

Supplement of

Water and carbon balance of rubber trees modelled under changing climate and management-driven disturbances

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Supplementary material

Tables

Table S1: Summary of historical meteorological input data for model forcing (1994-2019)

Dataset	Input variable (unit)	Data type	Period	Temporal resolution	Reference	URL	Last access
NASA's POWER dataset	Solar radiation (MJ hr^{-1}),	Reanalysis data	1994	1 hr	NASA Langley Research Center (2025)	https://power.larc.nasa.gov/	24/03/2025
	PAR ($\mu\text{mol m}^{-2} \text{s}^{-1}$),		-				
	Temperature ($^{\circ}\text{C}$),		2011				
	Relative humidity (%), Wind Speed (m/s)						
EC tower / Weather station data	Solar radiation (W m^{-2}),	Measured	2012	30 min	This study		
	PAR ($\mu\text{mol m}^{-2} \text{s}^{-1}$),		-				
	Temperature ($^{\circ}\text{C}$),		2019				
	Relative humidity (%), Wind Speed (m/s)						

Table S2: Summary of measured variables and parameters for parameterization at both sites, including the measurement methods, periods, and frequencies

Site		Variable	Measurement period	Measurement frequency	Method / Instrument	Note / Source
CRRC & SKRS	Hydro-meteorological	Air temperature	2015-2018 & 2019-2021	Half-hourly	Vaisala sensors (Vaisala Inc. Model HMP45-C)	Wang et al. (2022) & this study
		Relative humidity	2015-2018 & 2019-2021	Half-hourly	Vaisala sensors (Vaisala Inc. Model HMP45-C)	Wang et al. (2022) & this study
		Photosynthetically active radiation	2015-2018 & 2019-2021	Half-hourly	Quantum sensors (Li-190, Li-Cor Inc., USA)	Wang et al. (2022) & this study
		Global incident solar radiation	2015-2018 & 2019-2021	Half-hourly	Pyranometer (Li200, Li-Cor Inc., USA)	Wang et al. (2022) & this study
		Precipitation	2015-2018 & 2019-2021	Half-hourly	Tipping bucket rain gauges (TE525, Campbell Scientific, Inc., USA)	Wang et al. (2022) & this study
		Soil volumetric water content	2015-2018 & 2019-2021	Half-hourly	Thermocouple probes (TCAV, Campbell Scientific, Inc., USA)	Wang et al. (2022) & this study
CRRC	Carbon dioxide and water vapor fluxes	Latent heat flux	2015-2018	Half-hourly	Eddy Covariance instruments: three-dimensional ultrasonic anemometer (CSAT-3, Campbell Scientific Inc., USA), & CO2/H2O open-path infrared gas analyzer (LI-7500, LI-COR Inc., USA). Carbon fluxes partitioning	Wang et al. (2022)
		Evapotranspiration	2015-2018	Half-hourly		
		Canopy transpiration	2015-2018	Half-hourly		
		Vapor pressure deficit	2015-2018	Half-hourly		
		Net ecosystem exchange	2015-2018	Half-hourly		
		Gross primary production	2015-2018	Half-hourly		
		Ecosystem respiration	2015-2018	Half-hourly		
CRRC	Leaf photosynthesis	Maximum rate of rubisco carboxylation (Vcmax)	2006-2007	Monthly	Assimilation-Intercellular CO ₂ response curve (A/Ci curve)	This study
		Maximum rate of electron transport supporting ribulose-1.5-bisphosphate regeneration (Jmax)	2006-2007	Monthly		
		Mitochondrial respiration rate in the light (Rd0)	2006-2007	Monthly		
CRRC	Phenology	Litterfall biomass	2016-2020	Monthly	Litter trap	This study
		LAI	2017-2020	Weekly	Hemispherical photography (fisheye)	This study
CRRC & SKRS	Biomass and growth	Girth	2012-2020 & 2014-2021	Monthly	Ruler	This study
		Trunk, branches, stump, root biomasses	2012-2020 & 2014-2020	Yearly	Allometric equations for biomass	Hytönen et al., (2018)
		Proportion of living wood in trunk and branches	-	Single measurement	Mortality rate???	Cherelli et al., (2023)

CRRC	Biochemical composition	C and N content of leaves, branches, stem, stump and roots	-	Single	Biochemical composition analysis	Hytönen et al., (2019)
CRRC SKRS	Latex	Latex yield	Monthly Daily	2012-2020 2014-2021	Tapping 1/2 S d/2 Tapping S/2 d2 7d7 10m	This study Chotiphan et al., (2019)
CRRC & SKRS	Soil properties	Soil texture	2012-2020	Single measurement	Soil sampling (10-90 cm)	This study
		Soil hydraulic properties per soil layer: parameters of soil retention and conductivity	-	-		Otoni et al. (2019) & Vereecken et al. (1989)
SKRS	Hydro-meteorological	Soil water content	2014-2021	Half-hourly	Thermocouple probes (TCAV, Campbell Scientific, Inc., USA)	This study

Table S3. Soil hydraulic parameters used for the parameterization of the van Genuchten soil water retention model and saturated hydraulic conductivity (layer 0.33, 0.66 and 1 m). Parameters include the van Genuchten inverse air-entry suction ($\alpha\Psi$), saturated volumetric water content (θ_{vs}), residual volumetric water content (θ_{vr}), and pore-size distribution parameter (n), which collectively define the soil water retention curve. Saturated hydraulic conductivity (KSAT) represents the ability of soil to transmit water under saturated conditions and was estimated following Ottoni et al. (2019). Soil hydraulic retention parameters were derived using pedotransfer functions of Vereecken et al. (1989). Soil input variables include texture, organic carbon content, bulk density and soil porosity

Depth (m)	$\alpha\Psi$ (Mpa ⁻¹)	θ_{vs} (m ³ m ⁻³)	θ_{vr} (m ³ m ⁻³)	n (-)	KSAT (mol m ⁻¹ s ⁻¹ Mpa ⁻¹)
CRRC					
0.33	248.50	0.29	0.14	1.54	41.28
0.66	236.23	0.31	0.11	1.67	41.28
1	260.35	0.32	0.14	1.77	41.28
SKRS					
0.33	220.44	0.26	0.05	1.73	751.4
0.66	190.44	0.30	0.09	1.63	892.6
1	193.66	0.22	0.11	1.69	781.7

Table S4. Key variables and parameter values used in the photosynthesis, respiration, allocation, and latex yield model. For photosynthesis, respiration, and carbon allocation, only parameters modified relative to the Eucalyptus model Cornut et al. (2023a, b) are reported

Variable	Description	Value (Unit)	Reference
Canopy dynamics			
N_{START0}	Starting date for accumulating temperature values for leaf re-foliation	1 (doy)	Calibrated
N_{START2}	Starting date for accumulating temperature values for leaf fall	200 (doy)	Calibrated
T_0	Base temperature defining the seasonal reference threshold for re-foliation	28 (°C)	Calibrated
T_1	Base temperature defining the seasonal reference threshold for senescence	28 (°C)	Calibrated
S_{max}	Threshold of cumulative thermal index triggering leaf production	45 (°C)	Calibrated
S_{maxl}	Threshold of cumulative thermal index triggering leaf fall	25 (°C)	Calibrated
D_{min}	Reference minimum re-foliation period	14 (day)	Calibrated
D_{max}	Reference maximum re-foliation period	25 (day)	Calibrated
H_{min}	Reference minimum height when deciduous behavior starts	2.36 (m)	Calibrated
H_{max}	Reference maximum height at the end of the rotation	22 (m)	Estimated
k_f	Leaf senescence rate parameter	0.0002 & 0.00012 (-)	Calibrated
Photosynthesis			
$JMAX25$	Maximum rate of electron transport at 25 degC	91.3 ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Measured
$VCMAX25$	Maximum velocity of the carboxylase at 25 degC	60.43 ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Measured
AJQ	Quantum yield of electron: transport	0.28 ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Measured
$THETA$	Quantum yield of electron: curvature parameter	0.53 (-)	Measured
Respiration			
TC	C content dry matter	0.503 (frac)	Hytönen et al. (2019)
NTV	N content living stem	0.0019 (gN/gDM)	Hytönen et al. (2019)
NRF	N content fine roots	0.0023 (gN/gDM)	Hytönen et al. (2019)
NF	N content leaves	0.0332 (gN/gDM)	Hytönen et al. (2019)
NBR	N content branches	0.0033 (gN/gDM)	Hytönen et al. (2019)
NRG	N content coarse roots	0.0023 (gN/gDM)	Hytönen et al. (2019)
$NBRy$	N content young branches	0.0044 (gN/gDM)	Hytönen et al. (2019)
$Propaubier$	ratio of sapwood	0.5165 (-)	Cherelli et al. (2023)
$PropaubierBR$	ratio of sapwood in branches	0.5165 (-)	Cherelli et al. (2023)
RD	Dark respiration at 25 degC	1.31 ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Measured
Biomass and allocation			
GSS_{min}	Minimum allocation coefficient to storage	0.02 (-)	-

GSS_{max}	Maximum allocation coefficient to storage	0.3 (-)	-
Latex yield model			
DBH_{min}	Minimum diameter at breast height for tapping	16 (cm)	Yang et al. (2019)
$START_{jour}$	Start of tapping season	121 (doy)	Observed
END_{jour}	End of tapping season	365 (doy)	Observed
T_f	Tapping frequency	2 (day)	Observed
T_{fmin}	Minimum tapping frequency	1 (day)	Reported
T_{fmax}	Maximum tapping frequency	7 (day)	Reported
R_s	Fraction of the storage harvested on tapping day	0.0008 (-)	Calibrated
R_{ymin}	Minimum resource fraction allocated to latex	0.3 (-)	Calibrated
R_{ymax}	Maximum resource fraction allocated to latex	0.6 (-)	Calibrated
a	Correction factor accounting for increased reserve mobilization under very low leaf area conditions	1.25 (-)	Calibrated
$Ethephon$	Simulate ethephon application	FALSE	Reported
T_{max}^{opt}	Optimal max temperature for tapping	30.21 (°C)	Computed
T_{min}^{opt}	Optimal min temperature for tapping	22.67 (°C)	Computed
W^{opt}	Optimal soil water content for tapping	0.6 (-)	Computed
ΔT_{max}	Maximum temperature tolerance ranges	10 (°C)	Calibrated
ΔT_{min}	Minimum temperature tolerance ranges	10 (°C)	Calibrated
ΔW	Soil water tolerance range	0.15 (-)	Calibrated



Figure S1: Photographs illustrating seasonal leaf phenological dynamics of rubber trees at the CRRRC study site. From left to right: (a) leafless period at the beginning of the year; (b-d) progressive stages of refoliation, from onset to completion; (e) fully expanded canopy stage; and (f) defoliation period at the end of the year.

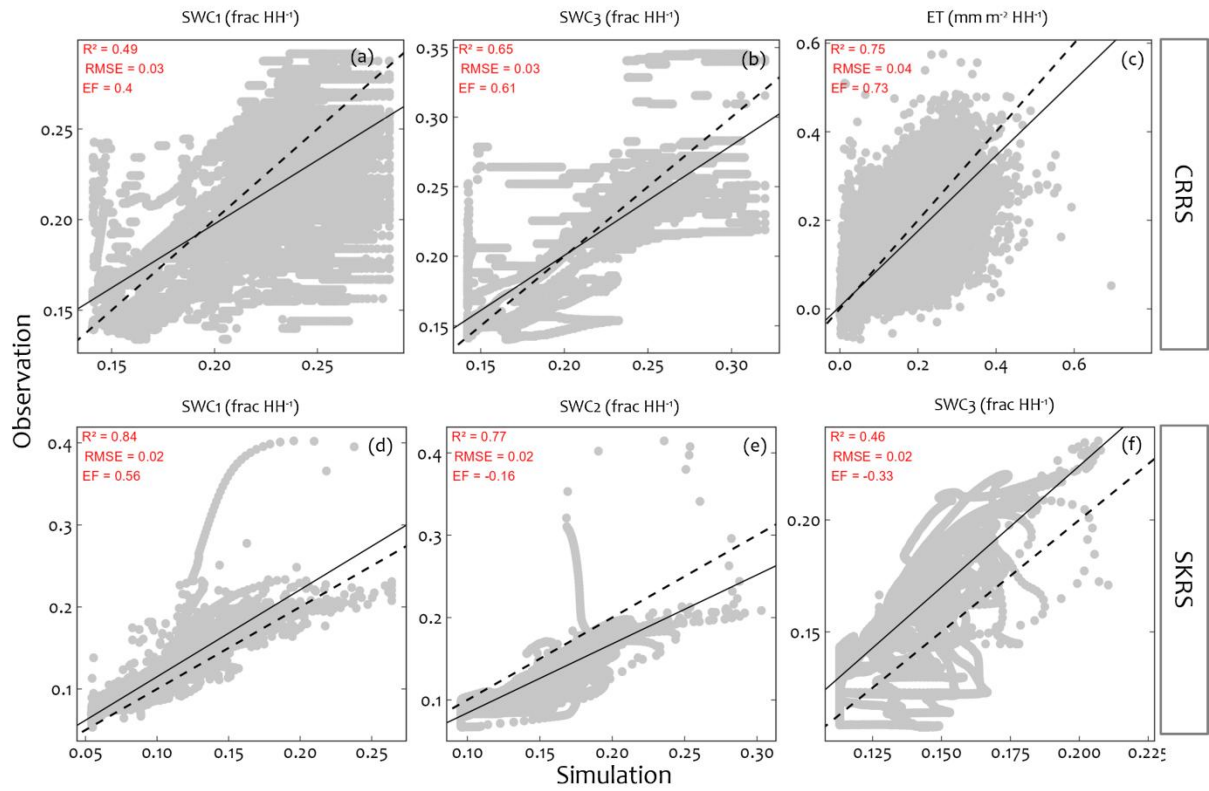


Figure S2: Scatter plots comparing observed vs. simulated soil water content (SWC) at CRRC and SKRS, and evapotranspiration (ET) at CRRC. Thick black lines represent linear regressions, and dashed black lines indicate 1:1 relationship. (a) SWC layer 1 (depth = 0.33 m) at CRRC, (b) SWC layer 3 (depth = 1.0 m) at CRRC, (c) ET at CRRC, (d-f) SWC layers 1-3 (depth = 0.33, 0.66, 1.0 m) at SKRS.

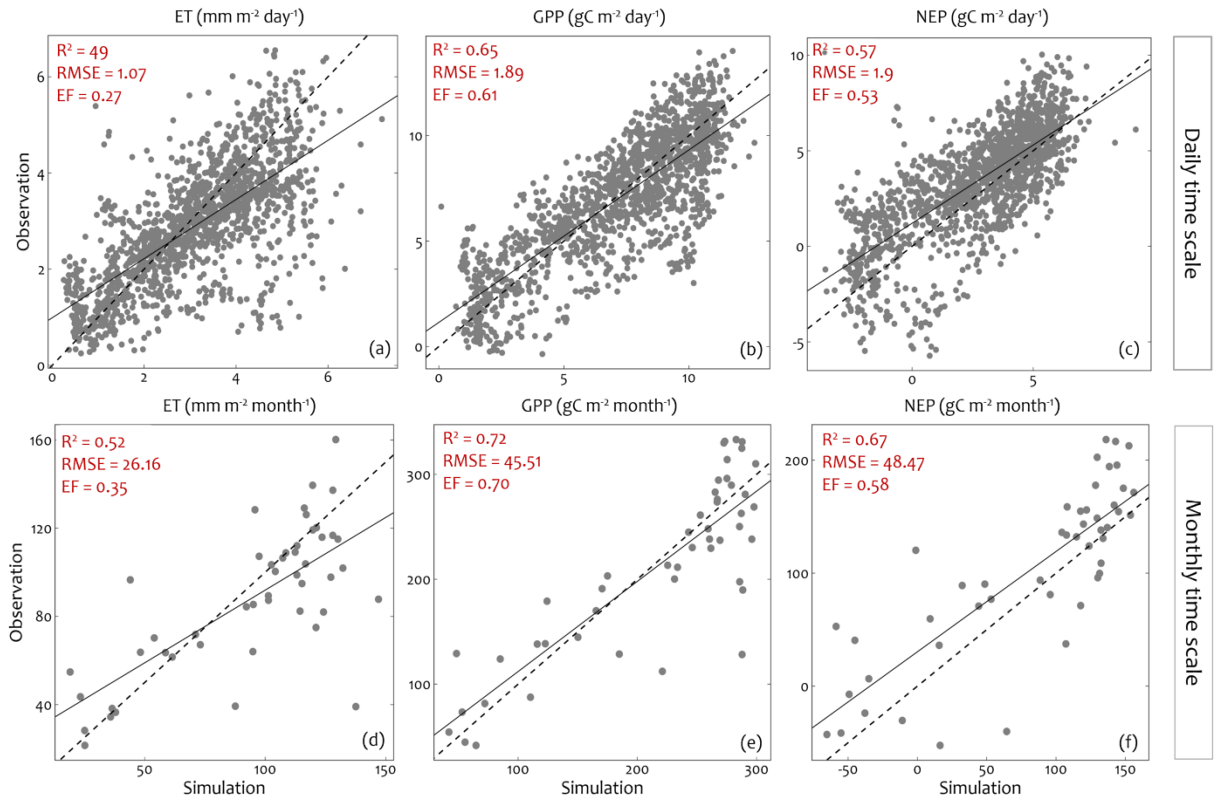


Figure S3: Scatter plots comparing observed and simulated (a) leaf area index (LAI), (b) gross primary production (GPP), and (c) net ecosystem production (NEP) at CRRC. Thick black lines represent linear regression fits, and dashed black lines indicate the 1:1 relationship.

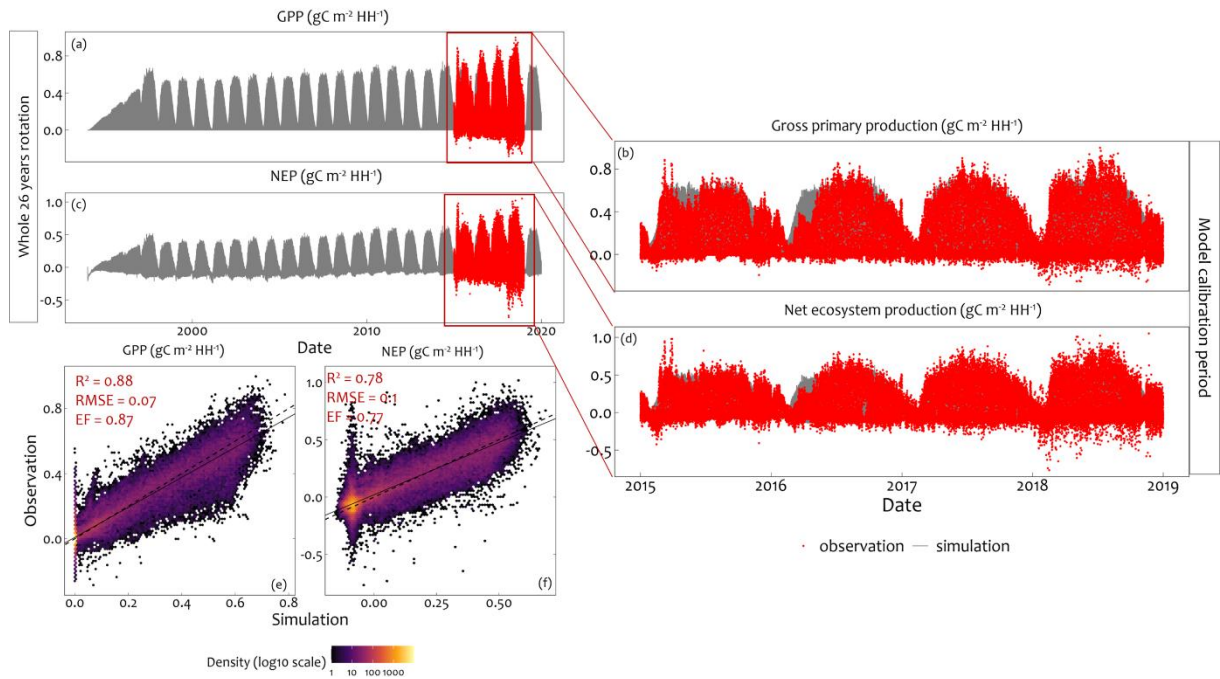


Figure S4: Time series (a-d) and scatter plots (e-f) comparing half-hourly simulated and observed gross primary production (GPP) and Net ecosystem production (NEP) at CRRRC. Red dots represent observations, and black lines represent simulation results. Panels (a) and (b) show simulated and observed GPP for the full 26-year rotation and a zoomed view of the model calibration period, respectively. Panels (c) and (d) show simulated and observed NEP for the full 26-year rotation and a zoomed view of the calibration period. Panel (e) presents the scatter plot comparing simulated and observed GPP, and panel (f) presents the scatter plot comparing simulated and observed NEP. In (e-f), thick black lines show linear regression fits, and dashed black lines denote 1:1 relationship.

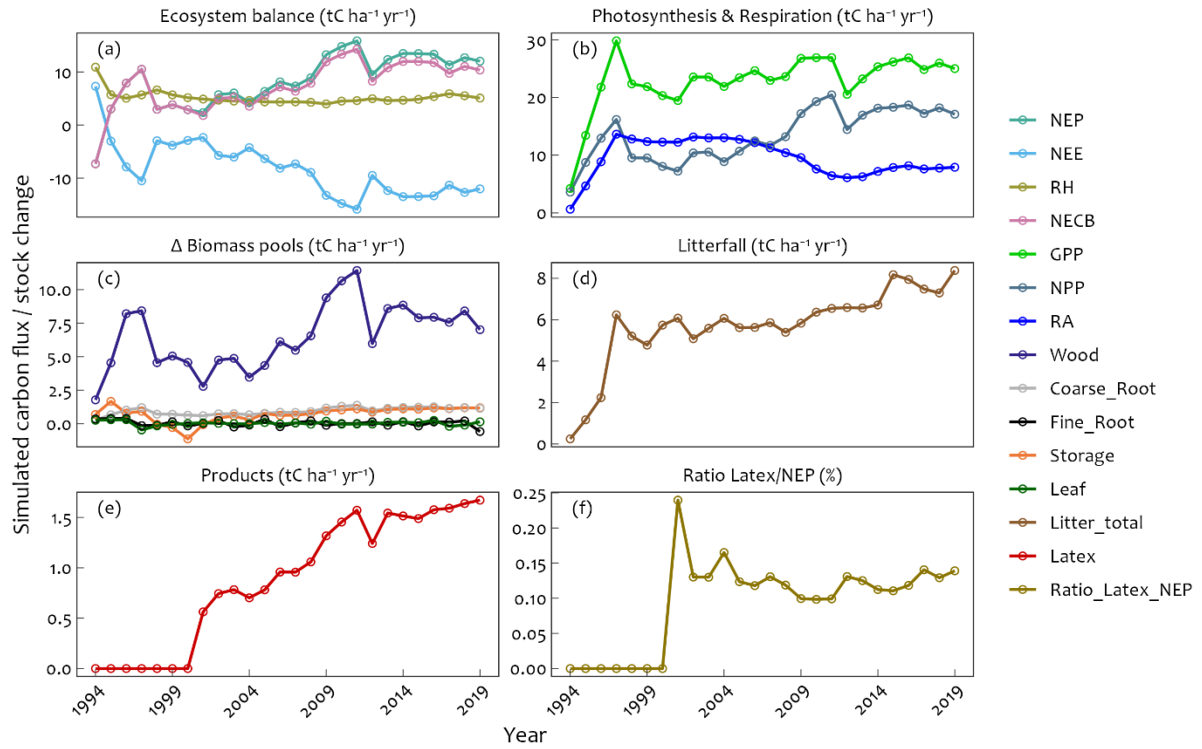


Figure S5: Simulated annual carbon fluxes and stock changes from 1994 to 2019. (a) Ecosystem carbon balance, showing net ecosystem production (NEP), net ecosystem exchange (NEE), heterotrophic respiration (RH), and net ecosystem carbon balance (NECB). (b) Carbon flux components, including gross primary production (GPP), net primary production (NPP), and autotrophic respiration (RA). (c) Biomass pool dynamics, including wood biomass (Wood), coarse root biomass (Coarse_Root), leaf biomass (Leaf), fine root biomass (Fine_Root), and storage biomass (storage). (d) Litterfall biomass (Litterfall). (e) Latex yield biomass (Latex). (f) Ratio latex/NEP (Ratio_Latex_NEP)

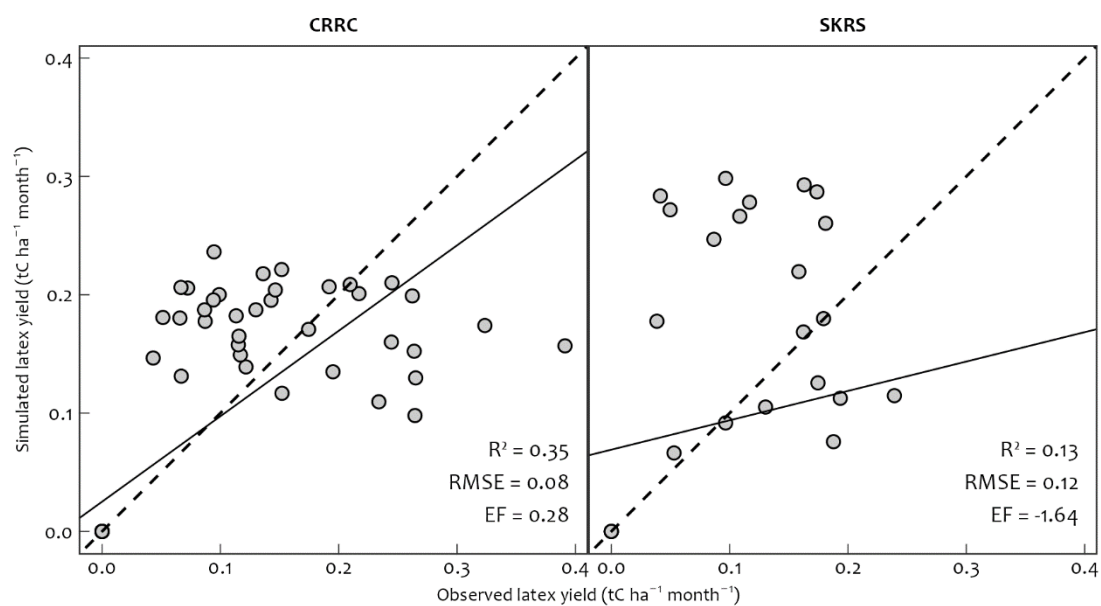


Figure S6: Scatter plots comparing observed and simulated latex yield. Thick black lines represent linear regression fits, and dashed black lines indicate the 1:1 relationship. (a) CRRC parameterization site and (b) SKRS validation site.

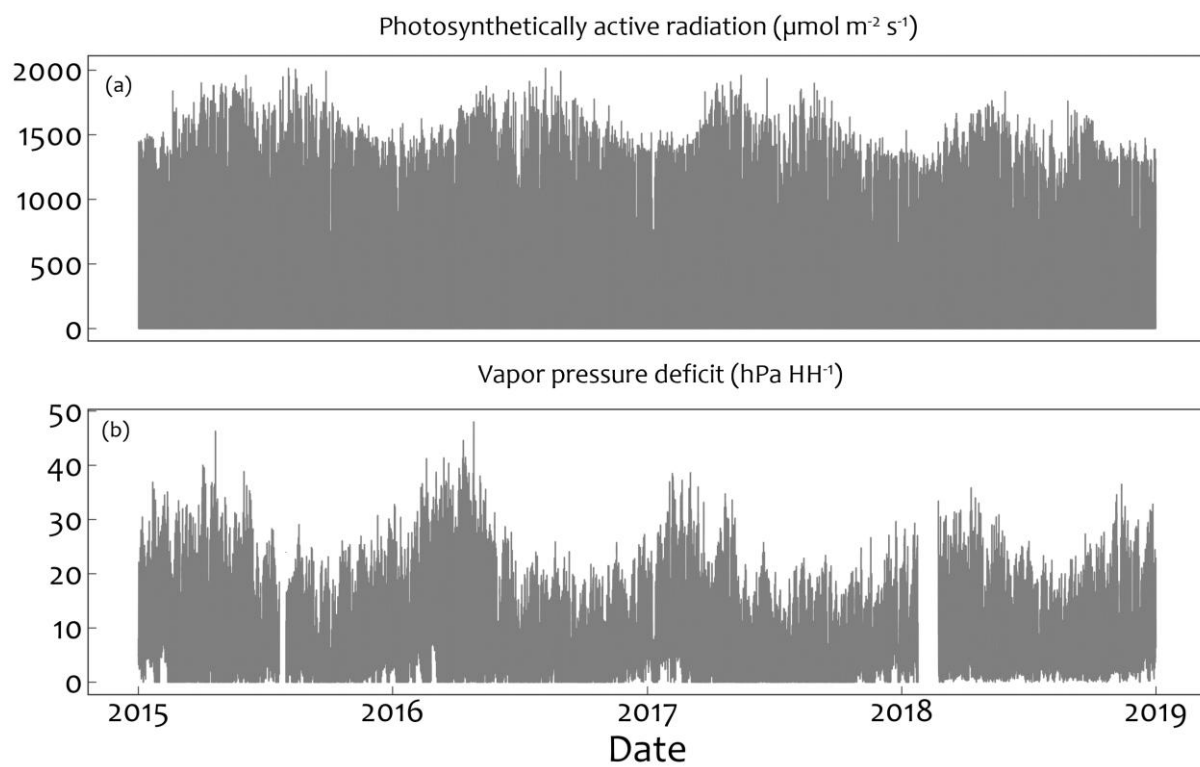


Figure S7: Time series of measured (a) Photosynthetically active radiation (PAR) and (b) Vapor pressure deficit at CRRC

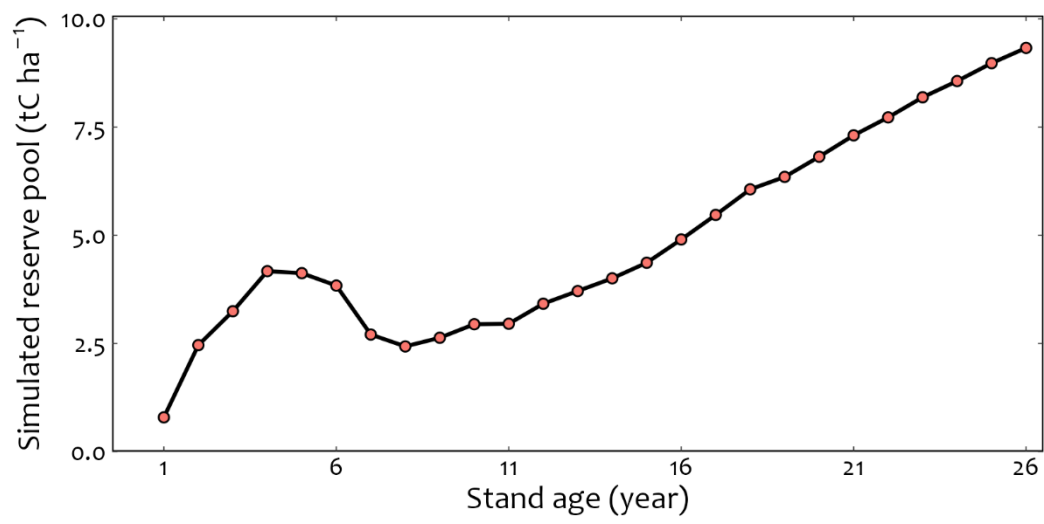


Figure S8: Simulated reserve pool of the rubber plantation at CRRC

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