

1 **Quantification of hydraulic trait control on plant hydrodynamics and risk of hydraulic**
2 **failure within a demographic structured vegetation model in a tropical forest (FATES-**
3 **HYDRO V1.0)**

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25 **Abstract:** Vegetation plays a key role in the global carbon cycle and thus is an important
26 component within Earth system models (ESMs) that project future climate. Many ESMs are
27 adopting methods to resolve plant size and ecosystem disturbance history using vegetation
28 demographic models. These models make it feasible to conduct more realistic simulation of
29 processes that control vegetation dynamics. Meanwhile, increasing understanding of the processes
30 governing plant water use, and ecosystem responses to drought in particular, has led to the adoption
31 of dynamic plant water transport (i.e., hydrodynamic) schemes within ESMs. However, the impact
32 of plant hydraulic trait variation in trait-diverse tropical forests is understudied. In this study, we
33 report on a sensitivity analysis of an existing hydrodynamics (HYDRO) model that is updated and
34 incorporated into the Functionally Assembled Terrestrial Ecosystem simulator (FATES). The size
35 and canopy structured representation within FATES is able to simulate how plant size and
36 hydraulic traits affect vegetation dynamics and carbon/water fluxes. To better understand this new
37 model system and its functionality in tropical forest systems in particular, we conducted a global
38 parameter sensitivity analysis at Barro Colorado Island, Panama. We assembled 942 observations
39 of plant hydraulic traits on 306 tropical plant species for stomata, leaves, stems, and roots, and
40 determined the best-fit statistical distribution for each trait, which was used in model parameter
41 sampling to assess the parametric sensitivity. We showed that, for simulated leaf water potential
42 and loss of hydraulic conductivity across different plant organs, the four most important traits were
43 associated with xylem conduit taper (buffers increasing hydraulic resistance with tree height),
44 stomatal sensitivity to leaf water potential, maximum stem hydraulic conductivity, and the
45 partitioning of total hydraulic resistance above vs. belowground. Our analysis of individual
46 ensemble members revealed that trees at a high risk of hydraulic failure and potential tree mortality
47 generally have higher conduit taper, maximum xylem conductivity, stomatal sensitivity to leaf

48 water potential, and lower resistance to xylem embolism for stem and transporting roots. We
49 expect that our results will provide guidance on future modeling studies using plant hydrodynamic
50 models to predict the forest responses to droughts, and future field campaigns that aim to better
51 parameterize plant hydrodynamic models.

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1. Introduction

Tropical forests play a critical role in regulating regional and global climates (Bonan, 2008). Under ongoing and future climate change, they are subjected to substantial risks of climate extremes such as drought and heat waves (Mcdowell et al., 2018). Studies have already shown that tropical forests were experiencing elevated tree mortality rates due to mega droughts related to ENSO events. For example, the 2015–16 El Niño led to the death of an estimated 2.5 ± 0.3 billion stems in the Lower Tapajós river basin of the Amazon and the associated carbon loss had not yet been compensated by new plant growth three years after the event (Berenguer et al., 2021). Such extreme climate events are projected to increase in frequency and intensity under a warming future (Seneviratne et al., 2021). A statistical analysis based on the projection of 13 ESMs under a high greenhouse emission scenario showed that the frequency of extreme droughts as defined by rhizosphere soil moisture (occurring once every 50 years) could increase by a factor of nearly four and this increase would have a disproportionate impact on tropical forests (Xu et al., 2019). The high species diversity found in tropical forests may result in increased resilience to climate extremes, based on the demonstrated resilience of temperate forests in relationship to trait diversity (Anderegg et al., 2018). However, due to limited data to parameterize and constrain models for tropical forests, there is a large uncertainty in our predictive understanding of how tropical forests will respond to these climate extremes (Bonal et al., 2016). This tropical forest uncertainty is a key source of the global uncertainty in projections of land carbon fluxes and future climates (Arora et al., 2020).

75 Earth System Models (ESMs) have been developed to project future changes to the coupled
76 climate and biosphere system. Typically, ‘big leaf’ approximations of vegetation with no
77 explicit presentation of tree size and canopy structure have been used to predict the impact of
78 vegetation on carbon and water cycles. These models do not represent the fundamental
79 elements of vegetation dynamics including growth, mortality, competition, and their response
80 to disturbances. In the last decade, many ESMs have incorporated vegetation demographic
81 models (VDMs) that represent plant size, canopy structure and disturbance histories, with the
82 goal of better representing the competitive dynamics among different size classes of trees and
83 plant functional types in response to climate and disturbances (Fisher et al., 2018). Most of
84 these VDMs can differentiate plants’ light, water and carbon use strategies and can thus
85 represent some part of the functional diversity of tropical forests (Massoud et al., 2019; Koven
86 et al., 2020).

87 Following the ‘big leaf’ model, water limitation on plant gas exchange in these VDMs is
88 generally calculated based on three factors: 1) soil water potential; 2) root distribution; and 3)
89 water potential for stomata openness and closure, all of which differ by plant functional types
90 (Koven et al., 2020). While these soil-moisture-dependent water limitation functions are able
91 to capture trait diversity in leaf-level stomatal behaviors, they fail to capture plant functional
92 diversity in many other observable plant hydraulic traits, such as xylem capacitance, water
93 potentials for loss of xylem hydraulic conductivity, stem hydraulic safety margin, and turgor
94 loss point (Hochberg et al., 2018). Many studies have shown that plant hydraulic traits play an
95 important role in plant responses to droughts (Su et al., 2022; Anderegg et al., 2016), which
96 could shape the landscape distribution of plant functional types (Kunert et al., 2021). In view
97 of this limitation, plant hydrodynamic models have been developed with the aim of better

98 simulating forest response to droughts (Powell et al., 2018; Christoffersen et al., 2016; Xu et
99 al., 2016; Kennedy et al., 2019; Mcdowell et al., 2013). These models not only incorporate
100 hydraulic functional diversity, but also mechanistically simulate the risk of plant mortality due
101 to hydraulic functional failure, as a result of an inability to move water in the xylem due to
102 embolism in conduits (Hammond et al., 2019).

103 One key challenge for these plant hydrodynamic models is that they have many more
104 parameters than simple water limitation functions based on soil water potentials and thus
105 inherently possess more uncertainty in the model parameterization and subsequent simulations.
106 In this study, we describe the implementation of a hydrodynamic scheme within DOE-
107 sponsored functionally assembled terrestrial ecosystem simulator (FATES) (Koven et al.
108 2020), and assess this new configuration with two goals: 1) quantify the parametric sensitivity
109 of different hydraulic traits in determining plant hydrodynamics; and 2) identify key hydraulic
110 traits that are important for predicting the risk of mortality due to hydraulic failure. We expect
111 that our results will provide guidance on model parameterization for future modeling studies
112 using plant hydrodynamic models to predict tropical forest response to droughts, and future
113 field campaigns that aim to collect observational data that can be used to better parameterize
114 and benchmark plant hydrodynamic models.

115 **2. Methodology**

116 **2.1. Model description**

117 We use FATES, a VDM that is coupled within the Energy Exascale Earth System Model
118 (E3SM) (Caldwell et al., 2019). FATES represents size-structured groups of plants (cohorts)
119 and successional trajectory-based patches using the ecosystem demography approach (Fisher
120 et al., 2015; Moorcroft et al., 2001). FATES simulates growth by integrating photosynthesis

121 across different leaf layers for each cohort. FATES allocates this photosynthate to different
122 tissues including leaves, fine and coarse roots, and stem, based on the allometry of different
123 plant functional types, as well as a carbon storage pool (Fisher et al., 2015). Mortality within
124 FATES is simulated by several mechanisms, including carbon starvation caused by depletion
125 of the storage pool, hydraulic function failure, as well as impact mortality during disturbance,
126 fire, logging, freezing, age-related and ‘background’ constant turnover (Fisher et al., 2015;
127 Huang et al., 2020; Fisher et al., 2010; Needham et al., 2020).

128 **2.1.1. Plant Hydrodynamics**

129 The default (non-hydrodynamic) FATES model contains a simplistic algorithm that
130 approximates plant hydraulic failure thresholds based on soil water potential. An important
131 feature of the plant hydrodynamic scheme (HYDRO), which explicitly simulates water flow
132 from the soil through leaves to the atmosphere, is that it enables direct representation of percent
133 loss of conductance as a predictor of hydraulic failure mortality rates. FATES-HYDRO is
134 based on the hydrodynamic model implemented in the Traits-based Forest Simulator (TFS)
135 (Christoffersen et al., 2016) and the features most relevant to the present analysis are
136 summarized below. The model approximates water transport in a single vertical dimension,
137 approximating the canopy as a single leaf layer at the top of a beam, according to the Shinozaki
138 pipe model (Shinozaki et al., 1964) in which the hydraulic path length from the trunk base to
139 each leaf is assumed constant. Following the ‘porous media’ approach, the model simulates
140 the water transport across four main organs (leaves, stem- trunk/branches, transporting roots,
141 and absorbing roots) and different rhizosphere shells (Fig. 1). Resistors connect the different
142 compartments.

143 The water flow is calculated based on water pressure gradients across different
 144 compartments (rhizosphere, absorbing roots, transporting roots, stem, and leaf). Specifically,
 145 flow between compartment i and $i + 1$ (Q_i) is given by,

$$146 \quad Q_i = -K_i \Delta h_i, \quad (1)$$

147 where K_i is the total conductance ($\text{kg MPa}^{-1} \text{s}^{-1}$) at the boundary of compartments i and $i + 1$
 148 and Δh_i is the total matric potential difference between the compartments,

$$149 \quad \Delta h_i = \rho_w g (z_i - z_{i+1}) + (\psi_i - \psi_{i+1}), \quad (2)$$

150 where z_i is compartment elevation difference above (+) or below (-) the soil surface (m), ρ_w
 151 is the density of water (10^3 kg m^{-3}), g is acceleration due to gravity (9.8 m s^{-2}), and ψ_i is
 152 tissue or soil matric water potential (MPa). K_i is treated here as the product of a maximum
 153 boundary conductance between compartments i and $i + 1$ ($K_{max,i}$), and the fractional
 154 maximum hydraulic conductance of the upstream compartments (FMC_i or FMC_{i+1}), which is
 155 a function of the tissue water potential as follows,

$$156 \quad FMC_i = \left[1 + \left(\frac{\psi_i}{P_{50,x}} \right)^{a_x} \right]^{-1}, \quad (3)$$

157 where ψ_i is the compartmental water potential, $P_{50,x}$ is the water potential at 50% loss of
 158 maximum conductivity for different plant tissues (absorbing root, transporting root, stem), a_x
 159 is the corresponding vulnerability curve shape parameter, with a larger number indicating a
 160 steeper reduction of conductivity in response to more negative water potentials (Choat et al.,
 161 2012). The maximum percentage loss of conductivity (PLC) across different organs [i.e., PLC_i
 162 $= 100 (1 - FMC_i)$] is used to measure the risk of tree mortality (M_{hf}) resulting from hydraulic
 163 failure as follows,

$$164 \quad M_{hf} = M_{hf,base} \frac{\max(0, PLC_{max,organ} - PLC_c)}{100 - PLC_c}, \quad (4)$$

165 where PLC_c is the critical percentage loss of conductivity with risk of mortality, $PLC_{max,organ}$
 166 is the maximum percentage loss of conductivity across different organs, $M_{hf,base}$ is the
 167 baseline mortality rate [fraction/year] when percentage loss of conductivity exceeds PLC_c . In
 168 this version of model, we assume that xylem cavitation can fully recover as long as the trees
 169 do not die.

170 The previous version of this model (TFS-Hydro) presented water in terms of relative water
 171 content (RWC; g H₂O g⁻¹ H₂O at saturation) in line with most empirical work on plant water
 172 relations. While the underlying equations remain unchanged, here we present water in terms
 173 of volumetric water content (θ ; m³ H₂O m⁻³ plant tissue), since this what is accounted by the
 174 model and is consistent with what is tracked in the soil as well. The two quantities are related
 175 via the equation $RWC = \theta / \theta_{sat}$, where θ_{sat} indicates saturated volumetric water content. The
 176 water potential for tissue x [ψ_x] is related to θ_x (the PV curve) following three stages of water
 177 tissue drainage as follows (Tyree and Yang, 1990; Bartlett et al., 2012),

$$178 \quad \psi_x = \begin{cases} \psi_{0,x} + m_{cap} \left(\frac{\theta_x}{\theta_{sat,x}} - 1 \right) & \theta_{ft} < \theta_x \leq \theta_{sat,x} \\ \psi_{sol}(\theta_x) + \psi_p(\theta_x) & \theta_{tlp,x} < \theta_x \leq \theta_{ft,x} \\ \psi_{sol}(\theta_x) & \theta_{r,x} < \theta_x \leq \theta_{tlp,x} \end{cases} \quad (5)$$

179 Stage one applies to stem and roots only and represents the water draw from capillary reserves
 180 (embolized conduits or airspaces in wood) when wood water content is in between full turgor
 181 ($\theta_{ft} = RWC_{ft} \theta_{sat,x}$) and saturation ($\theta_{sat,x}$) and only represents a small fraction of the total
 182 PV curve. It is linear with constant slope $m_{cap} = 11.3 \text{ MPa m}^3 \text{ m}^{-3}$ and $RWC_{ft} = 0.958$ as
 183 estimated from sapwood PV curves on 28 tropical and subtropical species (Christoffersen et
 184 al. 2016). RWC_{ft} is assumed to be 1.0 in leaves. Xylem water potential is assumed zero at full
 185 saturation. The second stage is between full turgor ($\theta_{ft,x}$) and the turgor loss point ($\theta_{tlp,x}$),

186 when the xylem water potential is in balance with solute ($\psi_{sol}[\theta_x]$) and pressure water
 187 potential ($\psi_p[\theta_x]$) of living cells. The third stage is after the turgor loss point ($\theta_{tlp,x}$), but
 188 above the point of residual water content ($\theta_{r,x} = RWC_{r,x} \theta_{sat,x}$) where the water potential is
 189 only a function of the solute water potential. $RWC_{r,x}$ is synonymous with the apoplastic
 190 fraction (Bartlett et al. 2012).

191 The solute water potential is given as,

$$192 \quad \psi_{sol}[\theta_x] = \frac{\pi_0(\theta_{sat,x}RWC_{ft} - \theta_{r,x})}{(\theta_x - \theta_{r,x})}, \quad (6)$$

193 where π_0 is the tissue osmotic potential at full turgor. The pressure potential is calculated as
 194 follows,

$$195 \quad \psi_p[\theta_x] = -|\pi_0| + \varepsilon \frac{(\theta_x - \theta_{sat,x}RWC_{ft})}{(\theta_{sat,x}RWC_{ft} - \theta_{r,x})}, \quad (7)$$

196 where ε is the bulk elastic modulus (MPa).

197 The realized conductivity of the above ground portion of the plant per unit of leaf area (
 198 $K_{l,max,tree,ag}$) is calculated based on xylem hydraulic conductivity at petiole ($k_{s,max,petiole}$),
 199 aboveground tree height (H, meters), and a xylem taper factor (X_{tap}) as follows,

$$200 \quad K_{l,max,tree,ag} = \frac{k_{s,max,petiole}}{H \left(\frac{A_l}{A_s}\right)} X_{tap}, \quad (8)$$

201 where $k_{s,max,petiole}$ is scaled from the xylem conductivity measured from the branch ($k_{s,max}$)
 202 (Christoffersen et al., 2016). $\frac{A_l}{A_s}$ [i.e., la2sa in Table 1] is the ratio of leaf area (A_l) to sapwood
 203 area (A_s). X_{tap} is the xylem taper factor representing the ratio of aboveground xylem
 204 conductance with taper to that without, which for intermediate values of conduit taper (p_taper
 205 = 1/6; see below) represents a factor increase in total conductance of 23–50 for trees of heights
 206 10–30 meters (Christoffersen et al., 2016). Savage et al. (2010) highlighted how opposing

207 selective forces will both increase hydraulic conductance by the tapering of conduit radii
 208 ($p_taper > 0$) while at the same time protect against embolism by minimizing conduit taper
 209 (no taper implies $p_taper = 0$). They defined p_taper as the exponent on an external branching
 210 parameter (2 daughter branches per parent branch in their model) that sets the degree of internal
 211 branching of xylem conduits (and thus the tapering of conduit radii as well) and, using a fractal
 212 network model, derived an effective exponent q that describes how aboveground conductance
 213 increases with tree size. q is a monotonically increasing and saturating function of the taper
 214 exponent p (see Fig 2b of Savage et al. 2010); we used this relationship to estimate q , and thus
 215 X_{tap} in eq. (8) as

$$216 \quad X_{tap} = \left[\frac{r_{base}}{r_{petiole}} \right]^{q_{tap} - q_{notap}}, \quad (9)$$

217 where r_{base} and $r_{petiole}$ are the trunk and petiole radii, respectively. The ratio $r_{base}/r_{petiole}$ is
 218 related to tree height following the fractal tree model of Savage et al. (2010) (see equations
 219 S12-S13 in Christoffersen et al. 2016).

220 Eq. (8) only gives the aboveground component of whole-plant conductance. In the
 221 absence of a simple first-principles approach to estimating the belowground component, we
 222 estimate the total tree maximum conductance (above- and belowground components) as

$$223 \quad K_{max,tree,total} = R_{frac,stem} K_{max,tree,ag}, \quad (10)$$

224 where $R_{frac,stem}$ is the fraction of total resistance that is aboveground.

225 Stomatal conductance [g_s , $\mu\text{mol m}^{-2} \text{s}^{-1}$] is simulated through a modified Ball-Berry
 226 equation,

$$227 \quad g_s = g_0 + g_1 \frac{A_n}{C_s/P_{atm}} h_s, \quad (11)$$

228 where g_1 is the stomatal conductance slope in response to environmental condition changes,
 229 g_0 is the minimum (cuticular) stomatal conductance ($\mu\text{mol m}^{-2} \text{s}^{-1}$), C_s is the leaf surface CO_2
 230 partial pressure (Pa), P_{atm} is the atmospheric pressure (Pa), h_s is the leaf surface humidity,
 231 and A_n is leaf net photosynthesis rate ($\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$). Stomatal conductance (i.e.,
 232 both g_0 and g_1) is further modified by a plant water stress factor, β , calculated as

$$233 \quad \beta = \left[1 - \left(\frac{\psi_{\text{leaf}}}{P_{50,gs}} \right)^{a_{gs}} \right]^{-1}, \quad (12)$$

234 where ψ_{leaf} is the leaf water potential, $P_{50,gs}$ is leaf water potential at 50% loss of maximum
 235 stomatal conductance, and a_{gs} is the stomatal vulnerability shape parameter.

236 The total fine root surface area affects the amount of water a plant can take up through its
 237 influence on rhizosphere conductance and is determined by both the specific root length (srl)
 238 and absorbing root radius (rs_2). Specifically, the model has a specified number of soil shells
 239 (5 in this study) around fine root surfaces and the conductance between soil shell $k+1$ and k ,
 240 $K_{\text{shell},k}$, is calculated as,

$$241 \quad K_{\text{shell},k} = K_s \frac{\pi l_{\text{aroot,common}}}{\ln(r_{k+1}/r_k)}, \quad (13)$$

242 where r_k is the mean radi of k th shell, $l_{\text{aroot,common}}$ is the total length of absorbing roots
 243 calculated as a product of total fine root biomass and specific root length (srl). K_s is set to be
 244 the conductance for soil (K_{soil}) when $k > 1$. For $k = 1$,

$$245 \quad K_s = \frac{1}{\frac{1}{K_{\text{soil}}} + \frac{1}{K_{\text{root,soil}}}}, \quad (14)$$

246 where $K_{\text{root,soil}}$ is the conductance between fine root surface and soil. An update to the TFS-
 247 Hydro approach is to make this conductance direction-specific, in view that water loss rate
 248 from root could be substantially lower than water uptake rate either through osmotic regulation
 249 (Dichio et al., 2006) or by lacunae caused by rupture of cortical cells (North and Nobel, 1992)

250 during drought. It is determined by either the maximum uptake of water per unit of absorbing
251 root surface area ($k_{r1,max}$, $\text{kg m}^{-1} \text{s}^{-1} \text{MPa}^{-1}$) when root water potential is more negative than
252 adjacent rhizosphere soil water potential, or the maximum root water loss rate per unit surface
253 area ($k_{r2,max}$, $\text{kg m}^{-1} \text{s}^{-1} \text{MPa}^{-1}$) when rhizosphere water potential becomes more negative than
254 root water potential, which may occur, for example, in frozen soils or in very dry soil layers
255 (Schmidhalter, 1997).

256 The plant hydrodynamic representation and numerical solver scheme within FATES-
257 HYDRO follows the 1-D solver laid out by Christoffersen et al. (2016), which is the default
258 solver in FATES-HYDRO and used in this study. The model also has an option of a 2-D solver,
259 which is slower and detailed by Fang et al. (2022) and Lambert et al. (2022). The equations
260 are solved for tissue water content at a 30 minutes time step. We made a few modifications to
261 accommodate multiple soil layers and improve the numerical stability. First, to accommodate
262 the multiple-soil layers, we sequentially solve the Richards' equation for each individual soil
263 layer, with each layer-specific solution proportional to each layer's contribution to the total
264 root-soil conductance. Second, to improve the numerical stability, we now linearly interpolate
265 the pressure/volume curve beyond the residual and saturated tissue water content to avoid the
266 rare cases of overshooting in the numerical scheme under very dry or wet conditions. See the
267 Supplementary Information [HYDRO_DESCRIPTION.pdf] for further details of the
268 implementation.

269 **2.1.2. Non-hydrodynamics processes**

270 FATES-HYDRO can be coupled to different host land models (HLMs) including the
271 E3SM land model (ELM) (Caldwell et al., 2019) or the Community Terrestrial Systems Model
272 (CTSM) (Lawrence et al., 2019). In this study, the model is coupled to ELM. In this section,

273 we layout the key non-hydrodynamic processes in the FATES or the ELM for a better
274 understanding of parameter importance in the results.

275 Canopy radiative transfer is calculated using a multi-layer scheme based on the iterative
276 Norman radiation scheme (Norman, 1979). Leaf and stem area is binned into a matrix of
277 canopy layer, leaf layer and plant functional types. Reflectance, absorption, and transmittance
278 are calculated for each leaf layer. Between canopy layers, light streams are averaged between
279 plant functional types (PFTs), such that all PFTs in understory layers receive equal radiation
280 on their top leaf layer. Fractional absorption of visible and near infra-red light is calculated
281 separately for direct and diffuse light. For the direct stream, transmitted and reflected light is
282 converted into diffuse fluxes. In FATES, the absorbed PAR is used to calculate photosynthesis
283 rates for each of the canopy layer x leaf layer x PFT bins, after which rates across layers are
284 re-aggregated into cohort level carbon fluxes. Please see the Supplementary file in Fisher et al.
285 (2015) for details.

286 The energy balance is handled by the host land model. In this study, it is based on the land
287 component of DOE's Exascale Energy Earth System Model (E3SM). The E3SM land model
288 (ELM) is based on the Community Land Model 4.5 (Oleson, 2013). Specifically, in ELM, the
289 average canopy temperature is calculated based on the energy balance of latent heat, sensible
290 heat, and absorbed radiation as determined by the radiative transfer model. The latent heat is
291 determined by the transpiration, which is determined by the vapor pressure deficit from inside
292 of leaf to the air, canopy stomatal conductance, and boundary layer conductance. FATES
293 calculated mean canopy stomatal conductance averaged across different cohorts, which is fed
294 to ELM to calculate the energy balance. The Newton-Raphson numerical scheme is used to
295 solve for the canopy temperature.

296 All aspects of soil water balance (infiltration, water transfer among soil layers, and
297 drainage) happen at the ‘column’ scale at 30-min time steps and are handled within the Host
298 Land Model (see Oleson et al. 2013 for a detailed description of hydrology in CLM4.5, the
299 parent model of ELM). FATES-HYDRO handles soil water operations at the patch and cohort
300 scales. It simulates root water uptake and changes in plant water potential from roots to leaves
301 based on current time step transpiration. The belowground conductance for each soil layer is
302 weighted by root biomass with an exponential vertical distribution. Sections 2 and 3 in the
303 Supplement of this manuscript provide full details on boundary conditions, sequence of
304 operations among HYDRO and the HLM, downscaling of soil moisture to rhizosphere shells,
305 and downscaling of transpiration from the patch to individual scale.

306 **2.2. Sensitivity analysis**

307 We identified 35 parameters for the FATES-HYDRO model to conduct the parametric
308 sensitivity analysis (Table 1). To estimate the parameter distributions, we started with
309 published meta-analyses (Christoffersen et al., 2016; Choat et al., 2012; Bartlett et al., 2012;
310 Bartlett et al., 2014; Bartlett et al., 2016; Klein, 2014) and supplemented them with select new
311 data from individual studies. Focal data were tissue- or individual-level hydraulic traits
312 spanning water transport and embolism resistance, tissue water storage and retention (PV curve
313 traits), hydraulic architecture (i.e., leaf area to sapwood area ratio), stomatal responses to
314 dehydration, and fine root traits (Table 1). For each dataset, we standardized taxonomic names
315 using the TNRS package in R (Boyle et al., 2013). This allowed us to join datasets together
316 based on species, averaging multiple observations per species if necessary, resulting in a
317 species-specific sparse matrix of all hydraulic traits for all databases and individual studies that

318 we compiled. This pantropical hydraulic trait dataset is included in the Supporting Information
319 [traits_master_trop.csv].

320
321 This trait dataset consisted of anywhere from 1 - 323 observations for each trait, where
322 each observation corresponds to a different species (multiple observations for the same species
323 are first averaged; see above). Before fitting distributions to these data, some traits were first
324 transformed to be positive (e.g., P50) or normalized within [0, 1] when upper and lower bounds
325 were well-defined (Table 1). Then, for each trait separately, we used the fitdistr package in R
326 to estimate best-fit parameters for uniform, beta, normal, lognormal, and gamma statistical
327 distributions in order to estimate central tendencies and spread for each trait. The distribution
328 with the largest log likelihood and best-fit parameters are given in Table 1. Each model
329 simulation consisted of a single PFT: all trees (across all cohort sizes and patches) had the
330 same traits.

331 We augmented observations with extratropical data to increase sample size for traits with
332 less than three tropics-specific observations. When trait data observations were not present, we
333 used a uniform distribution bounded on our best estimate of the theoretical range (Table 1).
334 As there is limited data on roots, we used the same distribution as that for branches if data were
335 lacking. Because our goal is to understand the model behaviors as determined by different
336 hydraulic traits, we assumed independence among traits. As we focused on the hydraulic traits
337 in this study, we used non-hydraulic trait values based on an optimal set of parameters that best
338 fit observed water and carbon fluxes in a set of FATES simulations run without hydrodynamics
339 (Koven et al., 2020).

340 We used the Fourier Amplitude Sensitivity Test (FAST) to assess the relative importance
341 of parameters in determining the variance of model outputs (Xu and Gertner, 2011a). The main
342 idea of FAST is to assign periodic signals in the sampled parameter values and use Fourier
343 transformation to identify the signals in the outputs. Sampled parameter values are based on
344 Latin hypercube sampling from the fitted statistical distributions (see previous section for more
345 details). We ran 1000 ensemble simulations of the FATES-Hydro to derive model outputs of
346 water potential and fraction of maximum conductivity. For each ensemble simulation, each
347 plant hydraulic trait was assigned with a random draw from each trait's distribution, and the
348 samples for different traits are randomly combined to sample the observed plant hydraulic trait
349 space for sensitivity analysis.

350 We used the Uncertainty Analysis and Sensitivity Analysis (UASA) tool
351 (<https://sites.google.com/site/xuchongang/uasatoolbox>) to estimate the parametric sensitivity
352 index, which is calculated based on the ratio of the partial variance in the model output
353 attributed to a specific parameter to the total variables in the model output. For details, please
354 refer to Xu and Gertner (2011a). We ran the model with 1000 ensemble members, in view that
355 an order of 100 times effective important number of parameters, which we estimate to be ~10,
356 is needed to achieve reasonable precision (Xu and Gertner, 2011b).

357 **2.3. Study area**

358 In this study, we used Barro Colorado Island (BCI), Panama, as our test site to evaluate
359 model behavior. We chose BCI because it has moderately strong dry and wet seasons that
360 allow us to assess the hydrodynamics under different levels of water availability. Moreover,
361 extensive field campaigns in recent years have provided comprehensive data needed for model

362 parameterization, initialization and climate drivers. Finally, we also leverage prior FATES
363 studies of non-hydraulic parameters at BCI (Koven et al., 2020).

364 BCI has an annual mean temperature of 26.3°C and an annual mean precipitation of 2656
365 mm with a strong seasonal precipitation signal. The dry season lasts from January to April,
366 with a mean precipitation of 228mm, while the wet season lasts from May-December with a
367 mean precipitation of 2428mm (Paton, 2020). In this study, we used hourly in-situ climate data
368 from 2008-2016 to drive the model. To run the model to equilibrium (in terms of soil moisture
369 content) takes 5-6 years, thus we choose February of 2016 as the target for analysis of dry
370 season hydrodynamics and August of 2016 as the target for analysis of wet season
371 hydrodynamics.

372 **2.4. Model setup**

373 In this study, as our focus is on the plant hydrodynamics, we used the static stand structure
374 mode of FATES that turns off the processes of competition, growth and mortality, to instead
375 hold the ecosystem structure constant. This reduced-complexity configuration (Fisher and
376 Koven, 2020) thus exercises only the primarily fast-timescale-processes of photosynthesis,
377 transpiration, water transport, and plant hydrodynamics (i.e., change in hydraulic conductivity,
378 water storage, and water potentials in plant tissues). By using static stand structure mode, as in
379 Chitra-Tarak et al. (2021), we isolate hydraulic trait controls on simulated hydrodynamics and
380 avoid confounding, and potentially biased, feedbacks from resulting changes in forest
381 structure. Using static stand structure mode also means that we do not need to spin up
382 vegetation state, thus reducing the simulation time. The forest stand structure, consisting of
383 tree size and composition for each patch, is initialized based on forest inventory data collected
384 in 2015 (<http://ctfs.si.edu/webatlas/datasets/bci/>). As the majority of species in BCI are

385 evergreen broad leaf trees, we ran the model with one PFT with different hydraulic traits (Table
386 1) to assess their impact on the hydrodynamically relevant outputs including water potentials
387 and fraction of maximum conductivity for different plant organs including absorbing root,
388 transporting root, stem, and leaves.

389 One key benefit of utilizing a hydrodynamic model is its ability to simulate the risk of
390 hydraulic failure by considering the loss of conductivity in various plant organs. As FATES
391 model was ran on the static stand mode, we did not specifically simulate the tree mortality
392 resulting from the hydraulic failure as shown in Eq. (4). Instead, we used the maximum of loss
393 of conductance across the continuum of plant nodes [i.e., $PLC_{max,organ}$ in eq. (4)] to assess
394 the hydraulic failure risk. If $PLC_{max,organ}$ reaches critical threshold PLC_c , which is set to
395 50% (Adams et al., 2017), trees are assumed to be faced with a high risk of mortality. Using
396 the ensemble simulations, we also aim to identify the most vulnerable plant organs and the
397 critical parameters that influence the likelihood of hydraulic failure. The HYDRO model only
398 considers the stem node (Fig. 1) without explicitly simulating the branch. In this analysis, we
399 calculated the branch vulnerability by using the PLC curve of xylem and the leaf water
400 potential, which approximates the water potential at the tip of the branch. The model does not
401 explicitly consider xylary or extraxylary resistance within and outside the leaf midrib.

402 FATES simulates the carbon and water fluxes for different size classes of trees. The forest
403 has 137 cohorts with diameters ranging from 10 cm to >2 meters and height ranging from 1 to
404 38 meters (see Fig. S1 for size distributions). Because large trees experience more fluctuations
405 in environmental conditions in the canopy and higher risk of mortality due to drought (Bennett
406 et al., 2015), we focused on hydrodynamic behaviors for large trees with diameter at breast

407 height (DBH) more than 60 cm; however, for comparison, we also derived the sensitivity for
408 smaller trees with DBH less than 60 cm.

409 3. Results

410 Our results showed that the simulated ranges across the ensemble of leaf water potential
411 (Fig. 2) and loss of conductivity (Fig. 3) are large. For leaf water potential of large trees with
412 diameter > 60 cm, the 95% percentile ranges are from -5 MPa to -0.5 MPa and -3 MPa to -0.5
413 MPa for February (dry) and August (wet) 2016, respectively. Correspondingly, the fraction of
414 maximum stem hydraulic conductivity is much higher during August compared to February
415 (Fig. 3); however, in both months, the modeled range spans almost the full range of between 0
416 and 1. For smaller trees with diameter less than 60 cm, our results show that smaller tree
417 experienced less negative water potential (Fig. S2 and Fig. 2) and lower loss of hydraulic
418 conductivity (Fig. S3 and Fig. 3).

419 Based on the FAST sensitivity indices (i.e., the variance in model output contributed by
420 different parameters), the key parameters that control the water potentials of different plant
421 organs (leaf, stem and root) for large trees (diameter >60 cm) include the taper exponent for
422 hydraulic conductivity (p_taper), the water potential leading to 50% loss of stomatal
423 conductance ($p50_gs$), maximum hydraulic conductivity for the stem ($kmax_node_stem$), and
424 the fraction of total hydraulic resistance in the above ground section ($rfrac_stem$), in decreasing
425 order (Fig. 4). For the fractional loss of conductivity, the most important parameter is the water
426 potential leading to 50% loss of hydraulic conductance (P_{50}) for the corresponding organs (Fig.
427 5). Other important parameters are similar to those for simulated water potentials. Notably, the
428 organ-specific P_{50} values are more important for the dry month (February) compared to the
429 wet month (August). For the wet month of August, p_taper is the dominant parameter

430 controlling the pre-dawn and midday loss of hydraulic conductivity, while organ-specific P_{50}
431 parameters are the second most important. For smaller trees with diameter less than 60 cm, the
432 corresponding parametric sensitivity patterns are similar to those of larger trees (Fig. S4 and
433 Fig. S5); however, compared to larger trees, the parametric sensitivity of p_taper for simulated
434 leaf water potential becomes lower for smaller trees (Fig. 4 and Fig. S4).

435 In terms of the risk of hydraulic failure, out of the 1000 ensemble members, ~40% of the
436 simulations for February and ~60% of simulation for August suggest that branches are the most
437 vulnerable plant organ, based on highest loss of conductivity across the continuum from root
438 to branch (Fig. 6). For the dry month of February, roots are at greater risk in comparison to the
439 wet season. If we consider the loss of conductivity more than 50% for February 2016 as a
440 threshold for a high risk of mortality (Adams et al., 2017), then 53% of ensemble simulations
441 reach this threshold. The key parameters affecting the risk of mortality, as measured by
442 percentage difference in parameter values for ensemble members reaching 50% loss of
443 conductivity or not, include the water potential leading to 50% loss of conductance for stomata
444 ($p50_gs$), stem ($p50_node_stem$), and transporting roots ($p50_node_root$), maximum
445 hydraulic conductivity of stem ($kmax_node_stem$), and the taper exponent (p_taper) (Fig. 7).
446 Ensemble members with high risk of mortality generally have a higher p_taper and
447 $kmax_node_stem$, less negative $p50_gs$, and less negative $p50$ for stem and transporting roots
448 (Fig. 8).

449 **4. Discussion**

450 Our analysis showed the importance of key plant hydraulic traits in simulating plant water
451 potential and risk of hydraulic failure. This analysis identifies these parameters as potential
452 targets of either model calibration or targeted measurement campaigns to achieve realistic

453 simulations. In our sensitivity analysis, the most influential parameter for both water potential
454 and loss of conductivity is the tapering of the radius of conduit with increasing plant height
455 (p_taper). As p_taper increases, the conduit radius increases from the top of the tree to its
456 base. According to Hagen-Poiseuille's equation, this increases the theoretical maximum total
457 conductance. Low values of p_taper thus limit the adverse effects of tree height by increasing
458 k_max along the whole continuum and reducing the soil-to-leaf water potential needed to
459 maintain transpiration. Our inference is that p_taper represents an overarching property of
460 plant architecture that influences the relative effect of each of the other traits related to
461 hydraulic safety and efficiency (Olson et al., 2021). The xylem architecture as determined by
462 p_taper parameter could change in response to age and development stages (Rodriguez-
463 Zaccaro et al., 2019), which is not considered in this study. Future studies evaluating the
464 importance of this change to hydraulic functions could be useful to guide size-dependent
465 growth and mortality. Another dimension of the hydraulic architecture with a critical role in
466 determining both water potential and loss of conductivity, though to a much lesser degree, was
467 the fraction of total tree resistance that is belowground (i.e., of the entire transporting and
468 absorbing root system; $1 - rfrac_stem$). Generally, a plant will match the growth of its trunk
469 and crown to maintain a degree of equilibrium in aboveground resistance as the distance water
470 needs to travel increases (Yang and Tyree, 1993). In this study, due to the lack of data on the
471 belowground resistance, we assigned a quite large range for this trait, which could be impacted
472 by many factors such as belowground root biomass, root network architecture, and interactions
473 between roots, fungi and bacteria (Poudel et al., 2021; Bhagat et al., 2021).

474 The second most sensitive parameter in determining loss of conductance was the leaf water
475 potential at 50% loss of stomatal conductance ($p50_gs$). This parameter controls the water loss

476 rate from leaves, with a less negative value providing protection from hydraulic failure during
477 water-limited periods. The *p50_gs* trait has been shown to play a key role in tree survival
478 during severe droughts (Breshears et al., 2009; Rowland et al., 2015). The ability to withstand
479 lower leaf water potentials is also a key indicator of sapling and seedling survival during
480 drought and determines species distribution across a moisture gradient (Kursar et al., 2009).
481 There may be a trade-off between drought tolerance (with a lower *p50_gs*) and drought
482 avoidance (a less negative *p50_gs* but with a high capacitance; the amount of water released
483 from reserves as leaf water potential declines), a crucial aspect in determining species drought
484 resistance (Pineda-Garcia et al., 2013). Additionally, loss of conductivity was sensitive to the
485 water potential at 50% loss of max conductivity within the stem (*p50_stem*) as it can largely
486 affect the whole plant conductance and thus the water supply to the leaves. *p50_stem*
487 negatively correlates with wood density and may be a marker of the trade-off between
488 hydraulic efficiency and safety within the stem (Chen et al., 2009; Manzoni et al., 2013);
489 however, other studies have shown that this trade-off is weak (Gleason et al., 2016). Liang et
490 al (2019) showed that the strength of this trade-off could be dependent on specie's drought
491 strategies.

492 Leaf water potential and loss of conductance were both sensitive to the maximum xylem
493 conductivity in the stem (*kmax_node_stem*). Higher maximum conductivity represents greater
494 xylem efficiency, which in the absence of drought or light limitations would result in greater
495 potential photosynthesis and less negative water potentials (Gleason et al., 2016). However,
496 xylem with higher *kmax_node_stem* could be more vulnerable to embolism as water potential
497 declines (Sperry and Love, 2015). In tropical rainforests, species with higher conductivity per
498 unit leaf area generally are less desiccation-tolerant, and thus exhibit higher mortality rates

499 (Kursar et al., 2009). Low *kmax_node_stem* along with high leaf-to-sapwood area ratio (*la2sa*)
500 also represents a vulnerability to reduced conductance which increases with height
501 (Christoffersen et al., 2016).

502 Traits with lower order of impacts on water potential modulate the amount of stored water
503 available during drought. The bulk modulus of elasticity in the root (*epsil_node_aroot*)
504 together with root saturated water content determines the amount of water available from
505 cellular storage between complete hydration and loss of turgor (Powell et al., 2017). This
506 represents the ability of the roots to continually supply water to the rest of the plant as drought
507 occurs. It also represents an investment in cellular structure, which may be an additional
508 indicator of adaptations with non-hydraulic origin. The residual water content in the stem
509 (*resid_node_stem*) determines the minimum amount of water xylem will hold and thus impact
510 the amount of water storage plant can use during drought as well (Bartlett et al. 2012). In this
511 study, we made the assumption that the traits are independent of each other, in order to
512 understand the hydrodynamic behaviors of FATES-HYDRO for different hydraulic traits
513 based on a single PFT. Understanding the trade-offs between these traits is crucial for
514 determining the competition among different PFTs. Future studies would greatly benefit from
515 assessing the significance of these trade-offs to predict vegetation dynamics under future
516 climate change.

517 In contrast to the majority of hydraulic traits in the model, conduit taper, the fraction of
518 total resistance belowground, and the leaf to sapwood area ratio are whole-plant hydraulic
519 traits. Our analysis highlights the importance of whole-plant hydraulic traits such as conduit
520 taper relative to tissue-level hydraulic traits for a range of plant hydraulic functions, including
521 whole-plant conductance and hydraulic failure risks. An important area for future work is to

522 better constrain and understand the consequences of intra- and interspecific variation in these
523 whole-plant hydraulic traits in tropical forests. Our choice of the range of variation in the
524 conduit taper exponent came from a study on temperate species, and was broad, encompassing
525 the entire range of observed values in that study (Savage et al. 2010). Further, we estimated
526 the effects of variation in the taper exponent on whole-plant conductance conditional on trees
527 following a simple set of optimality assumptions (space-filling, area-conserving, and self-
528 similar branching network structure). However, in practice, such assumptions are often not met
529 (Smith et al., 2014). Therefore, it is possible that the model sensitivity to xylem taper in terms
530 of whole-plant hydraulic function are overestimated. Nevertheless, our study highlights the
531 importance of better constraining this parameter as well as further experimentation with
532 alternate model structures to better account for non-optimal trees in tropical forests.

533 The sensitivity of vegetation to drought stress and hydraulic-failure-induced mortality is of
534 paramount importance for understanding how ecosystems may respond to shifting temperature
535 and rainfall patterns under a changing climate (McDowell et al., 2022). We recognize that
536 parametric sensitivity could be different for different sites depending on climate driver, soil
537 moisture and vegetation types. However, we expect the main parameter of importance could
538 be useful to guide model calibration to select the candidate parameters for different sites. As
539 understanding of plant hydrodynamics increases, linking model predictions to observable plant
540 traits has emerged as a promising means of constraining predictions of ecosystem resilience.
541 Such traits are challenging and costly to measure in the field and thus resources must be
542 directed carefully when planning measurement campaigns. The identified parameters in this
543 study could provide guidance on the limited measurement we could target in the field.

544 **5. Acknowledgment**

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550 Coming Century).

551 **6. CODE and Data Availability**

552 The FATES-HYDRO code is available from <https://doi.org/10.5281/zenodo.7686333>. The
553 traits data are in the supplementary file [traits_master_trop.csv].

554 **7. Supplement Information**

555 Three supplementary file are included. The HYDRO_DESCRIPTION.pdf provide the
556 summary of the hydrodynamic implementation that is different from Christoffersen et al.
557 (2016). The traits_master_trop.csv file include all the hydraulic traits we assembled for the
558 tropical region. The supplementary_figure.pdf provides additional figures for the main text.

559 **8. Author contribution**

560 CX and BC designed the sensitivity analysis experiments. BC collected the data and fitted
561 the trait distributions. CX conducted the analysis and drafted the manuscript. BC, CX, RF, RN
562 and CK designed the implementation of HYDRO codes. BC implemented the majority of
563 HYDRO codes with code improvement made by CX and RN. ZR conducted the ensemble
564 model simulations. MS provided the leaf cuticular conductance data. NM, CK and LK
565 provided guidance on the sensitivity analysis, code development and trait data synthesis. All
566 authors contributed to manuscript writing by providing edits and suggestions.

567 **9. Competing interests**

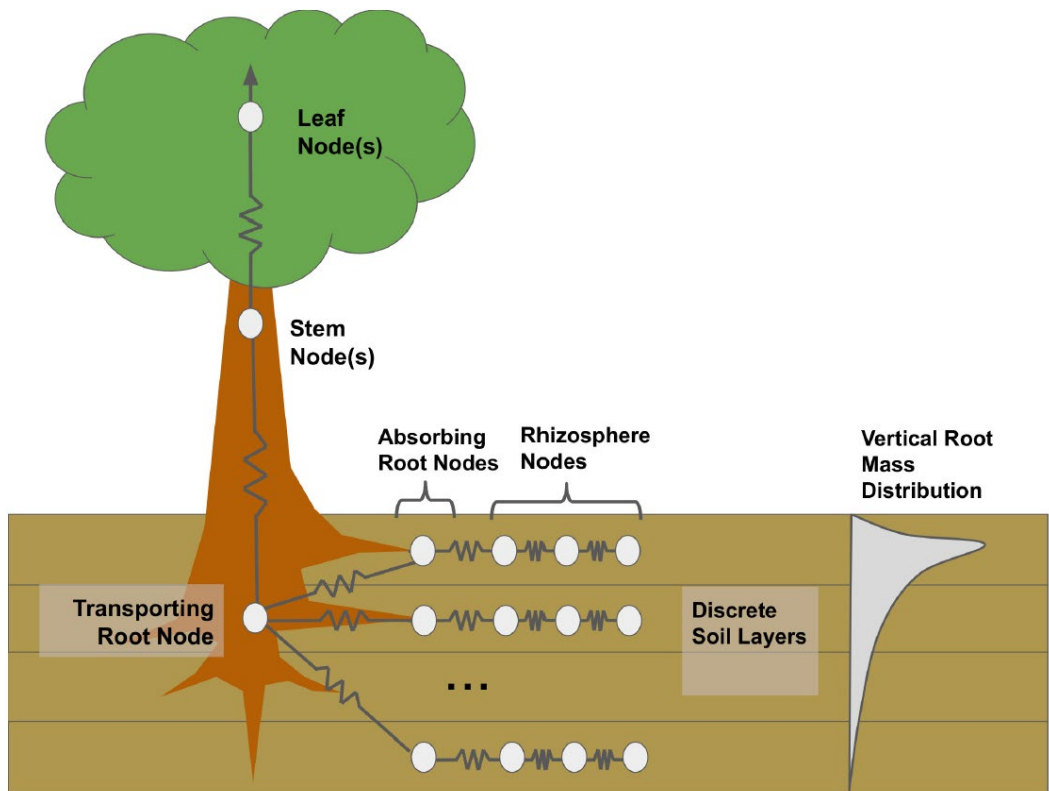
568 The contact author has declared that none of the authors has any competing interests.

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571 **Figures**

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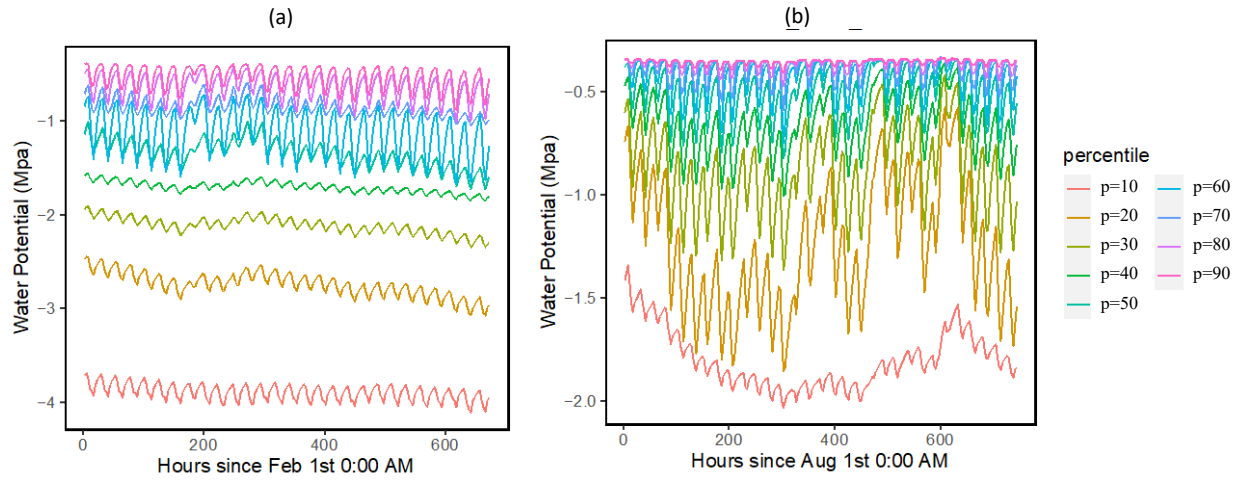
574 **Figure 1: Diagram of FATES-HYDO with simulation of rhizosphere shell, absorbing roots, transporting roots, stem and**

575 **leaves. The model is solved for different soil layers with different root distributions.**

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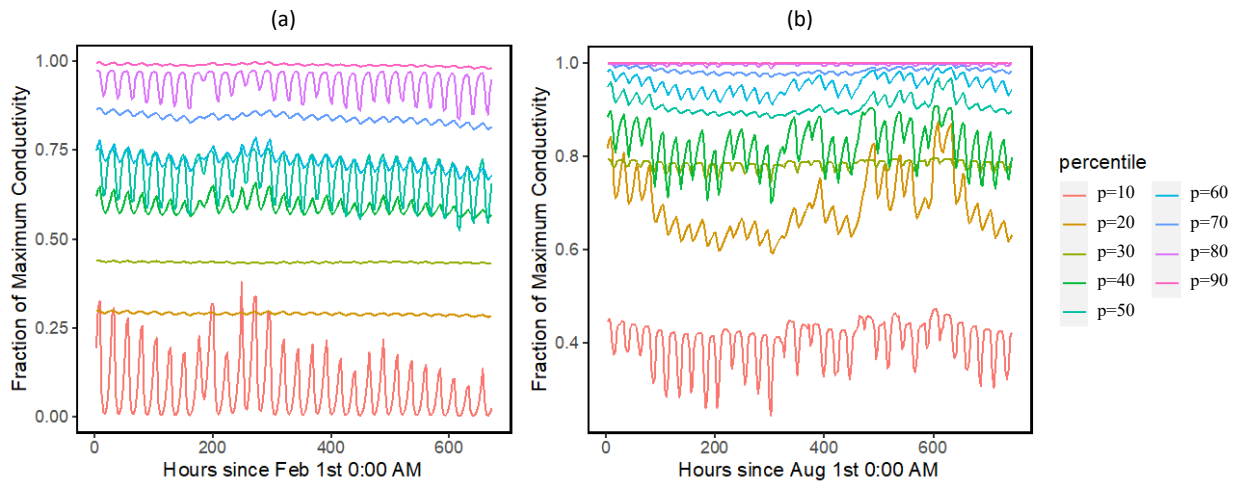
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580 **Figure 2: Simulated ranges of leaf water potential for February (a) and August (a), 2016 for trees with DBH > 60cm. The**

581 percentiles are calculated based on the monthly mean values of leaf water potentials for the 1000 ensemble simulations.

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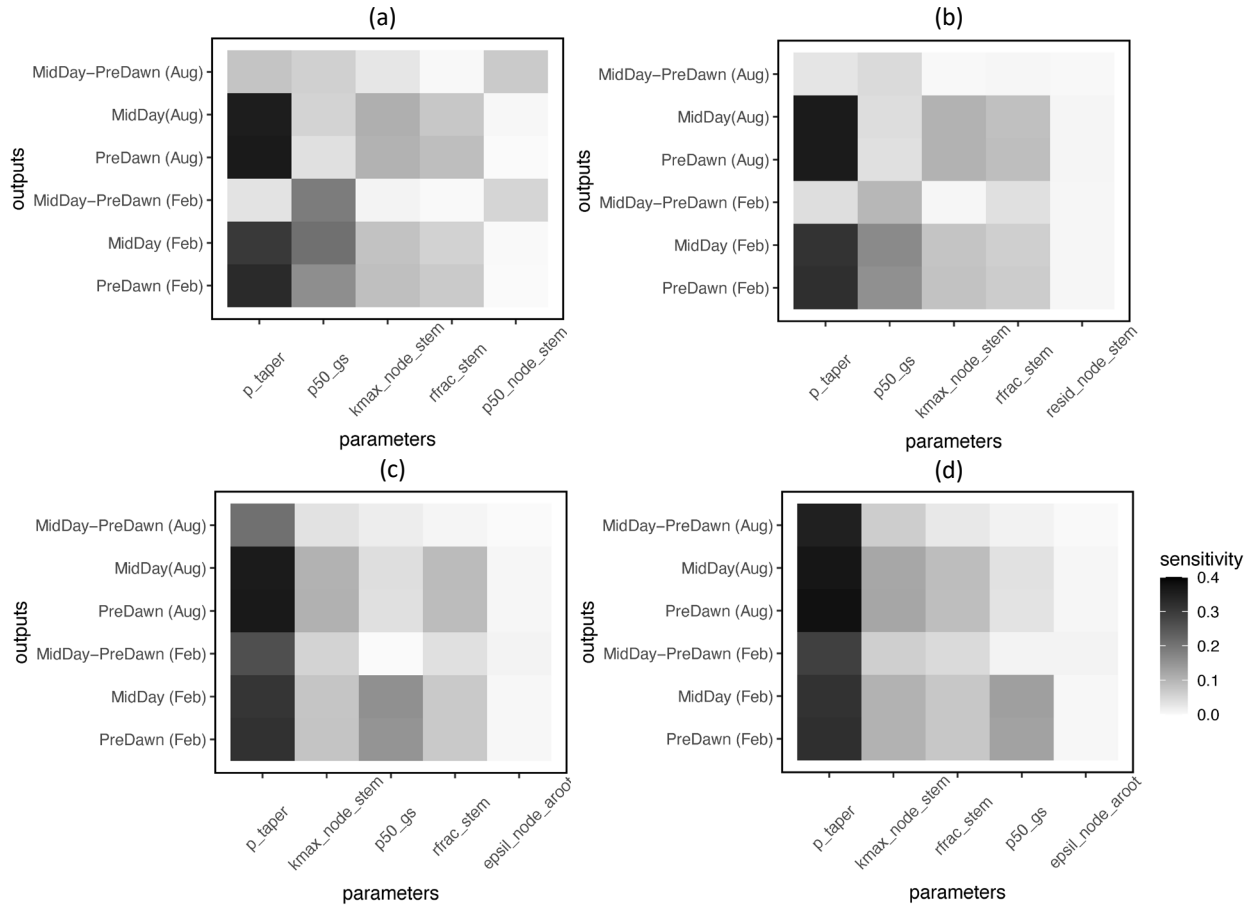


584

585 **Figure 3: Simulated ranges of fraction of maximum hydraulic conductivity of stem for February (a) and August (a), 2016**
586 **for trees with DBH > 60cm.** The percentiles are calculated based on the monthly mean values of leaf water potentials for the
587 1000 ensemble simulations.

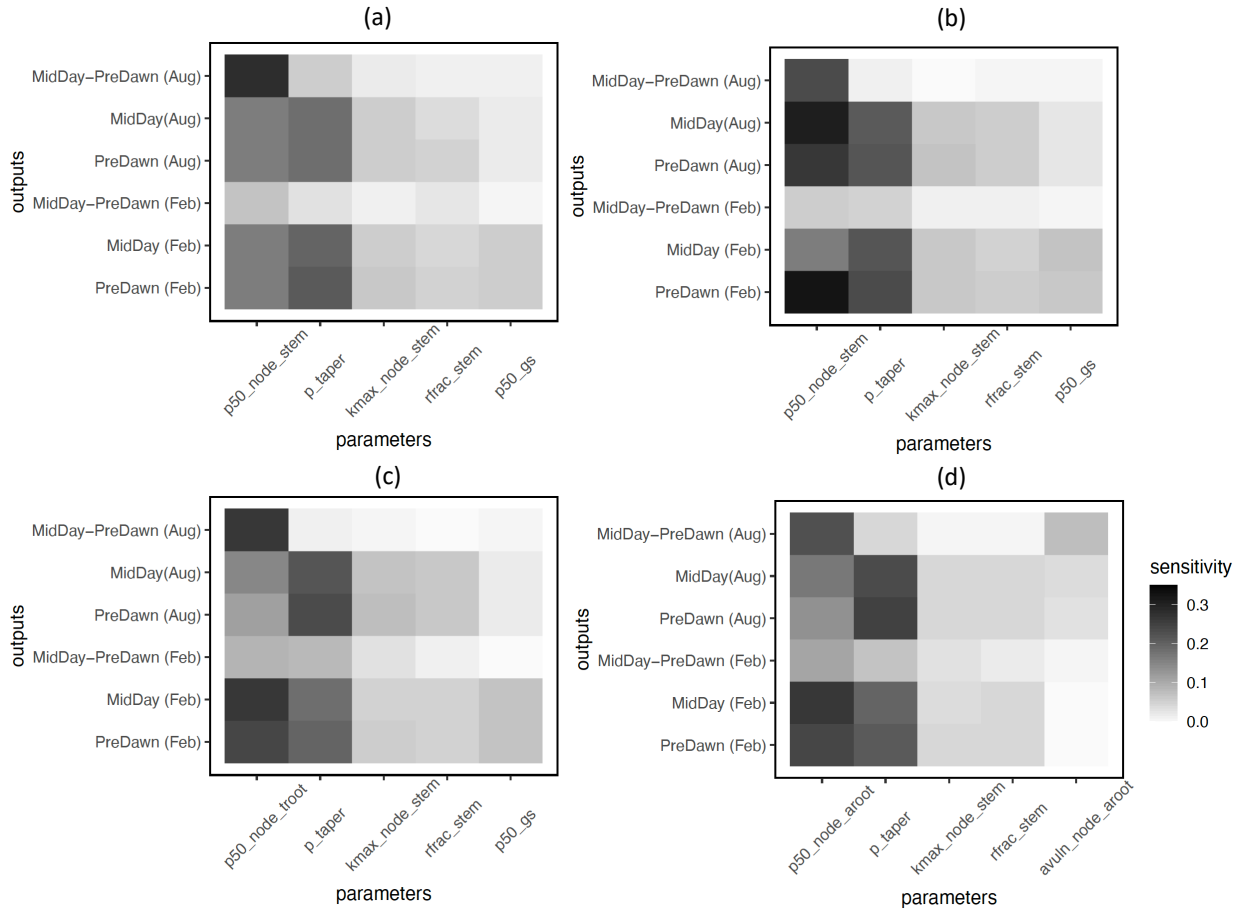
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 591 **Figure 4: Key parameters that control simulated water potentials for leaf (a), stem (b), transporting root (c) and**
 592 **absorbing root (d), for trees with DBH > 60cm.** The sensitivity value refers to the proportion of total model output variance
 593 contributed by a specific parameter (0-1). See Table 1 for the explanation of the parameters.

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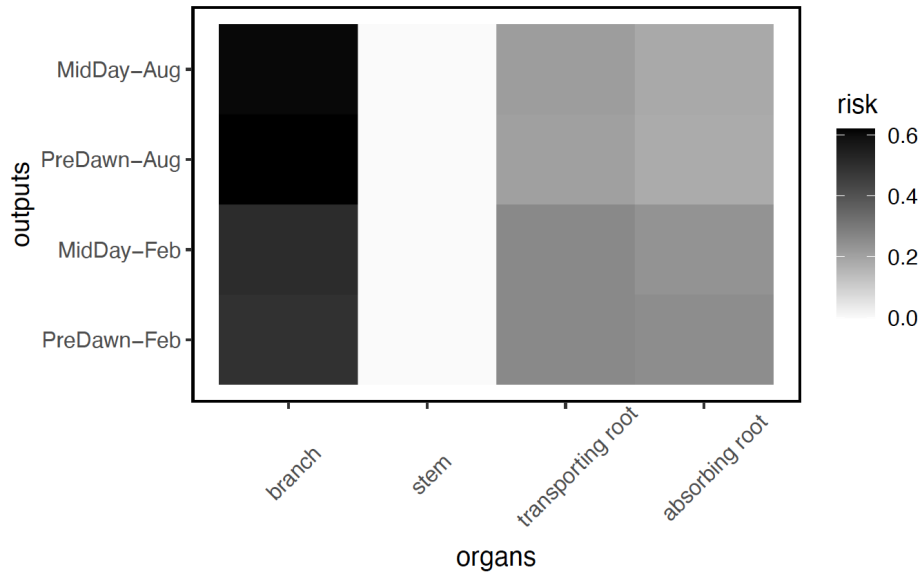
Figure 5: Key parameters that control simulated loss of conductivity for branch (a), stem (b), transporting root (c) and absorbing root (d), for trees with DBH > 60cm. The sensitivity value refers to the proportion of total model output variance contributed by a specific parameter. See Table 1 for the explanation of the parameters. See Table 1 for the description of parameters.

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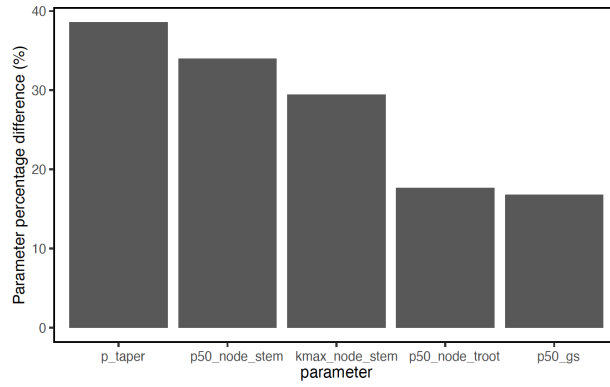
603 **Figure 6: Risk on the continuum for hydraulic failure as measured by percentage of total number of simulations with**
 604 **highest loss of conductivity for a specific organ (branch, stem, transporting root and absorbing root), for trees with DBH**
 605 **> 60cm.** As the model does not specifically simulate the branch, we calculated the risk of loss of conductivity based on the leaf
 606 water potential and hydraulic vulnerability curve from xylem.

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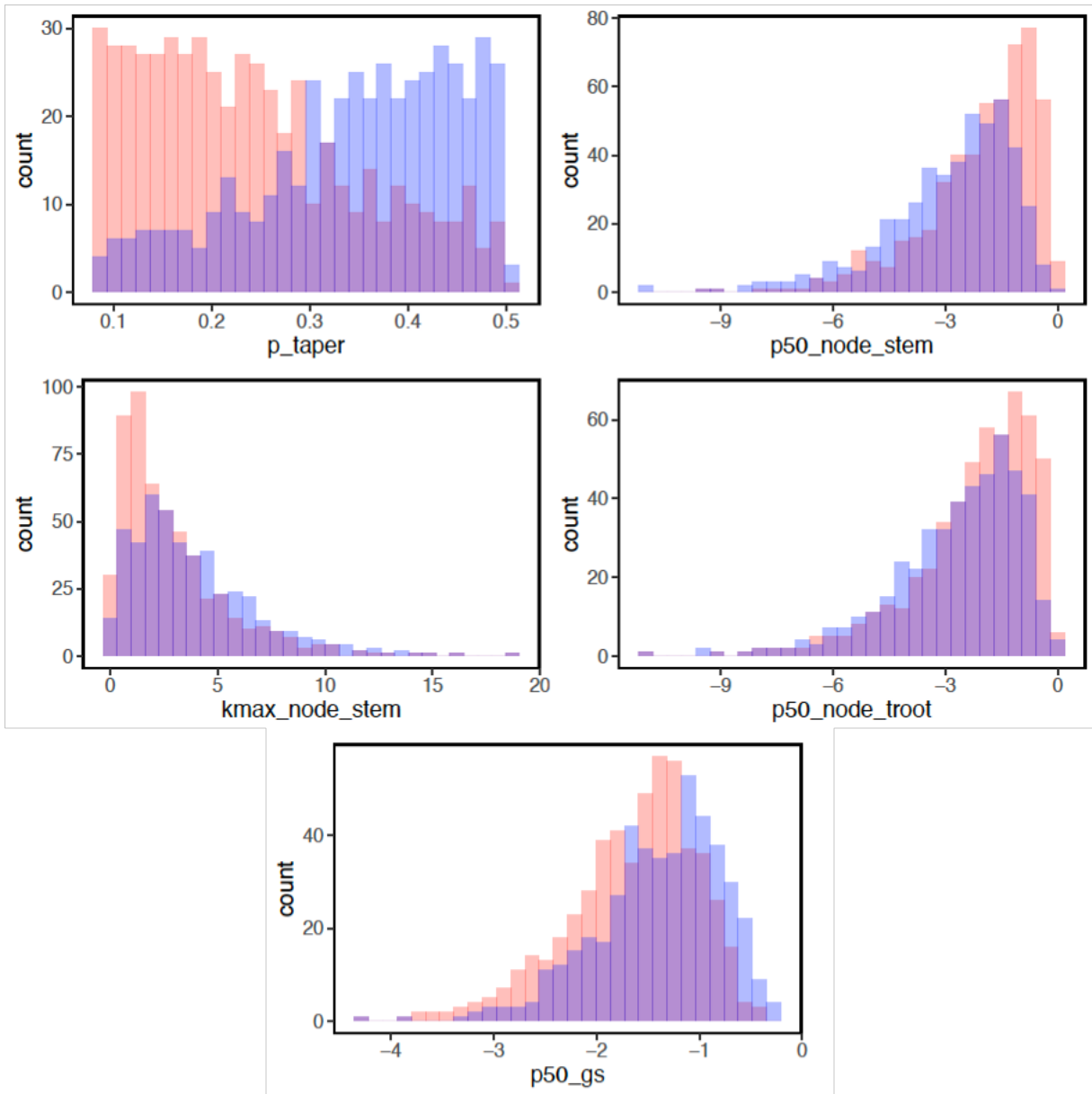
612 **Figure 7: Mean trait percentage difference for model ensemble simulations with loss of hydraulic conductivity larger**

613 **than 50% and ensemble simulations with loss of hydraulic conductivity less than 50%, for trees with DBH > 60cm. See**

614 Table 1 for the description of parameters.

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618 **Figure 8: Parameter difference for ensemble members with risk of mortality, for trees with DBH > 60cm.** Blue bars
 619 indicate parameter values with lower mortality risk (<50% loss of hydraulic conductivity). Red bars indicate parameter values
 620 with higher mortality risk ($\geq 50\%$ loss of hydraulic conductivity) and purple bars indicate parameter values stacked from
 621 transparent red/blue bars. See Table 1 for the description of parameters.

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Table 1 Hydraulic parameters considered in the sensitivity analysis

PARAMETER (EQUATION NUMBER) ¹	SYMBOL ²	UNITS	DISTRIBUTION ³	SOURCES& NOTES
Pressure-Volume (PV) curve (water content – water potential relationship)				
saturated water content (thetas_node_leaf, thetas_node_stem, thetas_node_troot, thetas_node_aroot) (Eq. 5)	$\theta_{sat,x}$	cm ³ cm ⁻³	Leaf: Beta (9.69, 6.20) Stem: Beta (12.67, 7.4626) TRoot and ARoot: Beta (22.98, 5.29)	Christoffersen et al. (2016) Iversen et al. (2017) Wright et al. (2010) Roderick et al. (1999) Sack et al. (2003) Binks et al. (2016)
turgor loss point (tlp_node_leaf, tlp_node_stem, tlp_node_troot, tlp_node_aroot) (Eq. 5)	$\pi_{tlp,x}$	MPa	$\pi_{tlp} = (\pi_0 \epsilon) / (\pi_0 + \epsilon)$	Bartlett et al. (2012) Christoffersen et al. (2016)
osmotic potential at full turgor (pinot_node_leaf, pinot_node_stem, pinot_node_troot, pinot_node_aroot) (Eq. 6)	$\pi_{0,x}$	MPa	Leaf: G [9.8,6.26], Stem, TRoot, ARoot: LN [0.32,0.39]	Bartlett et al. (2012, 2014, 2016) Christoffersen et al. (2016)
bulk elastic modulus (epsil_node_leaf, epsil_node_stem, epsil_node_troot, epsil_node_aroot) (Eq. 7)	ϵ_x	MPa	Leaf: G (4.07, 4.12) Stem, TRoot and ARoot: G [3.57, 3.84]	Bartlett et al. (2012, 2014) Christoffersen et al. (2016)
residual water fraction (resid_node_leaf, resid_node_stem, resid_node_troot, resid_node_aroot) (Eq. 5)	$RWC_{r,x}$	unitless	Leaf: B [2.14,4.10] Stem, TRoot and ARoot: B [2.71, 4.53]	Bartlett et al. (2012, 2014) Christoffersen et al. (2016)
Vulnerability Curve (water potential – hydraulic conductivity relationship)				
water potential at 50% loss of max conductivity (p50_node_stem, p50_node_troot, p50_node_aroot) (Eq. 3)	$P_{50,x}$	MPa	Stem, TRoot and ARoot: G [2.07, 1.18]	Choat et al. (2012)
vulnerability curve shape parameter (avuln_node_stem, avuln_troot, avuln_node_aroot) (Eq. 3)	a_x	unitless	Stem, TRoot and ARoot: LN [0.82,0.66]	Choat et al. (2012)
xylem conductivity per unit sapwood area (kmax_node_stem) (Eq. 8)	$k_{s,max}$	kg m ⁻¹ s ⁻¹ MPa ⁻¹	G [1.41, 2.37]	Choat et al. (2012)

Leaf hydraulics				
leaf water potential at 50% loss of max gs (p50_gs) (Eq. 12)	$P_{50,gs}$	MPa	G [5.73, 0.27]	Klein (2014)
stomatal vulnerability shape parameter(avuln_gs) (Eq. 12)	a_{gs}	unitless	$a_{gs} = -2.406 P_{50,gs} (-P_{50,gs})^{-1.25}$	Christoffersen et al. (2016)
Leaf cuticular conductivity (k0_leaf) (Eq. 11)	g_0	$\mu\text{mol m}^{-2}\text{s}^{-1}$	LN [1.04, 0.84]	Slot et al. (2021)
Plant Hydraulic Architecture				
Xylem taper exponent for sapwood (p_taper) (Eq. 9)	p	(-)	U (0.08, 0.5)	Savage et al. (2010)
Leaf area to sapwood area ratio (la2sa) (Eq. 8)	$\frac{A_l}{A_s}$	(-)	LN (-0.48, 0.77)	Choat et al. (2012)
Root hydraulic Traits				
specific root length (srl) (Eq. 13)	srl	m g^{-1}	G [1.70, 35.31]	Iversen et al. (2017)
absorbing root radius (rs2) (Eq. 13)	r	mm	LN [-1.91, 0.79]	Iversen et al. (2017)
fraction of total tree resistance that is aboveground (rfrac_stem) (Eq. 10)	$R_{frac,stem}$	Unitless	U [0.1,0.7]	This study; empirical
root-soil interface conductivity per unit surface area (K_{r1}) (Eq. 14)	$k_{r1,max}$	$\text{kg m}^{-1} \text{s}^{-1}$ MPa ⁻¹	G [1.41, 2.37]	This study; empirically set the same as xylem conductivity
maximum root water loss rate (K_{r2}) (Eq. 14)	$k_{r2,max}$	$\text{kg m}^{-1} \text{s}^{-1}$ MPa ⁻¹	LN [-6.80, 0.92]	Wolfe (2020); Empirically set as 1/1000 bark water loss rate

626 **Note:** 1: Several hydraulic parameters are used for different nodes of the plant including leaf, stem,
627 transporting root (troot), and absorbing root (aroot). For better reference in the text, we provided a list of
628 these parameters for specific nodes in the parenthesis; 2: Subscript x represents different tissue nodes in
629 the model; 3: B-Beta distribution; U- Uniform distribution [lower limit, upper limit]; N-Gaussian
630 distribution (mean, standard deviation); LN-Log Normal Distribution [mean, standard deviation]; G-
631 Gamma distribution (lambda, scale); TRoot-Transporting root; ARoot-Absorbing root.
632

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