DEVELOPMENT AND VALIDATION OF Sawit, AN OIL PALM GROWTH AND YIELD MODEL

By

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A study was undertaken to develop and validate Sawit, an oil palm growth and yield model that considers weather variables, planting densities and soil textures. Sawit consists of five components: meteorology, photosynthesis, energy balance, water balance, and crop growth. The meteorology component was parameterized using daily weather data recorded in oil palm plantations. The photosynthesis component was parameterized through leaf measurement on young to mature palms, where photosynthetic parameters were measured. Measurements of trunk and canopy heights, as well as the relationship between oil palm leaf stomatal conductance with photosynthetically active radiation and air vapour pressure deficit, were taken to parameterize the energy balance component using the Shuttleworth-Wallace model. These measurements were used to model evapotranspiration and leaf temperature. Water flow in the soil was modelled following the 'tipping bucket' system using Darcy's law. The crop growth component was parameterized based on the OPSIM model. Different ages of oil palms were destructively sampled to determine the dry matter partitioning and respiration coefficients. Sawit was validated by oil palm planting-density experiments in six different sites: Rengam, Merlimau, Kerayong, Sungai Buloh, Sabrang, and Seri Intan. The model showed good agreement in predicting oil palm growth and yield parameters. However, the accuracy of the simulation varied considerably between sites and parameters. The yield simulation was considered sufficiently accurate for Merlimau and Sungai Buloh, with the refined index of agreement (d_r) equal to 0.76 and 0.74, respectively, and the normalized mean absolute error (NMAE) equal to 0.19 and 0.20, respectively. However, the yield was simulated as less than satisfactory for Rengam, Kerayong, Sabrang and Seri Intan. Their d_r values were small (0.52-0.56), but NMAE (0.13-0.25) were comparable to Merlimau and Sungai Buloh.

The simulation of vegetative dry matter production was good for Rengam (d_r = 0.78, NMAE = 0.20), Kerayong (d_r = 0.71, NMAE = 0.14) and Sabrang (d_r = 0.76, NMAE = 0.11), but satisfactory for Merlimau (d_r = 0.62, NMAE = 0.23) and Sungai Buloh (d_r = 0.64, NMAE = 0.21). Total dry matter production was simulated sufficiently accurate with d_r ranging from 0.71-0.78 and NMAE ranging from 0.07-0.17 across all sites and planting densities. Rachis (d_r = 0.68-0.86, NMAE = 0.11-0.19), fronds (d_r = 0.65-0.83, NMAE = 0.11-0.20) and trunk (d_r = 0.69-0.82, NMAE = 0.24-0.39) were simulated more accurately than pinnae (d_r = 0.43-0.73, NMAE = 0.18-0.30) across all sites and planting densities except for the simulation of trunk biomass in Sungai Buloh (d_r = 0.38, NMAE = 0.77). The leaf area index was simulated sufficiently accurate for Merlimau, Rengam, and Seri Intan, with d_r ranging from 0.78-0.84 and NMAE ranging from 0.03-0.16. In contrast, the leaf area index was simulated as less than satisfactory for Kerayong, Sungai Buloh, and Sabrang, with d_r ranging from 0.57-0.62 and NMAE ranging from 0.13-0.17. The simulation of trunk height was especially good for Merlimau, Kerayong, Seri Intan and Sabrang, with large d_r values (0.87-0.93) and small NMAE values (0.06-0.12). However, trunk height was simulated satisfactory for Rengam (d_r = 0.67, NMAE = 0.39) and Sungai Buloh (d_r = 0.69, NMAE = 0.32). In addition, Sawit effectively simulated the impacts of El Niño event on oil palm yield. It also accounted for the influence of soil textures, rainfall, planting densities, and meteorological factors on water deficits. However, the simulation errors increased with increasing planting density due to insufficient characterization of microclimate conditions and plant water uptake under dense oil palm canopies, and higher variability of measurements for higher planting densities. In conclusion, an oil palm model called Sawit was developed and has been parameterized to simulate the growth and yield of oil palms under the influence of weather conditions, planting densities and soil textures. Improving the representation of oil palm microclimate and plant water uptake under dense canopies, incorporating fruiting activity, and refining the trunk's dry matter partitioning mechanism could enhance Sawit's accuracy.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
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PEMBANGUNAN DAN PENGESAHAN Sawit, MODEL PERTUMBUHAN DAN HASIL KELAPA SAWIT

Oleh

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Januari 2023

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Satu kajian telah dijalankan untuk membangunkan dan mengesahkan Sawit, sebuah model pertumbuhan dan hasil kelapa sawit yang mengambil kira pembolehubah cuaca, kepadatan penanaman, dan tekstur tanah. Pembangunan model ini terdiri daripada lima komponen: kesan meteorologi, kadar fotosintesis, kadar keseimbangan tenaga, kadar keseimbangan air, dan kadar pertumbuhan tanaman. Kesan meteorologi berparameterkan data cuaca harian yang direkodkan di ladang kelapa sawit. Kadar fotosintesis diukur pada daun muda dan matang di pokok sawit. Kadar keseimbangan tenaga dikira dengan menggunakan model Shuttleworth-Wallace, yang mana ketinggian batang serta kanopi sawit dan hubungan antara konduktiviti stomata daun yang aktif dalam julat spektrum cahaya untuk fotosintesis (photosynthetically active radiation) dengan defisit air akibat pengewapan diambilkira untuk menilai kadar evapotranspirasi dan suhu daun. Pergerakan air dalam tanah dinilai menggunakan sistem 'tipping bucket' yang berasaskan Darcy law. Kadar pertumbuhan tanaman diukur dengan menggunakan model OPSIM. Pokok sawit yang berlainan umur telah disampel secara destruktif untuk penentuan berat bahagian-bahagian pokok dan pekali kadar respirasi. Sawit telah disahkan oleh eksperimen kepadatan penanaman kelapa sawit di enam lokasi berbeza: Rengam, Merlimau, Kerayong, Sungai Buloh, Sabrang dan Seri Intan. Sawit menunjukkan persetujuan yang baik dalam meramalkan parameter pertumbuhan dan hasil kelapa sawit. Walau bagaimanapun, ketepatan simulasi berbeza dengan ketara antara lokasi dan parameter. Hasil telah disimulasikan dengan cukup tepat untuk Merlimau dan Sungai Buloh, dengan indeks persetujuan yang ditapis (d_r) bersamaan dengan 0.76 dan 0.74, masing-masing, dan ralat min mutlak ternormal (NMAE) bersamaan dengan 0.19 dan 0.20, masing-masing. Bagaimanapun, hasil disimulasikan sebagai kurang

memuaskan bagi Rengam, Kerayong, Sabrang dan Seri Intan. Nilai d_r mereka adalah kecil (0.52-0.56), tetapi NMAE (0.13-0.25) adalah setanding dengan Merlimau dan Sungai Buloh. Simulasi pengeluaran bahan kering vegetatif adalah baik untuk Rengam (d_r = 0.78, NMAE = 0.20), Kerayong (d_r = 0.71, NMAE = 0.14) dan Sabrang (d_r = 0.76, NMAE = 0.11), tetapi memuaskan untuk Merlimau (d_r = 0.62, NMAE = 0.23) dan Sungai Buloh (d_r = 0.64, NMAE = 0.21). Jumlah pengeluaran bahan kering telah disimulasikan dengan cukup tepat dengan d_r antara 0.71-0.78 dan NMAE antara 0.07-0.17 merentasi semua lokasi dan kepadatan penanaman. Rachis (d_r = 0.68-0.86, NMAE = 0.11-0.19), pelepah (d_r = 0.65-0.83, NMAE = 0.11-0.20) dan batang (d_r = 0.69-0.82, NMAE = 0.24-0.39) lebih tepat daripada yang disimulasikan (d_r = 0.43-0.73, NMAE = 0.18-0.30) merentasi semua lokasi dan kepadatan tanaman kecuali simulasi biojisim batang di Sungai Buloh (d_r = 0.38, NMAE = 0.77). Indeks luas daun telah disimulasikan dengan cukup tepat untuk Merlimau, Rengam, dan Seri Intan, dengan d_r antara 0.78-0.84 dan NMAE antara 0.03-0.16. Sebaliknya, indeks luas daun disimulasikan sebagai kurang memuaskan untuk Kerayong, Sungai Buloh, dan Sabrang, dengan d_r antara 0.57-0.62 dan NMAE antara 0.13-0.17. Simulasi ketinggian batang sangat baik untuk Merlimau, Kerayong, Seri Intan dan Sabrang, dengan nilai d_r besar (0.87-0.93) dan nilai NMAE kecil (0.06-0.12). Walau bagaimanapun, ketinggian batang telah disimulasikan memuaskan untuk Rengam (d_r = 0.67, NMAE = 0.39) dan Sungai Buloh (d_r = 0.69, NMAE = 0.32). Selain itu, Sawit berjaya mensimulasikan kesan kejadian El Niño terhadap hasil kelapa sawit. Sawit juga memperhitungkan pengaruh tekstur tanah, taburan hujan, kepadatan penanaman, dan faktor-faktor meteorologi terhadap defisit air. Walau bagaimanapun, kesilapan simulasi meningkat dengan peningkatan kepadatan penanaman disebabkan kurangnya pencirian keadaan mikroiklim dan penyerapan air tumbuhan di bawah kanopi kelapa sawit yang padat, serta keragaman pengukuran yang lebih tinggi untuk kepadatan penanaman yang lebih tinggi. Secara kesimpulannya, model kelapa sawit yang bernama Sawit telah dibangunkan dan diparameterkan untuk mensimulasikan pertumbuhan dan hasil kelapa sawit di bawah pengaruh keadaan cuaca, kepadatan penanaman, dan tekstur tanah. Peningkatan dalam representasi mikroiklim kelapa sawit dan penyerapan air tumbuhan di bawah kanopi kelapa sawit yang padat, penyertaan aktiviti pembungaan, dan penyempurnaan mekanisme pemartitionan bahan kering batang boleh meningkatkan ketepatan Sawit.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

A_{max}	Maximum light-saturated photosynthesis rate
AET	Actual evapotranspiration
ASW	Available soil water content
BAR	Bunch CH_2O requirement
BARMAX	Maximum bunch CH_2O requirement
CH_2O	Carbohydrate
FASW	Fractional available soil water content
FvCB	Farquhar-von Caemmerer-Berry
GDM	Reproductive dry matter production
L	Leaf area index
LUE	Light use efficiency
gst	Stomatal conductance
MAE	Mean absolute error
MPOB	Malaysia Palm Oil Board
NMAE	Normalized mean absolute error
NMBE	Normalized mean bias error
PAR	Photosynthetically active radiation
PD	planting density
PET	Potential evapotranspiration
PNGOPRA	Papua New Guinea Oil Palm Research Association

RH	Relative humidity
RMSE	Root mean square error
SLA	Specific leaf area
TPU	Triose-phosphate untilization
TDM	Total dry matter production
USDA	United States Department of Agriculture
USDA-FAS	United States Department of Agriculture-Foreign Agriculture Service
VDMP	Vegetative dry matter production
VPD	Vapour pressure deficit
WUE	Water use efficiency
YAP	Year after field planting

LIST OF SYMBOLS USED BY SAWIT MODEL

Symbol	Description	Unit
α_1	fraction of PAR absorbed (0.8)	-
α_2	extinction coefficient for wind speed	-
β	solar elevation or height (from horizontal)	radians
δ	solar declination	radians
Δ	slope of the saturated vapor pressure curve	mbar K^{-1}
ϕ	solar azimuth (angle clockwise from North)	radians
ϕ_p	soil porosity	-
γ	psychometric constant (0.658)	mbar K^{-1}
Γ^*	CO_2 compensation point	μmol mol^{-1}
λ_1	site latitude	radians
λ_2	latent heat of vaporization of water (2454000)	J kg^{-1}
λ_3	slope of the logarithmic suction-soil moisture curve	-
λET	total latent heat flux density	W m^{-2}
λET_c	latent heat flux density of crop	W m^{-2}
λET_s	latent heat flux density of soil	W m^{-2}
Λ_{canopy}	gross canopy assimilation rate of CO_2 for the given hour	μmol CO_2 m^{-2} ground s^{-1}
$\Lambda_{sl/sh}$	gross leaf assimilation rate of CO_2 for sunlit (sl) or shaded (sh) leaves	μmol CO_2 m^{-2} leaf s^{-1}
π	pi constant (3.1428571)	-

θ	solar inclination (from vertical)	radians
θ_i	volumetric water content for soil layer i	$m^3\ m^{-3}$
θ_s	saturated volumetric water content	$m^3\ m^{-3}$
θ_{33}	volumetric water content at field capacity	$m^3\ m^{-3}$
θ_{1500}	volumetric water content at permanent wilting point	$m^3\ m^{-3}$
θ_{root}	volumetric water content in the root zone	$m^3\ m^{-3}$
$\theta_{cr,root}$	critical volumetric water content in the root zone	$m^3\ m^{-3}$
$\theta_{s,root}$, $\theta_{1500,root}$	volumetric water content at saturation and permanent wilting point in the root zone, respectively	$m^3\ m^{-3}$
Θ_i	soil water content for soil layer I, expressed as water depth	m
ρc_p	volumetric heat capacity of air (1221.09)	$J\ m^{-3}\ K^{-1}$
σ	Stefan-Boltzmann constant (5.67×10^{-8})	$W\ m^{-2}\ K^{-4}$
τ_1	hour angle	radians
τ_2	CO_2 / O_2 specificity factor	$\mu mol\ \mu mol^{-1}$
τ_3	soil tortuosity	-
$\tau_{dr,\alpha}$	penetration function for direct solar radiation (corrected for scattering)	-
ω	canopy clustering coefficient	-
ω_0	canopy clustering coefficient when the sun is at zenith	-
ψ_e	air entry suction	m

Age	tree age	days
A	total energy supply	W m^{-2}
A_c	fraction of energy available to the plant	W m^{-2}
A_s	fraction of energy available to the soil	W m^{-2}
C	fractional clay content in soil	-
C_a	ambient CO_2 concentration in air	μmol mol^{-1}
C_i	intercellular CO_2 concentration	μmol mol^{-1}
CVF, CVF_2	conversion from CH_2O to DM weight	kg DM kg^{-1} CH_2O
d	zero plane displacement	m
d_{root}	rooting depth	m
dg_{root}	rooting depth growth rate	m day^{-1}
D	vapor pressure deficit	mbar
D_0	vapor pressure deficit at the mean canopy flow	mbar
D_{leaf}	leaf vapour pressure deficit	mbar
D_{min}	minimum vapour pressure deficit	mbar
$D_{m,v}$	vapor diffusion coefficient in air (24.7×10^{-6})	m^2 s^{-1}
DL	day length	hour
DM_x	fraction of DM to plant part *x*, where *x* is for pinnae, rachis, trunk, and roots	-
e_a	air vapor pressure	mbar
e_m	quantum efficiency or quantum yield	μmol μmol^{-1}

$e_{s[\![T]\!]}$	function returning the saturated vapor pressure at air temperature T	mbar
E_a	actual soil evaporation	m day^{-1}
$E_{iso,sl/sh}$	emitted isoprene concentration by sunlit (sl) or shaded (sh) leaves	g C_5H_8 g^{-1} leaf s^{-1}
ET_c	potential transpiration	m day^{-1}
ET_s	potential evaporation	m day^{-1}
f_D	reduction to maximum stomatal conductance due to vapour pressure deficit	-
f_{PAR}	reduction to maximum stomatal conductance due to PAR	-
f_{water}	reduction to maximum stomatal conductance due to water stress	-
gst	stomatal conductance	m s^{-1}
$gst_{\max}$	maximum stomatal conductance	m s^{-1}
G	soil (ground) heat flux density	W m^{-2}
G_{gen}	assimilates available to generative organs growth	kg CH_2O palm^{-1} day^{-1}
G_{growth}	assimilates available to growth respiration	kg CH_2O palm^{-1} day^{-1}
$G_{maleflo}$, $G_{immbunch}$, $G_{matbunch}$	growth rate of male flowers, immature bunches, and mature bunches, respectively	kg DM day^{-1}
G_x	growth rate of plant part x, where x is for pinnae, rachis, trunk, and roots	kg DM palm^{-1} day^{-1}
$G_{death,leaves}$	death rate of both pinnae and rachis due to natural causes	kg DM palm^{-1} day^{-1}

$G_{death,roots}$	death rate of roots due to natural causes	kg DM palm^{-1} day^{-1}
h	full tree height (trunk + canopy)	m
h_{canopy}	canopy height	m
h_{trunk}	trunk height	m
h'_{trunk}	rate of growth for trunk height	m day^{-1}
H_i	soil hydraulic gradient for soil layer i	m
H_c	sensible heat flux density of crop	W m^{-2}
$H_{g,i}$	gravity head for soil layer i	m
$H_{m,i}$	matric suction head for soil layer i	m
H_s	sensible heat flux density of soil	W m^{-2}
I_c	solar constant	W m^{-2}
I_{df}	diffuse solar irradiance	W m^{-2}
I_{dr}	direct solar irradiance	W m^{-2}
I_{et}	extraterrestrial solar irradiance	W m^{-2}
$I_{sl/sh}$	total solar irradiance on sunlit (sl) or shaded (sh) leaves	W m^{-2}
I_t	total solar irradiance	W m^{-2}
$I_{df,d}$	daily diffuse solar irradiance	J m^{-2} day^{-1}
$I_{dr,d}$	daily direct solar irradiance	J m^{-2} day^{-1}
$I_{et,d}$	daily extraterrestrial solar irradiance	J m^{-2} day^{-1}
$I_{t,d}$	daily total solar irradiance	J m^{-2} day^{-1}
k	von Karman's constant (0.4)	-

k_{df}	canopy extinction coefficient for diffuse solar radiation (corrected for canopy clustering)	-
k_{dr}	canopy extinction coefficient for direct radiation	-
$K_{\theta,i}$	soil hydraulic conductivity for soil layer i	m day^{-1}
$\overline{K}_{\theta,i}$	logarithmic mean of hydraulic conductivity for soil layer i and (i-1)	m day^{-1}
K_c	Michaelis-Menten constant for CO_2	μmol mol^{-1}
K_o	Michaelis-Menten constant for O_2	μmol mol^{-1}
$K_{s,i}$	saturated hydraulic conductivity for soil layer i	m day^{-1}
K_T	sky clearness index	-
l_1	dry soil layer thickness	m
l_2	air mixing height	m
l_3	mean pinnae length	m
l_m	mean distance between pinnae	m
L	leaf area index	m^2 leaf m^{-2} ground
L_{cr}	critical leaf area index	m^2 leaf m^{-2} ground
L_{sh}	shaded leaf area index	m^2 leaf m^{-2} ground
L_{sl}	sunlit leaf area index	m^2 leaf m^{-2} ground
L_{maxPD}	maximum leaf area index for a given PD planting density (palms ha^{-1})	m^2 leaf m^{-2} ground

M_{total}, M'_{total}	total maintenance respiration requirement with and without temperature correction, respectively	kg CH_2O $palm^{-1}$ day^{-1}
M_x	maintenance requirement for plant part x, where x is for pinnae, rachis, trunk, roots, organs, metabolic, and total	kg CH_2O $palm^{-1}$ day^{-1}
$M_{c,x}$	maintenance coefficient for plant part x, where x is for pinnae, rachis, trunk, and roots	kg CH_2O kg^{-1} DM
$MAX[x_1, x_2, \ldots x_n]$, $MIN[x_1, x_2, \ldots x_n]$	functions to return the maximum and minimum values of x_1, x_2, …, x_n, respectively	-
n	extinction coefficient for eddy diffusivity	-
N_x	fraction by weight of nitrogen content in plant part x, where x is for pinnae, rachis, trunk, and roots.	-
O_a	ambient concentration of O_2 in air	µmol mol^{-1}
OM	organic matter content in soil	%
p	surface albedo (reflection)	-
P_a	atmospheric pressure (101)	kPa
PD	planting density	palms ha^{-1}
$P_{g,d}$	rainfall (above canopies) for the given day of year	mm
$\overline{P_{g,yr}}$	average rainfall in the year	mm
$P_{net,d}$	net rainfall (below canopies) for the given day of year	mm
PAR_{max}	maximum PAR	W m^{-2}
q_i	water flux into soil layer i	m day^{-1}

$\hat{q}_i$	net water flux into soil layer i	m day^{-1}
Q_{df}	diffuse PAR component (above canopies)	μmol m^{-2} leaf s^{-1}
Q_{dr}	direct PAR component (above canopies)	μmol m^{-2} leaf s^{-1}
Q_{sh}	total PAR absorbed by shaded leaves	μmol m^{-2} leaf s^{-1}
Q_{sl}	total PAR absorbed by sunlit leaves	μmol m^{-2} leaf s^{-1}
$Q_{10,\xi}$	relative change in a parameter ξ for every 10 °C change	-
$\bar{Q}_{p,df}$	mean diffuse component of PAR (within canopies)	μmol m^{-2} ground s^{-1}
$Q_{p,dr}$	unintercepted direct component of PAR (with scattering component) (within canopies)	μmol m^{-2} leaf s^{-1}
$Q_{p,dr,\alpha}$	PAR scattered component only (within canopies)	μmol m^{-2} ground s^{-1}
$Q_{p,dr,dr}$	unintercepted direct component of PAR (without scattering component) (within canopies)	μmol m^{-2} leaf s^{-1}
$r_{\Delta Ca}$	annual rate of change for ambient CO_2 concentration	μmol mol^{-1} yr^{-1}
$r_{\Delta Pg}$	annual rate of change for rainfall	mm yr^{-1}
$r_{\Delta RH}$	annual rate of change for relative humidity	% yr^{-1}
$r_{\Delta s}$	annual rate of change for sunshine hours	hour yr^{-1}
$r_{\Delta Tmax}$	annual rate of change for maximum air temperature	°C yr^{-1}
$r_{\Delta Tmin}$	annual rate of change for minimum air temperature	°C yr^{-1}
$r_{\Delta u}$	annual rate of change for wind speed	m s^{-1} yr^{-1}

R_n	net solar radiation	W m^{-2}
R_{nL}	net longwave radiation	W m^{-2}
$R_{D,e}$	reduction factor for evaporation	-
$R_{D,t}$	reduction factor for transpiration	-
RH	relative humidity for the given hour	%
RH_d	average relative humidity for the given day of year	%
s_d	sunshine hours for the given day of year	hour
s_i	thickness of soil layer *i*	m
S	fractional sand content in soil	-
S_i	cumulative thickness of soil layer *i*	m
SLA	specific leaf area	m^2 g^{-1}
t_c	the fraction of net radiation as soil heat flux under full canopies (0.05)	-
t_d	day of year	-
t_h	local solar time	hour
t_s	the fraction of net radiation as soil heat flux for bare soil (no canopies) (0.315)	-
t_{sr}	time of sunrise	hour
t_{ss}	time of sunset	hour
T_{air}	air temperature	^{o}C
T_a	actual plant transpiration	m day^{-1}
T_{avg}	average air temperature	^{o}C

T_b	base temperature for crop growth	°C
T_f	temperature of canopy	°C
$T_{a,i}$	root extraction of water by roots in soil layer i	m day^{-1}
T_{dew}	dew point temperature	°C
$T_{dew,cal}$	calibrated dew point temperature	°C
T_{max}	maximum air temperature	°C
T_{min}	minimum air temperature for the given hour	°C
T_{set}	air temperature at sunset	°C
u_*	friction velocity	m s^{-1}
u	wind speed at the current hour	m s^{-1}
u_A	highest wind speed in the year	m s^{-1}
u_d	mean wind speed for the given day of year	m s^{-1}
u_h	wind speed at canopy height h	m s^{-1}
u_{max}, u_{min}	maximum and minimum wind speed for the given day, respectively	m s^{-1}
$\overline{u_{yr}}$	average wind speed in the year	m s^{-1}
v_c	Rubisco-limited rate of CO_2 assimilation	µmol m^{-2} leaf s^{-1}
v_q	light-limited rate of CO_2 assimilation	µmol m^{-2} leaf s^{-1}
v_s	sink-limited rate of CO_2 assimilation	µmol m^{-2} leaf s^{-1}
V_{cmax}	Rubisco capacity rate (200)	µmol m^{-2} leaf s^{-1}
VDM_d	daily VDM requirement	kg DM palm^{-1} day^{-1}

VDM_{yr}	annual VDM requirement	kg DM palm^{-1} yr^{-1}
$VDM_{max,PD}$	maximum annual VDM for the given planting density	kg DM palm^{-1} yr^{-1}
w	mean pinnae width	m
W_x	dry weight of plant part *x*, where *x* is for pinnae, rachis, trunk, roots, male flowers (*maleflo*), immature bunches (*immbunch*), and mature bunches (*matbunch*).	kg DM palm^{-1}
X_c	correction for mineral content in all plant parts (2.0)	-
X_x	fraction by weight of mineral content in plant part *x*, where *x* is for pinnae, rachis, trunk, and roots.	-
z_0	surface roughness length	m
z_i	depth from soil surface to the middle of soil layer *i*	m
z_r	reference height	m
z_{s0}	roughness length of soil surface	m

CHAPTER 1

INTRODUCTION

1.1 Research Background

Oil palm (*Elaeis guineensis* Jacq.) is one of the world's major vegetable oil crops. Global consumption of palm oil over the last two decades has tripled, and annual consumption increased from 24.99 million tonnes in 2001 (USDA, 2006) to 74.90 million tonnes in 2020 (USDA, 2021) due to the extensive use of palm oil in a wide range of consumer products, and production of biofuel (Koh and Ghazoul, 2008). Malaysia, the second largest producer and exporter of palm oil in the world (USDA, 2021), has benefited considerably from the worldwide growing demand for palm oil. The area planted with oil palm had expanded from 540,000 hectares in 1960 to 5.87 million hectares in 2020 (MPOB, 2021), with Sarawak having the largest planted area and closely followed by Sabah (Figure 1.1). Peninsular Malaysia has the largest oil palm planted area in Malaysia, with 2.74 million hectares or 46.7% of the total planted area. In 2021, Malaysia exported 15.56 million metric tonnes of palm oil from a total production of 18.12 million. Together with other palm-based products, the Malaysian palm oil industry brought in RM108.52 billion of export earnings to the country (MPOB, 2022), signifying the economic importance of oil palm to the Malaysian economy.

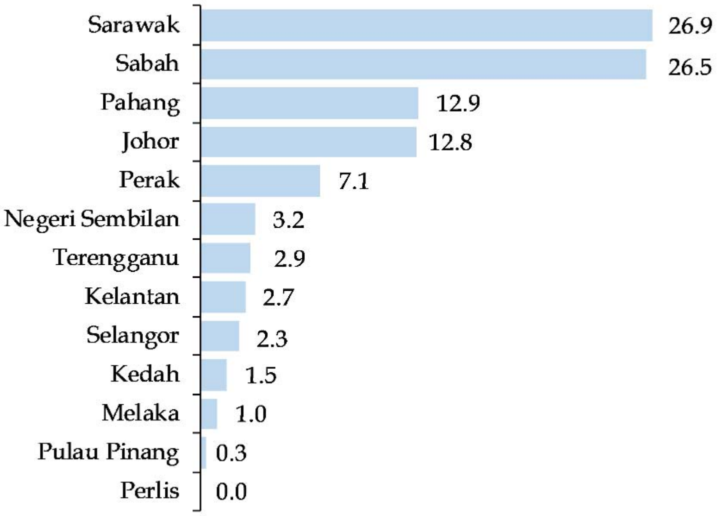

Figure 1.1: Distribution (%) of oil palm planted area in Malaysia, based on the total planted area of 5.87 million hectares recorded in 2020 (MPOB, 2021).

Oil palm requires an optimum mean temperature of 24–33 °C (Corley and Tinker, 2016; Paterson *et al*., 2015). Furthermore, it grows well with at least 5 hours of sunshine hours per day or equivalent solar radiation of 15–17 MJ m^{-2} day^{-1} (Corley and Tinker, 2016; Rhebergen *et al*., 2016) and requires an evenly distributed annual rainfall of 2000–2500 mm (Corley and Tinker, 2016; Bakoumé *et al*., 2013). Oil palm is, however, sensitive to water stress, and the production of palm oil is affected by the length and severity of drought (Oettli *et al*., 2018; Caliman and Southwood, 1998). Therefore, extreme weather events such as El Niño, which brings much lower rainfall, could significantly impact palm oil production through lower fruit bunch formation. This was most notable in 2015/2016, when an extreme El Niño event blanketed Malaysia and Indonesia (Lim *et al*., 2017), causing severe water stress to oil palms (Oettli *et al*., 2018; Azlan *et al*., 2016). As a result, palm oil production in Malaysia reduced as much as 11% in 2015 and 5% in 2016 compared to production in 2014, the year preceding the onset of El Niño (USDA–FAS, 2021). Such adverse impact of El Niño on palm oil yield underpinned the vulnerability of oil palm to the vagaries of climatic changes.

Global warming, mainly driven by rising atmospheric CO_2 concentration, is projected to continue in the years ahead regardless of efforts to reduce its emissions (IPCC, 2018). Under a warmer climate, Malaysia will experience drier and more extreme weather in the years ahead (Kwan *et al*., 2013), and weather anomalies such as El Niño will become more frequent and intense (Wang *et al*., 2019; Cai *et al*., 2018, 2014; Keupp *et al*., 2017). El Niño coupled with land-use change such as converting forest to oil palm, can change the partition of surface energy balance and increase sensible heat fluxes, which in turn could lead to higher surface temperature (Ma'rufah *et al*., 2021). Mean air temperature in Malaysia has increased at a rate of 0.14–0.25 °C per decade (NRE, 2015), and it is expected to increase further in tandem with the projected increase in global mean air temperature of at least 1.7 °C by the end of the 21st century (Loh *et al*., 2016). Furthermore, the rainfall patterns in Malaysia are projected to vary substantially in space and time, with a tendency for reduced rainfall from December to May by 20–40% (Loh *et al*., 2016). Thus, the imminent threat of climate change on palm oil production in Malaysia is real. Rising air temperature coupled with frequent water deficit will stress oil palm (Oettli *et al*., 2018) and, in turn, reduce palm oil production. Areas under oil palm cultivation in Malaysia might reduce substantially under future warmer and drier climates (Paterson *et al*., 2017, 2015).

However, elevated atmospheric CO_2 concentration is beneficial to C3 plants like oil palms because photosynthesis of C3 plants will be enhanced under elevated atmospheric CO_2 concentration (Ainsworth and Long, 2005). Thus, the adverse effects of heat and water stresses might be moderated by the increased rate of CO_2 assimilation. For example, oil palm was more tolerant to drought during the 2015/2016 El Niño event under high solar irradiance. However, increased

CO_2 concentration did not increase the photosynthesis rate under reduced solar irradiance (Stiegler *et al.*, 2019). On the other hand, oil palm seedlings (Jaafar and Ibrahim, 2012; Ibrahim *et al.*, 2010) and mature oil palm (Henson and Harun, 2005a, b) have shown increased growth after exposure to elevated CO_2 concentration a result of increased rates of CO_2 assimilation and lower transpiration rates. Therefore, we must understand how oil palm responds to weather variables so that crop management adaptation strategies can be developed to mitigate the detrimental impacts of weather irregularities on oil palm.

Given the complex interactions between weather variables and crop production system, crop models have been increasingly used to understand how weather variables affect crop production and to assist in the development of crop management adaptation strategies such as planting densities, cultivar selection, irrigation, fertiliser regimes and crop rotations (Challinor *et al.*, 2018; Asseng *et al.*, 2014; Rosenzweig *et al.*, 2014). Although the crop model is a simplified mathematical representation of a complex crop-soil-atmosphere system, it integrates essential biophysical functions that drive crop growth, such as meteorology, photosynthesis, respiration, transpiration, phenology, soil evaporation, and uptake of nutrients and water (Asseng *et al.*, 2014; Teh, 2006). As such, making it an effective means to study crop performance across diverse environments and management practices. Rival (2017) pointed out that breeding oil palm for climate change will require multidisciplinary research, and modelling responses of oil palm to changing climate is paramount in developing climate-resilient oil palm genotypes and crop management practices.

Many oil palm models such as OPSIM (van Kraalingen, 1989 *et al.*; Gerristma, 1988), SIMPALM (Dufrêne *et al.*, 1990), GPHOT, GPHOT2, OPLFSIM3, OPRODSIM (Henson, 2009, 2006b, 2000, 1989), WaNuLCAS (van Noordwijk *et al.*, 2011), ECOPALM (Combres *et al.*, 2012), PALMSIM (Hoffmann *et al.*, 2014), APSIM-Oil Palm (Huth *et al.*, 2014), CLM-Palm (Fan *et al.*, 2015), CLIMEX-Oil Palm (Paterson *et al.*, 2015) and ORCHIDEE–MICT–OP (Xu *et al.*, 2020) have been developed especially over the last two decades to meet different objectives of studies. These oil palm models differ in regard to model structure, parameterization of biophysical processes and model outputs. Though these models have been applicable, there are several key features that make them less versatile in terms of simulating the responses of oil palm to weather irregularities and crop management practices.

1.2 Problem Statement

Key features that make the current oil palm models less versatile in terms of simulating the responses of oil palm to weather irregularities and crop management practices are:

First, the prevailing approach is to use daily or monthly weather data to model physiological processes, such as photosynthesis, transpiration, and respiration. Nonetheless, according to Ephrath *et al*. (1996), the use of daily or monthly weather data frequently results in deviations when modelling crop responses to weather variables. This is because physiological processes immediately respond to weather variables, and daily or monthly weather data may not suffice to account for these instantaneous responses compared to hourly weather data. A potential solution to address this issue is to simulate the hourly patterns of weather variables based on available daily weather data. However, this approach has not yet been implemented in major oil palm growing regions in Malaysia.

Second, except for CLM-Palm (Fan *et al*., 2015) and ORCHIDEE–MICT–OP (Xu *et al*., 2020), all other oil palm models used oil palm's radiation use efficiency (RUE) function to convert the intercepted radiation into gross assimilates. Though this RUE function is useful but is empirical and hence less robust in simulating photosynthesis responses to rising atmospheric CO_2 concentration (Streck *et al*., 2012) and other environmental variables (Wu *et al*., 2016). In contrast, the biochemical photosynthesis model of Farquhar *et al*. (1980) is more mechanistic and has been used extensively to predict responses of photosynthesis to environmental variables (Xu *et al*., 2020; Fan *et al*., 2015; Medlyn *et al*., 2005; Cramer *et al*., 2001). However, this biochemical photosynthesis model requires the temperature dependency of Rubisco kinetics, such as maximum Rubisco carboxylation rate (V_{cmax}), electron transport rate (J), leaf day respiration rate in the light (R_d), CO_2 photocompensation point in the absence of leaf day respiration (Γ^*) and mesophyll conductance to CO_2 (g_m) (von Caemmerer, 2000). These parameters and their temperature dependency are, however, largely unknown for oil palm, although Xu *et al*. (2020), Nugroho (2018), Meijide *et al*. (2017) and Fan *et al*. (2015) had made some measurements to estimate the V_{cmax} of oil palm.

Third, simulations of evapotranspiration or transpiration of oil palm by most of oil palm models either use the Penman-Monteith model (Monteith, 1973) or a simple transpiration efficiency (TE) coefficient (Huth *et al*., 2014). Nevertheless, this approach appears inadequate to model the microclimate environment within and under the oil palm canopies. The transpiration efficiency coefficient is an empirical value which might vary seasonally and from place to place, depending on weather conditions and management practices (Tfwala *et al*., 2021;

Bennie *et al.*, 1997). Furthermore, it only accounts for water transpired from oil palm but ignores soil evaporation which is inadequate as soil evaporation under oil palm canopies can be substantial (Röll *et al.*, 2015). On the other hand, the Penman-Monteith model only simulates heat fluxes from either soil or crop but not both simultaneously.

In contrast, the Shuttleworth-Wallace model (Shuttleworth and Wallace, 1985) extends the Penman-Monteith model but allows simultaneous simulation of heat fluxes from both soil and crop. This has the advantage of getting a more accurate simulation of soil evaporation, especially during wet periods when the soil moisture content is high (Fisher et al., 2005). The Shuttleworth-Wallace model has done well in many studies (Yan and Oue, 2011; Iritz *et al.*, 1999; Vörösmarty *et al.*,1998; Farahani and Bausch, 1995). However, like its predecessor, the main drawback is the requirement to measure its parameters (Farahani and Ahuja, 1996) which has not been done for oil palm.

Fourth, the first oil palm model, OPSIM (van Kraalingen *et al.*, 1989; van Kraalingen, 1985), used respiration coefficients to simulate the maintenance respiration of oil palm. These coefficients were calculated from nitrogen and mineral content determined in different plant parts of oil palm. This approach is touted to be more mechanistic (Penning de Vries, 1975, 1972) and was adopted by SIMPALM (Dufrêne *et al.*, 1990), OPRODSIM (Henson, 2009) and PALMSIM (Hoffmann *et al.*, 2014). The maintenance respiration coefficients used in the SIMPALM (Dufrêne *et al.*, 1990) and PALMSIM (Hoffmann *et al.*, 2014) were computed from nitrogen and mineral contents determined from a single tenera x dura (L2T x D10D) oil palm progeny grown in Ivory Coast. On the other hand, OPSIM (van Kraalingen *et al.*, 1989; van Kraalingen, 1985) and OPRODSIM (Henson, 2009) determined their maintenance respiration coefficients using nitrogen and mineral contents reported by Ng *et al.* (1968), which were primarily obtained from dura oil palm grown under good growing conditions in Malaysia. These maintenance respiration coefficients are rather dated and may not apply today for the current high-yielding tenera oil palm.

Fifth, the growth of oil palm can be separated into vegetative and reproductive growth. Vegetative growth consists of leaf, trunk, and root growth (Corley and Tinker, 2016). However, the methods used to simulate vegetative growth are primarily empirical, based on the vegetative dry matter requirement of oil palm (Henson, 2009; Dufrêne *et al.*, 1990; van Kraalingen, 1985) or phytomer phenology of oil palm (Xu *et al.*, 2020; Fan *et al.*, 2015; Combres *et al.*, 2013). Therefore, to minimize errors in simulating vegetative growth, it would be necessary to use the updated data on phytomer phenology or dry matter requirement and partitioning derived from the current tenera oil palm.

Sixth, planting density is a crucial crop management strategy that drives palm oil yield (Palat *et al*., 2012; Nazeeb *et al*., 2008; Nazeeb *et al*., 1989; Breure, 1988; Corley, 1973). Although commercial oil palm plantations generally plant between 128 and 148 palms per hectare but planting densities higher than this range have been explored to increase palm oil yield (Palat *et al*., 2012; Breure, 2010; Nazeeb *et al*., 2008; Breure *et al*., 1990; Nazeeb *et al*., 1989; Breure and Corley, 1983). Changes in planting density will affect interception of solar irradiance by oil palm canopies, microclimate within and under oil palm canopies and soil water balance, consequently affecting the growth and yield of oil palm. Having able to use a crop model to characterize the interactions between planting density and environmental variables will give better insight into how planting density can be managed to drive palm oil production. However, except for OPRODSIM (Henson, 2009), the present oil palm models cannot essentially simulate the growth and yield of oil palm grown under different planting densities.

1.3 Objectives of Research

Given the drawbacks of the current oil palm models, the present study was undertaken to develop and validate a versatile and more mechanistic oil palm model that assesses the impacts of weather irregularities and crop management practices on the growth and yield of oil palm specifically under Malaysian environment and management. To achieve this overall objective, the following specific objectives were undertaken:

i. To parameterise the meteorological models for hourly estimations of air temperature, relative humidity, and solar irradiance.
ii. To parameterise the biochemical model of C3 leaf photosynthesis through photosynthesis measurements on different ages of tenera oil palm in the fields.
iii. To parameterise maintenance respiration and dry matter partitioning coefficients using nitrogen and mineral contents and dry matter production data from destructive measurements on different ages of current tenera oil palm.
iv. To parameterise the Shuttleworth-Wallace model through measurements on stomatal conductance, trunk, and canopy height of different ages of tenera oil palm.
v. To develop a new oil palm growth and yield model and validate its accuracy against observed data from six oil palm planting density trials conducted in Malaysia.
vi. To examine the impact of weather anomalies such as El Niño on oil palm growth and yield through simulations.

1.4 Limitation of the Study

The present study only focuses on developing an oil palm growth and yield model that is applicable to the Dura x Pisifera oil palm progeny. In addition, the present study does not examine the effects of La Niña and fertiliser on oil palm growth and yield through simulations.

1.5 Structure of the PhD Thesis

The thesis consists of seven chapters, with the first chapter outlining the research background and objectives. In Chapter 2, the growth and yield of oil palm and their simulation methods are reviewed. Chapters 3 through 5 have been published in peer-reviewed journals, while Chapter 6 appears as a book chapter. Chapter 7 concludes the thesis by summarizing the research findings and discussing how they relate to the research objectives. Additionally, recommendations for future research are provided.

1.5.1 Chapter 3

The third chapter is published by Cheah See Siang, Christopher Teh Boon Sung, Mohd Razi Ismail and Mohd Rafii Yusop (2020). **Modelling hourly air temperature, relative humidity and solar irradiance over several major oil palm growing areas in Malaysia**. *Journal of Oil Palm Research* Vol. 32(1): 34–49. In this chapter, a study was undertaken with the aim to assess the precision of various meteorological models in estimating hourly air temperature, relative humidity, and solar irradiance values across several significant oil palm cultivation regions in Malaysia. The validated meteorological models were used to generate hourly estimations of these weather variables, which were then used as inputs for the oil palm growth and yield model.

1.5.2 Chapter 4

The fourth chapter is published as S.S. Cheah and C.B.S. Teh (2020). **Parameterization of the Farquhar-von Caemmerer-Berry C3 photosynthesis model for oil palm**. *Photosynthetica* 58(3): 769-779. This research was undertaken to determine critical model parameters of the Farquhar-von Caemmerer-Berry (FvCB) C3 biochemical photosynthesis model for oil palm. The key FvCB model parameters such as photocompensation point (Γ^*), mesophyll conductance (g_m), maximum rates of Rubisco carboxylation (V_{cmax}) and electron transport (J_{max}), triose phosphate utilization (TPU) and their temperature dependencies between

25 and 40°C in oil palm were determined. The derived values of these parameters were then used to parameterize the photosynthesis module of the oil palm growth and yield model.

1.5.3 Chapter 5

The fifth chapter is published as Cheah See Siang, Siti Aishah Abd Wahid and Christopher Teh Boong Sung (2022). **Standing biomass, dry matter production, and nutrient demand of tenera oil palm**. *Agronomy* 12, 426. This research was undertaken to determine the aboveground vegetative biomass, dry matter production and partitioning, and nutrient contents in different plant parts of tenera oil palms grown under current crop management standards in Malaysia. The results were used to determine dry matter partitioning coefficients and maintenance respiration coefficients of oil palm.

1.5.4 Chapter 6

The sixth chapter was published as Christopher Teh Boon Sung and Cheah See Siang (2018). **Modelling crop growth and yield in palm oil cultivation**. In *Achieving sustainable cultivation of oil palm*. Volume 1: Introduction, breeding and cultivation techniques. Alain Rival (ed.) Burleigh Dodds Science Publishing, Cambridge, UK. This book chapter describes the development of a new oil palm growth and yield model called PySawit, and its validation using data collected from an oil palm planting density trial. Since the publication of PySawit in 2018, further improvements have been made and the oil palm growth and yield model has been renamed as Sawit. Additional trial data collected from six different locations in Malaysia were used to further validate Sawit. Further development of Sawit is described and additional validations are discussed in Chapter 6.

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