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Oil palm modelling in the global land surface model ORCHIDEE-MICT

Yidi Xu et al.

Correspondence to: Le Yu (leyu@tsinghua.edu.cn) and Wei Li (wli2019@tsinghua.edu.cn)

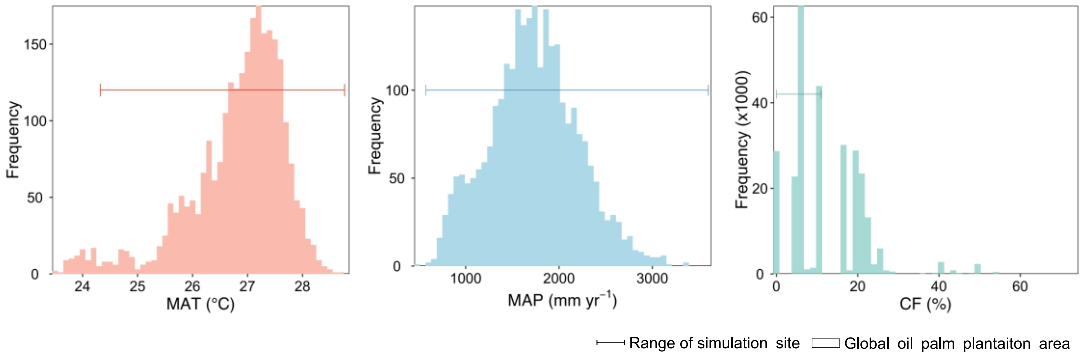

Figure S1. Representativeness of the collected observation sites in terms of mean annual temperature (MAT), mean annual precipitation (MAP) and clay fraction (CF) over the global oil palm plantation area. The lines show the range of the MAT, MAP and CF from the observation sites, while the bars show the frequency distribution of the three variables derived from the global oil palm plantation map (dataset from Cheng et al., 2018).

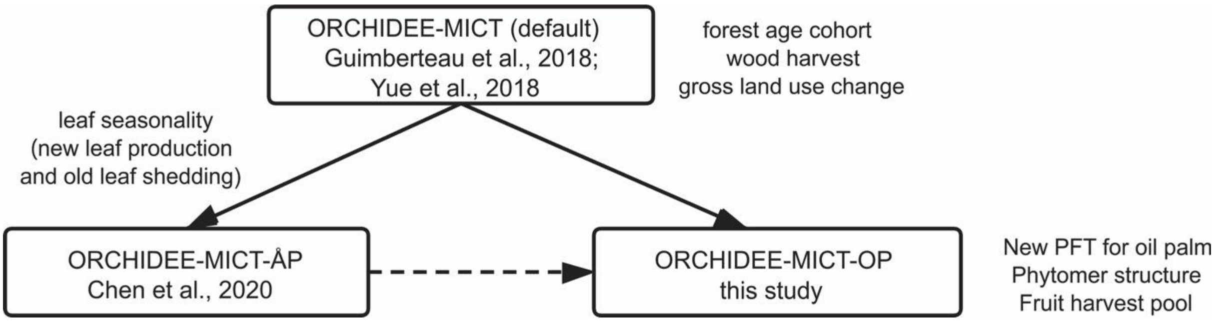

Figure S2. Different versions and developments of ORCHIDEE-MICT related to ORCHIDEE-MICT-OP.

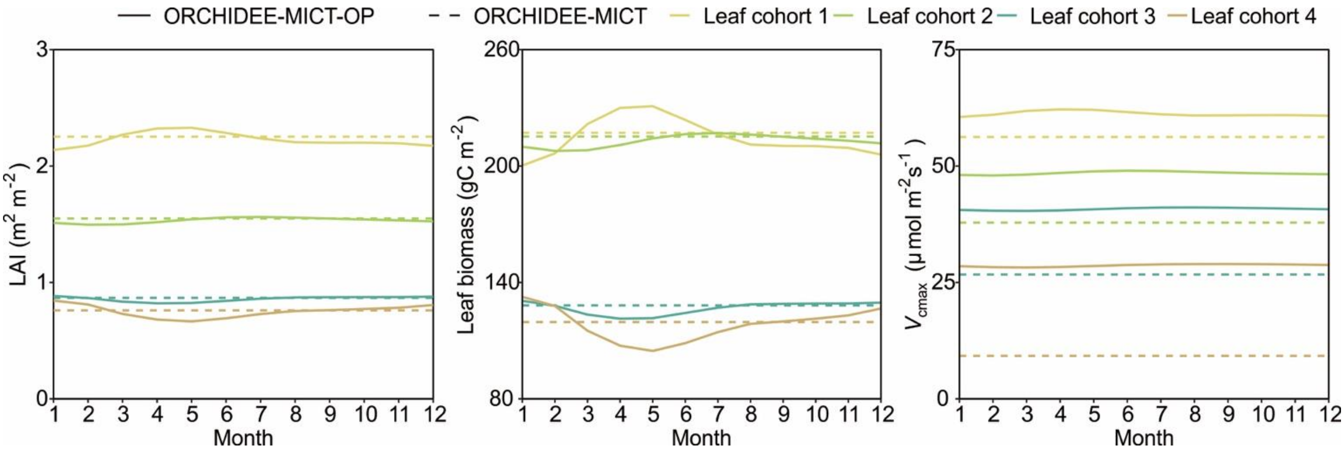

Figure S3 Comparison of the mean seasonality of simulated LAI, leaf biomass and $V_{c,max}$ across all sites between ORCHIDEE-MICT-OP and the default ORCHIDEE-MICT version. Leaf cohorts 1-4 indicate the youngest leaf cohort to the oldest. The new leaf phenology scheme in ORCHIDEE-MICT-LC (Chen et al., 2019) was implemented in ORCHIDEE-MICT-OP.

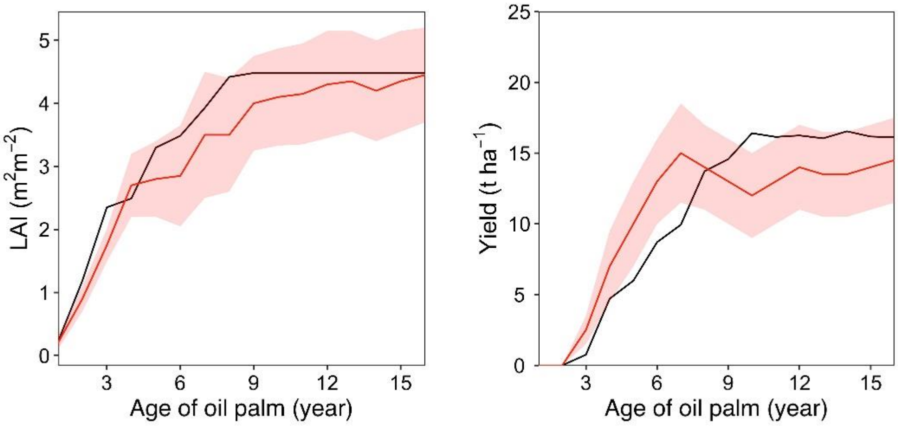

Figure S4. Comparison of model simulated (a) LAI and (b) yield dynamics with field measurements in Site 12 used for calibration (ORCHIDEE-MICT-OPv2). The red ranges refer to the given results for different oil palm planting densities varying from 120-200 palm ha^{-1}.

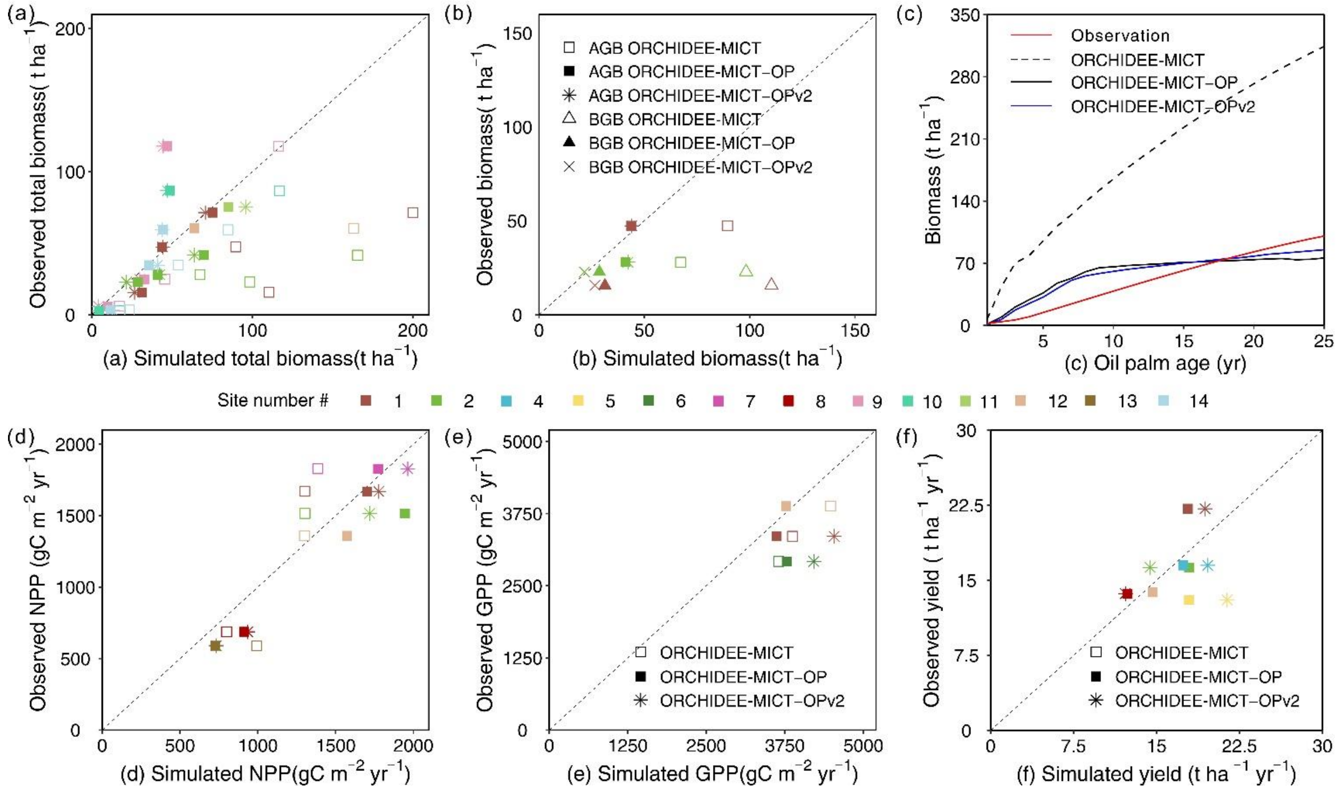

Figure S5. Comparison of simulated (a) NPP, (b) GPP, (c) fruit yield, (d) total biomass, (e) above ground biomass (AGB) and below ground biomass (BGB), temporal dynamics of estimated biomass for oil palm at (f) Site 3. "ORCHIDEE-MICT-OP" refers to the simulation results by the ORCHIDEE-MICT-OP using the newly oil palm PFT and the calibration scheme using all the 14 sites. "ORCHIDEE-MICT-OPv2" refers to the simulation results using independent calibration and independent validation sites. "ORCHIDEE-MICT" refers to the simulation results by the default ORCHIDEE-MICT version using TBE tree PFT. The dashed line indicates the 1:1 ratio line. The overall pattern of the simulation results was similar in the two calibration schemes and both showed great improvement compared with the default PFT2 (ORCHIDEE-MICT) version. The simulated total biomass, AGB and BGB were all similar in the two calibration schemes. Simulated NPP by the independent validation scheme is closer to observation while GPP and yields are more or less biased compared with the original scheme.

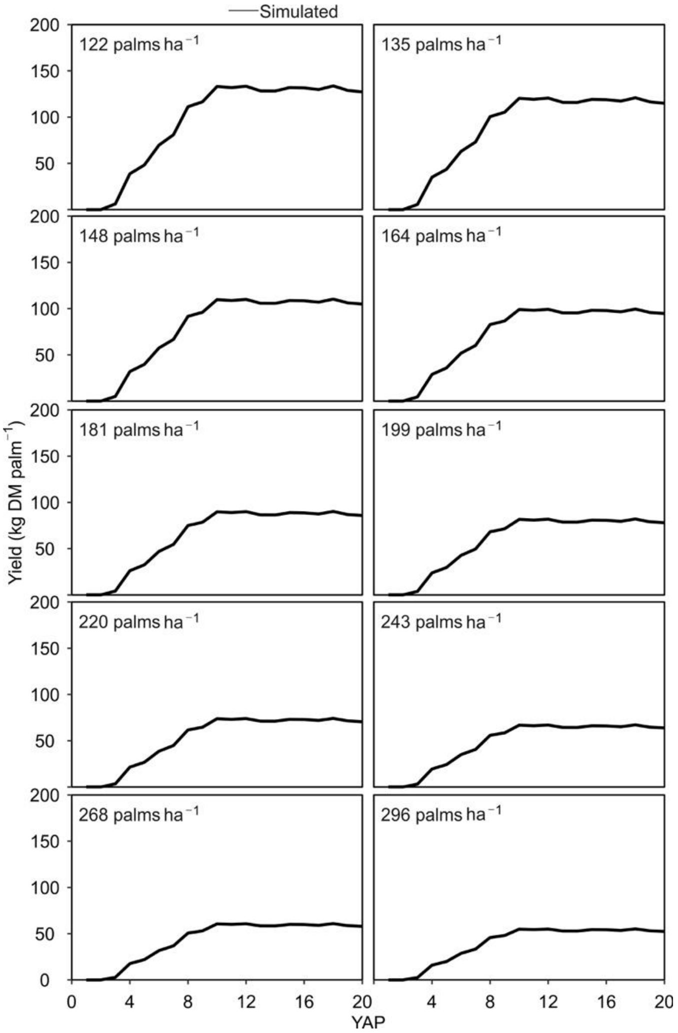

Figure S6 Temporal dynamics of simulated yields from the Merlimau estate, Melaka (2.25°N, 102.45°E) using ORCHIDEE-MICT-OP. The figure is the simulated results in the same site of Figure 11 in Teh and Cheah, 2018 with the same style and scales to visually compare the simulated results with the observations. In the previous study, the oil palm plantations were planted at following density of 120, 135, 148, 164, 181, 199, 220, 243, 268 and 296 palms ha^{-1} and the yields were given at the corresponding planting densities (Teh and Cheah, 2018). YAP is year after planting.

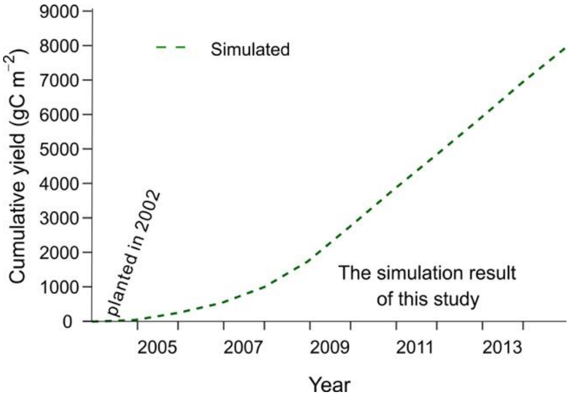

Figure S7 Simulated cumulative yields (2005-2014) from site PTPN-VI in Jambi, Sumatra (1°41.6′ S, 103°23.5′ E) using ORCHIDEE-MICT-OP. The figure is the simulated results in the same site of Figure 6 in Fan et al., 2015 with the same figure style and scales.

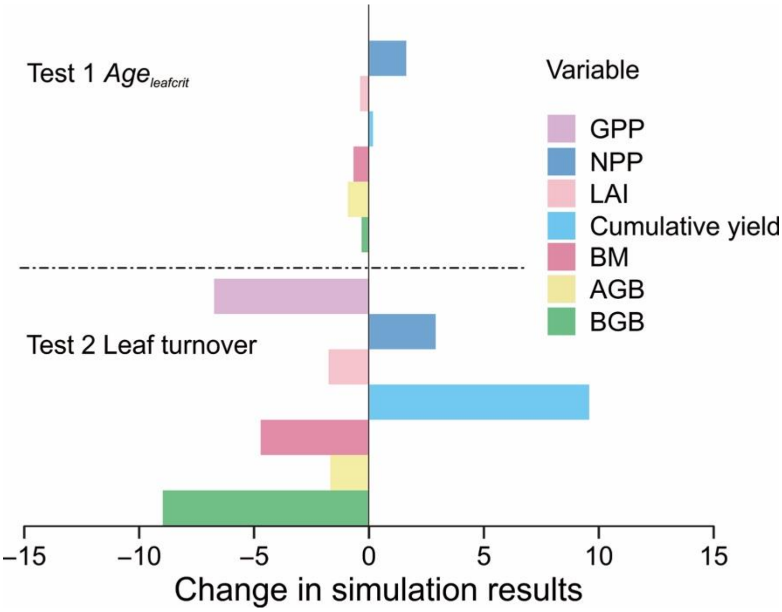

Figure S8. Changes in the simulated variables using different settings for longevity and shedding. 1) using the leaf longevity (620 days) shorter than phytomer longevity (640 days) and 2) turn off the extra old leaf turnover at the time of oldest phytomer pruning. In the first test, the decreased leaf longevity accelerates leaf shedding and causes a compensatory increase in leaf allocation. NPP and cumulative yields also increased because of the increase of new leaf proportion with higher photosynthesis capacity. In the second test, the results showed a decrease in the simulated GPP and biomass pool but an increase in NPP and cumulative yields.

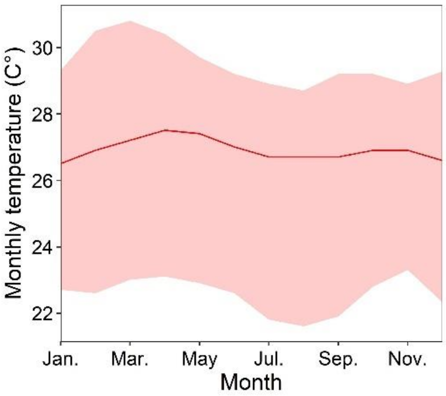

Figure S9 Seasonal temperature variations over the global oil palm plantation area during the past 30 years (1986-2015). The red solid red line and the shade indicate the median and range of seasonal temperature variations derived from the global oil palm plantation map (dataset from Cheng et al., 2018). The temperature was based on the climate data from the CRUNCEP gridded dataset (Viovy, 2011) and averaged by month.

Table S1 site level data information.

Site #	Site Name	Reference	Country	Type	Variable	Age	Measurement	soil
1	Harapan region	(Fan et al., 2015; Kotowska et al., 2015; Meijide et al., 2017)	Indonesia	smallholders，0.25 ha	Yield,NPP AGB,BGB, Biomass NPP component WUE	~13	field measurement and allometiric equation	loam Acrisols
2	Bukit Duabelas region	(Fan et al., 2015; Kotowska et al., 2015)	Indonesia	smallholders, 0.25 ha	Yield,NPP AGB,BGB, Biomass NPP component	~10	field measurement and allometiric equation	clay Acrisols
3	Genting plantation	(Tan et al., 2014)	Malaysia	industrial plantation,2815 ha	Yield, Biomass Biomass component	0-25	field measurement and allometiric equation statistical harvest data empirical equation	/
4	SMART, Kandista Estate	(Legros et al., 2009)	Indonesia	Research Institute, 30 ha	Yield	13	field measurement	sandy loam
5	Batu Mulia Estate	(Legros et al., 2009)	Indonesia	Research Institute, 9 ha	Yield	13	field measurement	silty clay loam
6	close to Kluang station	(Tan et al., 2011)	Malaysia	industrial plantation	GPP, LAI	matu re	field measurement	/
7	Marihat Research Station	(Lamade and Bouillet, 2005)	Indonesia	Research station	NPP	8	field measurement	/
8	SOCFINDO industrial plantation	(Lamade et al., 1996)	Benin	industrial plantation	Yield, NPP	20	field measurement	ferrallitic soil
9	PTPN XIV-Persero	(Sunaryathy et al., 2015)	Indonesia	industrial plantation,23625 ha	AGB	1-3 4-10 11-20	field measurement	/
10	SSSB	(Morel et al., 2011)	Malaysia	industrial plantation	AGB	3 4-19	field measurement and allometiric equation	/
11	close to Pasoh Forest Reserve	(Adachi et al., 2011)	Malaysia	/	Biomass	27.5	field measurement and allometiric equation	sandy clay loam
12	Teluk Intant Research station	(Henson and Dolmat, 2003)	Malaysia	Research Institute, 21.45 ha	Yield, NPP, GPP Biomass GPP/NPP component Biomass component	0-16	field measurement	deep peat soil
13	ESPEK estate	(Henson and Harun, 2005)	Malaysia	industrial plantation	NPP	4	field measurement, eddy tower	sandy clay loam
14	Sebungan and Sabaju Oil Palm Estate	(Lewis et al., 2020)	Malaysia	industrial plantation, 10200 ha	AGB	3-12	field measurement	clay, deap peat

Table S2 Summary of adjusted parameters for the new oil palm PFT in this model. Values of the default TBE tree PFT are also shown for comparison.

				PFT2, tropical broad-leaved evergreen	**PFT14, oil palm**	
Symbol	**Parameter**	**Description**	**Unit**	**Value**	**Value**	**Reference**
Photosynthesis parameter						
sla*	SLA SLA_MAX/SLA_MIN	specific leaf area	$m^2g^{-1}C$	0.0153	CFT 1: 0.012 CFT 2: 0.011 CFT 3: 0.010 CFT 4: 0.009 CFT 5: 0.008 CFT 6: 0.008	Varies from 0.008-0.016 in different studies (Kotowska et al., 2015;Legros et al., 2009;Van Kraalingen et al., 1989)
$V_{c,max25}$*	VCMAX25	Maximum rate of Rubisco activity-limited carboxylation at 25 °C	mol/ m^2s^{-1}	45	CFT 1: 35 CFT 2: 40 CFT 3: 45 CFT 4: 60 CFT 5: 75 CFT 6: 70	Varies from 42-100.47 in different studies (Fan et al., 2015;Meijide et al., 2017;Teh Boon Sung and See Siang, 2018)
LAI_{max}*	LAI_MAX	maximum leaf area index	/	7	CFT 1: 1.5 CFT 2: 2.5 CFT 3: 3.5 CFT 4: 4.5 CFT 5: 5.5 CFT 6: 5.0	Increased with age (Corley et al., 1971;Corley and Lee, 1992;Kallarackal, 1996;Kotowska et al., 2015;Legros et al., 2009;Noor et al., 2002;Noor and Harun, 2004;Tan et al., 2014;Wahid et al., 2004)

Respiration parameter						
f_{GR}	FRAC_GROWTHRESP	Fraction of GPP which is lost as growth respiration	/	0.35	CFT 1: 0.5 CFT 2: 0.425 CFT 3: 0.4 CFT 4: 0.375 CFT 5: 0.35 CFT 6: 0.3	calibration using the ratio between growth respiration/maintainance respiration from previous studies. AR consists of 60-75% GPP (Breure, 1988;Henson and Dolmat, 2003;Henson and Harun, 2005)
S_1	MAINT_RESP_SLOPE_C	constant define the slope of maintenance respiration coefficient	/	0.12	CFT 1: 0.04 CFT 2: 0.05 CFT 3: 0.06 CFT 4: 0.07 CFT 5: 0.08 CFT 6: 0.09	
Carbon allocation parameter						
θ *	DEMI_ALLOC	constant parameter for the function of partitioning allocation between aboveground sapwood as well as reproductive organ and belowground sapwood biomass	/	5	CFT 1: 0.2 CFT 2: 0.2 CFT 3: 0.5 CFT 4: 1.0 CFT 5: 2.0 CFT 6: 2.0	calibration
$f_{sab+rep,min}$ */ $f_{sab+rep,max}$ *	ALLOC_MIN/ALLOC_MAX	minimum/maximum value of allocation coefficient between aboveground sapwood as well as reproductive organ and belowground sapwood biomass	/	0.2/0.8	CFT 1: 0.2/0.3 CFT 2: 0.65/0.85 CFT 3: 0.7/0.9 CFT 4: 0.75/0.94	calibration

					CFT 5: 0.8/0.99 CFT 6: 0.750.95	
R_1*	RS_COEFF	empirical coefficient for the root allocation	/	/	0.95	calibration
$L_1/L_2/L_3$*	LSR_COEFF	empirical coefficient for the function of leaf allocation	/	/	0.45 100 6	calibration
$f_{leaf,max}$	MAX_LTOLSR	maximum leaf allocation fraction	/	0.5	0.35	(Fan et al., 2015;Kotowska et al., 2015)
$f_{leaf,min}$	MIN_LTOLSR	minimum leaf allocation fraction	/	0.2	0.25	(Fan et al., 2015;Kotowska et al., 2015)
$f_{root,max}$	MAX_RTOLSR	maximum root allocation fraction	/	/	0.35	(Kotowska et al., 2015)
$f_{root,min}$	MIN_RTOLSR	minimum root allocation fraction	/	/	0.25	(Fan et al., 2015;Kotowska et al., 2015)
$f_{br+fr,min}$ $f_{br+fr,max}$	PHYALLOC_MIN PHYALLOC_MAX	prescribed minimum and maximum value of aboveground sapwood and reproductive organ allocation fraction to branch and fruit	/	/	0.001 1	this paper
$P_1/P_2/P_3$*	PHY_COEFF	empirical coefficient for the phytomer allocation	/	/	0.265 2 0.8	calibration
$f_{fr,min}$/* $f_{fr,max}$*	FTOPHY_MIN/ FTOPHY_MAX	minimum/maximum fresh fruit bunch allocation fraction in phytomers	/	/	CFT 1: 0.2/0.7 CFT 2: 0.3/0.8 CFT 3: 0.4/0.82 CFT 4: 0.5/0.84 CFT 5: 0.6/0.9 CFT 6: 0.7/0.82	calibration

F_1*	FFB_COEFF	empirical coefficient for the fresh fruit bunch allocaion	/	/	0.02	calibration
ffblagday	LAGDAY	The lag day of fruit initiation after phytomer development	day	/	16	calibration
Other parameter						
$Age_{phycrit}$	PHYTOMERAGECRIT	critical phytomer age, the same as critical leaf age (leaf longevity)	day	730	640	Ranges from 600-700 (Corley and Tinker, 2015;Fan et al., 2015;Van Kraalingen et al., 1989)
$Age_{ffbcrit}$	FFBHARVESTAGECRIT	critical fruit harvest age	day	/	600	(Fan et al., 2015)
τ	RESIDENCE_TIME	residence time of trees	year	30	1000	
LO_1*	LOSS_COEFF	empirical coefficient for the leaf loss with the pruning of phytomer	/	/	2	this paper
ρ	PIPE_DENSITY	wood density	m^{-2}	2.00E-05	1.30E-05	(Ibrahim et al., 2010;Sunaryathy et al., 2015)
$nphs$	NPHS	Maximum number of phytomer		/	40	(Combres et al., 2013;Corley and Tinker, 2015)

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