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

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**Abstract**: Vegetation plays a key role in the global carbon cycle and thus is an important component within Earth system models (ESMs) that project future climate. Many ESMs are adopting methods to trace the size and succession-stage-structure of plants within demographic models. These models make it feasible to conduct more realistic simulation of processes that control vegetation dynamics. Separately, increasing understanding of the ecophysiological processes governing plant water use, and the need to understand ecosystem responses to drought in particular, has led to the adoption of physical plant hydrodynamic schemes within ESMs. In this study, we report on a new hydrodynamics (HYDRO) model incorporated in the Functionally Assembled Terrestrial Ecosystem simulator (FATES). The size and canopy structured representation within FATES is able to simulate how plant size and hydraulic traits affect vegetation dynamics and carbon/water fluxes. To better understand this new model system and its functionality in tropical forest systems in particular, we conducted a global parameter sensitivity analysis at Barro Colorado Island, Panama. We assembled observations of plant hydraulic traits for stomata, leaves, stems, and roots, and determined the best-fit statistical distribution for each trait. Our model analysis showed that the taper component determining hydraulic conductivity tapering from trunk to branch, the water potential leading to 50% loss ($P_{50}$) of stomatal conductance, the maximum hydraulic conductivity for the stem, and the fraction of total hydraulic resistance in the above ground section are the top 5 traits determining the simulated water potential and loss of conductivity for different plant organs. For the risk of hydraulic failure and potential tree mortality, we found that ensemble members with high risk of mortality generally have a higher taper exponent and a higher xylem conductivity, less negative $P_{50}$ for stomata conductance, and more negative $P_{50}$ for stem and transporting roots. We expect that our results will provide guidance on future modeling studies using plant hydrodynamic models to predict the forest responses to

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47 droughts, and future field campaigns that aim to better parameterize the plant hydrodynamic
48 model.

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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. 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 4 and this increase would have substantially more 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 parametrize 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 uncertainty is considered to be a key source of uncertainty in our projection of land carbon fluxes and future climates (Arora et al., 2020).

Earth System Models (ESMs) have been developed to project future changes to the coupled climate and biosphere system. Typically, ‘big leaf’ approximations of vegetation with no

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explicit presentation of tree size and canopy structure have been used to predict the impact of vegetation on carbon and water cycles. These models do not represent the fundamental elements of vegetation dynamics including mortality, competition, and growth, and their response to disturbances. In the last decade, many ESMs have incorporated vegetation demographic models (VDMs) that represent plant size, canopy structure and disturbance histories, with the goal of better representing the competitive dynamics among different size classes of trees and plant functional types in response to climate and vegetation disturbance (Fisher et al., 2018). Most of these VDMs can differentiate plants' light, water and carbon use strategies and can thus represent some part of the functional diversity of tropical forests (Massoud et al., 2019; Koven et al., 2020).

Following the 'big leaf' model, water limitation on plant gas exchange in these VDMs is generally calculated based on three factors: 1) soil water potential; 2) root distribution; and 3) water potential for stomata openness and closure, all of which differ by plant functional type (Koven et al., 2020). While such water limitation functions are able to capture trait diversity in leaf-level stomatal behaviors, they fail to capture plant functional diversity in many other observable plant hydraulic traits, such as xylem capacitance, water potentials for loss of xylem hydraulic conductivity, stem hydraulic safety margin, and turgor loss point (Hochberg et al., 2018). Many studies have shown that plant hydraulic traits play an important role in plant responses to droughts (Su et al., 2022; Anderegg et al., 2016), which could shape the landscape distribution of plant functional types (Kunert et al., 2021). In view of this limitation, plant hydrodynamic models have been developed with the aim of better simulating forest response to droughts (Powell et al., 2018; Christoffersen et al., 2016; Xu et al., 2016; Kennedy et al., 2019). These models not only allows us to better incorporate hydraulic functional diversity,

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but also allow us to mechanistically simulate the risk of plant mortality due to hydraulic functional failure resulting from embolism in xylem.

One key challenge for these plant hydrodynamic models is that they have many more parameters than simple water limitation functions based on soil water potentials and thus inherently possess more uncertainty in the model parameterization and subsequent simulations. In this study, we describe the implementation of a hydrodynamic scheme within FATES, and assess this new configuration with two goals: 1) assess the importance of different hydraulic traits in determining plant hydrodynamics; and 2) identify key hydraulic traits that are important for predicting the risk of mortality due to hydraulic failure. We expect that our results will provide guidance on model parameterization for future modeling studies using plant hydrodynamic models to predict tropical forest response to droughts, and future field campaigns that aim to collect observational data that can be used to better parameterize and benchmark plant hydrodynamic models.

## 2. Methodology

### 2.1. Model description

We use the functionally assembled terrestrial ecosystem simulator (FATES), a VDM that is coupled within the Energy Exascale Earth System Model (E3SM) (Caldwell et al., 2019). FATES represents size-structured groups of plants (cohorts) and successional trajectory-based patches using the ecosystem demography approach (Fisher et al., 2015; Moorcroft et al., 2001). FATES simulates growth by integrating photosynthesis across different leaf layers for each cohort. FATES allocates this photosynthate to different tissues including leaves, fine and coarse roots, and stem, based on the allometry of different plant functional types, as well as a carbon storage pool (Fisher et al., 2015). Mortality within FATES is simulated by several

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mechanisms, including carbon starvation caused by depletion of the storage pool, hydraulic function failure, as well as impact mortality during disturbance, fire, logging, freezing, age-related and 'background' constant turnover (Fisher et al., 2015; Huang et al., 2020; Fisher et al., 2010; Needham et al., 2020).

The default model contains a simplistic algorithm that approximates plant hydraulic failure thresholds based on soil water potential. An important feature of the plant hydrodynamic scheme (HYDRO), which explicitly simulates water flow from the soil through leaves to the atmosphere, is that it enables direct representation of percent loss conductance as a predictor of hydraulic failure mortality rates. FATES-HYDRO is based on the hydrodynamic model implemented in the Traits-based Forest Simulator (TFS) (Christoffersen et al., 2016). The water flow is calculated based on water pressure gradients across different plant compartments (rhizosphere, absorbing roots, transporting roots, stem, and leaf). Specifically, flow between compartment *i* and *i* + 1 ($Q_i$) is given by

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

where $K_i$ is the total conductance (kg MPa$^{-1}$ s$^{-1}$) at the boundary of compartments $i$ and $i+1$ and $\Delta h_i$ is the total matric potential difference between the compartments:

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

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

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The plant hydrodynamic representation and numerical solver scheme within FATES-HYDRO follows the 1-D solver laid out by Christoffersen et al. (2016). The equations are solved for tissue water content at a 30 minutes time step. We made a few modifications to accommodate the multiple-soil layers and improve the numerical stability. First, to accommodate the multiple-soil layers, we sequentially solve the Richards' equation for each individual soil layer, with each layer-specific solution proportional to each layer's contribution to the total root-soil conductance. Second, to improve the numerical stability, we now linearly interpolate the pressure/volume curve beyond the residual and saturated tissue water content to avoid the rare cases of overshooting in the numerical scheme under very dry or wet conditions. Please see the Supplementary Information [HYDRO_DESCRIPTION.pdf] for details of the implementation.

In this study, as our focus is on the plant hydrodynamics, we used the static stand structure mode of FATES that turns off the processes of competition, growth and mortality, to instead hold the ecosystem structure constant. This reduced-complexity configuration (Fisher and Koven, 2020) thus exercises only the primarily fast-timescale-processes of photosynthesis, transpiration, water transport, and plant hydrodynamics (i.e., change in hydraulic conductivity, water storage, and water potentials in plant tissues). By using static stand structure mode, as in Chitra-Tarak et al. (2021), we isolate hydraulic trait controls on simulated hydrodynamics and avoid confounding, and potentially biased, feedbacks from resulting changes in forest structure. The forest stand structure include tree size and composition is initialized based on the forest inventory data in 2017. As the majority of species in BCI is evergreen broad leave trees, we run the model with one PFT with different hydraulic traits (Table 1) to assess their impact on the hydrodynamically relevant outputs including water potentials and fraction of

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maximum conductivity for different plant organs including absorbing root, transporting root, stem, and leaves and risk of hydraulic failure. FATES simulates the carbon and water fluxes for different size classes of trees. Because large trees experience more fluctuation in environmental conditions in the canopy, here we focused on hydrodynamic behaviors for trees of diameter more than 60 cm.

### 2.2. Parametric uncertainty estimation

We identified 36 parameters for the FATES-HYDRO model (Table 1). To estimate the parameter distributions, we started with published meta-analyses (Christoffersen et al., 2016; Choat et al., 2012; Bartlett et al., 2012; Bartlett et al., 2014; Bartlett et al., 2016; Klein, 2014) and supplemented them with select new data from individual studies. Focal data were tissue- or individual-level hydraulic traits spanning water transport and embolism resistance, tissue water storage and retention (PV curve traits), hydraulic architecture (i.e., leaf area to sapwood area ratio), stomatal responses to dehydration, and fine root traits (Table 1). For each dataset, we standardized taxonomic names using the TNRS package in R (Boyle et al., 2013). This allowed us to join datasets together based on species, averaging multiple observations per species if necessary, resulting in a species-specific sparse matrix of all hydraulic traits for all databases and individual studies that we compiled. This pantropical hydraulic trait dataset is included in the Supporting Information [traits_master_trop.csv].

We then determined parametric distributions which best fit the trait data. Where necessary, traits were transformed to be positive, and certain traits with well-defined upper and lower bounds were normalized on [0, 1] according to (x - x.lowerbound)/(x.upperbound - x.lowerbound) for trait x (Table 1). For each trait, we used parameter estimates for the distribution with the largest log likelihood among all possible distributions using fitdistr

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package in R. We augmented observations with extratropical data to increase sample size for traits with less than three tropics-specific observations. Where trait data were mostly unmeasured, we used a uniform distribution bounded on our best estimate of the theoretical range (Table 1). As there is limited data on roots, we used the same distribution as that for branches if data was missing. Because our goal is to understand the model behaviors as determined by different hydraulic traits, we assumed independence among traits. As we focused on the hydraulic traits in this study, we used non-hydraulic trait values based on an optimal set of parameters that best fit observed water and carbon fluxes in FATES implemented without hydrodynamics (Koven et al., 2020).

### 2.3. Sensitivity analysis

We used the Fourier Amplitude Sensitivity Test (FAST) to assess the relative importance of parameters in determining the variance of model outputs (Xu and Gertner, 2011a). The main idea of FAST is to assign periodic signals in the sampled parameter values and use Fourier transformation to identify the signals in the outputs. Sampled parameter values are based on Latin hypercube sampling from the fitted statistical distributions (see previous section for more details). We ran 1000 ensemble simulations of the FATES-Hydro to derive model outputs of water potential and fraction of maximum conductivity. We used the Uncertainty Analysis and Sensitivyt Analysis (UASA) tool (https://sites.google.com/site/xuchongang/uasatoolbox) to estimate the parameter importance, which is defined as the proportion of total model output variance contributed by individual model parameters. For details, please refer to Xu and Gertner (2011a). We run the model with 1000 ensemble members, in view that an order of 100 times effective important number of parameters, which we estimate to be ~10, is needed to achieve reasonable precision (Xu and Gertner, 2011b).

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### 2.4. Study area and climate drivers

In this study, we used Barro Colorado Island (BCI), Panama, as our test site to evaluate model behavior. We chose BCI as it has moderately strong dry and wet seasons that allow us to assess the hydrodynamics under different levels of water availability. Moreover, extensive field campaigns in recent years have provided comprehensive data needed for model parameterization, initialization and climate drivers. Finally, we also leverage prior FATES studies of non-hydraulic parameters at BCI (Koven et al., 2020).

BCI has an annual mean temperature of 26.3ºC and an annual mean precipitation of 2656 mm with a strong seasonal precipitation signal. The dry season lasts from January to April, with a mean precipitation of 228mm, while the wet season lasts from May-December with a mean precipitation of 2428mm (Paton, 2020). In this study, we used hourly in-situ climate data from 2008-2016 to drive the model. To run the model to equilibrium (in terms of soil moisture content) takes 5-6 years, thus we choose February of 2016 as the target for analysis of dry season hydrodynamics and August of 2016 as the target for analysis of wet season hydrodynamics. Using static stand structure mode means that we do not need to spin up vegetation state and thus reducing the simulation time.

## 3. Results

Our results showed that the simulated ranges across the ensemble of leaf water potential (Fig. 1) and loss of conductivity (Fig. 2) are large. For leaf water potential, the 95% percentile ranges are from -5 MPa to -0.5 MPa and -3 MPa to -0.5 Mpa for February and August 2016, respectively. Correspondingly, the fraction of maximum stem hydraulic conductivity is much higher during August compared to February (Fig. 2); however, in both months, the modeled range spans almost the full range of between 0 and 1.

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Based on the FAST sensitivity indices (i.e., the variance in model output contributed by different parameters), the key parameters that control the water potentials of different plant organs (leaf, stem and root) include the taper exponent for hydraulic conductivity (*p_taper*), the water potential leading to 50% loss of stomatal conductance (*p50_gs*), maximum hydraulic conductivity for the stem (*kmax_node_stem*), and the fraction of total hydraulic resistance in the above ground section (*rfrac_stem*), in decreasing order (Fig. 3). For the fractional loss of conductivity, the most important parameter is the water potential leading to 50% loss of hydraulic conductance ($P_{50}$) for the corresponding organs (Fig. 4). Other important parameters are similar to those for simulated water potentials. Notably, the organ-specific $P_{50}$ values are more important for the dry month (February) compared to the wet month (August). For the wet month of August, *p_taper* is the dominant parameter controlling the pre-dawn and midday loss of hydraulic conductivity, while organ-specific $P_{50}$ parameters are the second most important.

In terms of the risk of hydraulic failure, out of the 1000 ensemble members, 40-60% of the simulations suggest that branches are the most vulnerable plant organ, based on highest loss of conductivity across the continuum from root to branch (Fig. 5). For the dry month of February, roots are at greater risk in comparison to the wet season. If we consider the loss of conductivity more than 50% for February 2016 as a threshold for a high risk of mortality (Adams et al., 2017), then 53% of ensemble simulations reach this threshold. The key parameters affecting the risk of mortality, as measured by percentage difference in parameter values for ensemble members reaching 50% loss of conductivity or not, include the water potential leading to 50% loss of conductance for stomata (*p50_gs*), stem (*p50_node_stem*), and transporting roots (*p50_node_troot*), maximum hydraulic conductivity of stem (*kmax_node_stem*), and the taper exponent (*p_taper*) (Fig. 6). Ensemble members with high risk of mortality generally have a

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higher *p_taper* and *kmax_node_stem*, less negative *p50_gs*, and more negative p50 for stem and transporting roots (Fig. 7).

## 4. Discussion

Our analysis showed the importance of key plant hydraulic traits in simulating plant water potential and risk of hydraulic failure. This analysis identifies these parameters as potential targets of either model calibration or targeted measurement campaigns to achieve realistic simulations. In our sensitivity analysis, the most influential parameter for both water potential and loss of conductivity is the tapering of the radius of conduit with increasing plant height (*p_taper*). As *p_taper* increases, the conduit radius increases from the top of the tree to its base. According to Hagen-Poiseuille's equation, this increases the theoretical maximum total conductance. Low values of *p_taper* thus limit the adverse effects of tree height by increasing *k_max* along the whole continuum and reducing the soil-to-leaf water potential needed to maintain transpiration. Our inference is that *p_taper* represents an overarching property of plant architecture that influences the relative effect of each of the other parameters with regard to hydraulic safety and efficiency. While *p_taper* is less directly related to plant adaptations to drought, the architecture of the plant itself determines the range of values that give rise to drought adaptive strategies. Another dimension of the hydraulic architecture with a critical role in determining both water potential and loss of conductivity, though to a much lesser degree, was the fraction of total tree resistance within the above-ground stem (*rfrac_stem*). Generally, a plant will maintain this resistance, matching the growth of trunk and crown height to maintain total resistance as the distance water needs to travel increases (Yang and Tyree, 1993). In this study, due to the lack of data on the belowground resistance, we assigned a quite large range

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for this trait, which could be impact by many factors such as belowground root biomass and interaction between root, fungi and bacteria.

The second most sensitive parameter in determining loss of conductance was the leaf water potential at 50% loss of stomatal conductance (*p50_gs*). The parameter controls the water loss rate from leaf and a less negative value provides protection from hydraulic failure during water limited periods. It has been shown to play a key role in tree survival during severe droughts (Breshears et al., 2009; Rowland et al., 2015). The ability to withstand lower leaf water potentials is also a key indicator of sapling and seedling survival during drought and determines species distribution across a moisture gradient (Kursar et al., 2009). There may be a trade-off between drought tolerance (with a lower *p50_gs*) and drought avoidance (a less negative *p50_gs* but with a high capacitance; the amount of water released from reserves as leaf water potential declines), a crucial aspect in determining species drought resistance (Pineda-Garcia et al., 2013). Additionally, loss of conductivity was sensitive to the water potential at 50% loss of max conductivity within the stem (*p50_stem*) as it can largely affect the whole plant conductance and thus the water supply to the leaves. *p50_stem* negatively correlates with wood density and may be a marker of the trade-off between hydraulic efficiency and safety within the stem (Chen et al., 2009; Manzoni et al., 2013). Even though we did not consider this trade-off as we mainly focused on the hydraulic traits in this study, this trade-off could be important to consider for competitions and co-existence among different plant functional types.

Leaf water potential and loss of conductance were both sensitive to the maximum xylem conductivity in the stem (*kmax_node_stem*). Higher maximum conductivity represents greater xylem efficiency, which in the absence of drought or light limitations would result in greater

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potential photosynthesis and less negative water potentials (Gleason et al., 2016). However, xylem with higher *kmax_node_stem* could be more vulnerable to embolism as water potential declines (Sperry and Love, 2015). In tropical rainforests, species with higher conductivity per unit leaf area generally are less desiccation tolerant and exhibit higher mortality rates (Kursar et al., 2009). Low *kmax_node_stem* along with high leaf-to-sapwood area ratio (*la2sa*) also represents a vulnerability to reduced conductance which increases with height (Christoffersen et al., 2016).

Traits with lower order of impacts on water potential modulate the amount of stored water available during drought. The fraction of water in the capillary reserve within the stem ($f_{cap}$) determines the amount of water stored within the stem. Water storage in the stem has been shown to help maintain higher water potentials as drought continues (Bartlett et al., 2019). The bulk modulus of elasticity in the root (*epsil_node*) determines the amount of water available from cellular storage between complete hydration and loss of turgor (Powell et al., 2017). This represents the ability of the roots to continually supply water to the rest of the plant as drought occurs. It also represents an investment in cellular structure, which may be an additional indicator of adaptations with non-hydraulic origin.

The sensitivity of vegetation to drought stress and hydraulic failure induced mortality is of paramount importance for understanding how ecosystems may respond to shifting temperature and rainfall patterns under a changing climate (Mcdowell et al., 2022). We recognize that parametric sensitivity could be different for different sites depending on climate driver, soil moisture and vegetation types. However, we expect the main parameter of importance could be could be useful to guide model calibration to select the candidate parameters for different sites. As understanding of plant hydrodynamics increases, linking

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model predictions to observable plant traits has emerged as a promising means of constraining predictions of ecosystem resilience. Such traits are challenging and costly to measure in the field and thus resources must be directed carefully when planning measurement campaigns. The identified parameters in this study could provide guidance on the limited measurement we could target in the field.

## 5. Acknowledgment

This research was supported as part of the Next Generation Ecosystem Experiments-Tropics, funded by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research.

## 6. CODE and Data Availability

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

## 7. Supplement Information

Two supplementary file are included. The HYDRO_DESCRIPTION.pdf provide the summary of the hydrodynamic implementation that is different from Christoffersen et al. (2016). The traits_master_trop.csv file include all the hydraulic traits we assembled for the tropical region.

## 8. Author contribution

CX and BC designed the sensitivity analysis experiments. BC collected the data and fitted the trait distributions. CX conducted the analysis and drafted the manuscript. BC, CX, RF, RN and CK designed the implementation of HDRO codes. BC implemented the majority of HDRO codes with code improvement made by CX and RN. ZR conducted the ensemble model simulations. MS provided the leaf cuticular conductance data. NM, CK and LK provided

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guidance on the sensitivity analysis, code development and trait data synthesis. All authors contributed to manuscript writing by providing edits and suggestions.

## 9. Competing interests

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

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## Figures

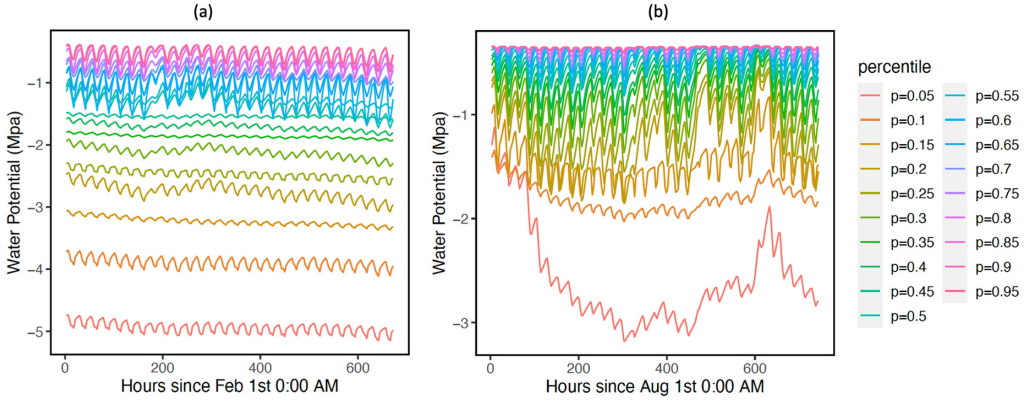


**Figure 1: Simulated ranges of leaf water potential for February (a) and August (a), 2016.** The percentiles are calculated based on the monthly mean values of leaf water potentials for the 1000 ensemble simulations.

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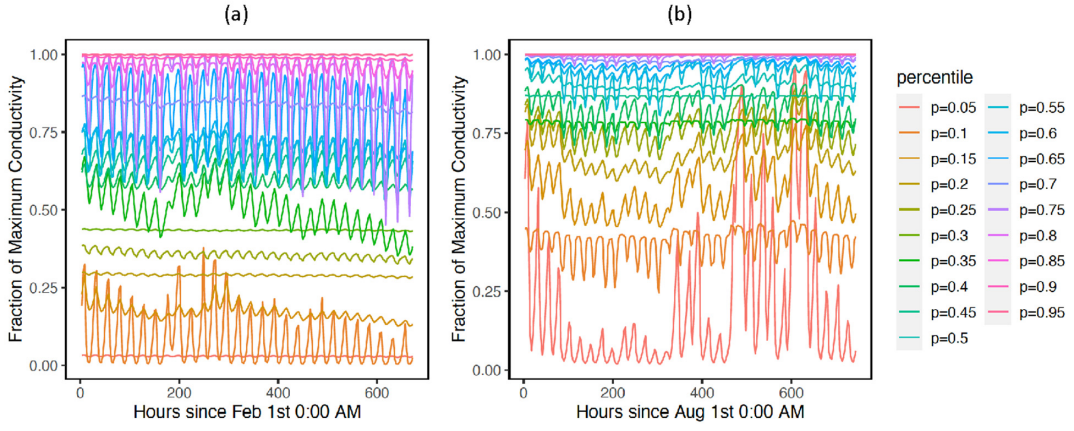


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361 **Figure 2: Simulated ranges of fraction of maximum hydraulic conductivity of stem for February (a) and August (a),**

362 **2016**. The percentiles are calculated based on the monthly mean values of leaf water potentials for the 1000 ensemble

363 simulations.

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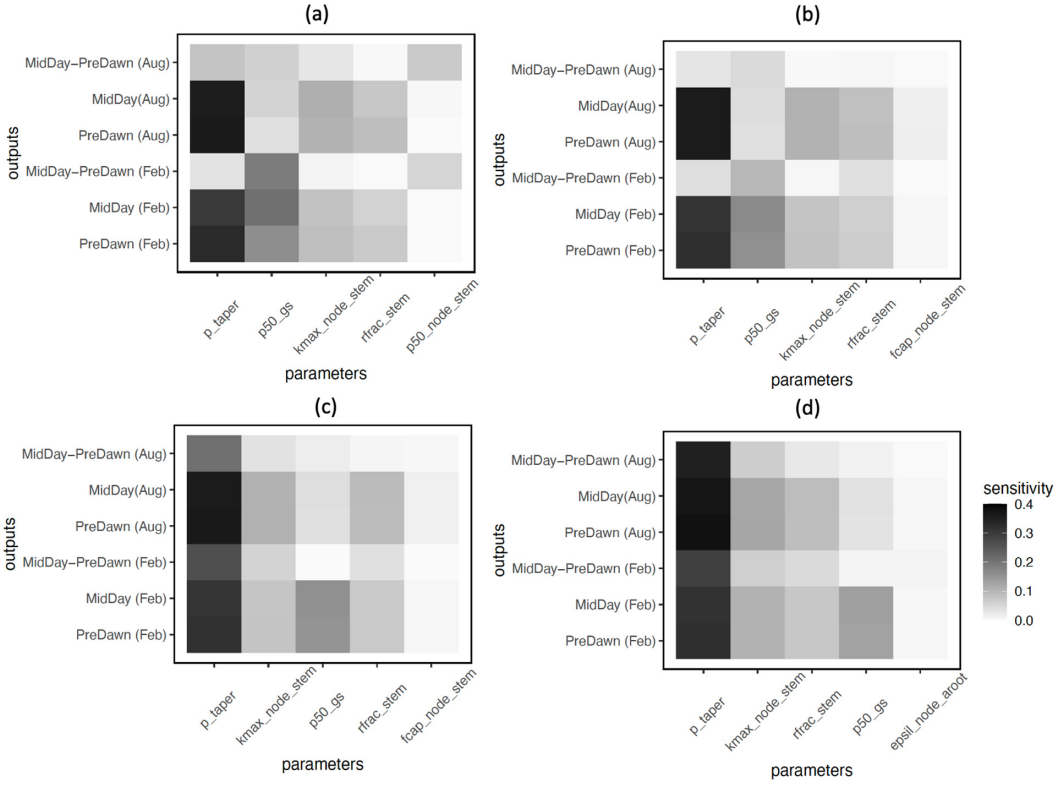


**Figure 3: Key parameters that control simulated water potentials for leaf (a), stem (b), transporting root (c) and absorbing root (d).** The sensitivity value refers to the proportion of total model output variance contributed by a specific parameter (0-1). See Table 1 for the explanation of the parameters.

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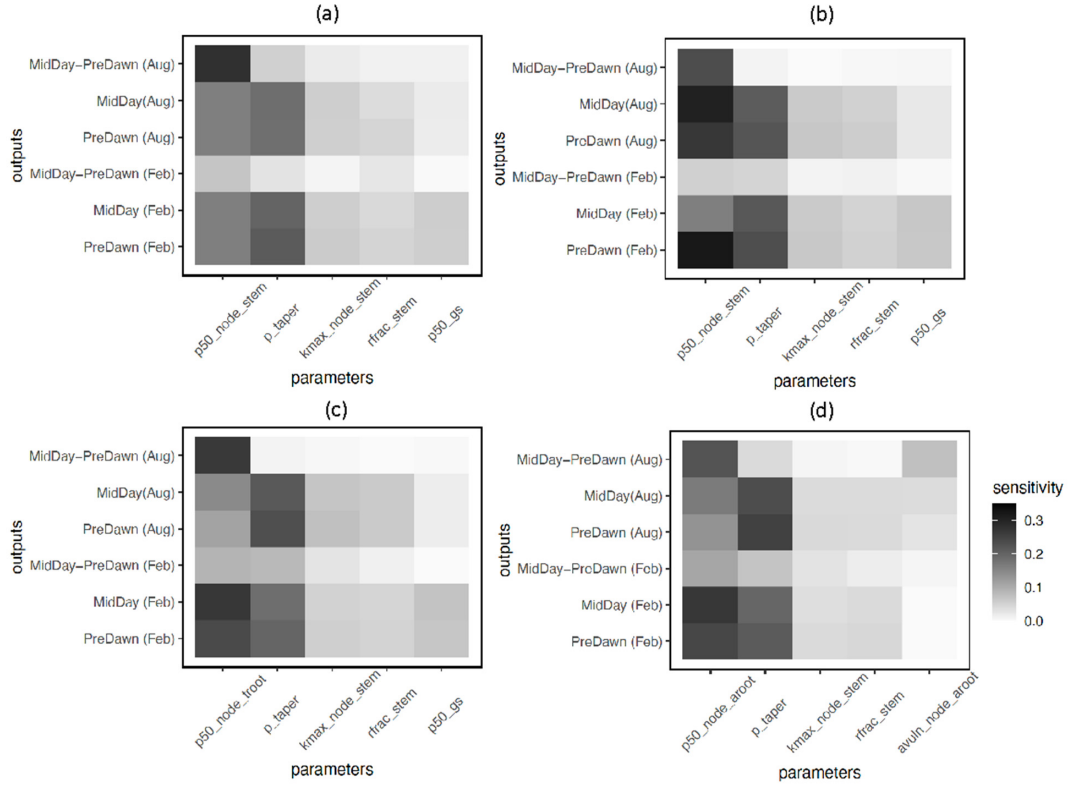


**Figure 4: Key parameters that control simulated loss of conductivity for branch (a), stem (b), transporting root (c) and absorbing root (d).** The sensitivity value refers to the proportion of total model output variance contributed by a specific parameter. See Table 1 for the explanation of the parameters. See Table 1 for the description of parameters.

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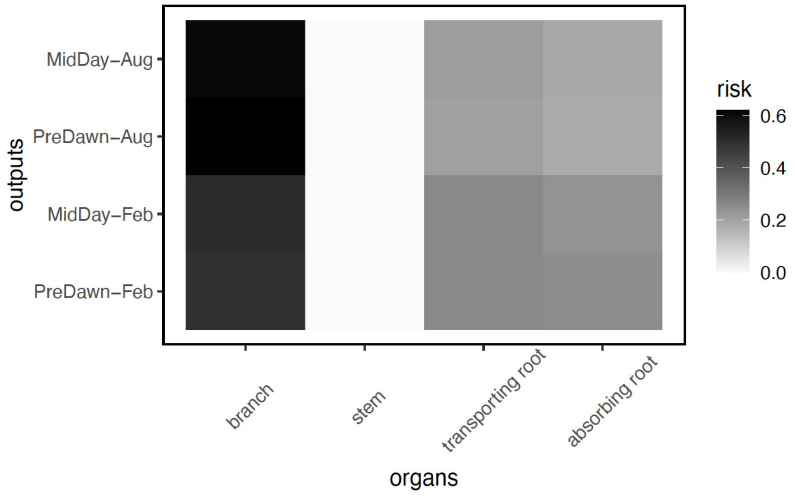


**Figure 5: Risk on the continuum for hydraulic failure as measured by percentage of total number of simulations with highest loss of conductivity for a specific organ (branch, stem, transporting root and absorbing root).** As the model does not specifically simulate the branch, we calculated the risk of loss of conductivity based on the leaf water potential and hydraulic vulnerability curve from xylem.

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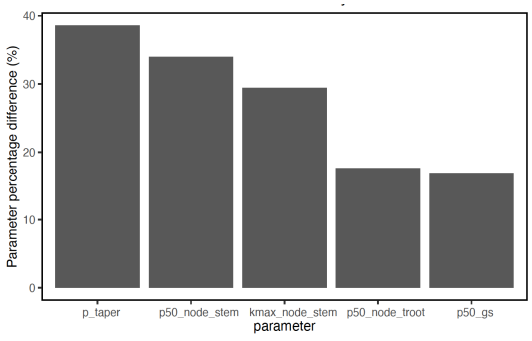


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387 **Figure 6: Mean trait percentage difference for model ensemble simulations with loss of hydraulic conductivity larger**
388 **than 50% and ensemble simulations with loss of hydraulic conductivity less than 50%.** See Table 1 for the description of
389 parameters.

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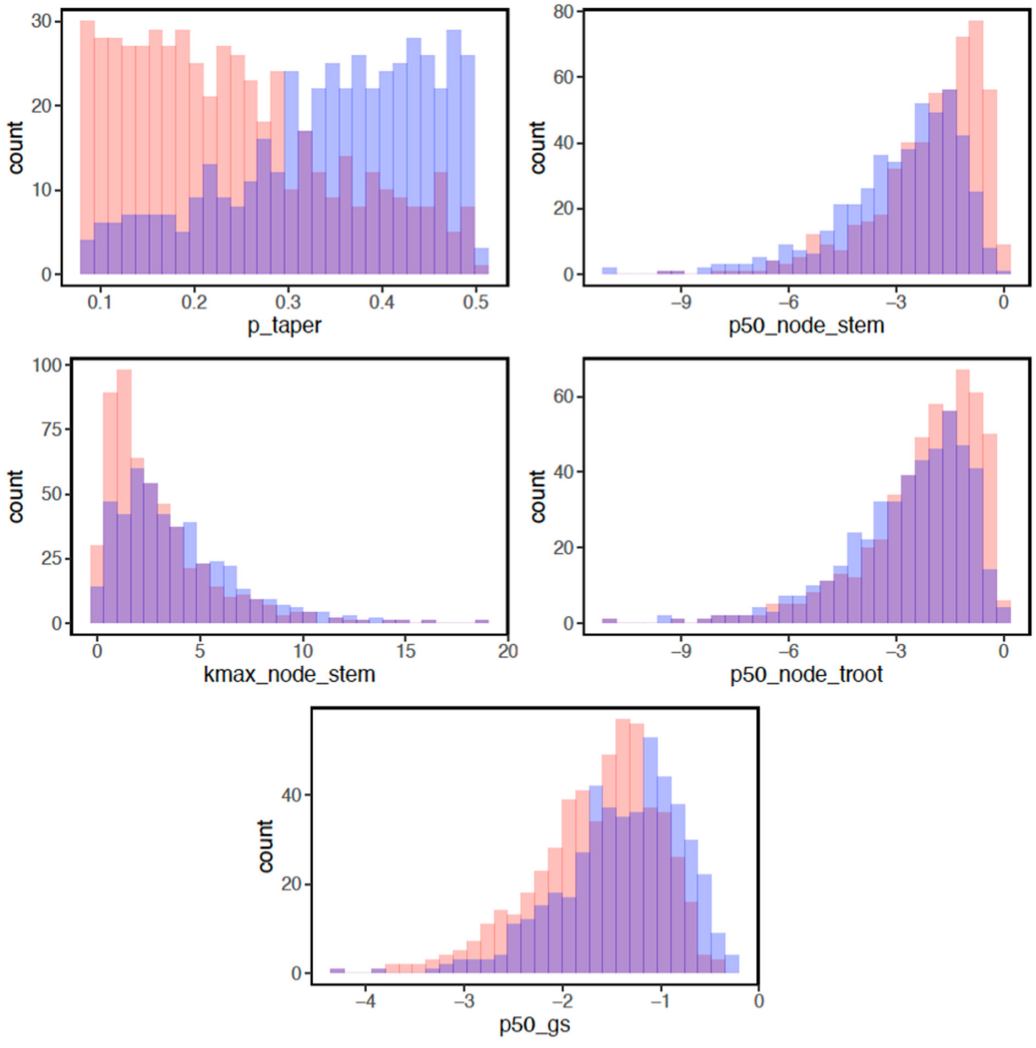


392

393 **Figure 7: Parameter difference for ensemble members with risk of mortality.** Blue bars indicate parameter values with
394 lower mortality risk (<50% loss of hydraulic conductivity). Red bars indicate parameter values with higher mortality risk (>=
395 50% loss of hydraulic conductivity) and purple bars indicate parameter values stacked from transparent red/blue bars. See Table
396 1 for the description of parameters.

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399
400 Table 1 Hydraulic parameters considered in the sensitivity analysis

| PARAMETER | SYMBOL | UNITS | DISTRIBUTION[1] | SOURCES& NOTES |
|---|---|---|---|---|
| **Pressure-Volume (PV) curve (water content – water potential relationship)** | | | | |
| saturated water content (thetas_node) | $\theta_s$ | $cm^3\ cm^{-3}$ | Leaf: Beta (9.69, 6.20)<br>Stem: Beta (12.67, 7.4626)<br>TRoot and AROOT: Beta (22.98, 5.29) | Christoffersen et al. (2016)<br>Iversen et al. (2017)<br>Wright et al. (2010)<br>Roderick et al. (1999)<br>Sack et al. (2003)<br>Binks et al. (2016) |
| turgor loss point (tlp_node) | $\pi_{tlp}$ | MPa | - | Bartlett et al. (2012);<br>$\pi_{tlp} = (\pi_0\ \varepsilon)\ /(\pi_0 + \varepsilon)$ |
| osmotic potential at full turgor (pinot_node) | $\pi_0$ | MPa | Leaf: G [9.8,6.26], Stem, TRoot, ARoot: LN [0.32,0.39] | Bartlett et al. (2012, 2014, 2016) and Christoffersen et al. (2016) |
| bulk elastic modulus (epsil_node) | $\varepsilon$ | MPa | Leaf: G (4.07, 4.12)<br>Stem, TRoot and ARoot: G [3.57, 3.84] | Bartlett et al. (2012, 2014), and Christoffersen et al. (2016) |
| residual water fraction(resid_node) | $RWC_r$ | unitless | Leaf: B [2.14,4.10]<br>Stem, TRoot and ARoot: B [2.71, 4.53] | Bartlett et al. (2012, 2014), Christoffersen et al. (2016) |
| fraction of water in capillary reserve (fcap_node) | $f_{cap}$ | unitless | U [0.1, 0.7] | Christoffersen et al. (2016) |
| **Vulnerability Curve (water potential – hydraulic conductivity relationship)** | | | | |
| water potential at 50% loss of max conductivity (p50_node) | $P_{50,x}$ | MPa | Stem, TRoot and ARoot: G [2.07, 1.18] | Choat et al. (2012) |
| vulnerability curve shape parameter (avuln_node) | $a_x$ | unitless | Stem, TRoot and ARoot: LN [0.82,0.66] | Choat et al. (2012) |

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| | | | | |
|---|---|---|---|---|
| xylem conductivity per unit sapwood area (kmax_node_stem) | $k_{s,max}$ | 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) | $P_{50,gs}$ | MPa | G [5.73, 0.27] | Klein (2014) |
| stomatal vulnerability shape parameter(avuln_gs) | $a_{gs}$ | unitless | - | Christoffersen et al. (2016); derived according to empirical equation: $a_{gs}$= -2.406 P50,gs (-P50,gs) $^{-1.25}$ |
| Leaf cuticular conductivity (k0_leaf) | $k_{0,l}$ | umol $m^{-2}s^{-1}$ | LN [1.04,0.84] | This study, based on data measured by Martijn Slot |
| **Plant Hydraulic Architecture** | | | | |
| Xylem taper exponent for sapwood (p_taper) | $p$ | (-) | U (0.08, 0.5) | Savage et al. (2010) |
| Leaf area to sapwood area ratio (la2sa) | la2sa | (-) | LN (-0.48, 0.77) | Choat et al. (2012) |
| **Root hydraulic Traits** | | | | |
| specific root length (*srl*) | $srl$ | m $g^{-1}$ | G [1.70, 35.31] | Iversen et al. (2017) |
| absorbing root radius (*rs2*) | $r$ | mm | LN [-1.91, 0.79] | Iversen et al. (2017) |
| fraction of total tree resistance that is aboveground (*rfrac_stem*) | *frac* | Unitless | U [0.1,0.7] | This study; empirical |
| root-soil interface conductivity per unit surface area (*Kr1*) | $k_{r1,max}$ | kg $m^{-1}$ $s^{-1}$ $MPa^{-1}$ | G [1.41, 2.37] | This study; empirically set the same as xylem conductivity |
| maximum root water loss rate (*Kr2*) | $k_{r2,max}$ | kg $m^{-1}$ $s^{-1}$ $MPa^{-1}$ | LN [-6.80, 0.92] | Wolfe (2020); Empirically set as 1/1000 bark water loss rate |

**Note:** 1:B-Beta distribution; U- Uniform distribution [lower limit, upper limit]; N-Gaussian distribution (mean, standard deviation); LN-Log Normal Distribution [mean, standard deviation]; G-Gamma distribution (lambda, scale); TRoot-Transporting root; ARoot-Absorbing root.

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