TREES Model Introduction

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The Terrestrial Regional Ecosystem Exchange Simulator (TREES) is a dynamic biophysical process-based simulation model. It is designed for simulating land-based systems, it uses leaf area and ground area as scalars, and so the model can be used at plant, stand, or landscape (regional) scales without any modification to the model code. TREES solves vertical, one-dimensional processes from a lower boundary, *e.g.* impermeable bedrock layer, to the atmosphere within the turbulent boundary layer of vegetation (see **Box 1**). This type of model is commonly called a soil-vegetation-atmosphere transfer (SVAT) model, but TREES has a few tricks that distinguish it from many other 1-D vegetation models. First, it couples canopy processes (*e.g.*, stomatal conductance, photosynthesis, and transpiration) to a soil-plant hydraulic system that supports cavitation in the plant xylem. This gives the model the ability to retain a memory of successive drought exposure on plants, and enables it to predict a wide range of emergent physiological responses to stressors using observational data (Mackay *et al.*, 2015; Tai *et al.*, 2017; Johnson *et al.*, 2018; McDowell *et al.*, 2019; Wang *et al.*, 2020). Second, a newer version of the model grows the canopy and roots as functions of resource (*e.g.*, carbon and nitrogen) limitations and hydraulic limitations on water accessibility and transport of water and nutrients from roots to leaves, and non-structural carbon and amino acids from the canopy down to roots (Mackay *et al.*, 2020). Third, a novel canopy growth model allows for linking genetic complexity and dynamic physiological responses to environmental conditions (Wang *et al.*, 2019), which also provides an alternative growth model for annuals to use instead of the climate-driven canopy phenology (Savoy and Mackay, 2015) used for simulating perennials. Fourth, TREES is equipped with both C3 and C4 photosynthesis models. Fifth, nitrogen cycling components connect microbial processes (*e.g.*, immobilization, ammonification, nitrification) to plant-mediated substrates (*e.g.*, organic material turnover and root exudates), affected by soil temperature and hydraulic properties, within rhizospheres tied to root growth dynamics.

TREES is a dynamic model, which means it updates its states (or pools) at each time step based on fluxes of water, carbon, nitrogen, and a memory of the lowest predawn leaf water potential to which the simulated xylem has been exposed. The model keeps track of carbon pools (*e.g.*, leaf, stem, fine and course roots, non-structural carbon, amino acids, soil organic material, microbial biomass), nitrogen (*e.g.*, organic, ammonium, nitrate, amino acids), and water in the soil in multiple layers. The model is forced with micrometeorological data (**Table 1**) at 30-minute time steps, and it is parameterized with two additional files (**Tables 2** and **3**). One file contains the parameters shown in **Table 2**, which allow for specification of site properties, physical traits of the plant canopy that influence energy transfers, biological traits for photosynthesis and hydraulics, soil physical properties, root growth traits, microbial traits, and traits associated with leaf growth. The second parameter file shown in **Table 3** provides a way of specifying the hydraulic architecture of the soil-plant system, including axial and lateral lengths, and initial proportional root areas in each layer. This “param_mod” file has a

There are three output files (**Table 4-6**). The primary flux and pool outputs are shown in **Table 4**. Note that the number of columns in this output file depends on how many soil-root layers are defined (see **Table 3**). **Table 5** provides information that can be used to reconstruct the cavitation status of each element of the plant at each time step. Specifically, all the information needed to reconstruct maximum (cavitated) hydraulic conductance and how the vulnerability curves have been modified from their native forms as a result of water stress. **Table 6** reports on the growth of individual leaves when the individual leaf growth model is used.

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Box 1. High-level view of processes in TREES. Functions in blue involve soil or xylem hydraulics, and those in red involve nitrogen cycling.

```
trees_main.cpp
        Read in parameter files
        Open output files and write out headers
        Call simulator()
simulator.cpp
        Compute soil hydraulic properties
        Initialize state variables
        Initialize bgc()
        Initialize hydraulicModel()
        Call hydraulic model setup()
        Time loop {
                Read in one line from the driver file
                Recall hydraulic model setup() to account for plant growth
                Call simulation_functions()
                Write results to output files }
simulation_functions.cpp
        Compute canopy phenology or leaf area growth, one of:
                compute_GSI_LAI() in process_functions.cpp, or
                bgc.updateLeafCarbonNitrogenPools(), or
                bgc.updateLeaf()
        Call infiltration() sub-model in process_functions.cpp
        Call aerodynamic conductance with stability corrections in process_functions.cpp
        Compute canopy absorb_rad() in process_functions.cpp
        Compute root weighted soil water potential
        Compute water stress function used to scale initial Gs
        Call compute_canopy_evaporation() in process_functions.cpp
        Loop until hydraulics converges {
                First iteration, calc_gvc(4 parameters) initial guess in process_functions.cpp
                Subsequently, call DoHydraulicModel() and calc_gvc(10 parameters)
                Compute sun and shade leaf temperatures
                Compute sun and shade photosynthesis, calling one of:
                        bgc.photosynthesis() or bgc.coupledA3_gc() or bgc.coupledA4_gc()
                Compute revised sun and shade stomatal conductances
                Call do_pm() in process_functions.cpp to compute transpiration for sun and shade
                Compute sun and shade leaf surface vapor pressure deficits
                Re-call aerodynamic conductance in process_functions.cpp }
        Compute rhizosphere fluxes
        Compute ground surface evaporation
        Compute transpiration removal from each rhizosphere
        Call capillary_rise() in process_functions.cpp
        Call bgc.storeGlycineAndSerine()
        Compute maintenance respiration and update NSC
        Compute cost of loading NSC into the phloem
        Compute growth potential
        Call bgc.computeLeafAllocation()
        Call bgc.updateStemCarbonNitrogenPools()
        Call bgc.updateRootCarbonNitrogenPools()
        Compute NSC needed for defense
        Compute the circadian control of chloroplast starch and sugar
        Call bgc.computeRootExudates()
        Call bgc.computeRootNitrogenUptake()
        Call bgc.computeLeaching()
        Call bgc.updateRhizospherePools()
        Compute total respiration, NPP, and NEE
        Compute snowmelt
        Call infiltration() in process_functions.cpp
```

Table 1. Information on the TREES driver (time-series of micrometeorological data) used as forcing for the model. Note that TREES must have data in 30-minute time steps (= 48 time steps per day).

Input Column	**Units**	**Description**	**Notes**
Date	YEARDAY	Using year as well as day the code will expect leap-years to have 366 days	For example, 2020300 is YEAR 2020 DAY 300
Time	Half-hours	Starting at 0 (midnight), incrementing by 0.5, ending with 23.5 (11:30 pm) for each day	The model expects 48 time steps per day
u_ref	m s-1	Wind velocity at the reference height (assumed to be above the canopy)	This cannot have zeroes; model will force value > 0.0
t_ref	deg C	Temperature at the reference height	This is a critical value to have
d_ref	kPa	Vapor pressure deficit of the atmosphere at the reference height	This is a critical value to have
precip	mm	Precipitation above the canopy or irrigation made directly to the soil surface	This is a critical value to have
q_par	umol m-2 s-1	Incoming photosynthetically active radiation	This is a critical value to have
t_canopy	deg C	Temperature within the canopy; use the same value as t_ref if you don't have this observation	
d_canopy	kPa	Vapor pressure deficit within the canopy; use d_ref if you don't have this observation	
p_atm	kPa	Atmospheric pressure observed at your location; can be computed from elevation	This is a critical value to have
CO2_atm	ppm	Concentration of carbon dioxide in the atmosphere	This is a critical value to have
T0	deg C	Temperature at the ground surface	
Tsurf	deg C	Temperature of the top soil layer	
Troot	deg C	Average temperature of the root zone	
Zw	m	Depth of the water table; can be used to provide a water source from below	This can be enabled or disabled in simulation_functions.c
xylem scalar	unitless	Has been used for multiple purposes; currently, a 1.0 does nothing, 0.99 forces xylem refilling	
Carbon flux	umol m-2 s-1	Legacy column for use with the Bayesian MCMC algorithm	Use -999 if you have no data
Water flux	mm 30min-1	Legacy column for use with the Bayesian MCMC algorithm	Use -999 if you have no data
		Note: There can be no missing entries on a line	
		Also: Missing time steps will yield unexpected results, as the model uses location (.p file), date, and time to compute clear-sky radiation and day length	

Table 2. TREES parameters. Colors are used to distinguish parameters associated with each photosynthesis model, an older C3 Farquhar model, an experimental C3 model that includes novel nitrogen assimilation, and a C4 model.

Type	Value	Description	Units	Parameter name in TREES code	Typical Range	Representative Reference
Site	550	Site Elevation	Meters	altitude	0 - 30000	
Site	47.438	Latitude	Degrees	latitude	-90 - 90	
Site	7.777	Longitude	Degrees	longitude	-180 - 180	
Site	30	Meteorological station reference height	Meters	z_ref	1 - 30	
Canopy	4.8	Leaf area index	m2 m-2	lai	0.05 - 10	
Canopy	20	Canopy height	Meters	canopy_height	0 - 100	
Canopy	4.8	Leaf area index at plant full height	m2 m-2	lai_at_full_canopy_height	0.05 - 10	
Canopy	1	Leaf angle distribution; vertical=0, spherical=1, horizontal>>1	unitless	l_angle	0 - infinity	Campbell & Norman 1998
Canopy	0.97	Canopy emissivity	unitless	canopy_emissivity	0.8 - 1.0	Campbell & Norman 1998
Canopy	0.5	Fraction of direct beam solar radiation that is photosynthetically active radiation	unitless	fPAR_beam	0.5 - 0.5	Campbell & Norman 1998
Canopy	0.5	Fraction of diffuse solar radiation that is photosynthetically active radiation	unitless	fPAR_diff	0.5 - 0.5	Campbell & Norman 1998
Canopy	0.92	Fraction of incident PAR abosrbed	unitless	alpha_PAR	0.85 - 0.92	Campbell & Norman 1998
Canopy	0.2	Fraction of near infrared energy absorbed	unitless	alpha_NIR	0.2 - 0.2	Campbell & Norman 1998
Canopy	0.5	Leaf clumping factor when viewed at nadir (<1 clumped; >1 uniform; 1 random)	unitless	omega	0.4 - 1.0	Campbell & Norman 1998
Canopy	1.5	Leaf clumping sun angle exponent (=3.8 - 0.46 * CrownDepth / CrownDiameter)	unitless	p_crown	1 - 3.34	Campbell & Norman 1998
Canopy	0.67	Height of the zero-plane displacement as a fraction of canopy height	unitless	d_factor	0.65 - 0.72	Campbell & Norman 1998
Canopy	0.1	Momentum roughness length as a fraction of canopy height	unitless	zm_factor	0.08 - 1.2	Campbell & Norman 1998
Canopy	0.2	Heat and vapor roughless length as a fraction of momentum roughness	unitless	zh_factor	0.2 - 0.2	Campbell & Norman 1998
Photosynthesis	2	Select photosynthesis model to use (1 = original C3; 2 = Experimental C3; C4)	integer	ps_model,	1, 2, or 3	
Photosynthesis	0.01	Dark respiration as a fraction of Vcmax	unitless	Rd_mult,	0.001 - 0.05	von Caemmerer 2013 PC&E
Photosynthesis	1.85	Ratio of Jmax to Vcmax, for use with PS model 1	unitless	Jmax_mult,	1.5 - 3.0	von Caemmerer 2013 PC&E
Photosynthesis	0.8	Curvature parameter for Rubisco regeneration limitation function	unitless	thetaJ,	0.7 - 0.9	von Caemmerer 2013 PC&E
Photosynthesis	0.3	Quantum yield of photosynthesis for sunlit leaves (well watered)	mol e- / mol photons	phiJ_sun,	0 - 0.5	von Caemmerer 2013 PC&E
Photosynthesis	0.3	Quantum yield of photosynthesis for shade leaves (well watered)	mol e- / mol photons	phiJ_shd,	0 - 0.5	von Caemmerer 2013 PC&E
Photosynthesis	0.001	Leaf nitrogen concentration, for use with PS model 1	kgN m-2 leaf	Nleaf	0.0001 - 0.003	
Photosynthesis	0	Fraction of Rubisco N that is not affected by N cycle, for use with PS model 1	unitless	N_fixed_proportion	0 - 1	
Photosynthesis	0.16	Fraction of leaf nitrogen in Rubisco, for use with PS model 1	unitless	Nrubisco,	0.1 - 0.2	
Photosynthesis	38.67764	Michaelis-Menten constant for carboxylase at 25 degree C	Pa	Kc25,		von Caemmerer 2013 PC&E
Photosynthesis	2.1	Q10 for kc	unitless	Q_10		von Caemmerer 2013 PC&E
Photosynthesis	26123.26	Michaelis-Menten constant for oxygenase at 25 degree C	Pa	Ko25,		von Caemmerer 2013 PC&E
Photosynthesis	1.2	Q10 for ko	unitless	Q_10		von Caemmerer 2013 PC&E
Photosynthesis	3.6	Michaelis-Menten constant for Rubisco activity at 25 degree C	umol/mgRubisco/min	Rubisco		von Caemmerer 2013 PC&E
Photosynthesis	2.4	Q10 for Rubisco activity	unitless	q10act,		von Caemmerer 2013 PC&E
Photosynthesis	30	Maximum Rubisco activity at 25 C, for use with PS models 2 and 3	umol m-2 s-1	Vcmax25,	10 - 200	von Caemmerer 2013 PC&E
Photosynthesis	460	Maximum PEP carboxylase activity at 25 C, for use with PS model 3	umol m-2 s-1	Vpmax25,	10 - 500	von Caemmerer 2013 PC&E
Photosynthesis	50	Maximum electron transport rate at 25 C, for use with PS models 2 and 3	umol m-2 s-1	Jmax25,	15 - 600	von Caemmerer 2013 PC&E
Photosynthesis	38.6	CO2 compensation point at 25 C	umol	gammaStar25,		von Caemmerer 2013 PC&E
Photosynthesis	80	Michaelis-Menten constant of PEP carboxylase for CO2 at 25 C, PS model 3	Kp25,	Kp25		von Caemmerer 2013 PC&E
Photosynthesis	80	PEP regeneration rate, PS model 3	umol m-2 s-1	Vpr,		von Caemmerer 2013 PC&E
Photosynthesis	0	Correction for spectral quality of light, PS models 2 and 3	unitless	f,		von Caemmerer 2013 PC&E
Photosynthesis	0.4	Partitioning factor of electron transport rate, for use with PS models 2 and 3	unitless	x,	0 - 0.15	von Caemmerer 2013 PC&E
Photosynthesis	0.92	Fraction of irradiance absorbed by mesophyll cells, PS models 2 and 3	unitless	absorptance,	0.85 - 0.92	von Caemmerer 2013 PC&E
Photosynthesis	56	Activation energy for the maximum carboxylation rate	kJ mol-1	E_Vcmax,		von Caemmerer 2013 PC&E
Photosynthesis	70.373	Activation energy for the maximum PEP carboxylation rate	kJ mol-1	E_Vpmax,		von Caemmerer 2013 PC&E
Photosynthesis	40	Activation energy for the electron transport rate	kJ mol-1	E_Jmax,		von Caemmerer 2013 PC&E
Photosynthesis	36.3	Activation energy for the Michaelis reaction of PEP	kJ mol-1	E_Kp,		von Caemmerer 2013 PC&E
Photosynthesis	59.36	Activation energy for the Michaelis reaction of carboxylation	kJ mol-1	E_kc,		von Caemmerer 2013 PC&E
Photosynthesis	35.94	Activation energy for the Michaelis reaction of oxygenation	kJ mol-1	E_ko,		von Caemmerer 2013 PC&E
Photosynthesis	66.3	Activation energy for the Michaelis reaction of mitochondrial respiration	kJ mol-1	E_Rd,		von Caemmerer 2013 PC&E
Photosynthesis	23.4	Activation energy for the Michaelis reaction of the CO2 compensation point	kJ mol-1	E_gammaStar,		von Caemmerer 2013 PC&E
Photosynthesis	1.78	Mesophyll conductance to CO2	mol m-2 s-1	gm,	0.5 - 3.0	von Caemmerer 2013 PC&E
Photosynthesis	0.003	Bundle sheath conductance to CO2	mol m-2 s-1	gbs,	0.003 - 0.003	von Caemmerer 2013 PC&E
Photosynthesis	0.09	Fraction of glycolate carbon diverted to glycine during photorespiration, PS model 3	unitless	alphaGmax,		Busch *et al.*, 2017 Nature Plants
Photosynthesis	0.38	Fraction of glycolate carbon diverted to serine during photorespiration, PS model 3	unitless	alphaSmax,		Busch *et al.*, 2017 Nature Plants
Photosynthesis	1.5	Maximum rate of de novo nitrogen supply to the chloroplast, PS model 3	umol N m-2 s-1	Nmax,		Busch *et al.*, 2017 Nature Plants
Diffusive Conductance	0.065	Initial reference canopy average stomatal conductance	mol m-2 s-1	GSref0	0.01 - 1.0	Oren *et al.*, 1999 PC&E
Diffusive Conductance	0.59	Sensitivity of canopy average stomatal conductance to vapor pressure deficit	unitless	m	0.45 - 0.59	Oren *et al.*, 1999 PC&E
Diffusive Conductance	0	Boolean to define either hypostomatus (=0) or amphistomatos (=1) leaves	boolean	isAmphistomatous,	0 or 1	
Soil-Plant Hydraulics	-0.05	Diagnostic to check if leaf water potential is more positive than this value	MPa	for	-0.01 to -1.0	Sperry et al., 1998 PC&E
Soil-Plant Hydraulics	-1.37	Midday leaf water potential at saturated hydraulic conductance	MPa	midday_at_sat_kl	-1.0 - -3.0	Sperry et al., 1998 PC&E
Soil-Plant Hydraulics	1.52	Transpiration at saturated hydraulic conductance	mmol m-2 s-1	e_at_saturated_kl	0.1 - 10.0	Sperry et al., 1998 PC&E
Soil-Plant Hydraulics	3	Rhizosphere width (recommend using values between 3 and 5)	mm	rhizosphere_width_(mm)	3 - 5	Sperry et al., 1998 PC&E
Soil-Plant Hydraulics	4	Number of soil shells in the rhizospheres (1 to 8)	integer	soilshells	2-6	Sperry et al., 1998 PC&E
Soil-Plant Hydraulics	0.025	Geometric mean soil particle diameter	mm	GMP	0.001 - 1.0	Sperry et al., 1998 PC&E
Soil-Plant Hydraulics	18	Geometric standard deviation of soil particle size	mm	GSD	2 - 32	Campbell 1985
Soil-Plant Hydraulics	0.76	Soil bulk density	MG m-3	BD	0.7 - 1.7	Campbell 1985
Soil-Plant Hydraulics	0.71	Soil porosity	unitless	porosity	0.35 - 0.75	Rawls et al 1994
Soil-Plant Hydraulics	0.3	Silt fraction	unitless	silt_fraction	0.01 - 0.7999	Rawls et al 1994
Soil-Plant Hydraulics	0.4	Clay fraction	unitless	clay_fraction	0.01 - 0.7999	Rawls et al 1994
Soil-Plant Hydraulics	0.04	Residual water content	unitless	residual	0.02 - 0.12	van Genuchten *et al.*, 1981
Soil-Plant Hydraulics	1	Fraction of absorbing length of lateral roots (usually keep at 1)	unitless	frac_absorbing_length,	0 - 1	Sperry et al., 1998 PC&E
Soil-Plant Hydraulics	0.01	Capacitance	mol/Mpa*m2	Capacitance_(mol/Mpa*m2)_on_lea	0.01 - 0.1	Sperry et al., 1998 PC&E
Soil-Plant Hydraulics	1	Ratio of shoot axial to lateral hydraulic conductances (usually keep at 1)	unitless	axK:latKr_shoot_modules,	1	Sperry et al., 1998 PC&E
Soil-Plant Hydraulics	1	Ratio of root axial to lateral hydraulic conductances (usually keep at 1)	unitless	axkr:latKr_root_modules,	1	Sperry et al., 1998 PC&E
Soil-Plant Hydraulics	50	Percent of total resistance in the root system (typically use 50)	percent	%total_R_in_root_system,	25 - 75	Sperry et al., 1998 PC&E
Soil-Plant Hydraulics	-0.45	Predawn leaf water potential at saturated hydraulic conductance	MPa	pd_at_sat_kl	-0.1 - -1.6	Sperry et al., 1998 PC&E
Soil-Plant Hydraulics	3.84247	Axial shoot vulnerability curve Weibull b parameter	-MPa	ax_Shoot-b_value_(weibull)	1.2 - 6.0	Sperry *et al.*, 1998 PC&E
Soil-Plant Hydraulics	6.43333	Axial shoot vulnerability curve Weibull c parameter	unitless	ax_Shoot-c_value_(weibull)	1.0 - 12.0	Sperry *et al.*, 1998 PC&E
Soil-Plant Hydraulics	3.84247	Lateral shoot vulnerability curve Weibull b parameter	-MPa	lat_Shoot-b_value_(weibull)	1.2 - 6.0	Sperry *et al.*, 1998 PC&E
Soil-Plant Hydraulics	6.43333	Lateral shoot vulnerability curve Weibull c parameter	unitless	lat_Shoot-c_value_(weibull)	1.0 - 12.0	Sperry *et al.*, 1998 PC&E
Soil-Plant Hydraulics	3.84247	Axial root vulnerability curve Weibull b parameter	-MPa	ax_Root-b_value_(weibull)	1.2 - 6.0	Sperry *et al.*, 1998 PC&E
Soil-Plant Hydraulics	6.43333	Axial root vulnerability curve Weibull c parameter	unitless	ax_Root-c_value_(weibull)	1.0 - 12.0	Sperry *et al.*, 1998 PC&E
Soil-Plant Hydraulics	3.84247	Lateral root vulnerability curve Weibull b parameter	-MPa	lat_Root-b_value_(weibull)	1.2 - 6.0	Sperry *et al.*, 1998 PC&E
Soil-Plant Hydraulics	6.43333	Lateral root vulnerability curve Weibull c parameter	unitless	lat_Root-c_value_(weibull)	1.0 - 12.0	Sperry *et al.*, 1998 PC&E
Soil-Plant Hydraulics	30	Initial conductivity used in setup routine to compute saturated Ks of roots	used	initial_conductivity(root),	10 - 40	Sperry *et al.*, 1998 PC&E
Soil-Plant Hydraulics	0.02	Decrement rate for computing saturated Ks of roots	default	decrement(root)-		Sperry *et al.*, 1998 PC&E
Soil-Plant Hydraulics	50	Initial conductivity used in setup routine to compute saturated Ks of stems	used	initial_conductivity(shoot),	20 - 80	Sperry *et al.*, 1998 PC&E
Soil-Plant Hydraulics	0.03	Decrement rate for computing saturated Ks of stems		decrement(shoot)		Sperry *et al.*, 1998 PC&E
Respiration	0.22	Optimal soil water content (% of saturation) for soil respiration	unitless	theta_opt	0.2 - 0.3	
Respiration	30	Optimal soil temperature for soil respiration	degrees C	optimal_soil_T	25 - 35	
Respiration	1	Growth respiration fraction of maximum (experimental, keep at 1)	unitless	growth_resp_proportion	1	
Respiration	0.0011	Root respiration coefficient	kg kg-1 day-1 deg	resp_coef_root,		Waring and Running 1995
Respiration	0.0002	Stem respiration coefficient	kg kg-1 day-1 deg	resp_coefficient_stem,		Waring and Running 1995
Respiration	0.0004	Leaf respiration coefficient	kg kg-1 day-1 deg	resp_coefficient_leaf,		Waring and Running 1995
Respiration	0.05	Respiration coefficient Q10	degC-1	resp_coefficient		Waring and Running 1995
Respiration	72.26	Parameter for the DAMM model	kjmol-1	EaSx,		Davidson *et al.*, 2011 GCB
Respiration	9.95E-07	Parameter for the DAMM model	gCcm-3soil	kMsx,		Davidson *et al.*, 2011 GCB
Respiration	5.38E-10	Parameter for the DAMM model	mgCcm-3soilh-1			Davidson *et al.*, 2011 GCB
Microbiome	0.00425	Microbial biomass mortaility rate constant	days-1	kd,	0.001 - 0.01	Porporato *et al.*, 2003 AWR
Microbiome	0.6	Nitrification rate constant	m3 days-1 gC-1	kn,	0.4 - 0.8	Porporato *et al.*, 2003 AWR
Microbiome	0.16	Amino acid exudate microbial consumption rate constant	m3 days-1 gC-1	kea,		
Microbiome	0.75	Sugar exudate microbial consumption rate constant	m3 days-1 gC-1	kes,		
Microbiome	0.000065	Labilie carbon (litter) microbial consumption rate constant	m3 days-1 gC-1	kl,		Porporato *et al.*, 2003 AWR
Microbiome	0.0000025	Recalcitrant carbon (humus) microbial consumption rate constant	m3 days-1 gC-1	kh,		Porporato *et al.*, 2003 AWR
Carbon and Nitrogen	14	Fine root minimum carbon:nitrogen ratio	kgC kgN-1	fr_minCN,	10 - 200	
Carbon and Nitrogen	55	Fine root maximum carbon:nitrogen ratio	kgC kgN-1	fr_maxCN,	10 - 200	
Carbon and Nitrogen	14	Leaf minimum carbon:nitrogen ratio	kgC kgN-1	leaf_minCN,	10 - 200	
Carbon and Nitrogen	55	Leaf maximum carbon:nitrogen ratio	kgC kgN-1	leaf_maxCN,	10 - 200	
Carbon and Nitrogen	79200	Total belowground carbon	kgC ha-1	Cbelowground,		
Carbon and Nitrogen	0.00015	Fraction of belowground carbon in litter - This is no longer used	unitless	Clitter_frac,		
Carbon and Nitrogen	0.05	Fraction of belowground carbon in fine roots (orders 1-5)	unitless	Croot_frac,		
Carbon and Nitrogen	10000	Total carbon in stems	kgC ha-1	Cstem,		
Carbon and Nitrogen	4000	Total carbon in sapwood	kgC ha-1	Csapwood,		
Carbon and Nitrogen	0.05	Fraction of belowground carbon in coarse roots (orders 6-10)	uniltess	Croot_coarse_frac,		
Hydrology	0.0000001	Interception of precipitation by canopy leaves on a per unit leaf area basis	m m-2 m2	interception_per_leafArea	0.00025 typical for conifers	
Hydrology	0.000001	Water storage capacity of ground surface litter	m	litter_capacity,		
Hydrology	0.32	Initial soil water content in soil layers 3 or deeper	m3 m-3	theta_deep0,		
Hydrology	0.3	Initial soil water content in soil layer 2	m3 m-3	theta_mid0,		
Hydrology	0.28	Initial soil water content in soil layer 1	m3 m-3	theta_shallow0,		
Hydrology	0	Initial water stored in ground surface litter	m	litter_store,		
Carbon and Nitrogen	9	Initial specific leaf area	m2 kgC-1	SLA,	3 - 400	
Root Growth	155.7	Specific root length at a root diameter of 0.25 mm	m gC-1	SRL1,	15 - 1500	Mackay *et al.*, 2020 New Phytol
Root Growth	0.00045	Finest order root diameter	m	minRootDiam,	0.0001 - 0.001	Mackay *et al.*, 2020 New Phytol
Root Growth	0.2	Root collar (or highest order) diameter	m	maxRootDiam,		Mackay *et al.*, 2020 New Phytol
Root Growth	0.5	Lifespan of the first order root at the lowest carbon:nitrogen ratio	years	minRootLifespan,	0.01 - 2.0	Mackay *et al.*, 2020 New Phytol
Legacy	0.5	Spring minimum leaf water potential, can be used if the hydraulic model is turned off	-Mpa	LWP_spring_minimum,		
Legacy	2.35	Leaf water potential at stomatal closure, can be used if the hydraulic model is turned off	-Mpa	LWP_stomatal_closure,		
Hydrology	0	A boolean variable to turn on if the system has bryophytes, e.g. sphagnum moss	boolean	is_bryophyte		
Hydrology	0	A scalar to linearly adjust capillary rise, which uses a steady state form of the Richards equatic	unitless	capRiseScalar,		
Hydrology	1	A scalar to linearly adjust precipitation (= scalar * precip in driver file)	unitless	precipReduction		
Hydrology	1	A scalar to adjust the leakiness of the lower boundary of the system (lowest soil layer)	unitless	drainScalar,		
Carbon and Nitrogen	0.1	A scalar to establish the target non-structural carbon in the leaf as a fraction of leaf structural c	kgC kgC-1	leafNSCscalar		
Canopy	1	A boolean to turn on the phenology model, which is used for perennial plants	boolean	usePhenology		
Canopy	5	The length of time for leaves/needles to remain alive (1 = deciduous; >= 2 for coniferous)	years	leafLifeSpan		
Soil-Plant Hydraulics	10	This sets an upper bound on the number of times the hydraulic model is called at each time ste	integer	max_iteration(the_max_number_of		
Microbiome	20	A scalar that adjusts the initial microbiome carbon (and nitrogen) from what is set in bgc.cpp	unitless	microbiomeScalar,		
Microbiome	0	This sets a rate of rain-in of microbial carbon (and nitrogen)	kgC ha-1 30min-1	microbialrainrate		
Microbiome	0	This sets a rate of rain-in of NH4+	kgN ha-1 30min-1	raininAmmonium		
Microbiome	0	This sets a rate of rain-in of NO3-	kgN ha-1 30min-1	raininNitrate		
Microbiome	0	This sets a rate of rain-in of mineral nitrogen	kgN ha-1 30min-1	raininMineralN		
Microbiome	0	This sets a rate of rain-in of labile carbon	kgC ha-1 30min-1	raininLabileC		
Hydrology	0	This variable is used to set the initial snowpack water equivalent	m	snowpack_water_equivalent,		
Hydrology	-10	This variable sets the lower boundary on the snowpack degree-day accumulation	deg	snowpack_E_deficit_max,		
Hydrology	0.0015	Melt rate coefficient used with the radiant energy balance driver of snowmelt	m decC-1 30min-1	melt_Rcoef,		
Soil-Plant Hydraulics	1	A boolean used to indicate that the full plant hydraulics is to be used during simulation (0 turns	0 or 1	useHydraulics,		
Soil-Plant Hydraulics	0	A boolean used to indicate that the xylem-scalar in the driver file is to be used as an effective h	0 or 1	useInputStress,		
Soil-Plant Hydraulics	0	A boolean used to turn on the xylem refilling - This parameter is no longer used	0 or 1	useInputWaterTable		
Soil-Plant Hydraulics	213	This is a parameter specifically added for simulating maize, to halt diel leaf refilling	day of the year	dayToStopMaizeRefilling,		
Leaf Growth	0	A boolean to turn on the leaf growth module designed for Brassica rapa and other annual crop	0 or 1	useLeafModule,		Wang *et al.*, 2019 JXB
Leaf Growth	11.211	Potential maximum leaf size, K parameter in the logistic growth curve	cm2	leafAreaMax		Wang *et al.*, 2019 JXB
Leaf Growth	0.939134	Initial leaf size, N paramter in the logistic growth curve	//A_pot_in	initialLeafSize		Wang *et al.*, 2019 JXB
Leaf Growth	0.0004958	Rate parameter, r parameter in the logistic growth curve	//r	leafArea_Rate		Wang *et al.*, 2019 JXB
Leaf Growth	11024.02	Duration of leaf expansion in degree		dur_LeafExpansion//d_exp		Wang *et al.*, 2019 JXB
Leaf Growth	16	Maximum specific leaf area		SLA_max		Wang *et al.*, 2019 JXB
Leaf Growth	6	Minimum specific leaf area		SLA_min		Wang *et al.*, 2019 JXB
Leaf Growth	60	Angle between leaf petiole and main stem	degrees	leaf_insertAngle		Wang *et al.*, 2019 JXB
Leaf Growth	2.5	Ratio between leaf length and width	cm cm-1	leaf_len_to_width		Wang *et al.*, 2019 JXB
Leaf Growth	0.9	Proportion of total time of leaf development that cell division phase occurs		proportion_CD		Wang *et al.*, 2019 JXB
Leaf Growth	1970.534	Thermal time between leaf appearance events		phyllochron		Wang *et al.*, 2019 JXB
Leaf Growth	13507.5	Thermal time to flowering		floweringTime		Wang *et al.*, 2019 JXB
Leaf Growth	0.96	Developmental base temperature		Tbase		Wang *et al.*, 2019 JXB
Leaf Growth	4926.335	Thermal time to third leaf initiation (approximated by leaf emergence/appearance)		therm_plant		Wang *et al.*, 2019 JXB
Leaf Growth	15	Projected shoot area at third leaf initiation (approximate by leaf emergence/appearance)	cm2	projectedArea_init		Wang *et al.*, 2019 JXB
Leaf Growth	40	Maximum projected area (or pot area)	cm2	pot_size		Wang *et al.*, 2019 JXB
Leaf Growth	0.43	Root to shoot carbon allocation		root_to_shoot		Wang *et al.*, 2019 JXB
Leaf Growth	1.59	Leaf to stem carbon allocation		leaf_to_stem		Wang *et al.*, 2019 JXB
Leaf Growth	0	A boolean to turn on stochastic leaf growth, which uses alpha and beta parameter below)		useLeafGamma		Wang *et al.*, 2019 JXB
Leaf Growth	439.166	Shape parameter of gamma distribution for leafAreaMax		Kalpha		Wang *et al.*, 2019 JXB
Leaf Growth	39.1181	Rate parameter of gamma distribution for leafAreaMax		Kbeta		Wang *et al.*, 2019 JXB
Leaf Growth	23.6077	Shape parameter of gamma distribution for initialLeafSize		Nalpha		Wang *et al.*, 2019 JXB
Leaf Growth	25.0841	Rate parameter of gamma distribution for initialLeafSize		Nbeta		Wang *et al.*, 2019 JXB
Leaf Growth	123.08	Shape parameter of gamma distribution for leafArea_Rate		ralpha		Wang *et al.*, 2019 JXB
Leaf Growth	248167	Rate parameter of gamma distribution for leafArea_Rate		rbeta		Wang *et al.*, 2019 JXB
Bayesian MCMC	10	Standard error of transpiration, for use with Bayesian Metropolis-Hastings MCMC algorithm	100	sd_err_Ec		Mackay *et al.*, 2012 J. Hydrol.
Bayesian MCMC	2.12692	Standard error of net ecosystem exchange, for use with Bayesian Metropolis-Hastings MCMC	15	sd_err_NEE		Mackay *et al.*, 2012 J. Hydrol.
Bayesian MCMC	0	Weight apply to the standard errors (1 = 100% Ec; 0.5 = equal weight; 0 = 100% to NEE)	1	sd_err_Ec_weight		Mackay *et al.*, 2012 J. Hydrol.

Table 3. This 'param_mod' file describes the plant hydraulic segments, including lateral and axial shoot module (one) and six lateral and axial root modules with soil-root layer thicknesses of 5, 10, 15, 10, 5, and 55 cm. The sixth layer contains no roots.

Name in param mod file	Value	Description
#_of_shoot_modules	1	TREES is currently set up to use one lateral shoot in the hydraulic model
leaf_area_fraction	1	By default with one shoot module this should be set to 1
length_lateral	0.1	This is a scalar that is multiplied by length_axial to get lateral stem length
length_axial	20	Length of the axial stem in meters
#_of_root_modules	6	This can be from 1 to 21; typical numbers are 4 to 7
leaf_area_fraction	0.213	This sets the initial fraction of leaf (and root) area supported by this layer
length_lateral	2	This is a scalar that is multiplied by the sum of axial lengths to get lateral root length in this layer
length_axial	0.05	This layer has a thickness of 5 cm
leaf_area_fraction	0.213	
length_lateral	2	
length_axial	0.1	This layer has a thickness of 10 cm
leaf_area_fraction	0.32	
length_lateral	1.5	This layer has a lateral root extent that is 75% of that of the surface layer
length_axial	0.15	
leaf_area_fraction	0.213	
length_lateral	1	
length_axial	0.1	
leaf_area_fraction	0.041	
length_lateral	0.1	
length_axial	0.05	
leaf_area_fraction	0.0000001	Setting this to a very small number sets the fine root area for this layer to near zero
length_lateral	0.0000001	Setting this to a very small number (<0.00001) means this layer will never grow fine roots
length_axial	0.55	

Table 4. TREES main outputs (.sim). Each column is output at each 30-minute time step. This can produce a big file of about 20 MB per year of simulation.

Output Column	Units	Description	Notes
ti		year-date-hour	
simET	mm s-1	evapotranspiration	This can be compared to eddy covariance tower ET data
WPlant_K	mmol m-2 s-1 MPa-1	whole plant hydraulic conductance	This is the full rhizosphere-plant hydraulic conductance
Soil_Psi	MPa	soil water potential	This is a root profile weighted average
Leaf_Psi	MPa	leaf water potential	
Psi_Crit	MPa	critical leaf water potential	
Ecrit	mmol m-2 s-1	critical transpiration	Maximum transpiration without causing hydraulic failure
Ec	mmol m-2 s-1	transpiration	
RhizFluxX	mmol m-2 s-1	rhizosphere flux - one column per soil-root layer	X = 0, 1, 2…N soil-root layers
Gs	mol m-2 s-1	stomatal conductance	This is a canopy average stomatal conductance
LAI	m2 -m-2	actual leaf area index	
SLA	m2 kgC-1	Specific leaf area	
liveLAI	m2 -m-2	forecast live leaf area index	This variable is used internally to compute LAI potential for next year in perennials
Rmaint	kgC ha-1	maintenance respiration	Whole plant
Rgrowth	kgC ha-1	growth respiration	Whole plant
leafNSC	kgC ha-1	non-structural carbon	
stemNSC	kgC ha-1	non-structural carbon	
rootNSC	kgC ha-1	non-structural carbon	
chloroStarch	kgC ha-1	non-structural carbon	Follows a diel cycle; drives allocation of carbon for growth
chloroSugar	kgC ha-1	non-structural carbon	Follows a diel cycle; drives allocation of carbon for growth
waterStress	unitless	stress = Ecrit / Esat, plant is water stressed when this value is less than 1.0	Used for initial guess at stomatal conductance; used to reduce quantum yield
litterH2O	m3 m-3	litter layer water content	
thetaX	m3 m-3	layer soil water content - one column per soil-root layer	X = 0, 1, 2…N soil-root layers
thetaRoot	m3 m-3	root average soil water content	
Can_Evap	mm s-1	free evaporation from wet canopy	
Snowpack	m	snow water equivalent	
SnowEdef	deg C-1	snow energy deficit	
Vcmax25	umol m-2 s-1	maximum carboxylation at 25 C	Currently writes out zeros for photosynthesis models 2 and 3
Vcmax_sun	umol m-2 s-1	leaf level Vcmax	Currently writes out zeros for photosynthesis models 2 and 4
Vcmax_shd	umol m-2 s-1		Currently writes out zeros for photosynthesis models 2 and 5
Jmax25	umol m-2 s-1	maximum J at 25 C	Currently writes out zeros for photosynthesis models 2 and 6
J_sun	umol m-2 s-1	leaf level J	Currently writes out zeros for photosynthesis models 2 and 7
J_shd	umol m-2 s-1		Currently writes out zeros for photosynthesis models 2 and 8
Asun	umol m-2 s-1	leaf level photosynthesis	
Ashd	umol m-2 s-1		
Lsun	m2 m-2	leaf level area	
Lshd	m2 -m-2		
Tsun	deg C	leaf level temperature	
Tshd	deg C		
Dsun	kPa	leaf level vapor pressure defiit	
Dshd	kPa		
Ci_sun	ppm	leaf level intercellular CO2	
Ci_shd	ppm		
PARsun	umol m-2 s-1	leaf level absorbed PAR	
PARshd	umol m-2 s-1		
gs_sun	mol m-2 s-1	leaf level stomatal conductance	
gs_shd	mol m-2 s-1		
NEE	umol m-2 s-1	net ecosystem exchange	This can be compared to eddy covariance tower ET data
NPP	umol m-2 s-1	net primary production	
R_total	umol m-2 s-1	total respiration	
R_ag	umol m-2 s-1	aboveground respiration	
R_bg	umol m-2 s-1	belowground respiration	
Rd_sun	umol m-2 s-1	dark respiration	
Rd_shd	umol m-2 s-1		
Csapwood	kgC ha-1	stem carbon	
FibRootCX	kgC ha-1	root order 1 carbon content, one column per soil-root layer	X = 0, 1, 2…N soil-root layers
FineRootCX	kgC ha-1	root order 2 carbon content, one column per soil-root layer	X = 0, 1, 2…N soil-root layers
TotRootCX	kgC ha-1	total root carbon content, one column per soil-root layer	X = 0, 1, 2…N soil-root layers
FineRootCNX	kgC kgN-1	root orders 1&2 carbon to nitrogen ratio, one column per soil-root layer	X = 0, 1, 2…N soil-root layers
LeafCN	kgC kgN-1	leaf C:N	
humusCX	kgC ha-1	humus carbon content, one column per soil-root layer	X = 0, 1, 2…N soil-root layers
RhizClX	kgC ha-1	labile organic carbon, one column per soil-root layer	X = 0, 1, 2…N soil-root layers
RhizNlX	kgN ha-1	labile organic nitrogen, one column per soil-root layer	X = 0, 1, 2…N soil-root layers
AAexudateCX	kgC ha-1	amino acid content, one column per soil-root layer	X = 0, 1, 2…N soil-root layers
SugarExudateCX	kgC ha-1	sugar exudate content, one column per soil-root layer	X = 0, 1, 2…N soil-root layers
MicrobCX	kgC ha-1	live microbial carbon, one column per soil-root layer	X = 0, 1, 2…N soil-root layers
MicrobNX	kgN ha-1	live microbial nitrogen, one column per soil-root layer	X = 0, 1, 2…N soil-root layers
RhizN-	kgN ha-1	rhizosphere nitrate content	
RhizN+	kgN ha-1	rhizosphere ammonium content	
PlantN	kgN ha-1	total plant nitrogen	
PlantNstat	unitless	Combined index of N available to the plant relative to N needed for incremental growth	
RLA	m2 root m-2 leaf	root-to-leaf area ratio	
arX	m2 root layer m-2 total root	fraction of root area in layer, one column per soil-root layer	X = 0, 1, 2…N soil-root layers

Table 5. Hydraulic outputs used to reconstruct vulnerability to cavitation curves and identify hydraulic conductance changes in different xylem elements.

Output Column	Units	Description	Notes
ti		year-date-hour	
latStemK	mmol m-2 s-1 MPa-1	Lateral stem hydraulic conductance	Ignore this variable
latRootKX	mmol m-2 s-1 MPa-1	Lateral root hydraulic conductance, one column for each soil-root layer	X = 0, 1, 2, …, N; ignore this variable
StemAxialYm	MPa	Axial stem minimum water potential reached	
StemLatYm	MPa	Lateral stem minimum water potential reached	
RootAxialYmX	MPa	Axial root minimum water potential reached, one column for each soil-root layer	X = 0, 1, 2, …, N
RootLatYmX	MPa	Lateral stem minimum water potential reached, one column for each soil-root laye	X = 0, 1, 2, …, N
StemAxialKm	mmol m-2 s-1 MPa-1	Axial stem maximum hydraulic conductance	
StemLatKm	mmol m-2 s-1 MPa-1	Lateral stem maximum hydraulic conductance	
RootAxialKmX	mmol m-2 s-1 MPa-1	Axial root maximum hydraulic conductance, one column for each soil-root layer	X = 0, 1, 2, …, N
RootLatKmX	mmol m-2 s-1 MPa-1	Lateral root maximum hydraulic conductance, one column for each soil-root layer	X = 0, 1, 2, …, N
StemAxial_b	-Mpa	Axial stem Weibull b parameter	
StemLat_b	-Mpa	Lateral stem Weibull b parameter	
RootAxial_bN	-Mpa	Axial root Weibull b parameter, one column for each soil-root layer	X = 0, 1, 2, …, N
RootLat_bN	-Mpa	Lateral root Weibull b parameter, one column for each soil-root layer	X = 0, 1, 2, …, N
StemAxial_c	unitless	Axial stem Weibull c parameter	
StemLat_c	unitless	Lateral stem Weibull c parameter	
RootAxial_cN	unitless	Axial root Weibull c parameter, one column for each soil-root layer	X = 0, 1, 2, …, N
RootLat_cN	unitless	Lateral root Weibull c parameter, one column for each soil-root layer	X = 0, 1, 2, …, N
Notes: These outputs are used to reconstruct vulnerability curves and hydraulic conductance of each plant segment at any point in time			
Reference: Mackay et al 2015 Water Resources Research			

Table 6. Individual leaf model output of time series of each leaf area.

Output Column	Units	Description	Notes
ti		year-date-hour	
Area_Leaf_X	cm2	Area of individual leaf, one column per leaf	X = 0, 1, 2, …, N
Reference: Wang et al 2019 Journal of Experimental Botany			