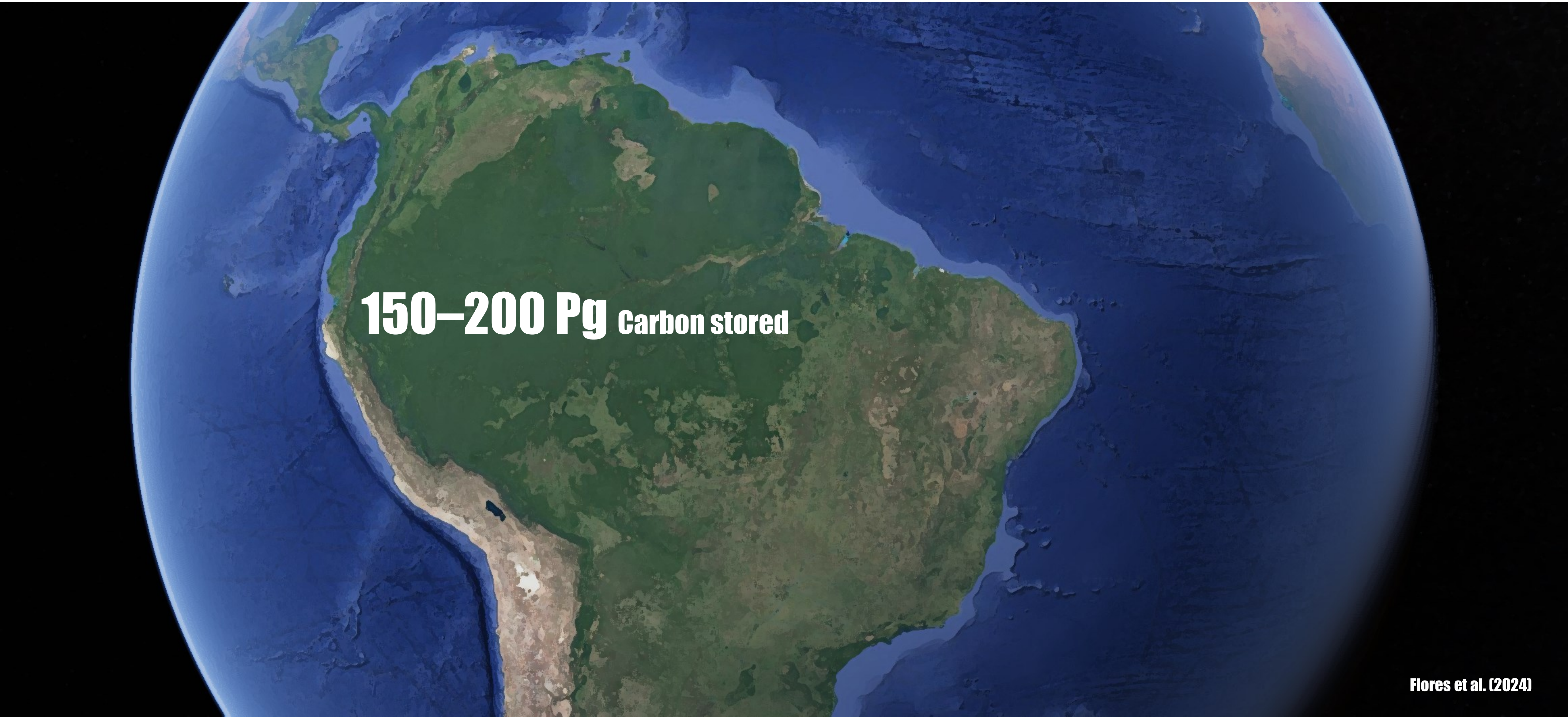
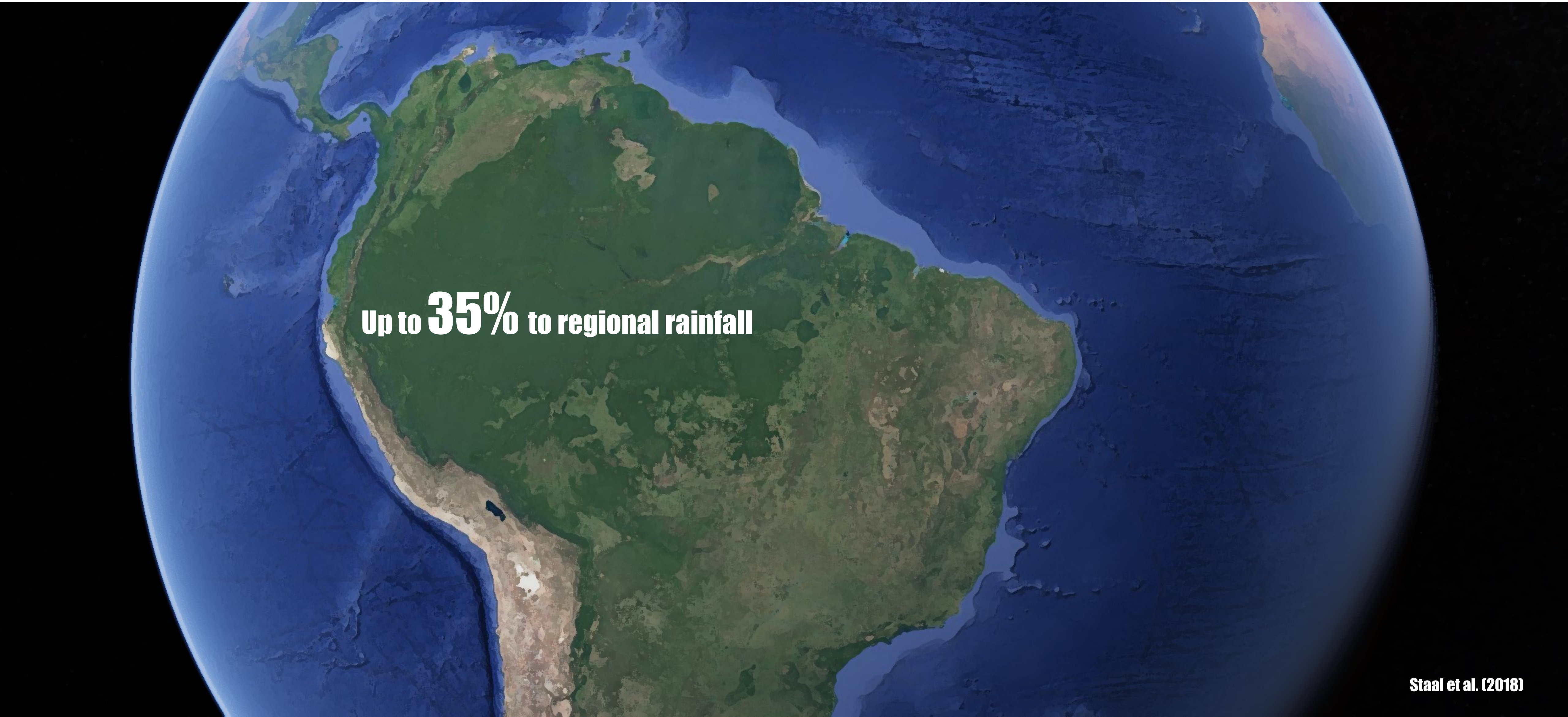
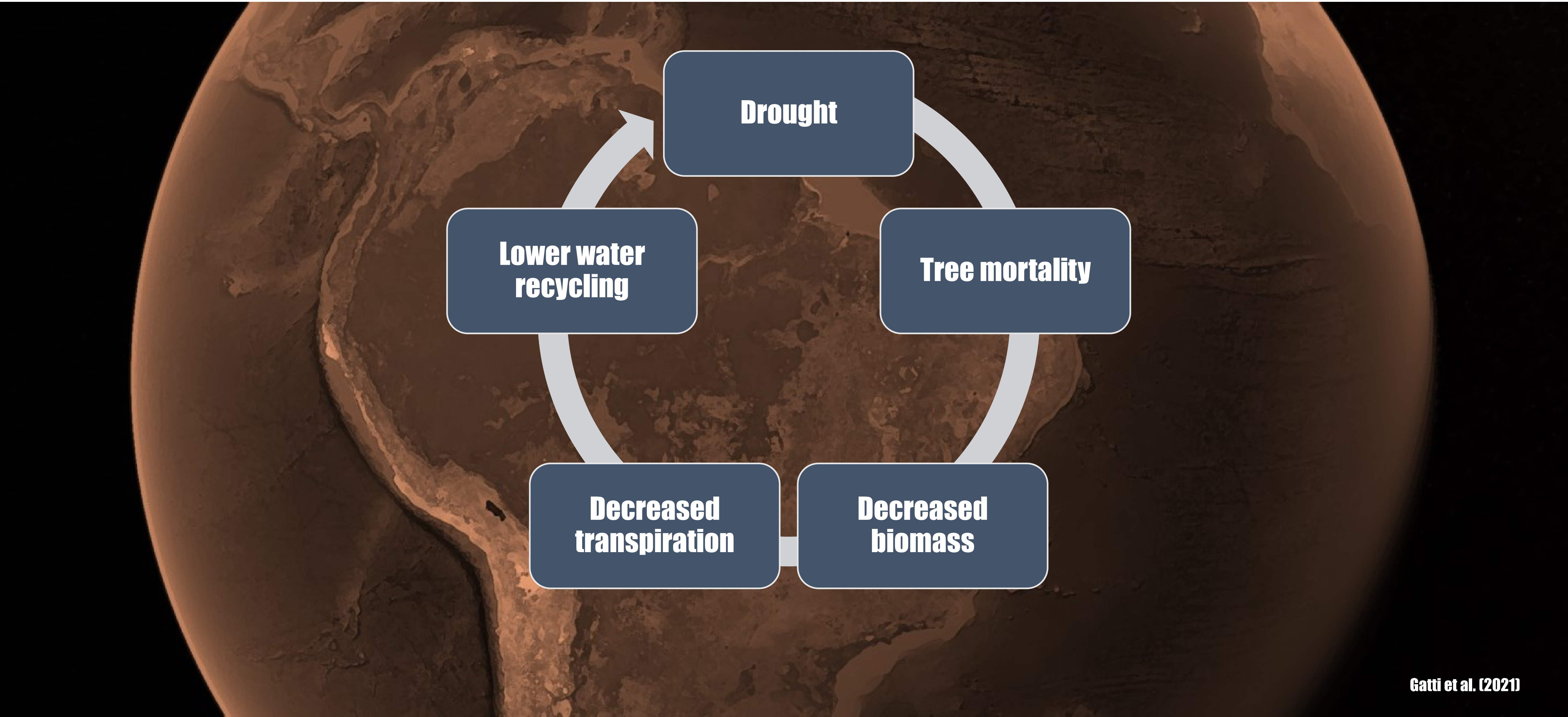


The importance of the Amazon forest

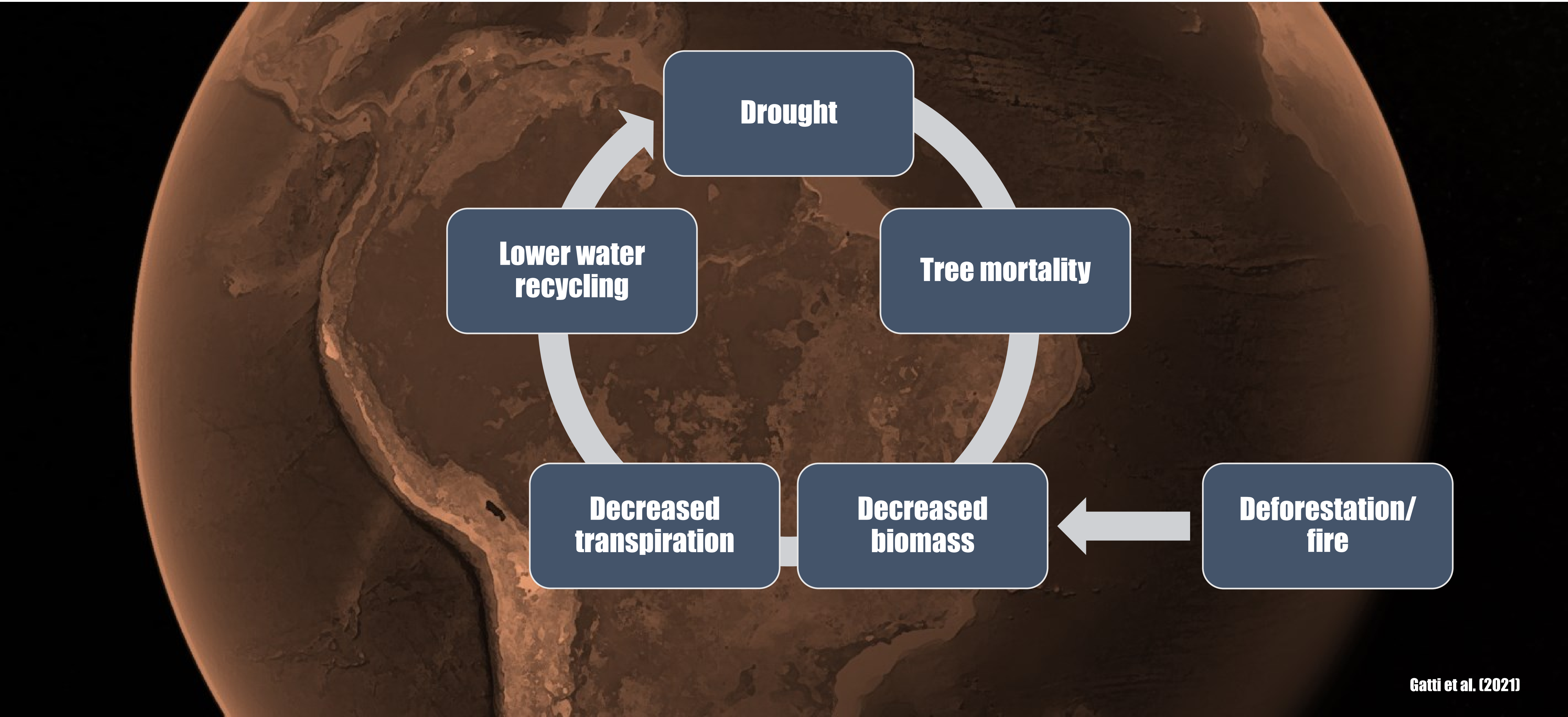


The impacts of drought on the Amazon forest



Gatti et al. (2021)

The impacts of drought on the Amazon forest



Gatti et al. (2021)

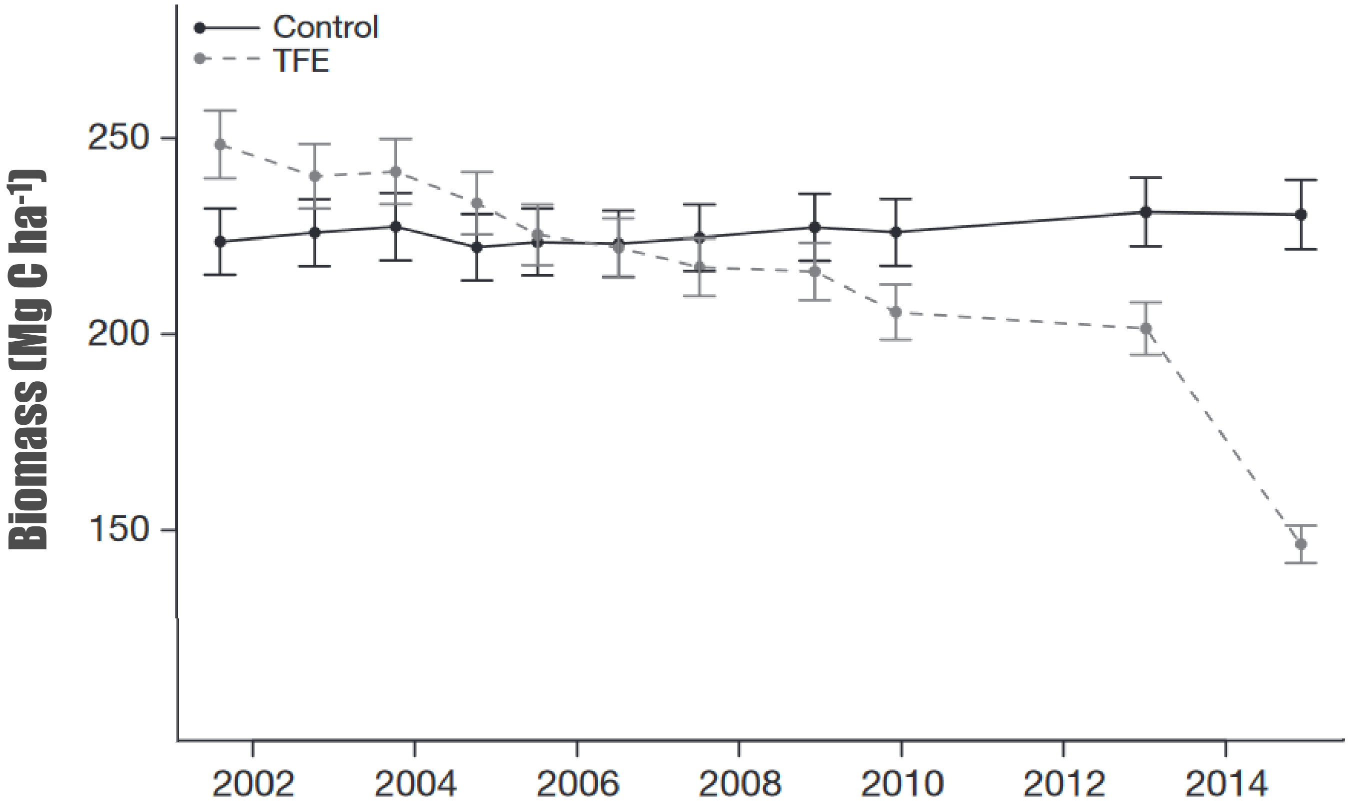
Esecaflor project in Floresta Nacional de Caxiuanã (Br)

Da Costa et al. (2010); Meir et al. (2018)

Experimental setting

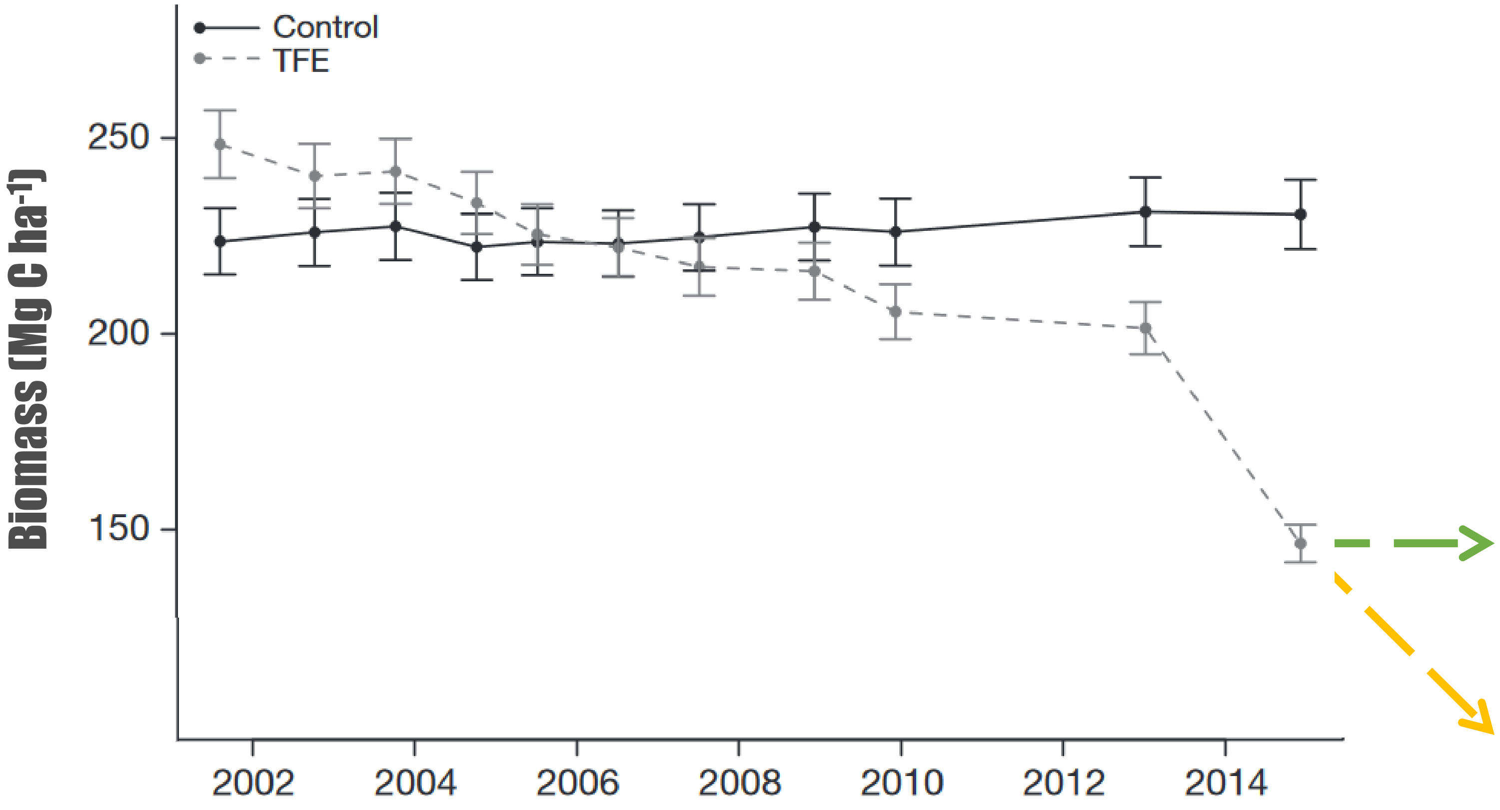
Experimental setting

Previous studies showed biomass decrease in the drought plot



Rowland et al. (2015)

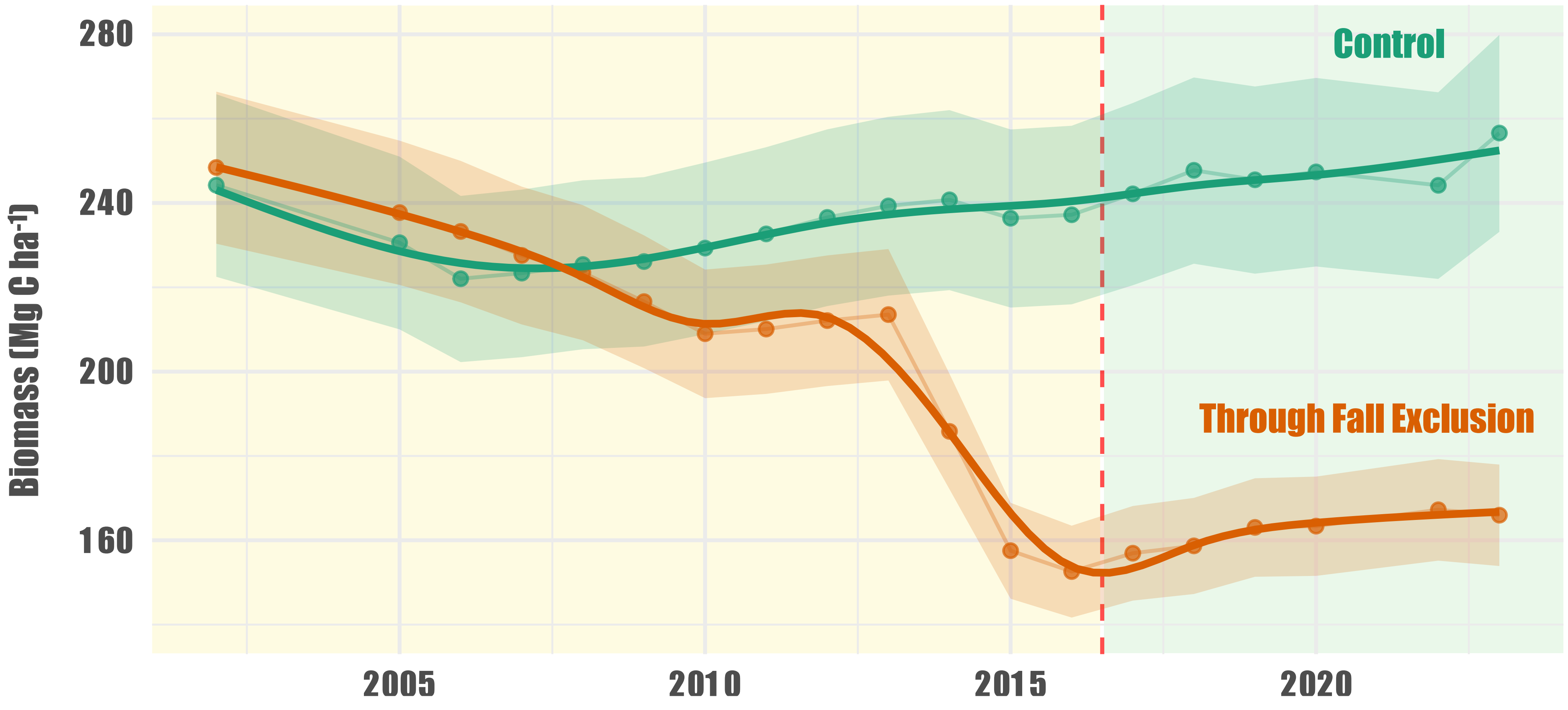
Previous studies showed biomass decrease in the drought plot



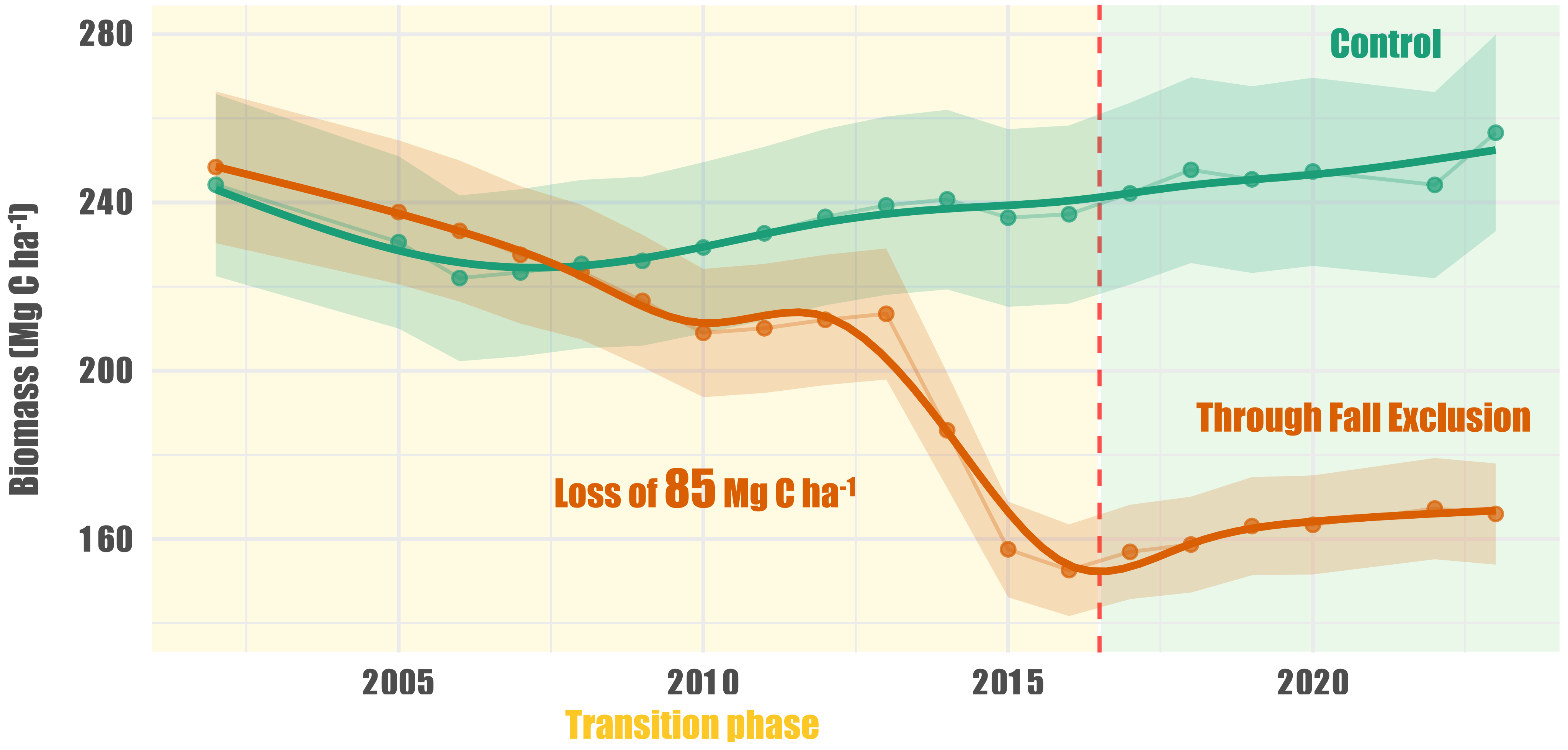
Collapse or stabilization after long-term drought?

Rowland et al. (2015)

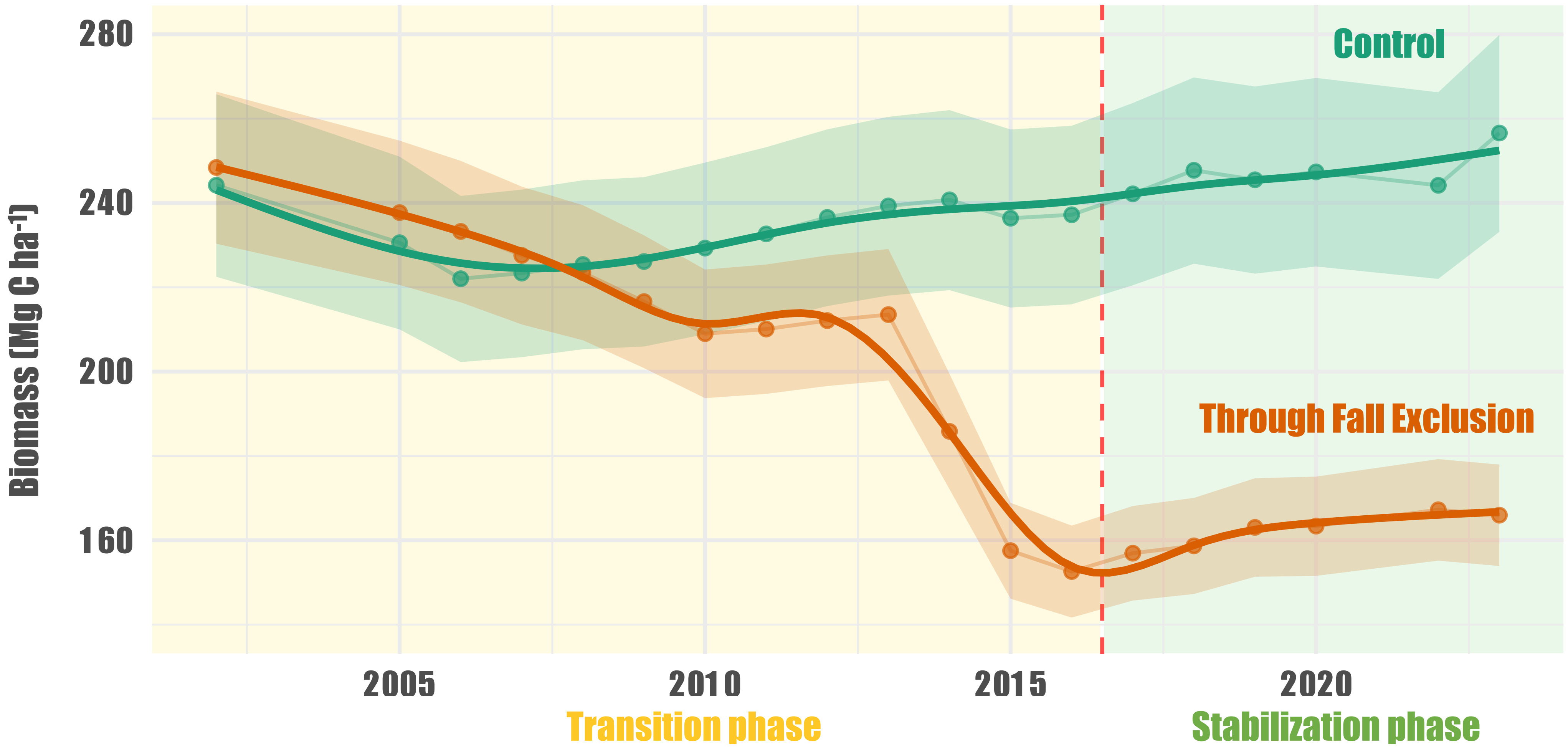
Biomass stabilized after 15 years of drought



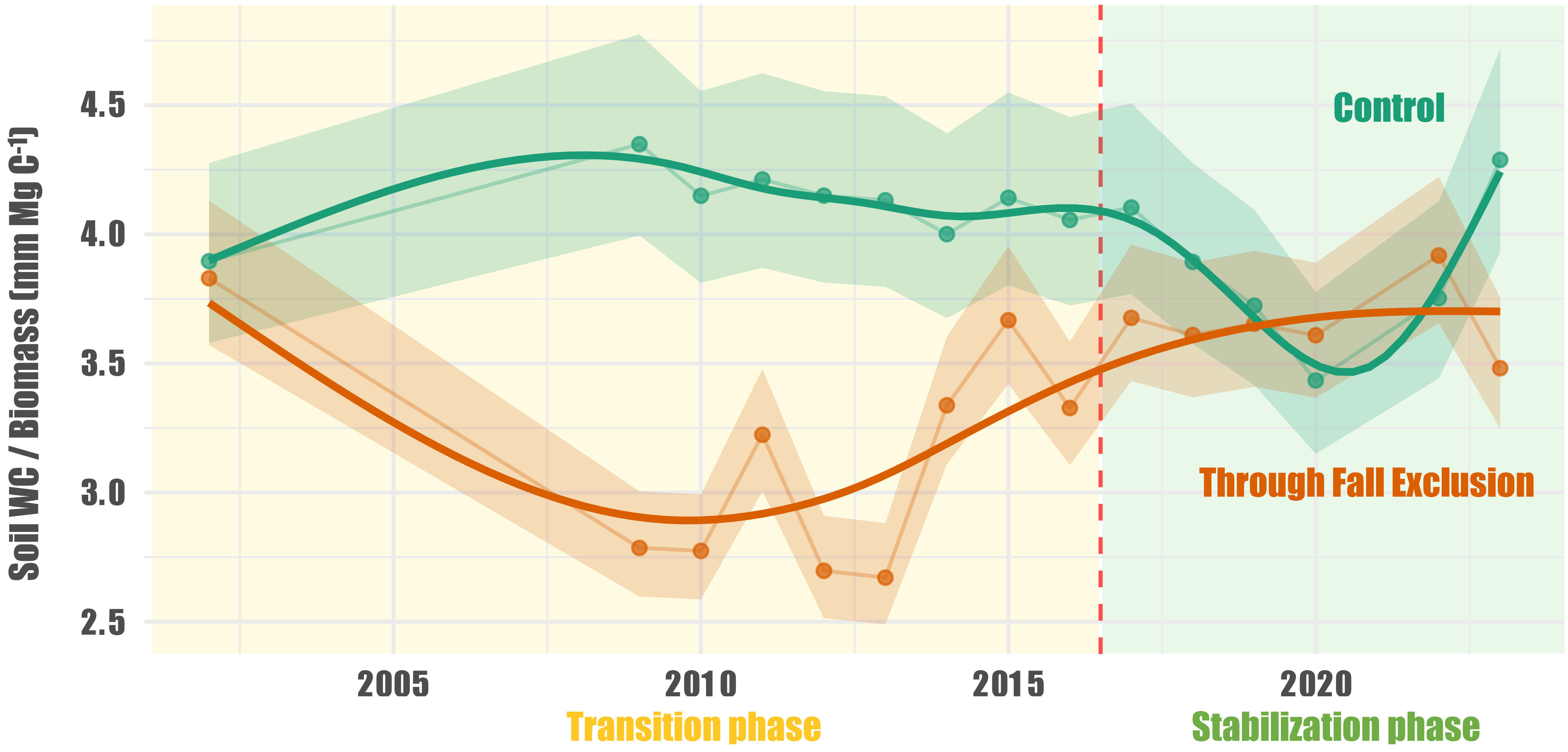
Biomass stabilized after 15 years of drought



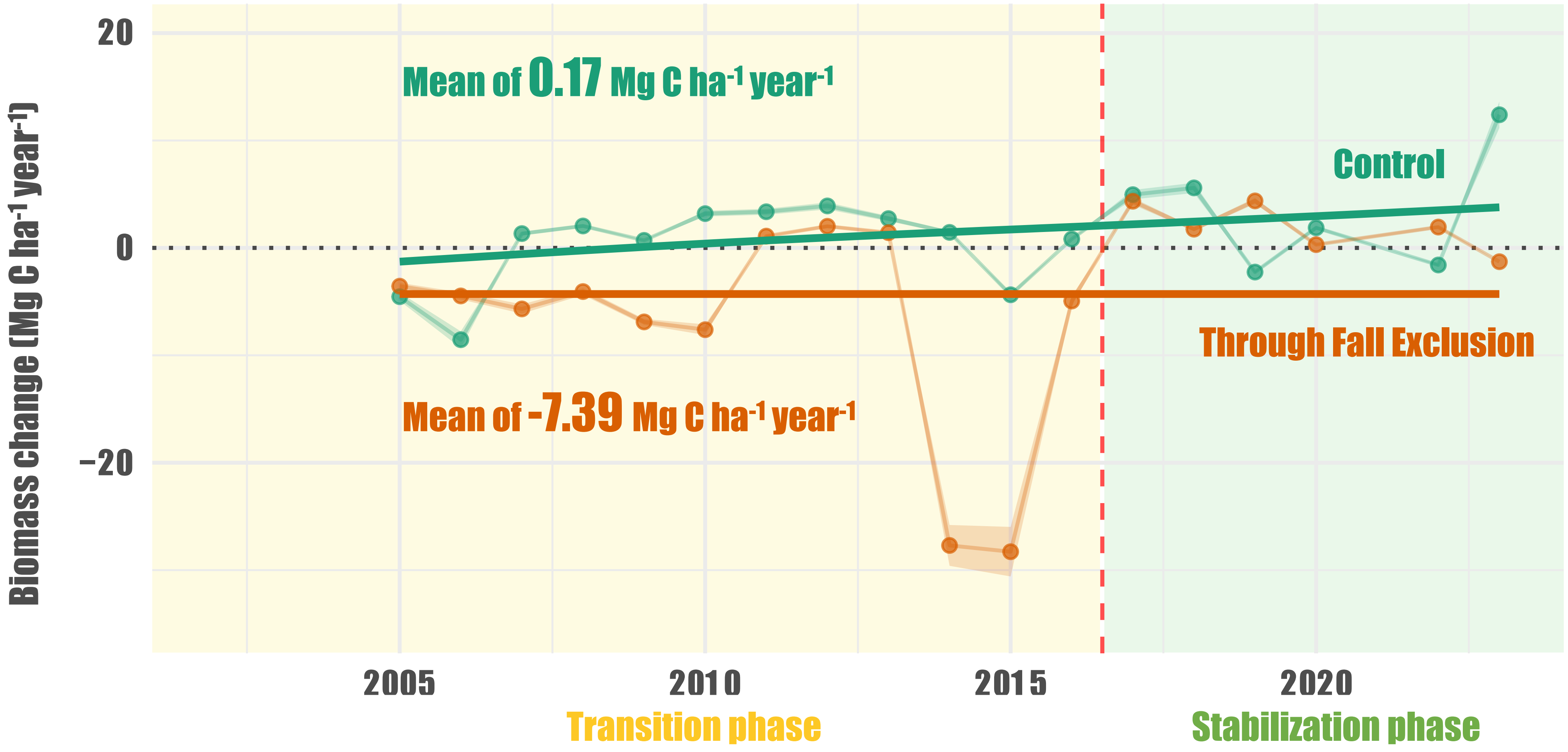
Biomass stabilized after 15 years of drought



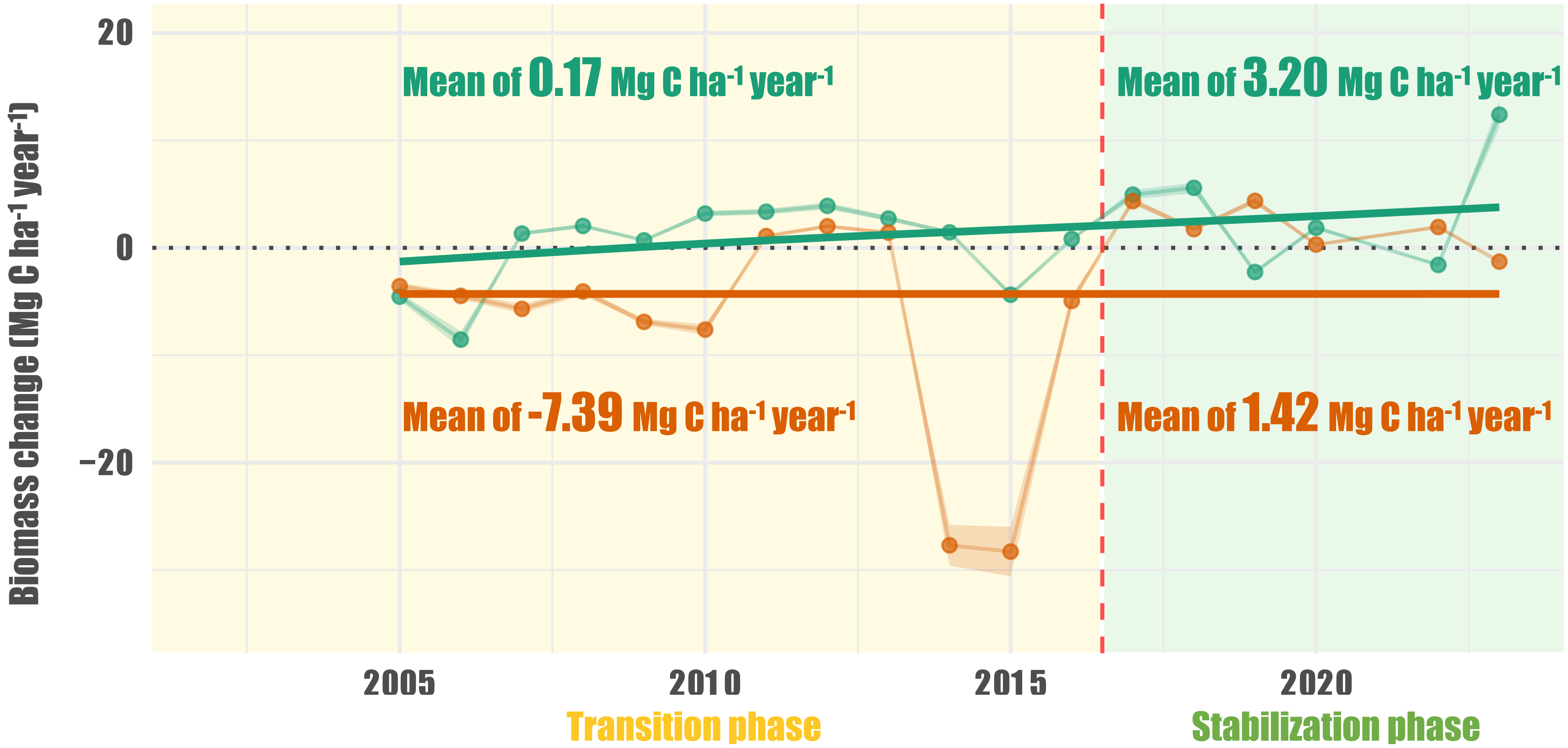
Increase of biomass-relative soil water content



Wood productivity stabilized



Wood productivity stabilized



Do trees show signs of current hydraulic stress?

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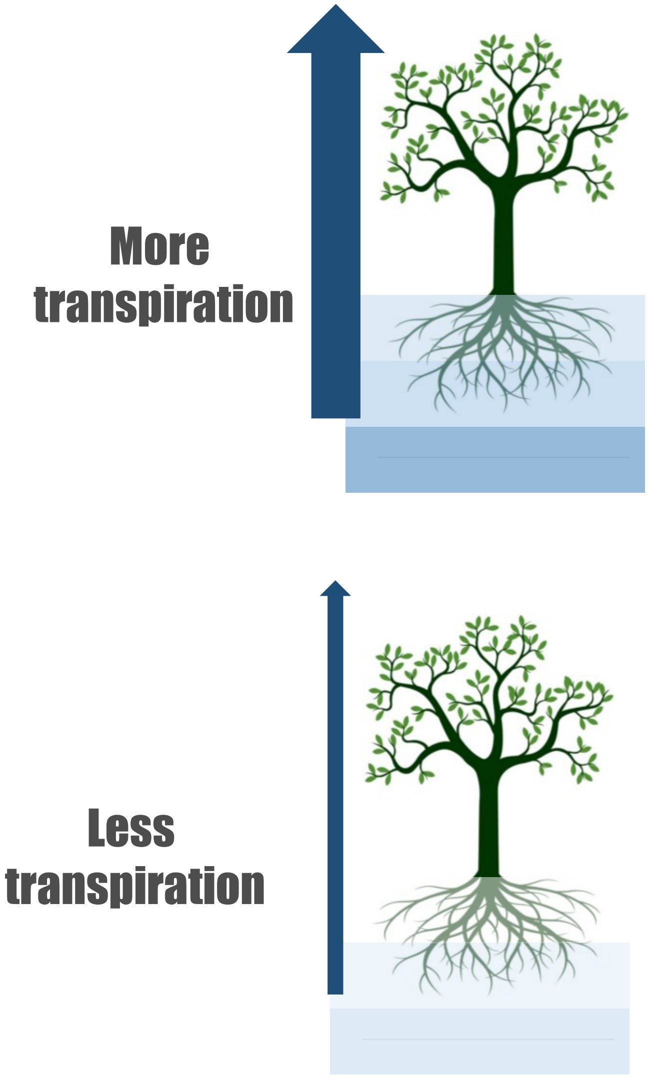
42 Monitored trees (21 per plot) 2023-2024

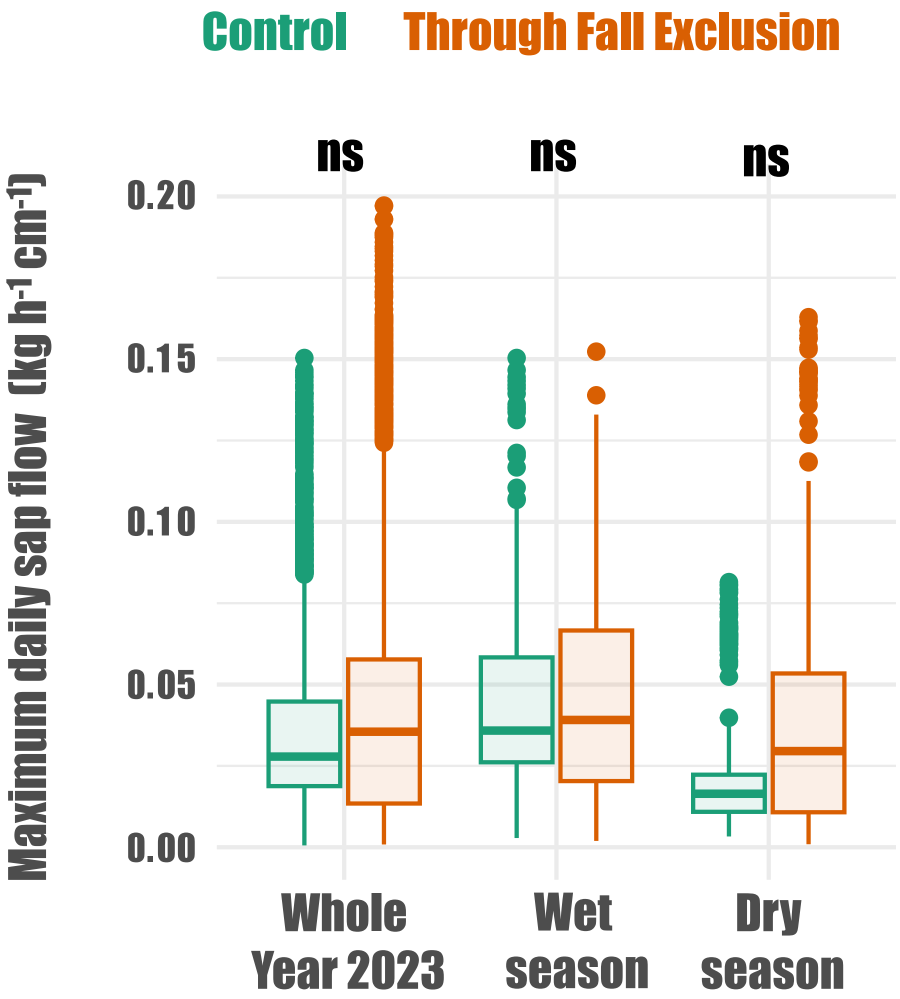
- **Sap flow** → **Transpiration**
- **Stem and leaf water content** → **Tissue hydration**
- **Leaf water potential** → **Hydraulic stress**

Large scale assessment 352 trees (176 per plot) at the peak of the dry and wet seasons

- **Leaf water potential** → **Hydraulic stress**

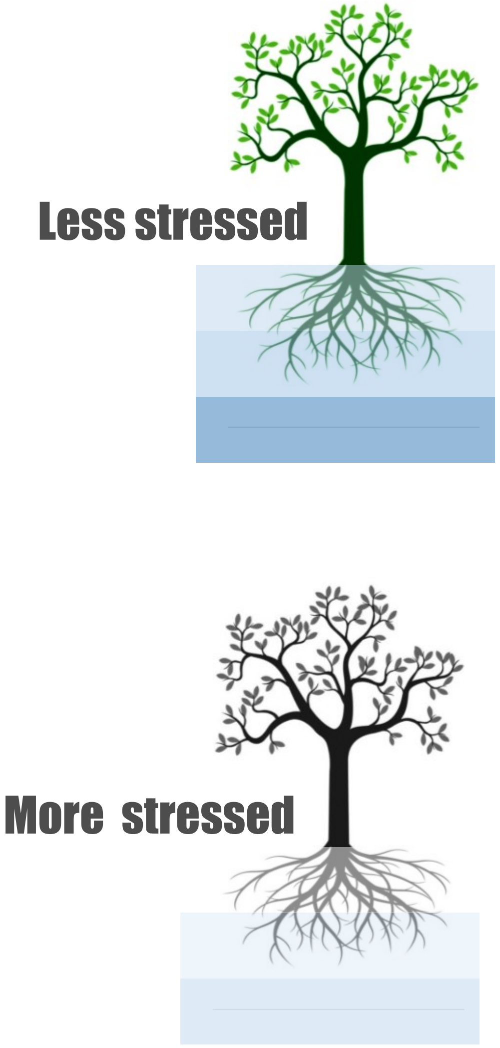
No differences in transpiration

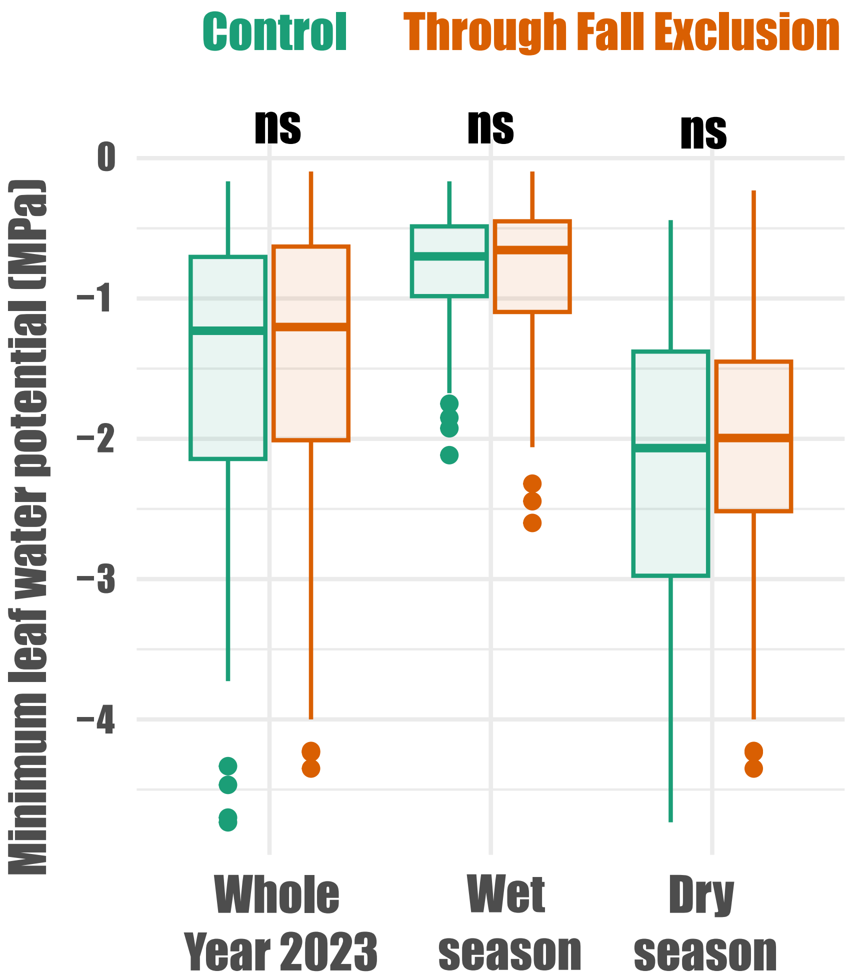




EMS to measure sap flow

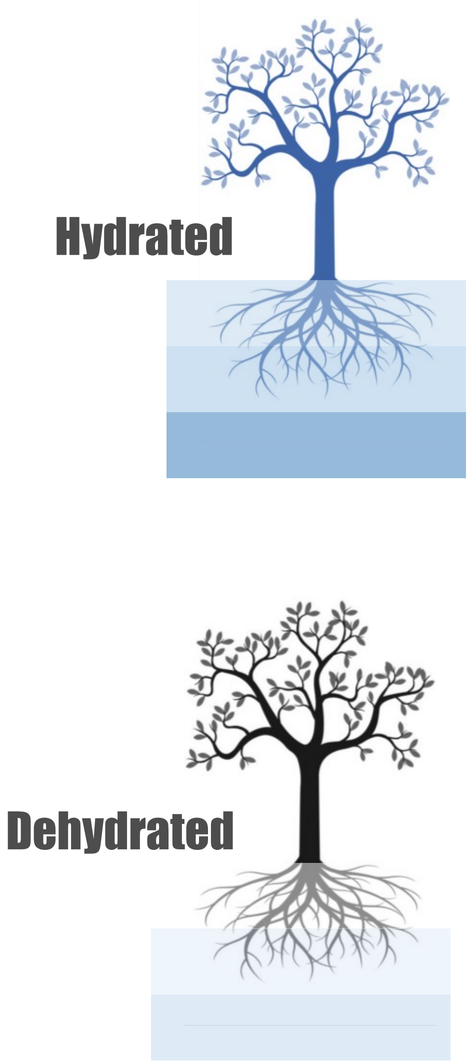
No differences in maximum hydraulic stress

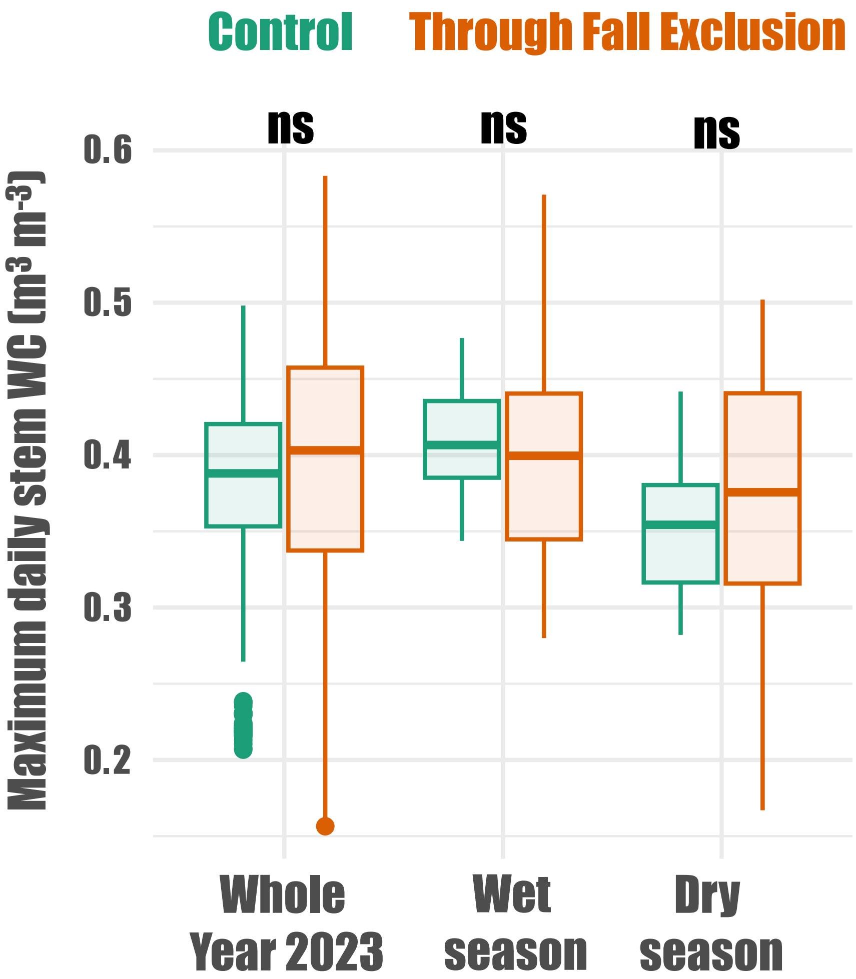




Lion Martius and Vanessa Negrão-Rodrigues + pressure chamber system to measure leaf WP

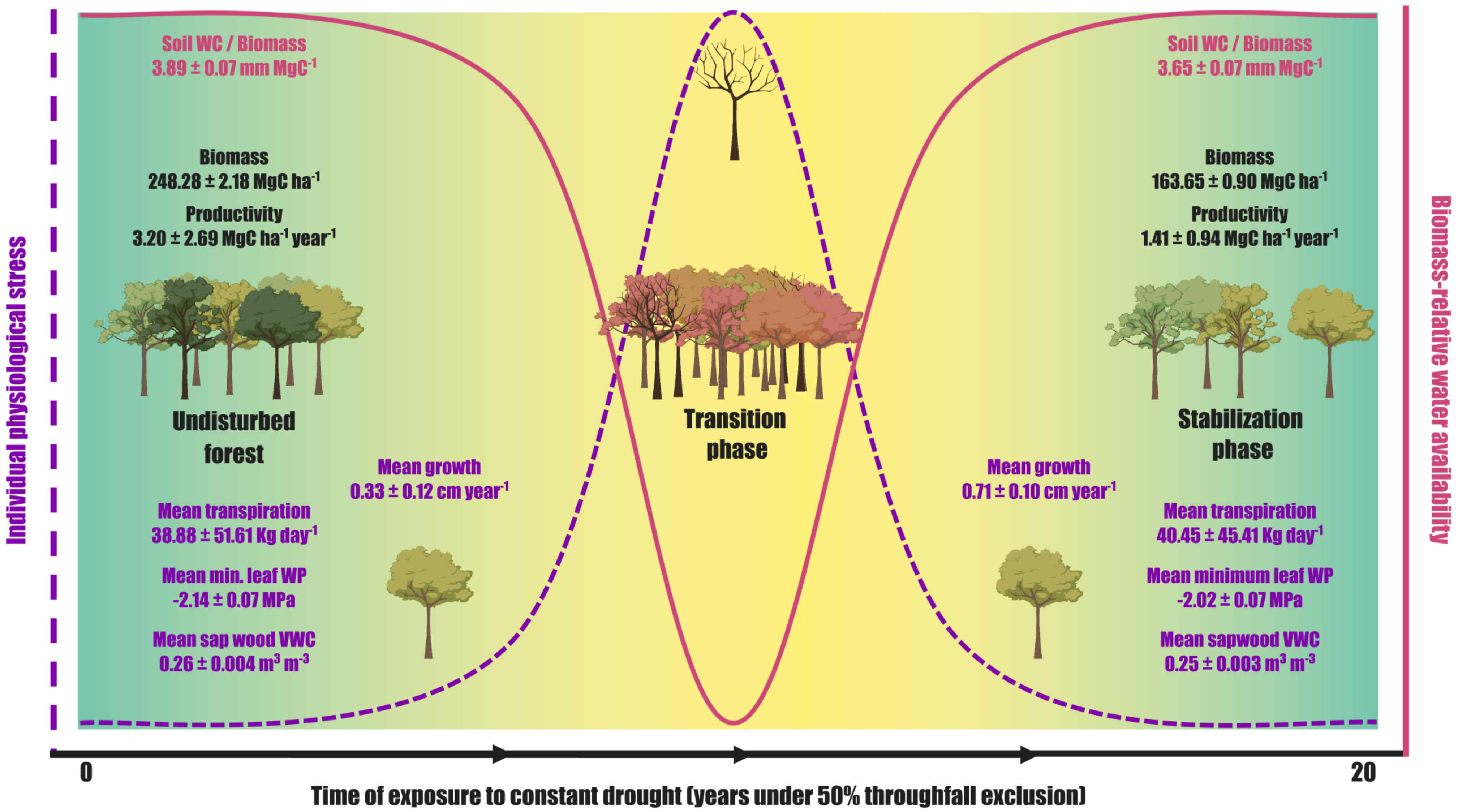
No differences in tissue hydration





Scary spider + Teros 12 sensor to measure water content

Eco-hydrological stability under drought



Conclusions

Amazon forest do not collapse after 20 years of 50% through fall exclusion

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Individual trees do not show signs of higher hydraulic stress compared to normal conditions

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Forest biomass stabilizes after losing >80 Mg C ha^{-1} and wood productivity becomes slightly positive

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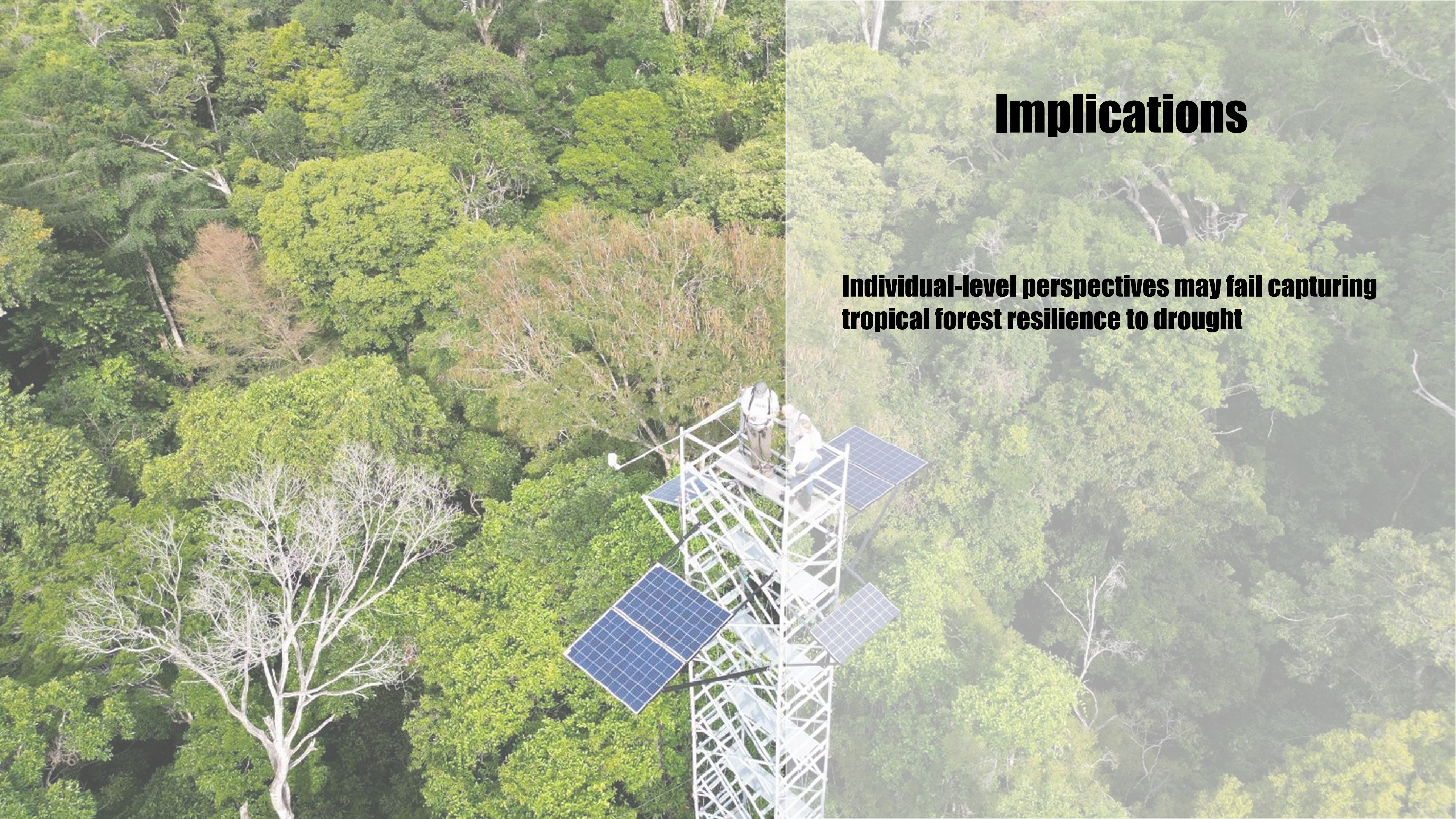
Individual trees do not show signs of higher hydraulic stress compared to normal conditions

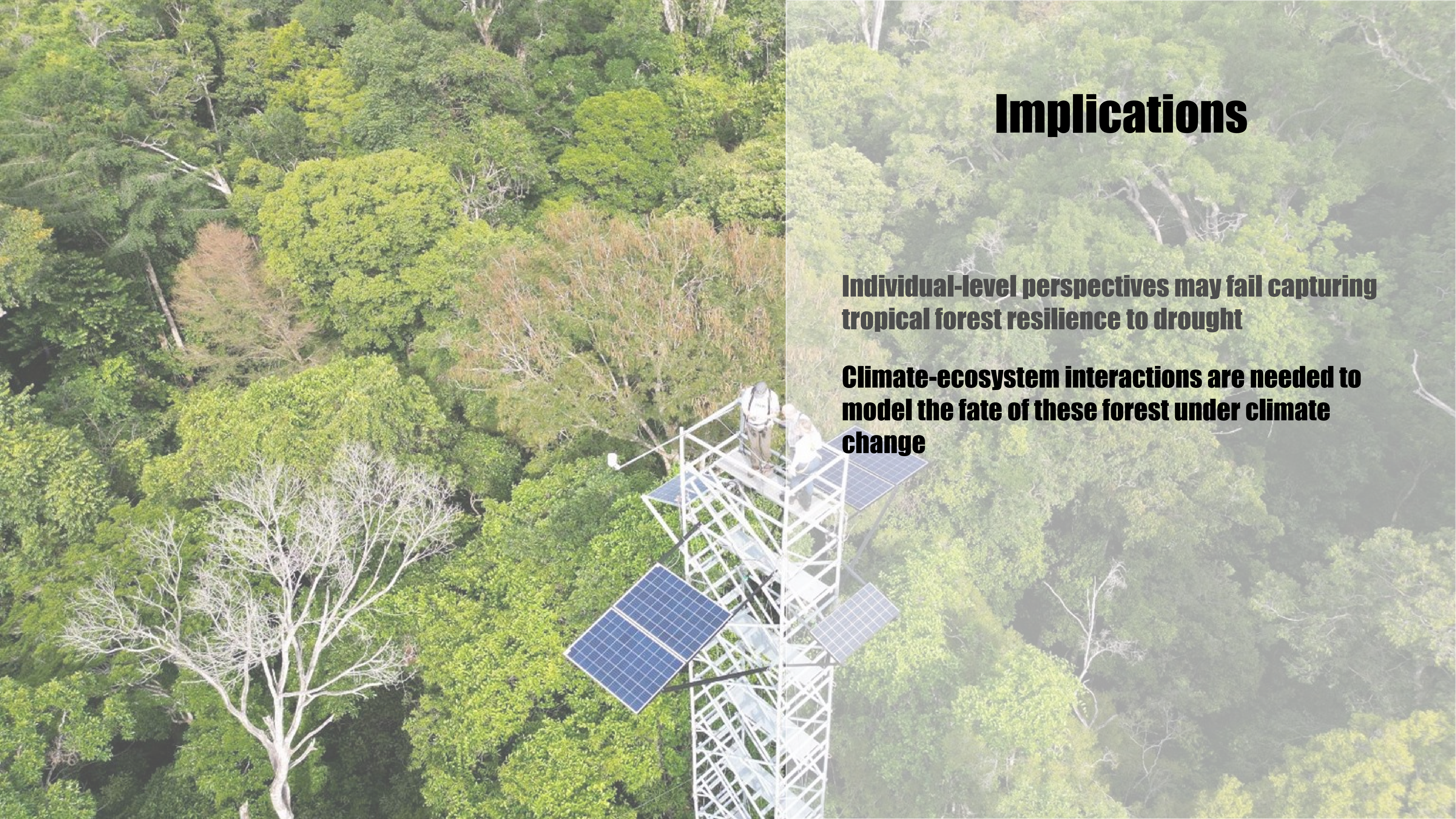
Forest biomass stabilizes after losing >80 Mg C ha^{-1} and wood productivity becomes slightly positive

Resilience to drought emerges from structural changes, consistent with a low physiological acclimation at the individual level (Bittencourt et al. 2020, Giles et al. 2022)



Implications

Individual-level perspectives may fail capturing tropical forest resilience to drought



Implications

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Climate-ecosystem interactions are needed to model the fate of these forest under climate change

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Climate-ecosystem interactions are needed to model the fate of these forest under climate change

Amazon forest may have higher resilience than previously expected, but they become an important carbon source through the transition phase when exposed to drought

Implications

Individual-level perspectives may fail capturing tropical forest resilience to drought

Climate-ecosystem interactions are needed to model the fate of these forest under climate change

Amazon forest may have higher resilience than previously expected, but they become an important carbon source through the transition phase when exposed to drought

We need to act to mitigate this carbon loss to minimize its positive feedback with drought, which may eventually overcome the resilience capacity of the system

Thank you for your attention!

The paper will be out soon! Sanchez-Martinez et al. 2025. Amazon rainforest adjusts to long-term experimental drought. (In press) Nature Ecology and Evolution

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Supplementary information

Amazon Basin contextualization

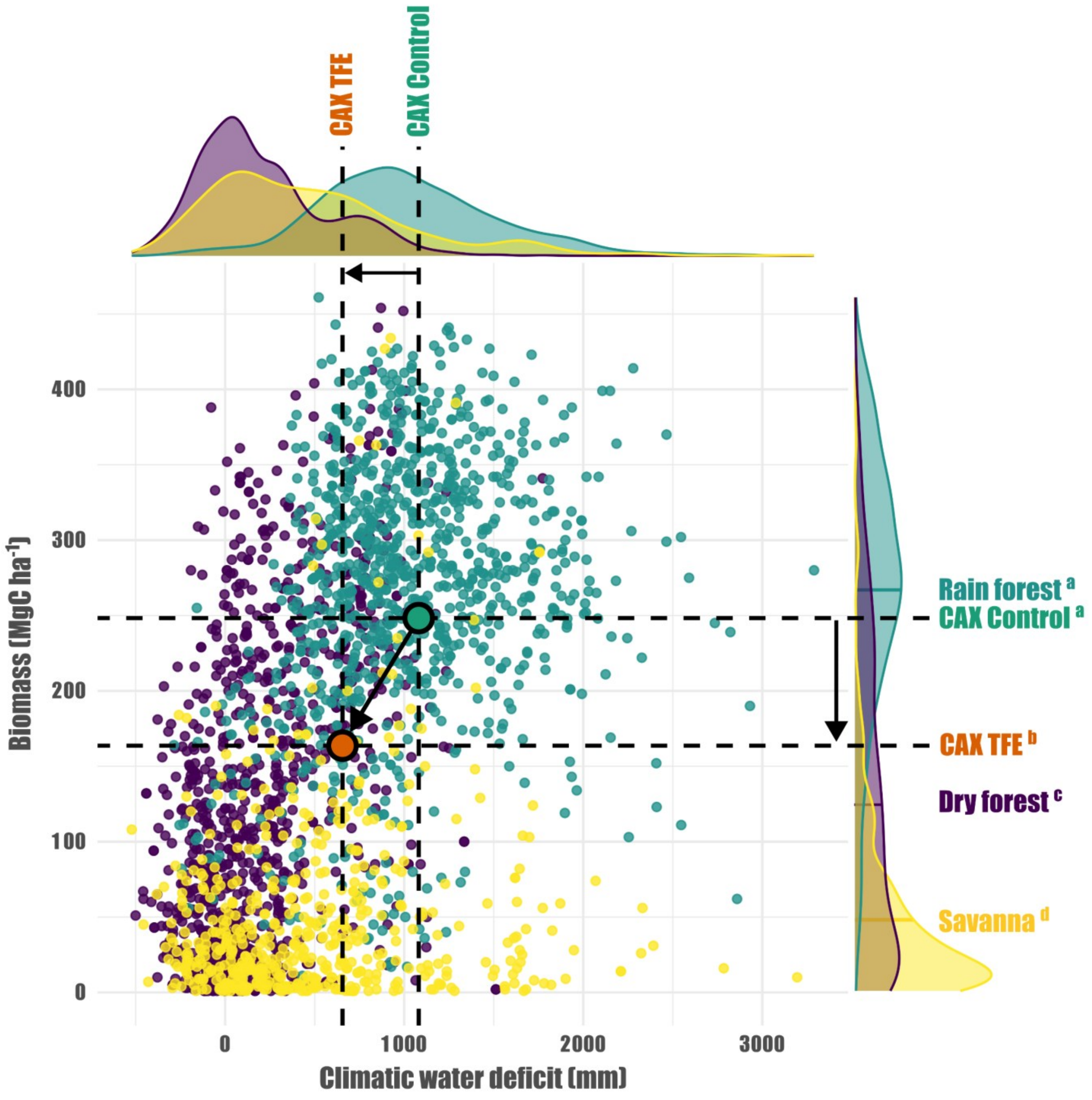


Figure S1. Size-biomass

Time series of emergent and subcanopy tree density (a and b, respectively) and their relationship with total above ground wood biomass (c, d) and mean above ground wood biomass (e, f). In a and b, red dotted line represents the approximate time at which the TFE plot changed from transition to steady phase. The two phases are represented by the shape of the points, triangles referring to transition phase and points to the steady phase. In c, d, e and f, consecutive years are connected by a line in the scatterplot, showing the first year of experiment (2002), the year after which the forest entered the steady phase (2016) and the latest year of experiment in our dataset (2023). Regression lines are represented when statistically significant and R^2 reported by linear models for each plot are also shown jointly with the model significance. Signif. codes: '***': P < 0.001; '**': P < 0.01; '*': P < 0.05 'ns': P > 0.05.

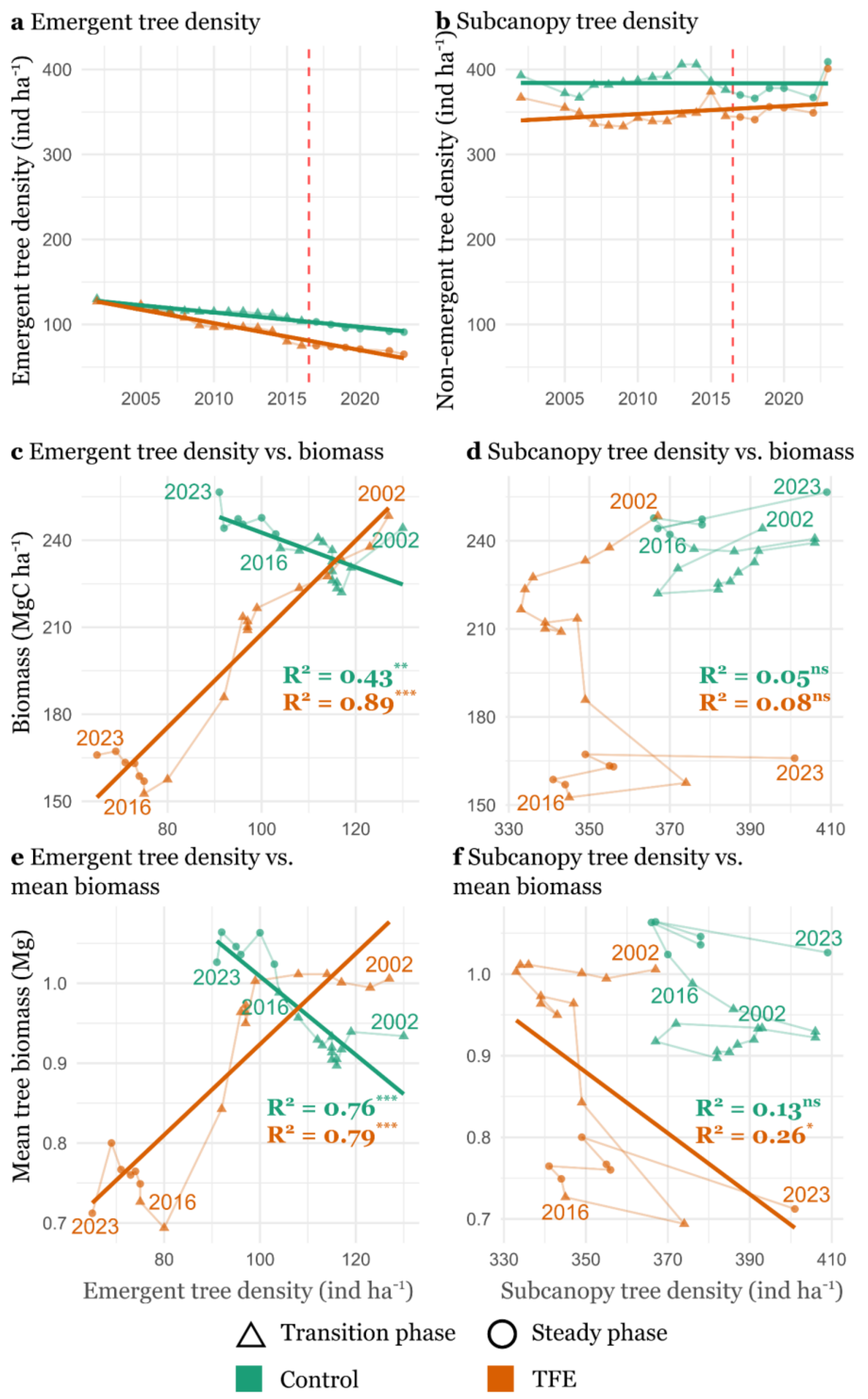


Figure S2. Growth

Time series of plot effect on emergent and subcanopy annual stem growth reported by linear models (a and b) and the relationship between emergent and subcanopy annual stem growth with total above ground wood biomass (c and d). In a and b, red dotted line represents the approximate time at which the TFE plot changed from transition to steady phase. The two phases are represented by the shape of the points, triangles referring to transition phase and points to the steady phase. In e and f, consecutive years are connected by a line in the scatterplot, showing the first year with soil water content per unit biomass and growth (2008), the year after which the forest entered the steady phase (2016) and the latter year of experiment (2023). Statistically significant linear relationships are represented and R2 reported by linear models for each plot are also shown jointly with the model significance. Signif. codes: ‘***’: P < 0.001; ‘**’: P < 0.01; ‘*’: P < 0.05 ‘ns’: P > 0.05.

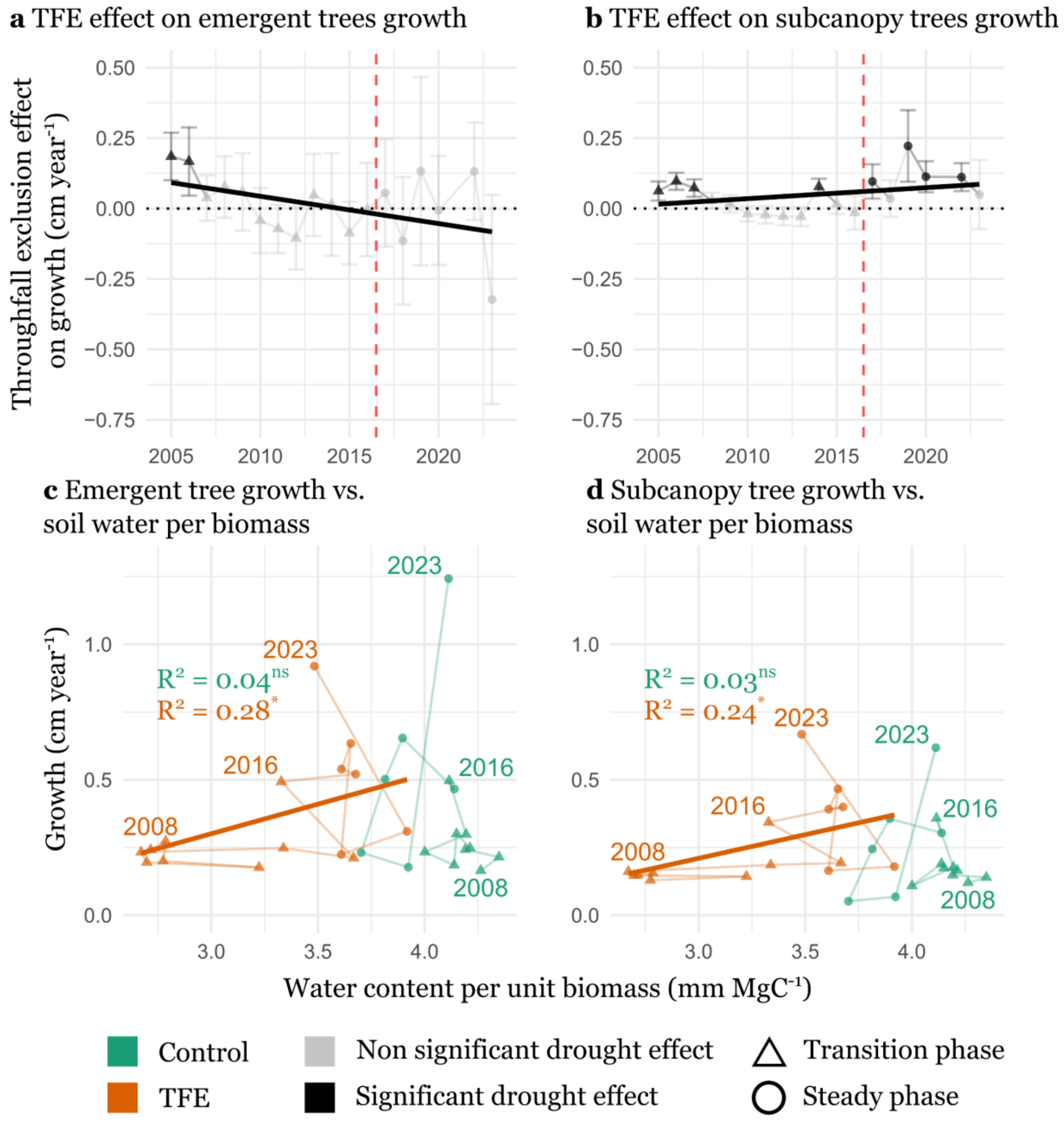


Figure S3. Transpiration

Transpiration (measured as sap flow) differences between trees from the Through Fall Exclusion plot (TFE) and the Control plot. Daily maximum sap flow per unit sapwood represented for each plot and month (represented by the quantile 90%) (a); percentage of reduction of maximum daily sap flow compared to annual maxima (b) and total daily sap flow (c) from May 2023 to December 2023. Statistical significance was tested by means of linear mixed models (see Methods). Signif. codes: '***': P < 0.001; '**': P < 0.01; '*': P < 0.05 'ns': P > 0.05.

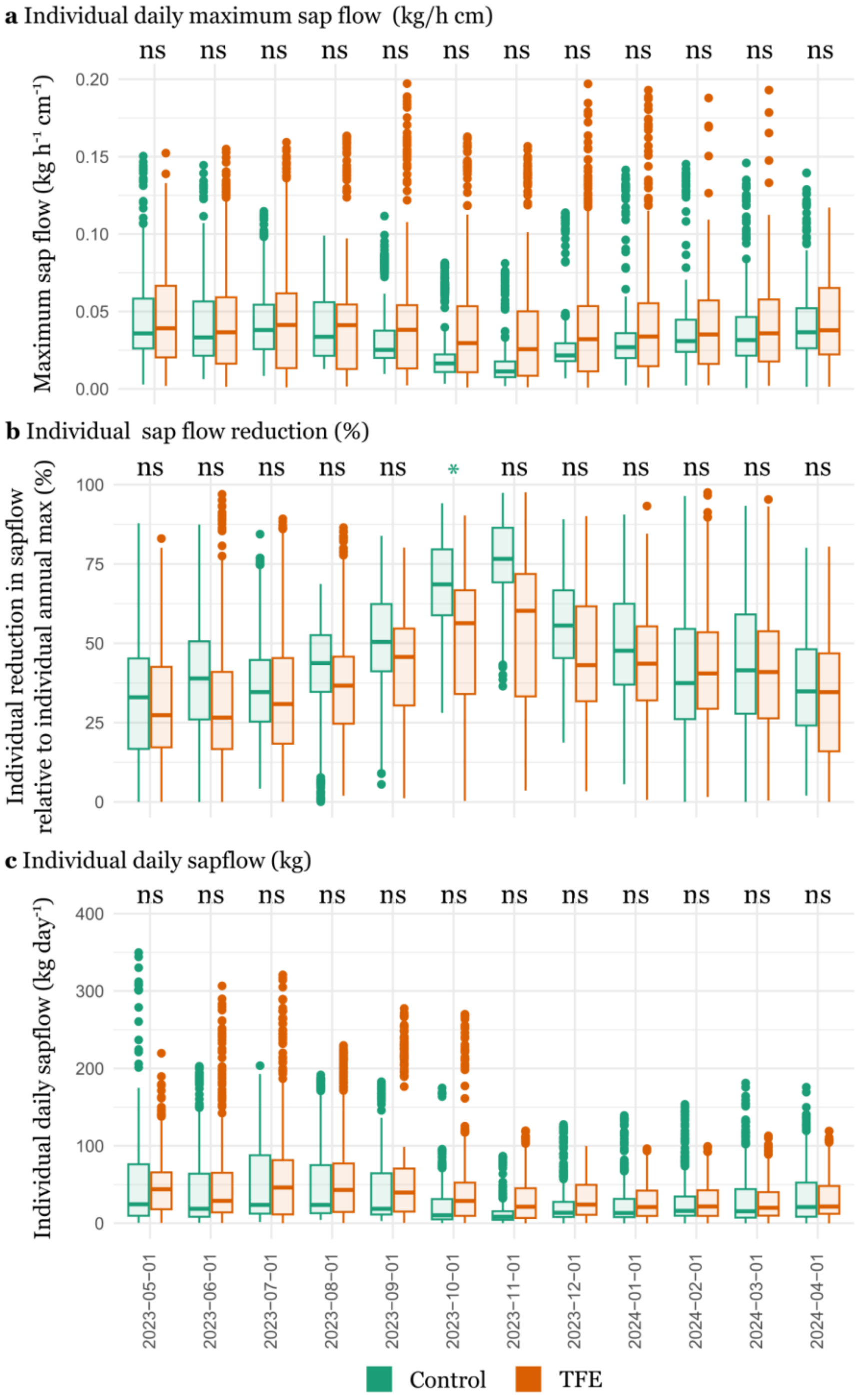


Figure S4. Leaf water status

Leaf water potential and water content measured in individual trees from the Through Fall Exclusion plot (TFE) and the Control plot. Water potential was measured for all trees (>352 trees) at the peak of the wet (05/2023) and the dry (05/2023) season. For a subset of this large sample of trees (i.e., the 42 monitored trees, see table S1), water contents were also measured and an extra campaign at the beginning of the dry season (07/2023) was added. Predawn samples were taken from 4 am to 6 am and show water status at equilibrium with soil water. Midday samples were taken from 11:45 am to 2 pm and show water status at maximum stress (maximum atmospheric water demand). Mean values for each plot and campaign are shown. Statistical significance was tested by means of linear mixed models (see Methods). Signif. codes: '***': P < 0.001; '**': P < 0.01; '*': P < 0.05 'ns': P > 0.05.

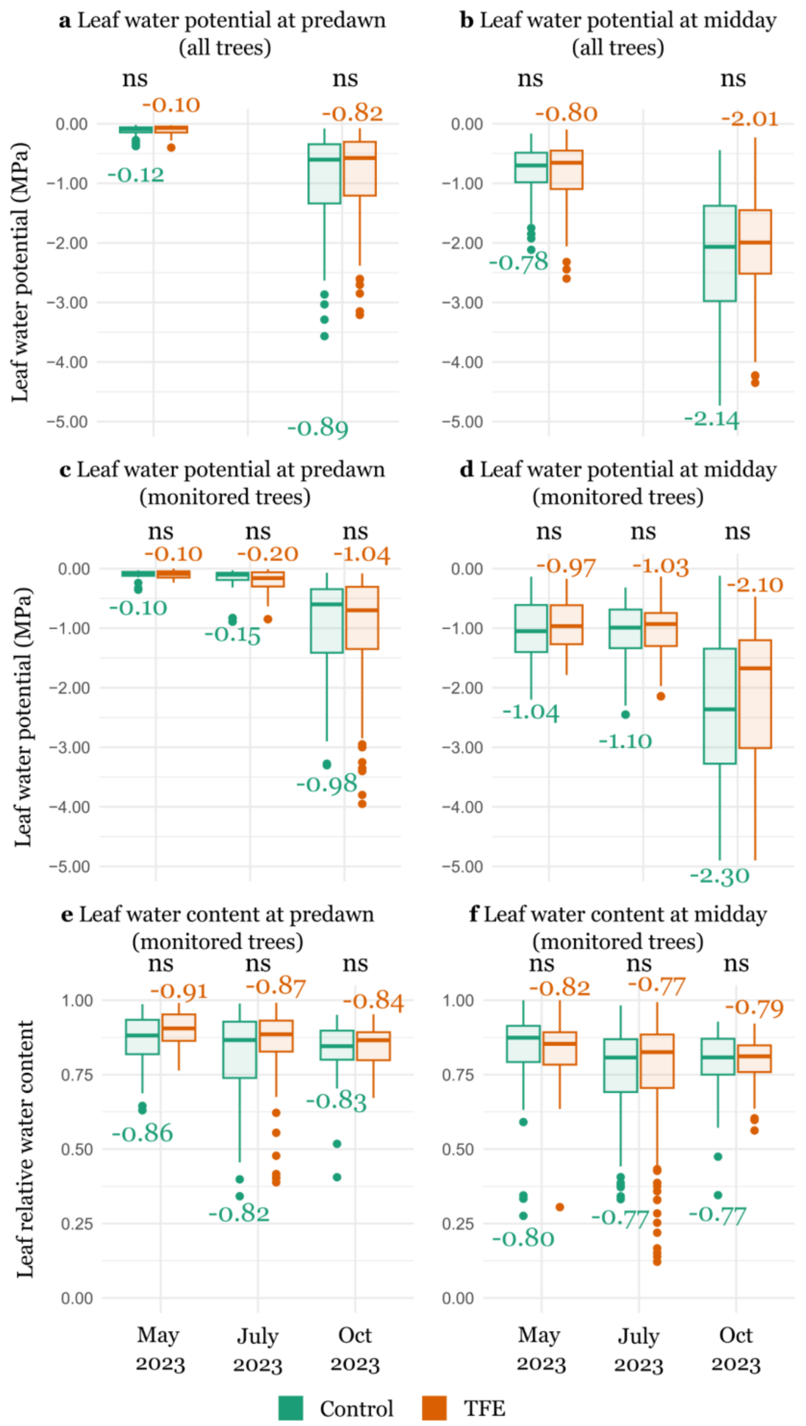
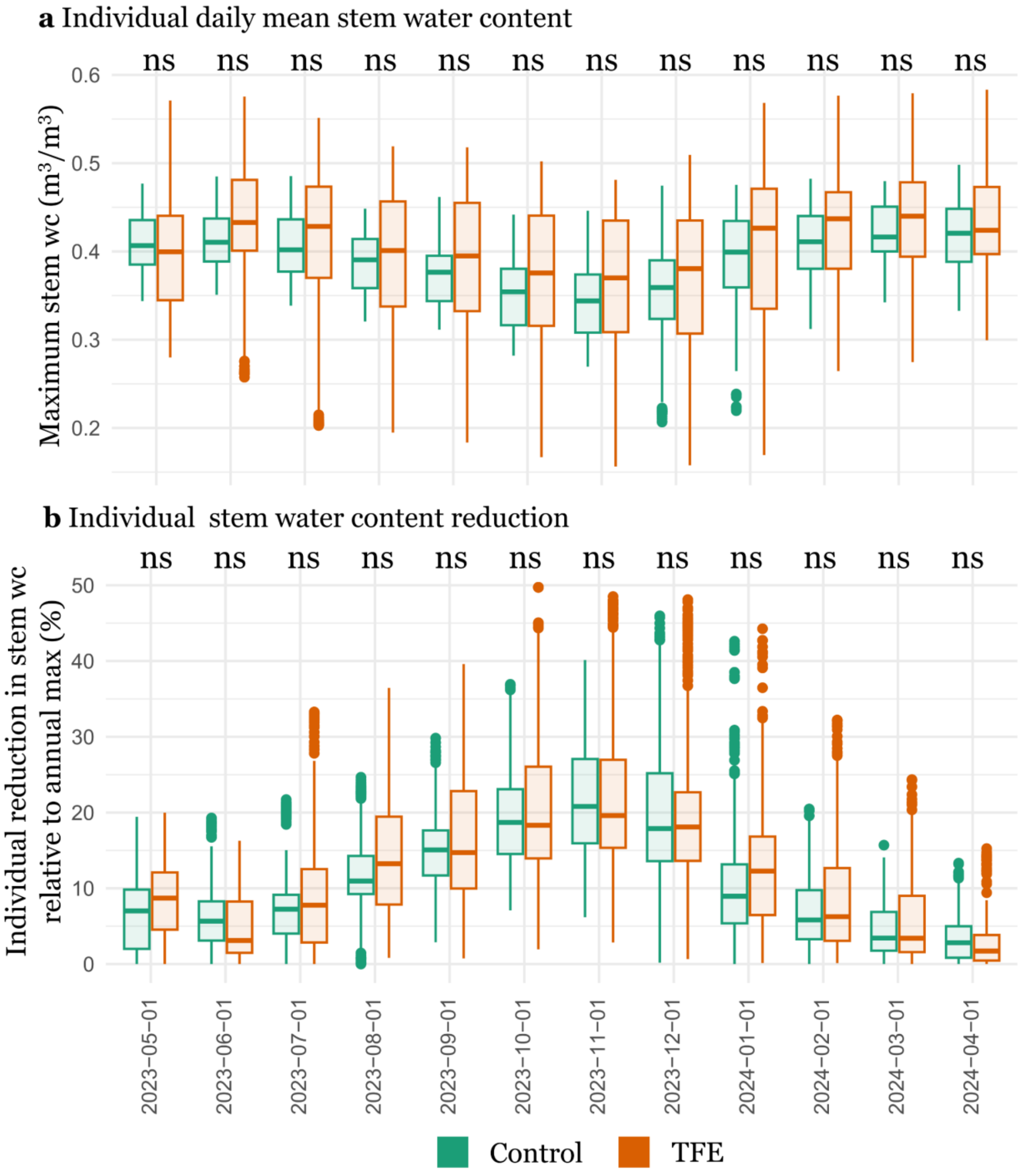


Figure S5. Stem water content



Stem water content differences between trees from the Through Fall Exclusion plot (TFE) and the Control plot. Daily maximum sap flow per unit sapwood represented for each plot and month (represented by the quantile 90%) (a); reduction in maximum daily sap flow from annual maxima (b) from May 2023 to December 2023. Statistical significance was tested by means of linear mixed models (see Methods). Signif. codes: '***': $P < 0.001$; '**': $P < 0.01$; '*': $P < 0.05$ 'ns': $P > 0.05$.

Figure S6. Branch water content

Branch volumetric water content sampled in the dry season (October 2023) in individuals from the Through Fall Exclusion plot (TFE) and from the Control plot. Statistical significance was tested by means of linear mixed models (see Methods). Signif. codes: '***': P < 0.001; '**': P < 0.01; '*': P < 0.05 'ns': P > 0.05.

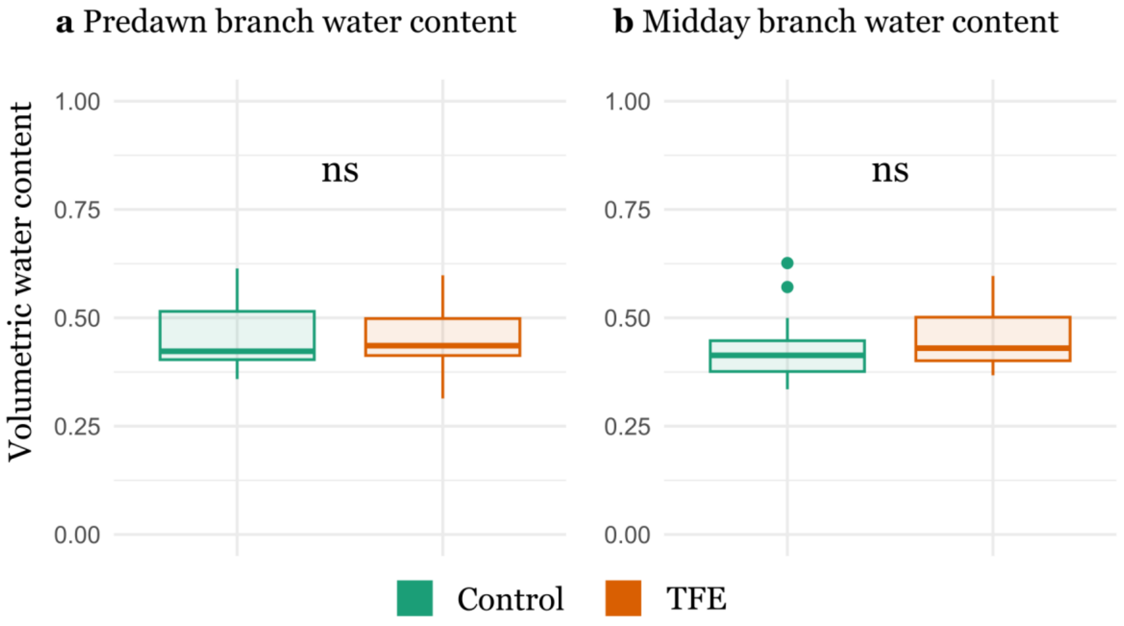


Figure S7. Meteorology

Meteorological data from the study site from May 2023 to April 2024 (period during which tree hydraulics were monitored).

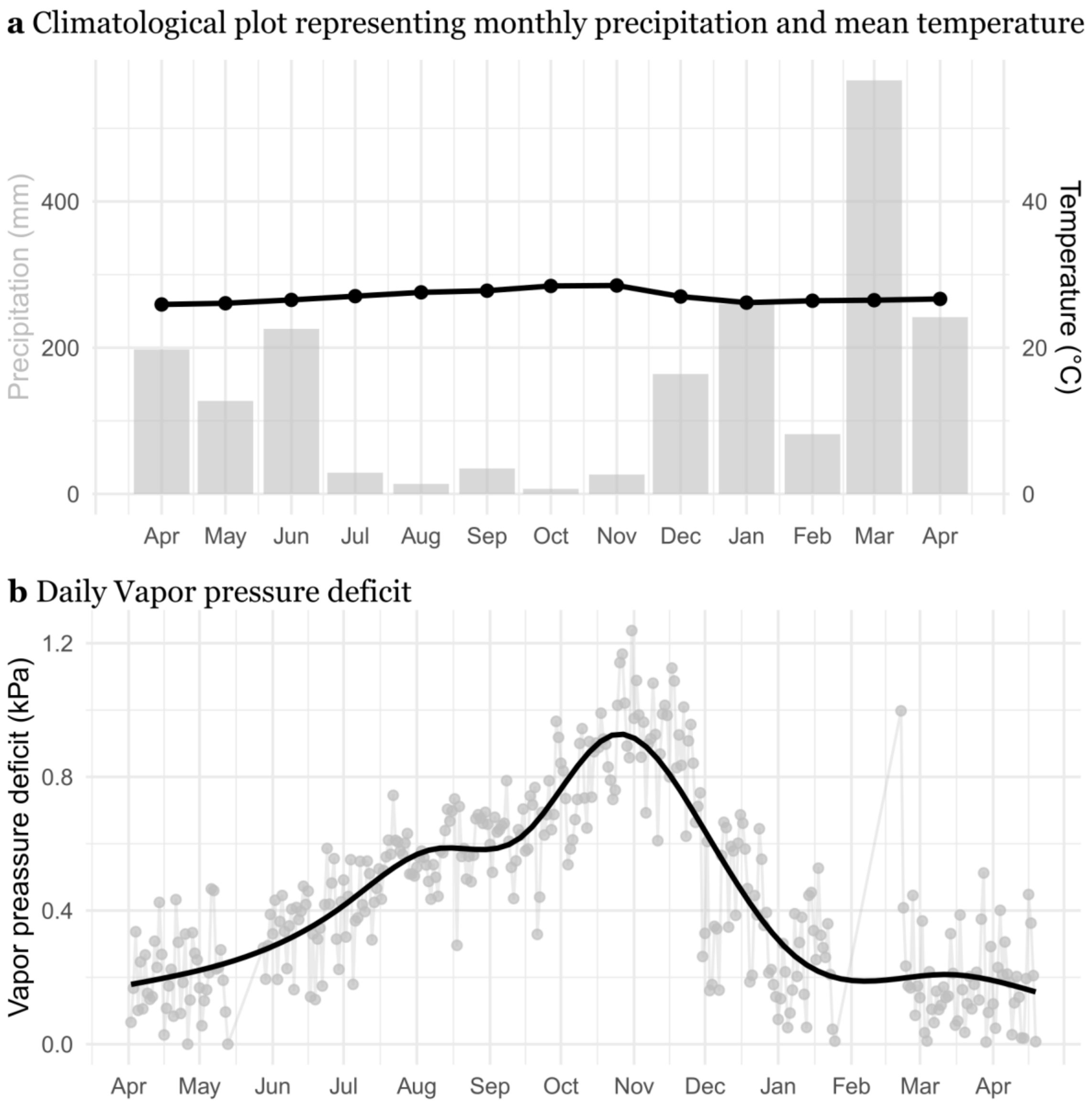


Figure S8. Biomass using dbh

Estimated above ground wood biomass for Control and Throughfall Exclusion (TFE) plots during the whole drought experiment period (from 2002 to 2023) calculated from diameter measured by measuring tapes. Tendency lines are reported using general additive models. Red dotted line represents the approximate time at which the TFE plot changed from transition to stabilization phase (i.e., stabilization of biomass). The two phases are also represented by background colour.

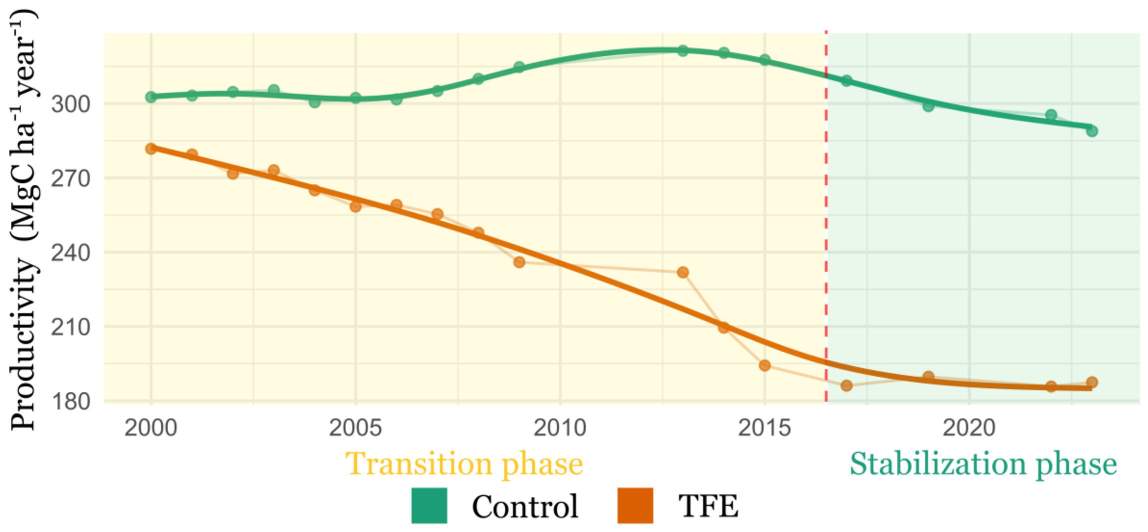


Figure S9. Soil water availability

Soil water availability estimated as the 95% quantile of the annual water content (mm) in the top 4m of soil for Control and Throughfall Exclusion (TFE) plots during the whole drought experiment period (from 2002 to 2023).

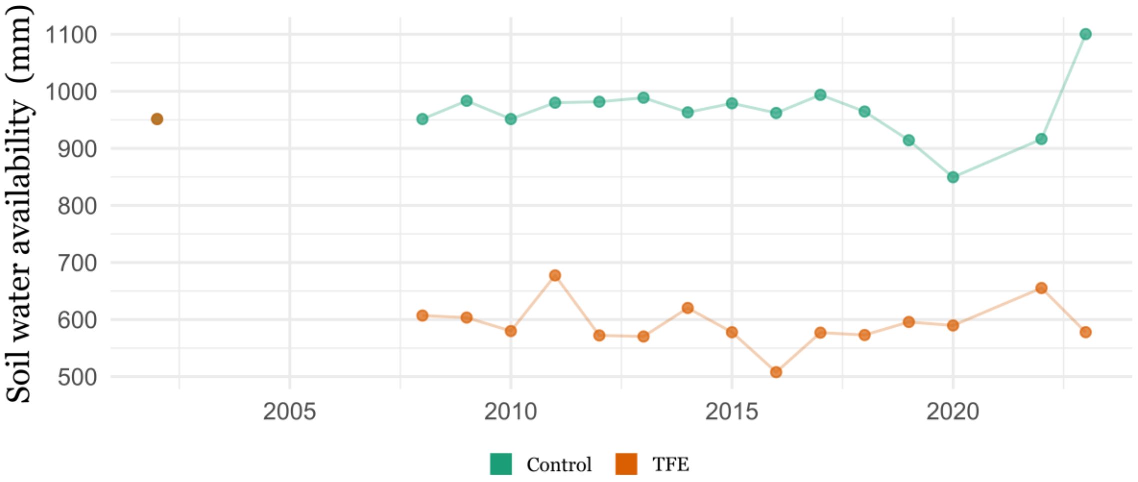


Table S1. Sampled individuals (Control)

ID	Size class	Plot	Species	DBH (cm)
Control_312	Intermediate	Control	Pouteria cladantha	28.65
Control_354	Intermediate	Control	Manilkara bidentata	51.41
Control_359	Intermediate	Control	Micropholis venulosa	34.70
Control_211	Intermediate	Control	Licania octandra	29.92
Control_216	Intermediate	Control	Vouacapoua americana	44.25
Control_262	Intermediate	Control	Eschweilera coriacea	40.11
Control_279	Intermediate	Control	Rinorea guianensis	17.19
Control_218	Intermediate	Control	Swartzia racemosa	29.44
Control_316	Large	Control	Swartzia racemosa	60.16
Control_259	Large	Control	Manilkara paraensis	77.35
Control_215	Large	Control	Pouteria cladantha	70.66
Control_308	Large	Control	Pseudopiptadenia suaveolens	87.22
Control_220	Large	Control	Goupia glabra	67.80
Control_313	Small	Control	Licania octandra	22.44
Control_315	Small	Control	Pouteria decorticans	17.83
Control_317	Small	Control	Vouacapoua americana	20.53
Control_357	Small	Control	Eschweilera grandiflora	15.92
Control_264	Small	Control	Micropholis venulosa	29.28
Control_249	Small	Control	Protium tenuifolium	12.41
Control_256	Small	Control	Pouteria decorticans	15.60
Control_322	Small	Control	Vouacapoua americana	26.42

Table S1. Sampled individuals (TFE)

ID	Size class	Plot	Species	DBH (cm)
TFE_267	Intermediate	TFE	Quararibea guianensis	63.18
TFE_205	Intermediate	TFE	Eschweilera decolorans	29.60
TFE_207	Intermediate	TFE	Swartzia racemosa	47.27
TFE_111	Intermediate	TFE	Manilkara bidentata	50.93
TFE_178	Intermediate	TFE	Manilkara bidentata	31.51
TFE_200	Intermediate	TFE	Protium tenuifolium	34.38
TFE_82	Intermediate	TFE	Erisma uncinatum	33.42
TFE_168	Intermediate	TFE	Geissospermum sericeum	37.24
TFE_217	Intermediate	TFE	Eschweilera coriacea	38.52
TFE_266	Large	TFE	Trattinnickia burserifolia	159.47
TFE_270	Large	TFE	Erisma uncinatum	70.98
TFE_119	Large	TFE	Vouacapoua americana	63.98
TFE_169	Large	TFE	Manilkara bidentata	58.57
TFE_211	Small	TFE	Licania kunthiana	29.28
TFE_116	Small	TFE	Pouteria ramiflora	24.83
TFE_121.1	Small	TFE	Erisma uncinatum	14.96
TFE_122.1	Small	TFE	Protium pilosissimum	11.46
TFE_78	Small	TFE	Hymenolobium flavum	
TFE_213	Small	TFE	Manilkara huberi	22.92
TFE_214.1	Small	TFE	Pouteria decorticans	10.50
TFE_214.3	Small	TFE	Micropholis venulosa	13.37

Table S2. ariance explained

Variance explained by diameter at the breast height (DBH) and genus for leaf water potential at midday and predawn (WP md, WP pd), maximum daily sap flow (Max. sap flow) and maximum daily stem water content (Max. stem wc) for the whole year and peak of the wet (May 2023) and dry (October 2023) season.

Response	Predictor	Variance explained
WP md (whole year)	DBH	0.01
WP md (whole year)	genus	0.1
WP md (wet season)	DBH	0.03
WP md (wet season)	genus	0.24
WP md (dry season)	DBH	0
WP md (dry season)	genus	0.27
WP pd (whole year)	DBH	0
WP pd (whole year)	genus	0.1
WP pd (wet season)	DBH	0.01
WP pd (wet season)	genus	0.02
WP pd (dry season)	DBH	0
WP pd (dry season)	genus	0.42
Max. sap flow (all year)	DBH	0
Max. sap flow (all year)	genus	0.28
Max. sap flow (wet season)	DBH	0
Max. sap flow (wet season)	genus	0.24
Max. sap flow (dry season)	DBH	0
Max. sap flow (dry season)	genus	0.57
Max. stem wc (all year)	DBH	0.01
Max. stem wc (all year)	genus	0.35
Max. stem wc (wet season)	DBH	0
Max. stem wc (wet season)	genus	0.31
Max. stem wc (dry season)	DBH	0
Max. stem wc (wet season)	genus	0.35