PySAWIT:
OIL PALM GROWTH AND YIELD MODEL

Brief report (draft)

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CHAPTER 1. METEOROLOGY

Calculations begin with the meteorology section. Properties such as solar irradiance, solar position, wind speed, air temperature and vapour pressure must be determined at the outset before calculating other factors that affect plant growth and yield.

1.1 Daily properties

Daily meteorological properties refer to meteorological properties for a given day of year (or date). For each day, daily values for solar radiation, rainfall (if any), relative humidity, minimum and maximum air temperature, and wind speed must be calculated.

The weather generator WGEN by Richardson (1981) is followed to generate daily values of rainfall (if any), solar radiation, and minimum and maximum air temperature.

1.1.1 Rainfall

The distribution of daily rainfall amounts is described using the two-parameter gamma distribution, given as:

$$f[\![r]\!] = \frac{r^{\alpha-1}\exp\left(-r/\beta\right)}{\beta^{\alpha}\Gamma[\![\alpha]\!]}$$

where $f[\![r]\!]$ is the probability density function for the rainfall amount r (mm); α and β are the shape and scale distribution parameters, respectively; and $\Gamma[\![\alpha]\!]$ is the gamma function. The cumulative distribution function (CDF) of rainfall can be represented as

$$F[\![r]\!] = \int_0^r f[\![x]\!]dx$$

so that for a wet day, its amount of rainfall is determined by taking the inverse of the gamma distribution as

$$r = F^{-1}[\![1-p]\!]$$

where p is a uniformly distributed random probability value (0 to 1). Note that $F^{-1}[\![1-p]\!]$ is taken rather than $F^{-1}[\![p]\!]$ because large rainfall amounts are associated with smaller probabilities, whereas small rainfall amounts with larger probabilities. In other words, smaller rainfalls are more typical (*i.e.*, occur more frequently) than larger rainfalls.

In the model, 12 monthly values of (α, β) must be provided; one set of (α, β) for each month. For each month, (α, β) can be estimated by

$$\alpha = \left(\frac{\text{mean rainfall for the month}}{\text{std. dev of rainfall for the month}}\right)^2$$

$$\beta = \frac{\text{mean rainfall for the month}}{\alpha}$$

Whether rain would occur for a given day depends on whether it had rained on the previous day. A first-order Markov chain is used to generate the occurrence of wet and dry days. For each month, a set of [P(W|W), P(W|D)] must be provided, where P(W|W) is the probability of rain (W) on a given day (*e.g.*, today) when it had rained the previous day (*e.g.*, yesterday). Similarly, P(W|D) is the probability of rain on a given day when it had been dry (D) the previous day.

1.1.2 Air temperature and solar radiation

The following must be provided to the model to generate daily minimum and maximum air temperature and solar radiation:

a) Minimum air temperature (°C): mean annual value for dry days, amplitude (difference between the maximum and mean air temperature), CV (coefficient of variation), amplitude for the CV, and the mean annual value for wet days.

b) Maximum air temperature (°C): the same as for minimum air temperature, as shown above.

c) Solar radiation (MJ m^{-2} day^{-1}): mean annual value for dry days, amplitude (difference between the maximum and mean solar radiation), and the mean annual value for wet days.

1.1.3 Wind speed

Wind speed is described by the Weibull probability density function:

$$f[\![u_d]\!] = \frac{k}{c}\left(\frac{u_d}{c}\right)^{k-1} \exp\left[-\left(\frac{u_d}{c}\right)^k\right]$$

where $f[\![u_d]\!]$ is the probability density function for the daily wind speed u (m s^{-1}), and k and c are the shape (unitless) and scale (m s^{-1}) distribution parameters, respectively. The cumulative distribution function (CDF) of daily windspeed can be represented as

$$F[\![u_d]\!] = 1 - \exp\left[\left(\frac{u_d}{c}\right)^k\right]$$

so that the wind speed for a given day is determined by taking the inverse of the cumulative probability distribution as

$$u_d = c\left[-\ln(p)\right]^{1/k}$$

where p is a uniformly distributed random probability value (0 to 1).

In the model, 12 monthly values of (k, c) must be provided to generate the daily wind speed for any day in a given month. These (k, c) data set can be obtained from literature.

1.1.4 Solar declination

$$\delta = -0.4093\cos\left[\frac{2\pi}{365}\left(t_d + 10\right)\right]$$

where δ is the solar declination (radians); and t_d is the day of year (Goudriaan and van Laar, 1994).

1.1.5 Sunrise, sunset, and day length

$$t_{sr} = 12 - \frac{12}{\pi}\text{acos}\left(-\frac{\sin\delta\cdot\sin\lambda}{\cos\delta\cdot\cos\lambda}\right) = 24 - t_{ss}$$
$$t_{ss} = 12 + \frac{12}{\pi}\text{acos}\left(-\frac{\sin\delta\cdot\sin\lambda}{\cos\delta\cdot\cos\lambda}\right)$$
$$DL = \frac{24}{\pi}\text{acos}\left(-\frac{\sin\delta\cdot\sin\lambda}{\cos\delta\cdot\cos\lambda}\right) = t_{ss} - t_{sr}$$

where t_{sr}, t_{ss} and DL are the sunrise, sunset and day length, respectively (all expressed in unit hour); δ is the solar declination (radians); and λ is the site latitude (radians) (Goudriaan and van Laar, 1994).

1.1.6 Solar constant

$$I_c = 1370\times\left\{1 + 0.033\cos\left[2\pi\left(t_d - 10\right)/365\right]\right\}$$

where I_c is the solar constant (W m^{-2}); and t_d is the day of year (Goudriaan and van Laar, 1994).

1.1.7 Daily extraterrestrial solar irradiance

$$I_{et,d} = 3600\times I_c\times\frac{24}{\pi}\left[a\times\text{acos}\left(-\frac{a}{b}\right) + b\sqrt{1-\left(\frac{a}{b}\right)^2}\right]$$
$$a = \sin\lambda\sin\delta$$
$$b = \cos\lambda\cos\delta$$

where $I_{et,d}$ is the daily extraterrestrial solar irradiance (J m^{-2} day^{-1}); I_c is the solar constant (W m^{-2}); δ is the solar declination (radians); and λ is the site latitude (radians) (Goudriaan and van Laar, 1994).

1.1.8 Daily total solar irradiance and its direct and diffuse components

$$I_{t,d} = \int_{t_{sr}}^{t_{ss}} I_t dt$$

$$I_{dr,d} = \int_{t_{sr}}^{t_{ss}} I_{dr} dt$$

$$I_{df,d} = \int_{t_{sr}}^{t_{ss}} I_{df} dt$$

where $I_{t,d}$ and I_t are the daily (J m^{-2} day^{-1}) and instantaneous (W m^{-2}) total solar irradiance, respectively; $I_{df,d}$ and I_{df} are the daily (J m^{-2} day^{-1}) and instantaneous (W m^{-2}) diffuse solar irradiance, respectively; and $I_{dr,d}$ and I_{dr} are the daily (J m^{-2} day^{-1}) and instantaneous (W m^{-2}) direct solar irradiance, respectively. These daily solar components are obtained by integrating their respective instantaneous values (I_t, I_{df}, or I_{dr}) over the period from sunrise (t_{sr}) to sunset (t_{ss}).

1.2 Instantaneous (hourly) properties

Instantaneous properties refer to meteorological properties for a given hour and day of year (or date and time).

1.2.1 Hour angle

$$\tau = \frac{\pi}{12}\left(t_h - 12\right)$$

where τ is the hour angle (radians); and t_h is the local solar time (hour) (Goudriaan and van Laar, 1994).

Note: hour angles will be negative for before solar noon ($t_h < 12$), positive for after solar noon ($t_h > 12$), and zero at exactly solar noon.

1.2.2 Solar position

Solar inclination (and solar height)

$$\theta = \operatorname{acos}\left(\sin\delta\sin\lambda + \cos\delta\cos\lambda\cos\tau\right)$$

where θ is the solar inclination (angle from vertical) (radians); δ is the solar declination (radians); τ is the hour angle (hour); and λ is the site latitude (radians) (Goudriaan and van Laar, 1994).

Note: Rather than its angle from vertical, solar angle can be specified alternatively as β, the solar height or solar elevation, which is the solar angle from horizontal, determined by $\pi/2$ - θ (radians).

Solar azimuth

$$\phi = \begin{cases} \pi - \operatorname{acos}\left(\dfrac{\sin\lambda\sin\beta - \sin\delta}{\cos\lambda\cos\beta}\right) & t_h \le 12 \\ \pi + \operatorname{acos}\left(\dfrac{\sin\lambda\sin\beta - \sin\delta}{\cos\lambda\cos\beta}\right) & t_h > 12 \end{cases}$$

where ϕ is the solar azimuth (angle from North in a clockwise direction) (radians); δ is the solar declination (radians); τ is the hour angle (hour); and λ is the site latitude (radians) (Goudriaan and van Laar, 1994).

1.2.3 Extraterrestrial solar irradiance

$$I_{et} = I_c \sin\beta = I_c \cos\theta$$

where I_{et} is the instantaneous extraterrestrial solar irradiance (W m^{-2}); I_c is the solar constant (W m^{-2}); θ is the solar inclination (radians); and β is the solar height (or solar elevation) (radians) (Goudriaan and van Laar, 1994).

Note: $\beta = \pi/2 - \theta$.

1.2.4 Total solar irradiance and its direct and diffuse components

$$I_t = I_{dr} + I_{df}$$

where I_t is the instantaneous total solar irradiance (W m^{-2}); I_{dr} is the instantaneous direct solar irradiance (W m^{-2}); and I_{df} is the instantaneous diffuse solar irradiance (W m^{-2}). The calculations from Liu and Jordan (1960) are followed to determine both these solar radiation components as

$$I_{dr} = I_{et} \cdot \tau^m$$
$$I_{df} = 0.3\left(1 - \tau^m\right) I_{et}$$

where I_{et} is the instantaneous extraterrestrial solar irradiance (W m^{-2}), and τ is the atmospheric transmittance; and m is the optical mass number. The optical mass number m is determined from Campbell and Norman (1998) as

$$m = \frac{P_a}{101.3\cos(\theta)}$$

where θ is the solar inclination (radians), and P_a is the atmospheric pressure (kPa), assumed constant at 101 kPa. And the determination of the atmospheric transmittance τ is determined by

$$\tau = 1.1857 - 0.0112RH$$

This equation was obtained by fitting the best function to the relationship between measured RH and atmospheric transmittance τ (ratio between I_t and I_{et}) for five oil palm estates in Malaysia: Bukit Selarong, Kedah (5.462824 °N, 100.597084 °E); Diamond Jubilee, Melaka (2.33333 °N, 102.483333 °E); Imam, Sabah (4.333333 °N, 117.833333 °E); Seri Intan, Perak (3.976583 °N, 100.9739 °E); and Ulu Remis, Johor (1.827778 °N, 103.461944 °E) for the period between 2015 and 2016.

1.2.5 Air temperature

It is assumed that air temperature varies sinuously with time in the period between 1.5 hours after the time of minimum air temperature and time of sunset. For time outside this period, air temperature is assumed to change linearly with time.

$$T_a = \begin{cases} T_{set} + \dfrac{(T_{\min} - T_{set})(24 + t_h - t_{ss})}{(t_{sr} + 1.5) + (24 - t_{ss})} & t_h < (t_{sr} + 1.5) \\ T_{\min} + (T_{\max} - T_{\min}) \sin\left[\dfrac{\pi(t_h - t_{sr} - 1.5)}{t_{ss} - t_{sr}}\right] & (t_{sr} + 1.5) \le t_h \le t_{ss} \\ T_{set} + \dfrac{(T_{\min} - T_{set})(t_h - t_{ss})}{(t_{sr} + 1.5) + (24 - t_{ss})} & t_h > t_{ss} \end{cases}$$

$$T_{set} = T_{\min} + (T_{\max} - T_{\min}) \sin\left[\frac{\pi(t_{ss} - t_{sr} - 1.5)}{t_{ss} - t_{sr}}\right]$$

where T_a is the air temperature (°C) at local solar time t_h (hour); T_{min} and T_{max} are the minimum and maximum air temperature (°C), respectively; and t_{sr} and t_{ss} are the times of sunrise and sunset, respectively (hour); and T_{set} is the air temperature (°C) at sunset (t_{ss}).

1.2.6 Air vapour pressure

$$e_a = 6.1078 \exp\left(\frac{17.269 T_{dew,cal}}{T_{dew,cal} + 237.3}\right)$$

where e_a is the air vapour pressure (mbar); and $T_{dew,cal}$ is the calibrated dew point temperature (°C), and it should be lower than current air temperature, T_a:

$$T_{dew,cal} = MIN(T_a, T_{dew})$$

where T_{dew} is the average dew point temperature for the site (mean for Malaysia, 23 °C).

1.2.7 Wind speed

The instantaneous values for wind speed vary sinuously within the day as

$$u = MAX\left\{u_{\min}, u_{\min} + (u_{\max} - u_{\min}) \sin\left[\frac{\pi}{DL}(t_h - t_{sr} - 1.5)\right]\right\}$$

where u is the wind speed for the given hour (m s^{-1}); u_{max} and u_{min} are the maximum and minimum wind speed for the day, respectively (m s^{-1}); t_h is the local solar hour (hour); t_{sr} and t_{ss} are the hour of sunrise and sunset, respectively (hour); and DL is the day length (hour).

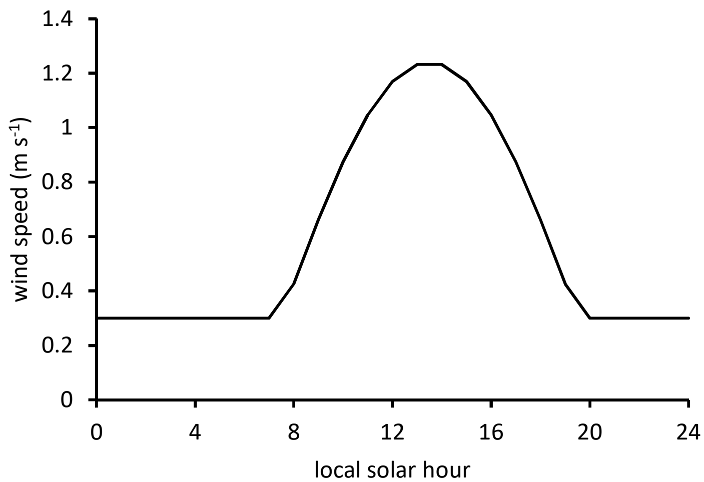

Fig. 1.1. Idealized distribution of wind speed in a day

The mean daily minimum and maximum wind speed can be estimated by the following empirical equations, developed from measured data from several towns in Malaysia:

$$u_{\min} = 0.5591 u_d^{1.25}$$
$$u_{\max} = 1.7976 u_d^{0.75}$$

where u_d is the mean daily wind speed (m s^{-1}).

1.2.8 Saturated air vapour pressure

$$e_s[\![T_a]\!] = 6.1078 \exp\left[\frac{17.269 T_a}{T_a + 237.3}\right]$$

where $e_s[\![T_a]\!]$ is the function returning the saturated vapour pressure (mbar) at air temperature T_a (°C).

1.2.9 Slope of the saturated vapour pressure curve

$$\Delta = \frac{25029.4 \exp\left[17.269 T_a / \left(T_a + 237.3\right)\right]}{\left(T_a + 237.3\right)^2}$$

where Δ is the slope of the saturated vapour pressure curve (mbar K^{-1} or equivalently, mbar $°C^{-1}$) at air temperature T_a (°C).

1.2.10 Relative humidity (RH)

$$RH = 100 \frac{e_a}{e_s[\![T_a]\!]}$$

where RH is the relative humidity (%) for the given hour; e_a is the air vapour pressure (mbar); and $e_s[\![T_a]\!]$ is the function returning the saturated vapour pressure (mbar) at air temperature T_a (°C).

CHAPTER 2. CANOPY PHOTOSYNTHESIS

This section describes the amount of CO_2 assimilated by the canopies. The method by Collatz *et al.* (1991) was adapted. Essentially, calculations involved determining the solar irradiance within the canopies, calculating the CO_2 assimilation rate by individual leaves, then scaling up to canopy assimilation rate.

2.1 PAR components within canopies

There are four flux components within the canopies, and they are determined from Campbell and Norman (1998) as

$$Q_{p,dr} = (1 - p_{dr})Q_{dr} \exp\left(-k_{dr}\omega\sqrt{\alpha}L\right)$$

$$Q_{p,dr,dr} = (1 - p_{dr})Q_{dr} \exp\left(-k_{dr}\omega L\right)$$

$$Q_{p,dr,\alpha} = \frac{\left(Q_{p,dr} - Q_{p,dr,dr}\right)}{2}$$

$$\bar{Q}_{p,df} = \frac{(1 - p_{df})Q_{df}\left[1 - \exp\left(-k_{df}\sqrt{\alpha}L\right)\right]}{k_{df}\sqrt{\alpha}L}$$

Canopies flux components

$Q_{p,dr}$ is the PAR irradiance for unintercepted beam *with* scattered beam (μmol photons m^{-2} ground s^{-1}); $Q_{p,dr,dr}$ is the PAR irradiance for unintercepted beam *without* scattering (μmol photons m^{-2} ground s^{-1}); $Q_{p,dr,\alpha}$ is the PAR irradiance of the scattered component *only* (μmol photons m^{-2} leaf s^{-1}); and $\bar{Q}_{p,df}$ is the mean diffuse irradiance (μmol photons m^{-2} leaf s^{-1}).

Note: Both $Q_{p,dr,\alpha}$ and $\bar{Q}_{p,df}$ are expressed based on a per unit leaf area (not per unit ground area). It is assumed that scattered and diffuse irradiance on a unit horizontal ground area is equal to their irradiance on a unit leaf area.

PAR direct and diffuse irradiance

$$Q_{dr} = I_{dr} \times 0.5 \times 4.55$$
$$Q_{df} = I_{df} \times 0.5 \times 4.55$$

where Q_{dr} and Q_{df} are, respectively, the instantaneous direct and diffuse PAR irradiance, both expressed in μmol photons m^{-2} ground s^{-1}; and I_{dr} and I_{df} are the instantaneous direct and diffuse solar irradiance, respectively (W m^{-2} ground).

Note: Total PAR irradiance is assumed 50% of total solar irradiance. It is then converted from unit W m^{-2} ground to μmol photons m^{-2} ground s^{-1} by multiplying it with 4.55 (Goudriaan and van Laar, 1994).

Canopy extinction coefficient for direct PAR

$$k_{dr} = \frac{0.5}{\sin\beta} = \frac{0.5}{\cos\theta}$$

where k_{dr} is the canopy extinction coefficient for direct PAR; β is the solar height (or solar elevation) (radians); and θ is the solar inclination ($\beta = \pi/2 - \theta$) (radians) (Goudriaan, 1977).

Note: random distribution of leaves in the canopies is assumed.

Canopy clustering coefficient (correcting for non-uniform distribution of canopies in the aerial space)

$$\omega = \omega_0 + 6.6557\left(1-\omega_0\right)\exp\left[-\exp\left(-\theta+2.2103\right)\right]$$
$$\omega_0 = -\frac{1}{k_{dr}L}\ln\left\{\tau_b + (1-\tau_b)\exp\left[-k_{dr}\frac{L}{(1-\tau_b)}\right]\right\}$$

where ω is the canopy clustering coefficient (0 to 1); ω_0 is the canopy clustering coefficient (0 to 1) when the sun is at zenith (highest point in the sky); L is the total leaf area index (m^2 leaf m^{-2} ground); θ is the solar inclination (radians); and k_{dr} is the canopy extinction coefficient for direct PAR (Kustas and Norman, 1999). τ_b is the canopy gap fraction (0 to 1) determined from Awal (2008) as

$$\tau_b = \left(1+1.33\sqrt{L}\right)^{-1}$$

where L is the total leaf area index (m^2 leaf m^{-2} ground).

Canopy extinction coefficient for diffuse PAR

$$k_{df} = \exp\left(0.038042 - 0.38845\sqrt{L}\right)$$

where k_{df} is the canopy extinction coefficient for diffuse PAR; and L is the total leaf area index (LAI) (m^2 leaf m^{-2} ground) (adapted from Teh, 2006).

Note that the equation for k_{df} already accounts for canopy gaps and that its assumption, like for k_{dr}, is the canopy is also randomly distributed in the aerial space.

Canopy reflection and leaf absorption coefficients for PAR

The canopy reflection coefficient for direct (p_{dr}) and diffuse (p_{dr}) PAR are determined by

$$p_{dr} = MAX\left[0.04,\ p_s\exp\left(-2k_{dr}\omega\sqrt{\alpha}L\right)\right]$$
$$p_{df} = MAX\left[0.04,\ p_s\exp\left(-2k_{df}\sqrt{\alpha}L\right)\right]$$

where k_{dr} and k_{df} are the canopy extinction coefficients for direct and diffuse PAR, respectively; ω is the canopy clustering coefficient (0 to 1); L is the total leaf area index (m^2 leaf m^{-2} ground); α is the leaf scattering coefficient for PAR, taken as 0.8 (Goudriaan, 1977; Goudriaan and van Laar, 1994); and p_s is the soil reflection coefficient, taken as 0.15.

2.2 PAR absorption by the leaves

$$Q_{sl} = \alpha\left(k_{dr}\omega Q_{dr} + \bar{Q}_{p,df} + Q_{p,dr,\alpha}\right)$$
$$Q_{sh} = \alpha\left(\bar{Q}_{p,df} + Q_{p,dr,\alpha}\right)$$

where Q_{sl} and Q_{sh} are the PAR flux densities absorbed by the sunlit leaves and shaded leaves, respectively (µmol photons m^{-2} leaf s^{-1}); k_{dr} is the canopy extinction coefficient for direct PAR; ω is the canopy clustering coefficient (0 to 1); Q_{dr} is the instantaneous direct PAR irradiance (µmol photons m^{-2} ground s^{-1}); $Q_{p,dr,\alpha}$ is the PAR irradiance of the scattered component *only* (µmol photons m^{-2} leaf s^{-1}); $\bar{Q}_{p,df}$ is the mean diffuse irradiance (µmol photons m^{-2} leaf s^{-1}); and α is the leaf scattering coefficient (where in this case, it is also the leaf absorption coefficient) for PAR (0.8) (Campbell and Norman, 1998).

Note: PAR flux densities absorbed (Q_{sl} and Q_{sh}) are based on a per unit leaf area (not per unit ground area).

2.3 Sunlit and shaded leaf area index

$$L_{sl} = \frac{1 - \exp(-k_{dr}\omega L)}{k_{dr}\omega}$$
$$L_{sh} = L - L_{sl}$$

where L_{sl} and L_{sh} are sunlit and shaded leaf area index, respectively (m^2 leaf m^{-2} ground); L is the total leaf area index (m^2 leaf m^{-2} ground); k_{dr} is the canopy extinction coefficient for direct PAR; and ω is the canopy clustering coefficient (0 to 1) (Goudriaan and van Laar, 1994).

2.4 Canopy temperature

$$T_f = \frac{H_c r_a^c + \left(H_s + H_c\right) r_a^a}{\rho c_p} + T_r$$

where T_f is the canopy (foliage) temperature (°C); T_r is the air temperature at reference level (°C); H_s and H_c are the soil and crop sensible heat fluxes, respectively (W m^{-2}); $r^a{}_a$ is the aerodynamic resistance between the mean canopy flow and reference level (s m^{-1}); $r^c{}_a$ is the bulk boundary layer resistance (s m^{-1}); and ρc_p is the volumetric heat capacity for air (1221.09 J m^{-3} K^{-1}) (Shuttleworth and Wallace, 1985).

2.5 Temperature-dependent parameters

There are some parameters whose values are sensitive to the canopy/foliage temperature T_f. Consequently, their values are adjusted according to

$$\xi = \xi_{(25)} \times Q_{10,\xi}^{(T_f - 25)/10}$$

where $\xi_{(25)}$ is the parameter value at 25 °C ($K_{c(25)}$, $K_{o(25)}$, $\tau_{(25)}$ or $V_{c,max(25)}$); T_f is the canopy temperature (°C); and $Q_{10,\xi}$ is the relative change in the parameter ξ for every 10 °C change. Values for the model parameters at 25 °C and their respective Q_{10} values are given below.

Table 2.1. Parameter values for the photosynthesis calculations. Parameters with subscript (25) denote their values at 25 ºC. Except for $V_{c,max}$, all values are from Bernacchi *et al.* (2001) and Bernacchi *et al.* (2002) for C3 plants.

$\xi_{(25)}$	Description	Value	Unit	$Q_{10,\xi}$
$K_{c(25)}$	Michaelis-Menten constant for CO_2	270	μmol mol^{-1}	2.786
$K_{o(25)}$	Michaelis-Menten constant for O_2	165000	μmol mol^{-1}	1.355
$\tau_{(25)}$	CO_2 / O_2 specificity factor	2800	μmol $μmol^{-1}$	0.703
$V_{c,max(25)}$	Maximum Rubisco capacity rate	79	μmol m^{-2} s^{-1}	2.573

The maximum Rubisco capacity rate for oil palm declines with tree age, from 91.1 μmol m^{-2} s^{-1} at year 1 to 69.8 μmol m^{-2} s^{-1} at year 19. The relationship between $V_{c,max(25)}$ at oil palm tree age can be described by

$$V_{c,\max(25)} = 87.935 - 0.0026 age$$

where *age* is the tree age (days).

Michaelis-Menten constant for CO_2

$$K_c = K_{c(25)} \times 2.786^{(T_f - 25)/10}$$

where K_c is the Michaelis-Menten constant for CO_2 (μmol mol^{-1}); and T_f is the canopy temperature (°C)

Michaelis-Menten constant for O_2

$$K_o = K_{o(25)} \times 1.355^{(T_f - 25)/10}$$

where K_o is the Michaelis-Menten constant for CO_2 (μmol mol^{-1}); and T_f is the canopy temperature (°C)

CO₂/O₂ specificity factor

$$\tau = \tau_{(25)} \times 0.703^{(T_f - 25)/10}$$

where τ is the CO_2/O_2 specificity factor (unitless); and T_f is the canopy temperature (°C)

CO₂ compensation point

$$\Gamma^* = \frac{O_a}{2\tau}$$

where Γ^* is the CO_2 compensation point (μmol mol^{-1}); O_a is the ambient O_2 concentration in air (210000 μmol mol^{-1}); and τ is CO_2/O_2 specificity factor (μmol μmol^{-1}) (Collatz *et al.*, 1991).

Rubisco maximum capacity rate

$V_{c,max}$ is the Rubisco maximum capacity rate (μmol CO_2 m^{-2} leaf s^{-1}), and its value changes according to temperature by:

$$V_{c,\max} = \frac{V_{c,\max(25)} \times 2.573^{(T_f - 25)/10}}{1 + \exp\left[0.29\left(T_f - 40\right)\right]}$$

where T_f is the canopy temperature (°C).

Note: $V_{c,max}$ is corrected additionally for temperatures greater than 40 °C after which the temperature causes a rapid decline in the capacity rate due to Rubisco degradation.

2.6 Gross leaf CO₂ assimilation

$$\Lambda_{sl/sh} = MIN\left(v_c,\ v_{q,sl/sh},\ v_s\right)$$

where $\Lambda_{sl/sh}$ is the gross leaf CO_2 assimilation (μmol CO_2 m^{-2} leaf s^{-1}) for either sunlit (subscript *sl*) or shaded (subscript *sh*) leaves; and *MIN*() is a function to select the minimum of the three assimilation rates (v_c, $v_{q,sl/sh}$ and v_s) (Collatz *et al.*, 1991).

Rubisco-limited assimilation (v_c)

$$v_c = \frac{V_{c,\max}\left(C_i - \Gamma^*\right)}{K_c\left(1 + O_a/K_o\right) + C_i}$$

where v_c is the Rubisco-limited leaf CO_2 assimilation rate (μmol CO_2 m^{-2} leaf s^{-1}); K_c is the Michaelis-Menten constant for CO_2 (μmol mol^{-1}); K_o is the Michaelis-Menten constant for CO_2 (μmol mol^{-1}); Γ^* is the CO_2 compensation point (μmol mol^{-1}); O_a is the ambient O_2

concentration in air (210000 μmol mol^{-1}); C_i is the intercellular CO_2 concentration (μmol mol^{-1}); and $V_{c,max}$ is the Rubisco capacity rate (μmol m^{-2} leaf s^{-1}) (Collatz *et al.*, 1991).

Note: $V_{c,max}$, Γ*, K_c and K_o must be corrected for canopy temperature.

Light-limited assimilation (vq)

$$v_{q,sl/sh} = e_m \alpha Q_{sl/sh} \frac{C_i - \Gamma^*}{C_i + 2\Gamma^*}$$

where $v_{q,sl/sh}$ is the light-limited leaf CO_2 assimilation rate (μmol CO_2 m^{-2} leaf s^{-1}) for either sunlit (subscript *sl*) or shaded (subscript *sh*) leaves; Γ* is the CO_2 compensation point (μmol mol^{-1}); C_i is the intercellular CO_2 concentration (μmol mol^{-1}); $Q_{sl/sh}$ is the PAR absorbed by either sunlit (subscript *sl*) or shaded (subscript *sh*) leaves (μmol m^{-2} leaf s^{-1}); α is the leaf absorption of PAR (0.8); and e_m is the intrinsic quantum efficiency or quantum yield (μmol CO_2 μmol^{-1} photons) (Collatz *et al.*, 1991). The value for e_m is taken as 0.051.

Sink-limited assimilation (vs)

$$v_s = 0.5 V_{c,\max}$$

where v_s is the sink-limited leaf CO_2 assimilation rate (μmol CO_2 m^{-2} leaf s^{-1}); and $V_{c,max}$ is the Rubisco capacity rate (μmol m^{-2} leaf s^{-1}) (Collatz *et al.*, 1991).

Note: $V_{c,max}$ must be corrected for canopy temperature.

Intercellular CO_2 concentration

The relationship between intercellular CO_2 concentration (C_i) to ambient CO_2 concentration (C_a) is described following Yin and van Laar (2005) as

$$\frac{C_i}{C_a} = 1 - \left(1 - \frac{\Gamma^*}{C_a}\right)\left(a + bD_{leaf}\right)$$

where C_i and C_a are the intercellular and ambient CO_2 concentration, respectively (μmol mol^{-1}); Γ* is the CO_2 compensation point (μmol mol^{-1}). D_{leaf} is the leaf vapour pressure deficit (mbar) which is determined by

$$D_{leaf} = e_s\left[\!\left[T_f\right]\!\right] - e_a$$

where $e_s(T_f)$ is the function returning the saturated vapour pressure (mbar) at foliage temperature T_f (°C); and e_a is the air vapour pressure (mbar).

Leaf measurements on various ages of oil palm tree (from 1 to 19 years) revealed that empirical coefficients *a* and *b* are 0.0615 and 0.0213, respectively.

2.7 Trend of change in CO_2 concentration

Ambient CO_2 concentration is assumed to change per day in a linear rate using the following equation:

$$C_{a,td2} = C_{a,td1} + \frac{r_{\Delta Ca}}{365}$$

where $C_{a,(td1)}$ and $C_{a,(td2)}$ are the ambient CO_2 concentration at day of ear t_{d1} and t_{d2}, respectively; and $r_{\Delta Ca}$ is the annual rate of change in ambient CO_2 concentration (μmol mol^{-1} yr^{-1}). The parameter $r_{\Delta Ca}$ is taken as a constant, which means that the rate of change follows a linear trend.

2.8 Gross canopy CO_2 assimilation

$$\Lambda_{canopy} = \Lambda_{sl} L_{sl} + \Lambda_{sh} L_{sh}$$

where Λ_{canopy} is the gross canopy CO_2 assimilation (μmol CO_2 m^{-2} ground s^{-1}); Λ_{sl} and Λ_{sh} are the gross leaf CO_2 assimilation rates for sunlit and shaded leaves, respectively (μmol CO_2 m^{-2} leaf s^{-1}); and L_{sl} and L_{sh} are the sunlit and shaded leaf area index, respectively (m^2 leaf m^{-2} ground) (Campbell and Norman, 1998).

2.9 Daily integration

The daily gross canopy photosynthesis is determined by

$$\Lambda'_{canopy,d} = 3600 \times 30 \times 10^{-9} \times \frac{10000}{PD} \times \int_{t_{sr}}^{t_{ss}} \Lambda_{canopy}\, dt'$$

where $\Lambda'_{canopy,d}$ is the daily gross photosynthesis (converted to kg CH_2O palm^{-1} day^{-1}); Λ_{canopy} is the gross canopy CO_2 assimilation for the hour (μmol CO_2 m^{-2} ground s^{-1}); PD is the planting density (palms ha^{-1}); and t_{sr} and t_{ss} are the sunrise and sunset hour (hour).

Numerical method Gaussian integration is used to obtain the daily gross canopy photosynthesis. Five points (N=5) over the diurnal period (from sunrise to sunset) are selected, and for each selected hour, the gross canopy CO_2 assimilation is calculated (Goudriaan and van Laar, 1994).

Note: to account for ozone effects, gross photosynthesis could be reduced further and linearly by

$$\Lambda''_{canopy,d} = \Lambda'_{canopy,d} \times (1 - f_{O3})$$

where $\Lambda''_{canopy,d}$ and $\Lambda'_{canopy,d}$ are the canopy photosynthesis with and without ozone effects, respectively (kg CH_2O palm^{-1} day^{-1}); and f_{O3} is the reduction in assimilates due to ozone (fraction).

CHAPTER 3. ENERGY BALANCE

The energy balance of the soil-plant-atmosphere system is described as a network of resistances in which heat fluxes must traverse within the system (Shuttleworth and Wallace, 1985). Solving the energy balance gives the water loss by soil evaporation and plant transpiration.

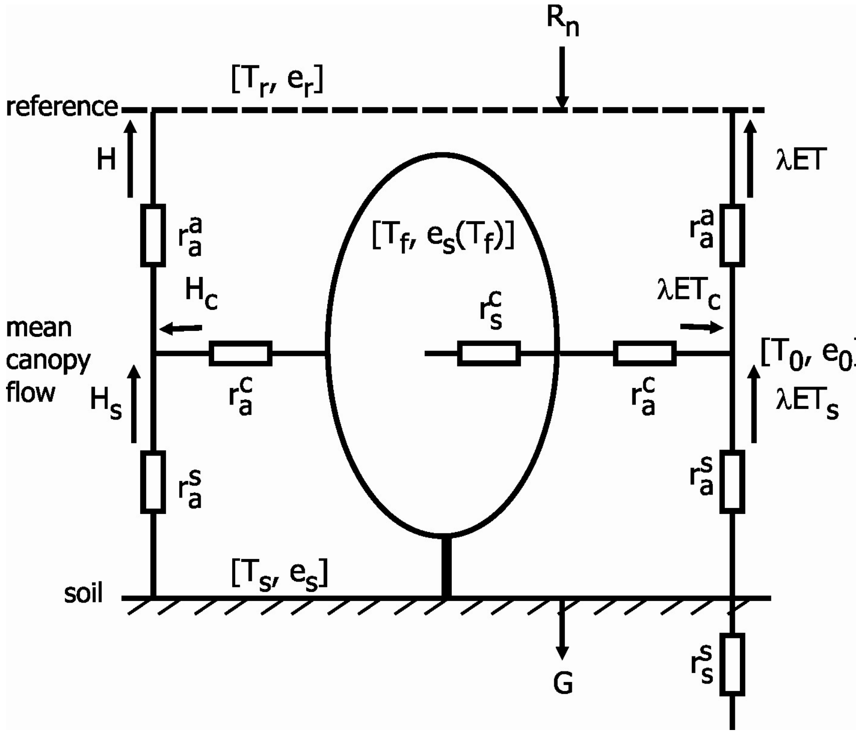

Fig. 3.1 Energy balance described as a network of resistances. Key: λET and λET_c and λET_s are the latent heat fluxes from the system, crop and soil, respectively; H, H_c and H_s are the sensible heat fluxes from the system, crop and soil, respectively; R_n is the net radiation flux into the system; G is the heat conduction into the soil; T_r, T_f, T_o and T_s are the temperatures for the reference height, crop, mean canopy flow and soil, respectively; e_r, e_s and e_o are the vapour pressure at the reference height, soil surface and mean canopy flow, respectively; $e_s(T)$ is saturated vapour pressure at temperature T; $r^a{}_a$ is the aerodynamic resistance between the mean canopy flow and reference height; $r^s{}_a$ is the aerodynamic resistance between the soil and mean canopy flow; $r^c{}_a$ is the bulk boundary layer resistance; $r^c{}_s$ and $r^s{}_s$ are the canopy and soil surface resistance, respectively.

3.1 Net radiation

$$R_n = (1-p)I_t + R_{nL}$$

$$R_{nL} = 0.98\sigma(T_a + 273.15)^4 \left[1.31\left(\frac{e_a}{T_a + 273.15}\right)^{1/7} - 1\right]$$

where R_n is the net radiation (W m^{-2}); R_{nL} is the net longwave radiation (W m^{-2}); I_t is the instantaneous total solar irradiance (W m^{-2}); p is the surface albedo (typically, 0.15); T_a is the air temperature (°C); e_a is the air vapour pressure (mbar); and σ is the Stefan-Boltzmann constant (5.67 x 10^{-8} W m^{-2} K^{-4}).

3.2 Energy available to crop and soil

$$A = A_c + A_s = R_n - G$$
$$A_c = \left(1 - \tau_{dr,\alpha}\right) R_n$$
$$A_s = \tau_{dr,\alpha} R_n - G$$
$$\tau_{dr,\alpha} = \exp\left(-k_{dr} \omega \sqrt{\alpha} L\right)$$

where A is the net radiation available to the system (soil and crop); A_c is the fraction of net radiation available to the crop (W m^{-2}); A_s is the fraction of net radiation available to the soil (W m^{-2}); G is the soil heat flux (W m^{-2}); L is the total leaf area index (LAI); k_{dr} is the canopy extinction coefficient for direct solar radiation; ω is the canopy clustering coefficient (0 to 1); and α is the scattering coefficient for total solar radiation (0.5 from Goudriaan and val Laar, 1994).

3.3 Soil/ground heat flux

$$G = R_n \left[t_c + \tau_{dr,\alpha} \left(t_s - t_c \right) \right]$$
$$\tau_{dr,\alpha} = \exp\left(-k_{dr} \omega \sqrt{\alpha} L\right)$$

where G is the soil heat flux (W m^{-2}); L is total leaf area index (LAI); k_{dr} is the canopy extinction coefficient for direct solar radiation; ω is the canopy clustering coefficient (0 to 1); α is the scattering coefficient for total solar radiation (0.5); R_n is the net radiation (W m^{-2}); and t_c and t_s are the fraction of net radiation as soil heat flux under full canopies and for bare soil (no canopies), respectively. t_c and t_s are taken as 0.05 (Monteith, 1973) and 0.315 (Kustas and Daughtry, 1990), respectively.

3.4 Wind speed profile

3.4.1 Crop roughness length and zero plane displacement

The method by Massman (1997) is used to determine the zero plane displacement height d and crop roughness length z_0:

$$d = hA$$

$$z_0 = h\left(1 - A\right)\exp\left(-k/0.32\right)$$

$$A = 1 - \frac{\exp\left(-2\alpha\right)\left[\exp\left(-2\alpha\right) - 1\right]}{2\alpha} \qquad 0.30 \le A \le 0.95$$

where d is the zero plane displacement height (m); z_0 is the crop roughness length (m); α is the vertical wind speed extinction coefficient; h is the plant height (m); k is the von Karman constant (0.4); and C_d is the foliage drag coefficient (0.32).

3.4.2 Friction velocity

$$u_* = \frac{ku}{\ln\left(\frac{z_r - d}{z_0}\right)}$$

where u_* is the friction velocity (m s^{-1}); k is the von Karman constant (0.4); and u is the wind speed (m s^{-1}) at the given hour; z_r is at the reference height (m); d is the zero plane displacement height (m); z_0 is the crop roughness length (m) (Shuttleworth and Wallace, 1985).

3.4.3 Wind speed at canopy height

$$u_h = \frac{u_*}{k}\ln\left(\frac{h - d}{z_0}\right)$$

where u_h is the wind speed function returning the wind speed (m s^{-1}) at full tree or canopy height h (m); d is the zero plane displacement height (m); z_0 is the crop roughness length (m); k is the von Karman constant (0.4); u_* is the friction velocity (m s^{-1}) (Shuttleworth and Wallace, 1985).

3.4.4 Eddy diffusivity and wind speed extinction coefficient

Vertical wind speed extinction coefficient α (assumed equal to eddy diffusivity n) increases with increasing leaf area index L. Simulations by Massman (1987) for hypothetical canopies with uniform foliage density suggested that the relationship between α can be approximated by the following function:

$$n = \alpha = 3\left[1 - \exp(-L)\right]$$

where L is the total leaf area index (LAI) (m^2 leaf m^{-2} ground) (Nikolov and Zeller, 2003).

3.5 Flux resistances

The heat fluxes have to traverse various types of resistances within the soil-plant-atmosphere system. This section describes each of those resistance types.

3.5.1 Aerodynamic resistances

3.5.1.1 Soil surface to mean canopy flow

$$r_a^s = \frac{\exp(n)}{nku_*}\left[\exp\left(-n\frac{z_{s0}}{h}\right) - \exp\left(-n\frac{z_0 + d}{h}\right)\right]$$

where r_a^s is the resistance between the soil surface and the mean canopy flow (s m^{-1}); h is the plant height (m); k is the von Karman constant (0.4); u_* is the friction velocity (m s^{-1}); n is the eddy diffusivity extinction coefficient; d is the zero plane displacement height (m); z_0 is the crop roughness length (m); and z_{s0} is the soil surface roughness length (m) (Shuttleworth and Wallace, 1985).

Note: For flat, tilled land, z_{s0} is taken as 0.004 m (Hansen, 1993).

3.5.1.2 Mean canopy flow to reference level

$$r_a^a = \frac{1}{ku_*} \ln\left(\frac{z_r - d}{h - d}\right) + \frac{1}{nku_*}\left\{\exp\left[n\left(1 - \frac{z_0 + d}{h}\right)\right] - 1\right\}$$

where r_a^a is the resistance between the mean canopy flow and the reference level (s m^{-1}); h is the plant height (m); k is the von Karman constant (0.4); u_* is the friction velocity (m s^{-1}); n is the eddy diffusivity extinction coefficient; d is the zero plane displacement height (m); z_0 is the crop roughness length (m); and z_r is the reference height (m) (Shuttleworth and Wallace, 1985).

3.5.2 Bulk boundary layer resistance

$$r_a^c = \frac{\alpha}{0.01 L_{eff}\left[1 - \exp(-\alpha/2)\right]\sqrt{u_h/w}}$$

where r_a^c is the bulk boundary layer resistance (s m^{-1}); L_{eff} is the effective leaf area index (m^2 leaf m^{-2} ground); w is the mean leaf width (m); u_h is the function returning the wind speed at the canopy top (*i.e.*, at plant height h) (m s^{-1}); and α is the wind speed extinction coefficient (Mitchell, 1976; Shuttleworth and Wallace, 1985).

Effective leaf area index is determined by

$$L_{eff} = MIN\left(L,\ \frac{L_{\max,PD}}{2}\right)$$

where L is the leaf area index (m^2 leaf m^{-2} ground); and $L_{max,PD}$ is the maximum leaf area index (m^2 leaf m^{-2} ground) for a given PD planting density (palms ha^{-1}) (Szeicz and Long, 1969) and it is calculated as:

$$L_{\max,PD} = 0.0274 PD^{\frac{1}{A}}$$

where A is 0.935.

The pinnae length and width can be determined by

$$l = 0.2191 Ln\left(\frac{age}{365}\right) + 0.475$$

$$w = 0.0152 Ln\left(\frac{age}{365}\right) + 0.0165$$

where l and w are the leaflet (pinnae) length and width, respectively (m); and *age* is the tree age (days). The equations for l and w were developed by fitting the best equation to the measured leaf dimension data from Rao et al. (1992).

3.5.3 Stomatal conductance

$$gst = gst_{\max} \times f_{PAR} \times f_{water} \times f_D$$

where gst is the leaf stomatal conductance (m s^{-1}); gst_{max} is the maximum leaf stomatal conductance (500 mmol m^{-2} s^{-1} or 0.012077 m s^{-1} from Kallarackal *et al.*, 2004); and f_{PAR}, f_{water}, and f_D are reductions, scaled from 0 to 1, to gst_{max} due to PAR irradiance, water stress, and vapour pressure deficit, respectively.

PAR function

f_{PAR} is determined by

$$f_{PAR} = \frac{gst[\![PAR]\!]}{gst[\![PAR_{\max}]\!]}$$

$$gst[\![PAR]\!] = a\left[1 - \exp(-bPAR)\right]$$
$$a = 0.014614$$
$$b = 0.008740$$

where $gst[\![PAR]\!]$ is the function returning the leaf stomatal conductance (m s^{-1}) at a given PAR irradiance (W m^{-2}) (a and b values were obtained from leaf measurements of stomatal conductance for various oil palm tree ages at various PAR levels); and PAR_{max} is the maximum PAR irradiance (W m^{-2}), taken as 330 W m^{-2} (light saturation at about 1500 μmol m^{-2} s^{-1} from Dufrêne and Saugier, 1993).

Water stress function

f_{water} is determined as the ratio between actual and potential transpiration, or

$$f_{water} = \frac{T_a}{ET_c}$$

where T_a is the actual transpiration (m day^{-1}); and ET_c is the potential transpiration (m day^{-1}) (Kropff, 1993).

Vapour pressure deficit function

f_D is determined by

$$f_D = \frac{gst[\![D]\!]}{gst[\![D_{\min}]\!]}$$

$$gst[\![D]\!] = a + b\ln(D)$$

$$a = 0.031970$$

$$b = -0.007516$$

where $gst[\![D]\!]$ is the function returning the leaf stomatal conductance (m s^{-1}) at a given vapour pressure deficit, D (mbar), determined by

$$D = e_s[\![T_a]\!] - e_a$$

where $e_s[\![T_a]\!]$ is the function returning the saturated vapour pressure (mbar) at air temperature T_a (°C); e_a is the air vapour pressure (mbar); and D_{min} is the minimum vapour pressure deficit (mbar), taken as 10 mbar, based on measurements.

The coefficients a and b values were derived from fitting the best function to measured leaf stomatal conductance for various oil palm tree ages (year 1 to 19) at various vapour pressure deficits.

Note: Leaf stomatal conductance decreases with increasing vapour pressure deficit. Hence, D_{min} gives maximum leaf stomatal conductance.

3.5.4 Canopy resistance

Leaf stomatal conductance gst is determined, then scaled up to canopy resistance (inverse of canopy conductance) by the following equations:

$$r_s^c = \frac{1}{gst \times L_{eff}}$$

where r_s^c is the canopy resistance (s m^{-1}); L is the total leaf area index (m^2 leaf m^{-2} ground); and L_{eff} is the effective leaf area index (m^2 leaf m^{-2} ground) (Szeicz and Long, 1969).

3.5.5 Soil surface resistance

The methods by Choudhury and Monteith (1988) and Farahani and Ahuja (1996) are used to determine the soil surface resistance as

$$r_s^s = r_{s,dry}^s \exp\left(-\frac{1}{\lambda} \times \frac{\theta_1}{\theta_{s,1}}\right)$$

$$r_{s,dry}^s = \frac{\tau l}{\phi_p D_{m,v}}$$

where r_s^s is the maximum soil surface resistance (s m^{-1}); $D_{m,v}$ is the vapour diffusion coefficient in air (24.7 x 10^{-6} m^2 s^{-1}); ϕ_p is the soil porosity (unitless); l is the dry soil layer thickness (taken as the first soil layer thickness) (m); θ_l is the soil water content of the first soil layer (m^3 m^{-3}); $\theta_{s,1}$ is the saturated soil water content (m^3 m^{-3}) in the first soil layer; and λ is the soil pore-size distribution index. τ is the soil tortuosity (unitless) determined from Shen and Chen (2007) as

$$\tau = \sqrt{\phi_p + 3.79\left(1 - \phi_p\right)}$$

where ϕ_p is the soil porosity (unitless).

Note: The soil profile is divided into two or more layers.

3.6 Total latent heat flux

$$\lambda ET = C_c PM_c + C_s PM_s$$

$$PM_c = \frac{\Delta A + \left(\rho c_p D - \Delta r_a^c A_s\right) / \left(r_a^a + r_a^c\right)}{\Delta + \gamma\left[1 + r_s^c / \left(r_a^a + r_a^c\right)\right]}$$

$$PM_s = \frac{\Delta A + \left[\rho c_p D - \Delta r_a^s A_c\right] / \left(r_a^a + r_a^s\right)}{\Delta + \gamma\left[1 + r_s^s / \left(r_a^a + r_a^s\right)\right]}$$

$$C_c = \left\{1 + R_c R_a / \left[R_s\left(R_c + R_a\right)\right]\right\}^{-1}$$

$$C_s = \left\{1 + R_s R_a / \left[R_c\left(R_s + R_a\right)\right]\right\}^{-1}$$

$$R_a = \left(\Delta + \gamma\right) r_a^a$$

$$R_c = \left(\Delta + \gamma\right) r_a^c + \gamma r_s^c$$

$$R_s = \left(\Delta + \gamma\right) r_a^s + \gamma r_s^s$$

where λET is the total latent heat flux (W m^{-2}); $r^a{}_a$ is the aerodynamic resistance between the mean canopy flow and reference height (s m^{-1}); $r^s{}_a$ is the aerodynamic resistance between the soil and mean canopy flow (s m^{-1}); $r^c{}_a$ is the bulk boundary layer resistance (s m^{-1}); $r^c{}_s$ and $r^s{}_s$ are the canopy and soil surface resistance, respectively (s m^{-1}); A, A_s and A_c are energy available to the system (total), soil and crop, respectively (W m^{-2}); Δ is the slope of the saturated vapour pressure curve (mbar K^{-1}); γ is the psychometric constant (0.658 mbar K^{-1}); D is the vapour pressure deficit (mbar); and ρc_p is the volumetric heat capacity for air (1221.09 J m^{-3} K^{-1}) (Shuttleworth and Wallace, 1985).

Note: To convert latent heat fluxes from unit W m^{-2} (equivalent to J m^{-2} s^{-1}) to depth of water per second (mm s^{-1}), simply divide it by λ, the latent heat of vaporization of water (2454000 J kg^{-1}).

3.7 Air vapour pressure deficit at the mean canopy flow

$$D_0 = D + \frac{r_a^a}{\rho c_p}\left[\Delta A - (\Delta + \gamma)\lambda ET\right]$$

where D_0 is the vapour pressure deficit at the mean canopy flow (mbar); λET is the total latent heat flux (W m^{-2}); $r^a{}_a$ is the aerodynamic resistance between the mean canopy flow and reference height (s m^{-1}); A is the total energy available to the system (W m^{-2}); Δ is the slope of the saturated vapour pressure curve (mbar K^{-1}); γ is the psychometric constant (0.658 mbar K^{-1}); D is the vapour pressure deficit (mbar); and ρc_p is the volumetric heat capacity for air (1221.09 J m^{-3} K^{-1}) (Shuttleworth and Wallace, 1985).

3.8 Latent heat fluxes for crop and soil

$$\lambda ET_s = \frac{\Delta A_s + \rho c_p D_0 / r_a^s}{\Delta + \gamma\left(r_s^s + r_a^s\right) / r_a^s}$$

$$\lambda ET_c = \frac{\Delta A_c + \rho c_p D_0 / r_a^c}{\Delta + \gamma\left(r_s^c + r_a^c\right) / r_a^c}$$

where λET_s and λET_c are the soil and crop latent heat fluxes, respectively (W m^{-2}); A_s and A_c are energy available to the soil and crop, respectively (W m^{-2}); $r^s{}_a$ is the aerodynamic resistance between the soil and mean canopy flow (s m^{-1}); $r^c{}_a$ is the bulk boundary layer resistance (s m^{-1}); $r^c{}_s$ and $r^s{}_s$ are the canopy and soil surface resistance, respectively (s m^{-1}); Δ is the slope of the saturated vapour pressure curve (mbar K^{-1}); γ is the psychometric constant (0.658 mbar K^{-1}); D_0 is the vapour pressure deficit at the mean canopy flow (mbar); and ρc_p is the volumetric heat capacity for air (1221.09 J m^{-3} K^{-1}) (Shuttleworth and Wallace, 1985).

3.9 Sensible heat fluxes for crop and soil

$$H_s = \frac{\gamma A_s\left(r_s^s + r_a^s\right) - \rho c_p D_0}{\Delta r_a^s + \gamma\left(r_s^s + r_a^s\right)}$$

$$H_c = \frac{\gamma A_c\left(r_s^c + r_a^c\right) - \rho c_p D_0}{\Delta r_a^c + \gamma\left(r_s^c + r_a^c\right)}$$

where H_s and H_c are the soil and crop sensible heat fluxes, respectively (W m^{-2}); A_s and A_c are energy available to the soil and crop, respectively (W m^{-2}); $r^s{}_a$ is the aerodynamic resistance between the soil and mean canopy flow (s m^{-1}); $r^c{}_a$ is the bulk boundary layer resistance (s m^{-1}); $r^c{}_s$ and $r^s{}_s$ are the canopy and soil surface resistance, respectively (s m^{-1}); Δ is the slope of the saturated vapour pressure curve (mbar K^{-1}); γ is the psychometric constant (0.658 mbar K^{-1}); D_0 is the vapour pressure deficit at the mean canopy flow, respectively (mbar); and ρc_p is the volumetric heat capacity for air (1221.09 J m^{-3} K^{-1}) (Shuttleworth and Wallace, 1985).

3.10 Daily integration

Numerical method Gaussian integration is used to obtain the daily latent heat fluxes. This is so that the daily amount of water transpired (by plants) and evaporated (by soil) can be known. Five points (N=5) over 24 hours in a day are selected, and for each selected hour, the heat fluxes are calculated (Goudriaan and van Laar, 1994).

CHAPTER 4. SOIL WATER

For accurate simulation of the water content in the soil, the soil profile has to be divided into several layers, and for each layer, the soil water content is simulated based on Darcy's law.

4.1 Partitioning of soil profile into several layers

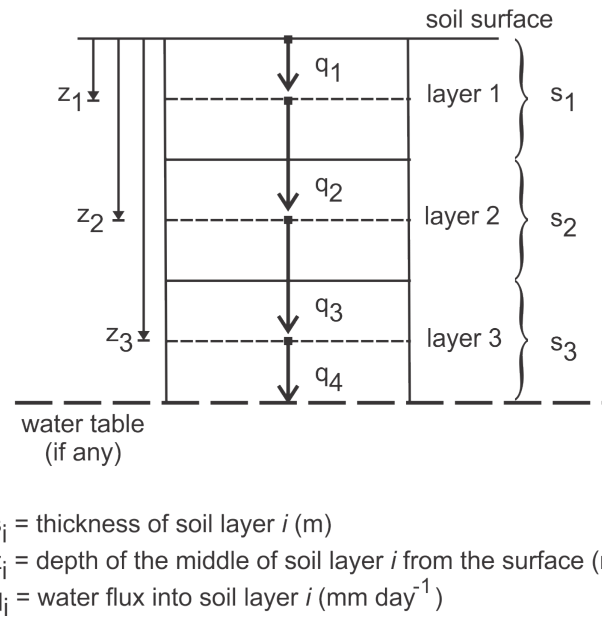

Fig. 4.1. Water flow in a soil profile which is divided into three successive layers, with the presence of a water table just beneath the third soil layer.

It is recommended to divide a soil profile into two or more consecutive layers, where soil layer i (i = 1 to n) has a thickness of s_i (m), and the depth from the soil surface to the middle of layer i is z_i (m). Water flux into soil layer i is denoted as q_i (m day^{-1}).

Assumptions

1. No irrigation is supplied and no surface run-off and run-in occurs.
2. Water table, if any, has a constant depth from the soil surface.
3. Without the presence of a water table, the soil below the last soil layer is uniformly wet, and it has the same water content as the last soil layer. This means that water flows out of the last soil layer (*i.e.*, q_4) due to gravitational pull alone (*i.e.*, no matric suction gradient).

4.2 Soil moisture characteristics

For each soil layer *i*, the volumetric soil water content at saturation, field capacity, and permanent wilting point are estimated based on clay, sand, and organic matter contents. Soil water characteristics (water content at saturation, field capacity, and permanent wilting points) are estimated based from Saxton and Rawls (2006).

Permanent wilting point

$$\theta_{1500} = \theta_{1500t} + \left(0.14\theta_{1500t} - 0.02\right)$$

$$\theta_{1500t} = -0.024S + 0.487C + 0.006OM + 0.005\left(S \times OM\right) - 0.013\left(C \times OM\right) + 0.068\left(S \times C\right) + 0.031$$

where θ_{1500} is the soil water content at permanent wilting point (m^3 m^{-3}); S and C are the sand and clay contents, respectively (fraction); and OM is the organic matter content (%).

Field capacity

$$\theta_{33} = \theta_{33t} + \left(1.283\theta_{33t}^2 - 0.374\theta_{33t} - 0.015\right)$$

$$\theta_{33t} = -0.251S + 0.195C + 0.011OM + 0.006\left(S \times OM\right) - 0.027\left(C \times OM\right) + 0.452\left(S \times C\right) + 0.299$$

where θ_{33} is the soil water content at field capacity (m^3 m^{-3}); S and C are the sand and clay contents, respectively (fraction); and OM is the organic matter content (%).

Saturation

$$\theta_s = \theta_{33} + \theta_{(S-33)} - 0.097S + 0.043$$

$$\theta_{(S-33)} = \theta_{(S-33)t} + 0.636\theta_{(S-33)t} - 0.107$$

$$\theta_{(S-33)t} = 0.278S + 0.034C + 0.022OM - 0.018\left(S \times OM\right) - 0.027\left(C \times OM\right) - 0.584\left(S \times C\right) + 0.078$$

where θ_s is the soil water content at saturation (m^3 m^{-3}); S and C are the sand and clay contents, respectively (fraction); and OM is the organic matter content (%).

4.3 Soil layer depth and cumulative thickness

$$z_i = \sum_{i=1}^{N} 0.5\left(s_i + s_{i-1}\right)$$

where z_i is the depth of soil layer i from the soil surface (m), taken from the middle of that soil layer to the soil surface; N is the number of soil layers (taken as 3); s_i and s_{i-1} are the thickness of soil layer i and i-1, respectively (m).

Note: $s_0 = 0$.

Cumulative thickness

$$S_i = \sum_{j=1}^{i} s_j$$

where S_i is the cumulative thickness of soil layer i (m); that is, the sum of the thickness of layer i and all its preceding layers.

4.4 Actual evaporation

$$E_a = ET_s \cdot R_{D,e}$$

$$R_{D,e} = \frac{1}{1 + \left[3.6073\left(\theta_1 / \theta_{s,1}\right)\right]^{-9.3172}}$$

where E_a is the actual evaporation (m day^{-1}); ET_s is the potential evaporation (m day^{-1}); $R_{D,e}$ is the reduction factor for evaporation (ranging from 0 to 1) (van Keulen and Seligman, 1987); and θ_1 and $\theta_{s,1}$ are the current and saturated soil water content in the first soil layer (i=1), respectively (m^3 m^{-3}).

Note: The soil water content from the first soil layer (i=1), θ_1, is taken because all evaporation occurs from this layer only (as this first layer is in contact with the atmosphere).

4.5 Actual transpiration

$$T_a = ET_c \cdot R_{D,t}$$

$$R_{D,t} = \begin{cases} 1 & \theta_{root} \geq \theta_{cr,root} \\ \dfrac{\theta_{root} - \theta_{1500,root}}{\theta_{cr,root} - \theta_{1500,root}} & \theta_{1500,root} < \theta_{root} < \theta_{cr,root} \\ 0 & \theta_{root} \leq \theta_{1500,root} \end{cases}$$

$$\theta_{cr,root} = \theta_{1500,root} + 0.6\left(\theta_{s,root} - \theta_{1500,root}\right)$$

where T_a is the actual transpiration (m day^{-1}); ET_c is the potential transpiration (m day^{-1}); $R_{D,t}$ is the reduction factor for transpiration (ranging from 0 to 1) (Kropff, 1993); θ_{root} is the total volumetric water content in the root zone (m^3 m^{-3}); $\theta_{1500,root}$ is the soil water content at wilting point (m^3 m^{-3}) in the root zone; $\theta_{s,root}$ is the soil water content at saturation (m^3 m^{-3}) in the root zone; and $\theta_{cr,root}$ is the volumetric water content in the root zone below which water stress occurs (m^3 m^{-3}). Soil water measurements in irrigated and non-irrigated oil palm trials by Foong (1999) from 1983 to 1990 suggested that the critical soil water content below which oil palm suffers from water stress is approximately 60% of $\left(\theta_{s,root} - \theta_{1500,root}\right)$. This critical point is equivalent to 45% of available water content (AWC) of Munchong soil series, the type of soil in Foong (1999). Rey *et al.* (1998) also observed that oil palm stomatal conductance would begin to decline when the soil water content fell below the level of 40 to 50% of AWC.

The algorithm to determine the total water content in the root zone, θ_{root}, is as follows:

$$\theta_{root} = \frac{1}{d_{root}} \times \sum_{i=1}^{N} MAX\left[0,\ \theta_i\left(s_i - n_i\right)\right]$$

$$n_i = MAX\left(0,\ S_i - d_{root}\right)$$

where d_{root} is the rooting depth (m); s_i is the thickness of soil layer i (m); and S_i is the cumulative thickness of soil layer i (m). The amount of water in the root zone is the summation of water content from the first soil layer (i=1) until the rooting depth.

4.6 Root extraction of water

The amount of water extracted by roots in each soil layer is based on the measured data for oil palm by Nelson *et al.* (2006) and on the water uptake algorithm by Miyazaki (2005):

$$T_{a,i} = T_a\left(\varphi_i - \varphi_{i-1}\right)$$

$$\varphi_j = 1.8c_j - 0.8c_j^{\,2}$$

$$c_j = MIN\left(1,\ \frac{S_j}{d_{root}}\right)$$

where $T_{a,i}$ is the amount of water extracted by roots in soil layer i (m day^{-1}); d_{root} is the rooting depth (m); S_j is the cumulative thickness of soil layer j (m); and $MIN()$ is the minimum of the enclosed values.

4.7 Saturated and unsaturated hydraulic conductivity

The method by Bittelli et al. (2015) is followed. The saturated hydraulic conductivity in soil layer i (K_{si}, m day^{-1}) is determined by

$$K_{s,i} = 864 \times 0.07 \times \left\{\theta_{s,i} - \left[1 - \left(\frac{\psi_e}{33}\right)^{\lambda}\right]\right\}^4$$

where $\theta_{s,i}$ is the soil water content at saturation for soil layer i (m^3 m^{-3}); and λ is slope of the logarithmic suction-soil moisture curve; and ψ_e is the air-entry suction (kPa), and they are determined by

$$\lambda = \frac{1}{B}$$

$$B = 8.25 - 1.26\ln\left(d_g\right)$$

$$\psi_e = 3.9 - 0.61\ln\left(d_g\right)$$

$$d_g = \exp\left[-1.96C + 2.3\left(1 - S - C\right) + 5.76S\right]$$

where d_g is the geometric mean distribution (μm) of the soil's particles sizes: clay C and sand S (both in fractions).

The unsaturated hydraulic conductivity in soil layer i (k_i, m day^{-1}) is determined by

$$K_{\theta,i} = K_{s,i}\left(\frac{\theta_i}{\theta_{s,i}}\right)^{3+2n_{corr}/\lambda}$$

where $K_{\theta,i}$ and $K_{s,i}$ are the unsaturated and saturated hydraulic conductivity in soil layer i, respectively (m day^{-1}); θ_i is the current volumetric soil water content in soil layer i (m^3 m^{-3}); $\theta_{s,i}$ is the soil water content at saturation (m^3 m^{-3}); λ is the slope of the logarithmic suction-soil moisture curve, as determined previously; and n_{corr} is the correction factor for soil layers, where n_{corr} = 1 for the first soil layer and 0.1 for the subsequent layers.

4.8 Matric suction head

The soil matric suction in soil layer i ($H_{m,i}$, m) is determined by

$$H_{m,i} = \begin{cases} 3.3 - \left[\dfrac{(33-\psi_e)(\theta_i - \theta_{33,i})}{10(\theta_{s,i} - \theta_{33,i})}\right] & \theta_i \ge \theta_{33,i} \\[2ex] \dfrac{\exp\left(\ln 33 + \dfrac{1}{\lambda}\ln \theta_{33,i}\right)}{10\theta_i^{1/\lambda}} & \theta_i < \theta_{33,i} \end{cases}$$

where $H_{m,i}$ is the soil matric suction in soil layer i (m); θ_i is the water content in soil layer i (m^3 m^{-3}); $\theta_{33,i}$, and $\theta_{s,i}$ are the soil water content at field capacity and saturation, respectively (m^3 m^{-3}); and λ is the slope of the logarithmic suction-soil moisture curve (Saxton and Rawls, 2006).

4.9 Gravity head

$$H_{g,i} = z_i$$

where $H_{g,i}$ is the gravity head in soil layer i (m); and z_i is the depth of the middle of soil layer i from the soil surface (m).

4.10 Hydraulic gradient

$$H_i = H_{m,i} + H_{g,i}$$

where in soil layer i, H_i is the hydraulic gradient (m), $H_{m,i}$ is matric suction head (m), and $H_{g,i}$ is the gravity head (m).

4.11 Water content

Water flux

Darcy's law is used to describe the water flow in the soil. Water flow is taken to occur from the middle of layer *i*-1 to the middle of layer *i*. The method based on Campbell (1994) is followed. Water flux into soil layer *i* is:

$$q_i = \begin{cases} MIN\left(K_{s,1},\ P_{net,d}\right) - E_a - T_{a,i} & i = 1 \\ \bar{K}_{\theta,i} \dfrac{\left(H_i - H_{i-1}\right)}{\left(z_i - z_{i-1}\right)} - T_{ai} & 1 < i \le N \\ K_{\theta,N} & i = N+1 \end{cases}$$

$$\bar{K}_{\theta,i} = \frac{K_{\theta,i-1} - K_{\theta,i}}{ln\left(K_{\theta,i-1}\right) - ln\left(K_{\theta,i}\right)}$$

where subscripts *i*-1 and *i* denote soil layer *i*-1 and *i*, respectively; q is the water flux (m day^{-1}); $P_{net,d}$ is the net daily rainfall (m day^{-1}; *discussed later*); E_a is the actual daily soil evaporation (occurs only from the first soil layer) (m day^{-1}); T_a is the daily extraction of water by roots (actual plant transpiration) (m day^{-1}); $\bar{K}$ is the logarithmic mean of the hydraulic conductivities of layer *i* and *i*-1 (m day^{-1}); K_θ and s are the soil layer's hydraulic conductivity and thickness, respectively (m); and H is the hydraulic gradient (m). Note that for the first soil layer, water entry is via net rainfall, $P_{net,d}$ whose entry into the soil is limited by the first soil layer's saturated hydraulic conductivity $K_{s,1}$.

Note: Water flux out of the last soil layer ($i = N$) is denoted by q_{N+1}, and it is merely equal to $K_{\theta,N}$ because of the assumption that the soil below the last layer is uniformly wet and it has the same water content as the last soil layer. Consequently, water flux is only due to gravity gradient (no matric suction gradient). In this case, $q_{N+1} = K_{\theta,N}$.

Also note that both E_a and $T_{a,i}$ must be expressed in unit m day^{-1}.

Net flux

$$\hat{q}_i = q_i - q_{i+1}$$

where $\hat{q}_i$ is the net flux in soil layer *i* (m day^{-1}); and q_i and q_{i+1} are the water flux into soil layer *i* and *i*+1, respectively (m day^{-1}).

Water content

$$\Theta_{i,t+1} = \Theta_{i,t} + \hat{q}_i$$

where $\Theta_{i,t}$ and $\Theta_{i,t+1}$ are the water depth in soil layer *i* (m) at time step *t* and *t*+1, respectively; and $\hat{q}_i$ is the net flux in soil layer *i* (m day^{-1}).

Water table (ground water)

The water table, if specified, is assumed to have a constant water table level or depth and is located just beneath the last soil layer. For instance, if three soil layers are specified, with a total soil layer thickess of 2 m, then the water table is located at a constant depth of 2 m from the soil surface. This water table is located just beneath the third (which is the last) soil layer.

Water flow from the water table follows Darcy's law as described earlier, where water flows upward, against the gravity, from the saturated water table into the drier soil layers above.

4.12 Net rainfall

Net rainfall refers to the amount of rain reaching the ground as both throughfall and stemflow. It is determined by

$$P_{net,d} = P_{g,d} \times MAX\left(0.7295,\ 1 - 0.0541L\right)$$

where $P_{net,d}$ is the daily net rainfall (m); $P_{g,d}$ is the daily gross rainfall (rainfall above the canopies, m); and L is the leaf area index (m^2 leaf m^{-2} ground).

Note: $P_{net,d}$ must be in unit m before it is used in the soil water balance model.

4.13 Daily integration

Hydraulic conductivity is sensitive to soil water content especially at near saturation. Consequently, it is vital that the water fluxes are calculated using very small time steps because using too large a time step (*e.g.*, 1 day) may cause unrealistically large fluctuations or changes in the soil water content.

To overcome this problem, a specified number of iterations (f) within a single time step is performed to simulate the daily water content. This method is the same as done by the Runge-Kutta numerical integration method.

Note: The larger the f value (*i.e.*, the more iterations within a single time step), the more accurate the simulation results, but the slower the simulation run. The value of f depends on the hydraulic conductivity value, k; a large k often means a large f is required for accurate results.

CHAPTER 5. MAINTENANCE RESPIRATION

Food produced via photosynthesis is used for plant maintenance (supporting processes for continual plant survival) and growth (synthesis of new cells). The method by van Kraalingen *et al.* (1989) for oil palm is adapted.

5.1 Pinnae

$$M_{pinnae} = W_{pinnae} \times M_{c,pinnae} \times (24 - DL)/24$$

where M_{pinnae} is the maintenance requirement for pinnae (kg CH_2O palm^{-1} day^{-1}); W_{pinnae} is the dry weight of the pinnae (kg DM palm^{-1}); DL is the day length (hour); and $M_{c,pinnae}$ is the maintenance coefficient for the pinnae (kg CH_2O kg^{-1} DM), determined by

$$M_{c,pinnae} = \left(N_{pinnae} \times 0.036 \times 6.25\right) + \left(X_{pinnae} \times 0.072 \times X_c\right)$$

where N_{pinnae} and X_{pinnae} are the fractions by weight of nitrogen and mineral content in the pinnae, respectively (fraction); and X_c is the correction factor for mineral content (unitless), taken as 2.

5.2 Rachis

$$M_{rachis} = W_{rachis} \times M_{c,rachis}$$

where M_{rachis} is the maintenance requirement for the rachis (kg CH_2O palm^{-1} day^{-1}); W_{rachis} is the dry weight of the rachis (kg DM palm^{-1}); and $M_{c,rachis}$ is the maintenance coefficient for the pinnae (kg CH_2O kg^{-1} DM), determined by

$$M_{c,rachis} = \left(N_{rachis} \times 0.036 \times 6.25\right) + \left(X_{rachis} \times 0.072 \times X_c\right)$$

where N_{rachis} and X_{rachis} are the fractions by weight of nitrogen and mineral content in the rachis, respectively (fraction); and X_c is the correction factor for mineral content (unitless), taken as 2.

5.3 Trunk

$$M_{trunk} = \left(W_{top,trunk} \times M_{c,trunk}\right) + \left(W_{bottom,trunk} \times M_{c,trunk} \times 0.06\right)$$

where M_{trunk} is the maintenance requirement for the trunk (kg CH_2O palm^{-1} day^{-1}); $W_{top,trunk}$ and $W_{bottom,trunk}$ are the dry weight of the upper and bottom trunk, respectively (kg DM palm^{-1}); and $M_{c,trunk}$ is the maintenance coefficient for the trunk (kg CH_2O kg^{-1} DM), determined by

$$M_{c,trunk} = \left(N_{trunk} \times 0.036 \times 6.25\right) + \left(X_{trunk} \times 0.072 \times X_c\right)$$

where N_{trunk} and X_{trunk} are the fractions by weight of nitrogen and mineral content in the trunk, respectively (fraction); and X_c is the correction factor for mineral content (unitless), taken as 2. Both $W_{top,trunk}$ and $W_{bottom,trunk}$ are determined by

$$W_{top,trunk} = MIN\left(W_{trunk},\ 45.0\right)$$
$$W_{bottom,trunk} = W_{trunk} - W_{top,trunk}$$

where W_{trunk} is the total dry weight of the trunk (kg DM palm^{-1}).

5.4 Roots

$$M_{roots} = W_{roots} \times M_{c,roots}$$

where M_{roots} is the maintenance requirement for the roots (kg CH_2O palm^{-1} day^{-1}); W_{roots} is the dry weight of the roots (kg DM palm^{-1}); and $M_{c,roots}$ is the maintenance coefficient for the roots (kg CH_2O kg^{-1} DM), determined by

$$M_{c,roots} = \left(N_{roots} \times 0.036 \times 6.25\right) + \left(X_{roots} \times 0.072 \times X_c\right)$$

where N_{roots} and X_{roots} are the fractions by weight of nitrogen and mineral content in the roots, respectively (fraction); and X_c is the correction factor for mineral content (unitless), taken as 2.

5.5 Generative organs

$$M_{organs} = \left(0.0027 \times W_{matbunch}\right) + \left(M_{c,rachis} \times W_{immbunch}\right) + \left(M_{c,rachis} \times W_{maleflo}\right)$$

where M_{organs} is the maintenance requirement for the generative organs (kg CH_2O palm^{-1} day^{-1}); $W_{matbunch}$, $W_{immbunch}$, and $W_{maleflo}$ are the dry weights of the mature bunches, immature bunches, and male flowers, respectively (kg DM palm^{-1}); and $M_{c,rachis}$ is the maintenance coefficient for the rachis (kg CH_2O kg^{-1} DM).

5.6 Total maintenance

$$M'_{total} = M_{pinnae} + M_{rachis} + M_{trunk} + M_{roots} + M_{organs} + M_{metabolic}$$

where M'_{total} is the total maintenance requirement for the whole tree, which is the summation of the maintenance requirement for pinnae (M_{pinnae}), rachis (M_{rachis}), trunk (M_{trunk}), roots (M_{roots}), generative organs (M_{organs}), as well as metabolic activity ($M_{metabolic}$) (all units in kg CH_2O palm^{-1} day^{-1}). $M_{metabolic}$ is determined by

$$M_{metabolic} = 0.16\Lambda_{canopy,d} / W_{total}$$

where $\Lambda_{canopy,d}$ is the daily canopy photosynthesis (kg CH_2O palm^{-1} day^{-1}); and W_{total} is the total dry weight of all plant parts:

$$W_{total} = W_{pinnae} + W_{rachis} + W_{trunk} + W_{roots} + W_{organs}$$

where the weights for pinnae (W_{pinnae}), rachis (W_{rachis}), trunk (W_{trunk}), roots (W_{roots}), generative organs (W_{organs}) are summed (all weights in kg DM palm^{-1}).

Note that maintenance respiration is not adjusted or corrected for air temperature. However, assimilates can all be diverted for maintenance respiration if the air temperature is lower than 15 °C or higher than 45 °C:

$$M_{total} = \begin{cases} M'_{total} \times T_c & 15°C < T_{mean} < 45°C \\ \Lambda_{canopy,d} & \text{otherwise} \end{cases}$$

where M_{total} is the corrected maintenance respiration for temperature (kg CH_2O palm^{-1} day^{-1}); T_{mean} is the daily average of the minimum (T_{min}) and maximum (T_{max}) air temperature (°C). Consequently, this means that oil palm only grows with air temperatures between 15 to 45 °C.

The amount of assimilates available for growth respiration is the leftover assimilates after maintenance respiration, or

$$G_{growth} = MAX\left(0,\ \Lambda_{canopy,d} - M_{total}\right)$$

where G_{growth} is the amount of assimilates available for growth respiration (kg CH_2O palm^{-1} day^{-1}).

CHAPTER 6. GROWTH RESPIRATION

6.1 Annual VDM requirement

Annual vegetative dry matter (VDM) requirement is determined based on leaf area index, following a rectangular hyperbola relationship, as

$$VDM_{yr} = MIN\left[20,\ \left(a + \frac{b}{L^{1.5}}\right)^{-1}\right]$$

where VDM_{yr} is the annual VDM requirement (kg DM palm^{-1} year^{-1}); L is the leaf area index (m^2 leaf m^{-2} ground); and coefficients a and b are determined by

$$a = \frac{A}{VDM_{\max,PD}}$$

$$b = 0.1\left(\frac{1}{A} - 1\right)\left(\frac{PD}{100}\right)^{\frac{1}{A}}$$

$$VDM_{\max,PD} = 231PD^{1-\frac{1}{A}}$$

$$A = 0.935$$

where PD is the planting density (palms ha^{-1}); and for the given planting density, $VDM_{max,PD}$ is the maximum VDM (kg DM palm^{-1} year^{-1}) and $L_{max,PD}$ is the maximum leaf area index (m^2 leaf m^{-2} ground) for a given PD planting density.

Coefficients, a, b, and A, as well as $VDM_{max,PD}$, were obtained from fitting the best functions to measured data from van Kraalingen *et al.* (1989).

6.2 Daily VDM requirement

$$VDM_d = \frac{VDM_{yr}}{365}$$

where VDM_{yr} and VDM_d are the annual and daily VDM requirement, respectively (kg DM palm^{-1} day^{-1}).

6.3 Dry matter partitioning

DM_{pinnae}, DM_{rachis}, DM_{trunk}, and DM_{roots} are the fractions of dry matter partitioned to pinnae, rachis, trunk, and roots, respectively (fraction). Their constant values are as follows:

$$DM_{pinnae} = 0.24$$

$$DM_{rachis} = 0.46$$

$$DM_{trunk} = 0.14$$

$$DM_{roots} = 1 - \left(DM_{pinnae} + DM_{rachis} + DM_{trunk}\right)$$

where *age* is the tree age (days). Dry matter partitioning for pinnae, rachis, and trunk are mean values of measured dry matter partitioning from Corley *et al.* (1971), Henson (1995), and Henson and Mohd Tayeb (2003).

6.4 Growth rates

G_{pinnae}, G_{rachis}, G_{trunk}, and G_{roots} are the growth rates for pinnae, rachis, trunk, and roots, respectively (kg DM palm^{-1} day^{-1}). They are determined by

$$G_{pinnae} = DM_{pinnae} \times A \times CVF$$

$$G_{rachis} = DM_{rachis} \times A \times CVF$$

$$G_{trunk} = DM_{trunk} \times A \times CVF$$

$$G_{roots} = DM_{roots} \times A \times CVF$$

where A (kg CH_2O palm^{-1} day^{-1}) is:

$$A = MIN\left(\frac{VDM_d}{CVF},\ G_{growth}\right)$$

and CVF is a factor (kg DM kg^{-1} CH_2O) to convert a weight expressed on a CH_2O weight basis to that on a dry matter (DM) basis. CVF is determined by

$$\begin{aligned} CVF = &\left(0.70 \times DM_{pinnae}\right) + \left(0.70 \times DM_{rachis}\right) \\ &+ \left(0.66 \times DM_{trunk}\right) + \left(0.65 \times DM_{roots}\right) \end{aligned}$$

where DM_{pinnae}, DM_{rachis}, DM_{trunk}, and DM_{roots} are the fractions of dry matter partitioned to pinnae, rachis, trunk, and roots, respectively (fraction) (van Kraalingen *et al.*, 1989). In the above equation, VDM_d is the daily VDM requirement (kg DM palm^{-1} day^{-1}) and G_{growth} is the amount of assimilates available for growth respiration (kg CH_2O palm^{-1} day^{-1}).

6.5 Death rates of pinnae and rachis

Leaves (pinnae and rachis) deaths are caused by aging, and they are determined by

$$G_{death,leaves} = \begin{cases} 0 & age \leq 600 \\ 0.0016\left(\dfrac{age-600}{2500-600}\right) & 600 < age \leq 2500 \\ 0.0016 & age > 2500 \end{cases}$$

where $G_{death,leaves}$ is the death rate of both pinnae and rachis due to natural causes (kg DM palm^{-1} day^{-1}); and *age* is the tree age (days). Values for the death rate of leaves were obtained from Dr. Ian E. Henson, then at Malaysian Palm Oil Board (personal communication).

6.6 Death rates of roots

$$G_{death,roots} = \begin{cases} 0 & age \leq 1200 \\ \dfrac{0.00009592age - 0.11510791}{365} & 1200 < age \leq 3285 \\ \dfrac{0.2}{365} & age > 3285 \end{cases}$$

where $G_{death,roots}$ is the death rate of roots due to natural causes (kg DM palm^{-1} day^{-1}); and *age* is the tree age (days) (based on unpublished data).

6.7 Assimilates available for generative growth

The amount of assimilates available for generative growth is the leftover assimilates after growth respiration, or

$$G_{gen} = MAX\left(0,\ G_{growth} - \frac{VDM_d}{CVF}\right)$$

where G_{gen} is the amount of assimilates available for generative organs growth (kg CH_2O palm^{-1} day^{-1}); VDM_d is daily VDM requirement (kg DM palm^{-1} day^{-1}); and CVF is a factor (kg DM kg^{-1} CH_2O) to convert dry matter weight into CH_2O weight.

6.8 Plant part weights

The plant part weights are incremented using Euler's integration method:

$$W_{t2} = W_{t1} + \left(rate_{t1} \times \Delta t\right)$$

where W_{t1} and W_{t2} are the weights at time t_1 and t_2, respectively; $rate_{t1}$ is the rate of increase at time *t1*; and Δt is the time interval, or $(t_2 - t_1)$. Since the model time step is always set at one day, $\Delta t = 1$. Thus, Δt can be ignored in subsequent calculations.

The various plant part weights are updated as follows:

$$W_{pinnae,t2} = W_{pinnae,t1} + \left(G_{pinnae} - G_{death,leaves}\right)$$

$$W_{rachis,t2} = W_{rachis,t1} + \left(G_{rachis} - G_{death,leaves}\right)$$

$$W_{trunk,t2} = W_{trunk,t1} + G_{trunk}$$

$$W_{roots,t2} = W_{roots,t1} + \left(G_{roots} - G_{death,roots}\right)$$

where W_{pinnae}, W_{rachis}, W_{trunk}, and W_{roots} are the dry weights for pinnae, rachis, trunk, and roots, respectively (kg DM palm^{-1}); G_{pinnae}, G_{rachis}, G_{trunk}, and G_{roots} are the growth rates for pinnae, rachis, trunk, and roots, respectively (kg DM palm^{-1} day^{-1}); $G_{death,leaves}$ is the death rate of both pinnae and rachis due to natural causes (kg DM palm^{-1} day^{-1}); and $G_{death,roots}$ is the death rate of roots due to aging (kg DM palm^{-1} day^{-1}) (van Kraalingen *et al.*, 1989).

6.9 Leaf area index

Leaf area index *LAI* (m^2 leaf m^{-2} ground) is determined by:

$$LAI = W_{pinnae} \times SLA \times PD / 10000$$

where *SLA* is the specific leaf area (m^2 leaf kg^{-1} DM); W_{pinnae} is the weight of the pinnae (kg DM palm^{-1}); and *PD* is the planting density (palms ha^{-1}).

CHAPTER 7. GENERATIVE ORGAN GROWTH

7.1 Boxcar train technique

The so-called boxcar train technique is used to track the growth progress of generative organs such as male flowers, and immature and mature bunches (van Kraalingen *et al.*, 1989). Three trains are used to represent the growth progress of these generative organs: one for male flowers, another for immature bunches, and the last for mature bunches. Each train comprises several boxcars whereby each boxcar represents an age class. The life span of both male flowers and immature bunches are taken as 240 days, and with a model time step of one day, the boxcar train for both male flowers and immature bunches consist of 240 one-day age classes (*i.e.*, 240 boxcars). Likewise, the life span for mature bunches before harvest is 180 days. Thus, the boxcar train for mature bunches consists of 180 boxcars.

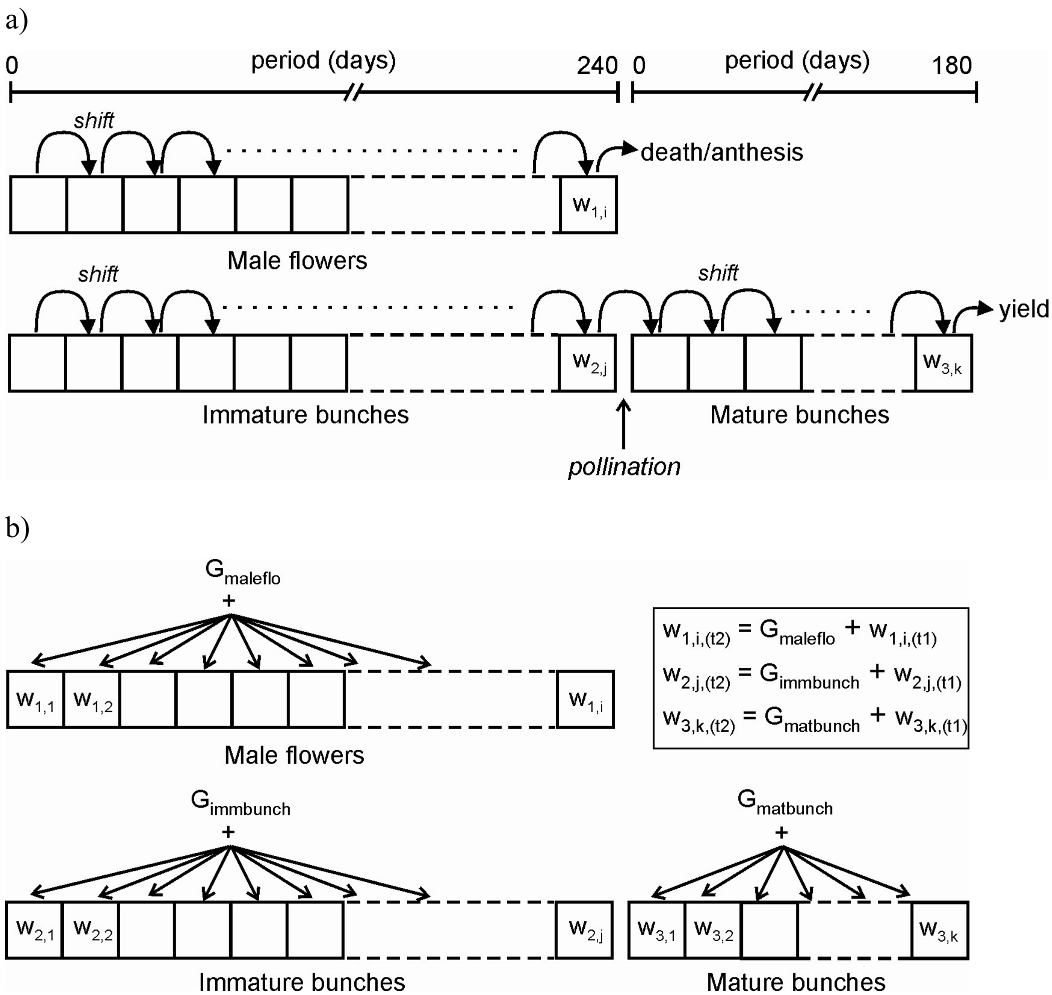

Fig. 7.1. Boxcar train schematic for growth of generative organs. In every model time step, a) weights are shifted to next age class, then b) they are incremented by the growth rate of the generative organs.

The algorithm of this boxcar train technique essentially consists of two steps: 1) the weight of a generative organ is shifted to successively older age classes, and 2) the weight is incremented according to the calculated growth rate. The lifespan of male flowers is set at 240 days, after which they will die. For immature bunches, however, the day after 240 days marks the point of pollination, after which the growth of the pollinated bunch (*i.e.*, mature bunch) will occur.

To determine the growth rates of the generative organs, the following equations are used:

$$G_{immbunch} = \frac{\left(f_{e,immbunch} \times G_{gen} \times CVF_2\right)}{C}$$

$$G_{matbunch} = \frac{\left(f_{e,matbunch} \times G_{gen} \times CVF_2\right)}{D}$$

$$G_{maleflo} = \frac{\left(f_{e,maleflo} \times G_{gen} \times CVF_2\right)}{E}$$

where $G_{immbunch}$, $G_{matbunch}$, and $G_{maleflo}$ are the growth rates for immature bunches, mature bunches, and male flowers, respectively (kg DM day^{-1}); G_{gen} is the amount of assimilates available for generative growth, after accounting for maintenance and growth respiration (kg DM day^{-1}); CVF_2 is a factor (kg DM kg^{-1} CH_2O) to convert dry matter weight into CH_2O weight, determined by

$$CVF_2 = \left(0.70 \times f_{e,immbunch}\right) + \left(0.44 \times f_{e,matbunch}\right) + \left(0.70 \times f_{e,maleflo}\right)$$

where $f_{e,immbunch}$, $f_{e,matbunch}$, and $f_{e,maleflo}$ are the scaled fraction of dry matter to immature bunches, mature bunches, and male flowers, respectively (fraction), and they are determined by

$$f_{e,immbunch} = f_{immbunch} / f_{total}$$

$$f_{e,matbunch} = f_{matbunch} / f_{total}$$

$$f_{e,maleflo} = f_{maleflo} / f_{total}$$

where

$$f_{total} = f_{immbunch} + f_{matbunch} + f_{maleflo}$$

$$f_{immbunch} = \frac{DM_{immbunch} \times C}{240}$$

$$f_{matbunch} = \frac{DM_{matbunch} \times D}{180}$$

$$f_{maleflo} = \frac{DM_{maleflo} \times E}{240}$$

where $DM_{immbunch}$, $DM_{matbunch}$, and $DM_{maleflo}$ are the fractions of available assimilates for generative growth partitioned to immature bunches, mature bunches, and male flowers, respectively (fraction); and *C*, *D*, and *E* are the numbers of non-zero weights for immature bunches, mature bunches, and male flowers, respectively (van Kraalingen *et al.*, 1989).

Note: $DM_{immbunch}$, $DM_{matbunch}$, and $DM_{maleflo}$ are taken as constants 0.159, 0.682, and 0.159, respectively, and denominator 240 is the growing time for both immature bunches and male flowers, whereas 180 is for mature bunches (van Kraalingen *et al.*, 1989).

Also note that plant storage is not modelled.

7.2 Organ weights and yield

The generative organ weights are incremented simply by

$$w_{1,i,(t2)} = \begin{cases} 0 & w_{1,i,(t1)} = 0 \\ w_{1,i,(t1)} + G_{maleflo} & w_{1,i,(t1)} > 0 \end{cases}$$

$$w_{2,j,(t2)} = \begin{cases} 0 & w_{2,j,(t1)} = 0 \\ w_{2,j,(t1)} + G_{immbunch} & w_{2,j,(t1)} > 0 \end{cases}$$

$$w_{3,k,(t2)} = \begin{cases} 0 & w_{3,k,(t1)} = 0 \\ w_{3,k,(t1)} + G_{matbunch} & w_{3,k,(t1)} > 0 \end{cases}$$

where $w_{1,i}$ is the dry weight of male flowers in age class *i* (kg DM); $w_{2,j}$ is the dry weight of immature bunches in age class *j* (kg DM); $w_{3,k}$ is the dry weight of mature bunches in age class *k* (kg DM); and $G_{immbunch}$, $G_{matbunch}$, and $G_{maleflo}$ are the growth rates for immature bunches, mature bunches, and male flowers, respectively (kg DM day^{-1}). The organ weights are only incremented for non-zero preceding weights (van Kraalingen *et al.*, 1989).

The total weight for a given generative organ is the summation of weights in all the age classes, or

$$W_{maleflo} = \sum_{i=1}^{240} w_{1,i}$$

$$W_{immbunch} = \sum_{j=1}^{240} w_{2,j}$$

$$W_{matbunch} = \sum_{k=1}^{180} w_{3,k}$$

where $W_{matbunch}$, $W_{immbunch}$, and $W_{maleflo}$ are the dry weights of the mature bunches, immature bunches, and male flowers, respectively (kg DM palm^{-1}); $w_{1,i}$ is the dry weight of male flowers in age class *i* (kg DM); $w_{2,j}$ is the dry weight of immature bunches in age class *j* (kg DM); and $w_{3,k}$ is the dry weight of mature bunches in age class *k* (kg DM) (van Kraalingen *et al.*, 1989).

Note: Oil palm yield is $w_{3,k+1}$.

CHAPTER 8. MISCELLANEOUS

8.1 Trunk, canopy, and tree height

The initial trunk height is a function of both tree age and planting density. It can be described by

$$h_{trunk,(t0)} = \exp\left(a + \frac{b}{PD^2} + \frac{c}{age}\right)$$

$$a = 2.845586$$
$$b = -1980.88805$$
$$c = -5166.36569$$

where $h_{trunk,(t0)}$ is the initial trunk height (m); *PD* is the planting density (palms ha^{-1}); and *age* is the tree age (days). Coefficients, *a*, *b*, and *c*, were calculated based on oil palm trunk height data from Jacquemard (1979, 1998), Breure and Powell (1988), Rao *et al.* (1992), Kwan (1994), and Henson and Mohd Tayeb (2003).

The rate of trunk height increase is described by

$$h'_{trunk} = -\frac{c}{0.7age^2} \times \exp\left(a + \frac{b}{PD^2} + \frac{c}{age}\right) \times \left(0.21 f_{water} + 0.553\right)$$

where h'_{trunk} is the rate of trunk height increase (m day^{-1}); *PD* is the planting density (palms ha^{-1}); and *age* is the tree age (days); f_{water} is the water stress function, determined as the ratio between actual and potential transpiration (0 to 1); and the values for the coefficients *a*, *b*, and *c* are as defined previously. Consequently, trunk height is updated at every model step of 1 day as

$$h_{trunk,(t2)} = h_{trunk,(t1)} + h'_{trunk}$$

The canopy height h_{canopy} (m) is determined by

$$h_{canopy} = 1.5091 + 0.001382age$$

where *age* is the tree age (days). Consequently, the full tree height *h* (m) is determined by

$$h = h_{trunk} + h_{canopy}$$

8.2 Rooting depth

The rooting depth is determined by

$$d_{root,(t2)} = MIN\left[S_N,\ d_{root,(t1)} + \left(dg_{root} \times f_{water}\right)\right]$$

where d_{root} is the rooting depth (m); dg_{root} is the rate of increase in the rooting depth (m day^{-1});); f_{water} is the water stress function, determined as the ratio between actual and potential transpiration (0 to 1); and S_N is the total thickness of the soil profile (m). In other words, the increase in rooting depth is adversely effected by water stress, and rooting depth will not exceed the total thickness of the soil profile being studied.

Note: dg_{root} is taken as a constant at 0.002 m day^{-1}.

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APPENDIX A. LIST OF MAIN SYMBOLS

The following lists all the main symbols used in the model. Note that some symbols have more than one meaning, depending on the context.

Symbol	Description	Unit
α	extinction coefficient for wind speed	-
α	fraction of PAR absorbed (0.8)	-
α	scattering coefficient (0.5 for total solar radiation, or 0.8 for PAR)	-
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	latent heat of vaporization of water (2454000)	J kg^{-1}
λ	pore-size distribution index	-
λ	site latitude	radians
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}
$\Lambda_{canopy,d}$, $\Lambda'_{canopy,d}$	daily gross photosynthesis with and without O_3 reduction effects, respectively	kg CH_2O $palm^{-1}$ day^{-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	hour angle	radians
τ	CO_2 / O_2 specificity factor	$\mu mol\ \mu mol^{-1}$
τ	atmospheric transmittance	-
τ	soil tortuosity	-
τ	O_3 residence time	s
$\tau_{dr,\alpha}$	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	$\mu mol\ mol^{-1}$
C_i	intercellular CO_2 concentration	$\mu mol\ mol^{-1}$

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 x 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_{iso}	CO_2-inhibited isoprene emission function	-
f_{O3}	fraction of assimilates reduced due to O_3 dose	-
f_{PAR}	reduction to maximum stomatal conductance due to PAR	-
f_{water}	reduction to maximum stomatal conductance due to water stress	-
F_{O3eff}	O_3 effective dose	mmol O_3 m^{-2} ground
F_{stom*}	instantaneous O_3 dose	μmol O_3 m^{-2} ground s^{-1}

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}
$\bar{K}_{\theta,i}$	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}
l	dry soil layer thickness	m
l	air mixing height	m
l	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	optical mass number	-
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
$MAX(x_1,x_2,...x_n)$, $MIN(x_1,x_2,...x_n)$	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}
O_z	ground level O_3 concentration for the given hour	nmol mol^{-1}
$O_{z,d}$	ground level O_3 concentration for the given day of year	nmol mol^{-1}
$O_{z,loss}$	fractional rate of O_3 chemical reaction in air	s^{-1}
$O_{z,net}$	total O_3 concentration (concentrations of both background O_3 and O_3 formed from isoprene emission)	μg O_3 m^{-2} ground s^{-1}
$O_{z,prod}$	total O_3 concentration created from isoprene emitted by sunlit and shaded leaves	g C_5H_8 g^{-1} leaf s^{-1}
$O_{z,sl/sh}$	O_3 concentration created from isoprene emitted by sunlit (sl) or shaded (sh) leaves	g O_3 palm^{-1} s^{-1}
$\overline{O_{z,yr}}$	average ground level O_3 concentration for the year	nmol mol^{-1}
$O_{z,yr,max}$, $O_{z,yr,min}$	maximum and minimum ground level O_3 concentration for the year	nmol mol^{-1}
OM	organic matter content in soil	%
p	surface albedo (reflection)	-
P_a	atmospheric pressure (101)	kPa
PD	planting density	palms ha^{-1}
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}
$r_{\Delta Oz}$	annual rate of change for ground level O_3 concentration	% 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_a^a	aerodynamic resistance between the mean canopy flow and reference height	s m^{-1}
r_a^c	bulk boundary layer resistance	s m^{-1}
r_s^c	canopy resistance	s m^{-1}
r_a^s	aerodynamic resistance between the soil surface and mean canopy flow	s m^{-1}
r_s^s	soil surface resistance	s m^{-1}
$r_{s,dry}^s$	soil surface resistance of dry soil	s m^{-1}
$P_{g,A}$	maximum rainfall in the year	mm
$P_{g,d}$	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}
R_{iso}	O_3–forming potential of isoprene (9.1)	g O_3 g^{-1} C_5H_8
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_a	air temperature	ºC
T_a	actual plant transpiration	m day^{-1}
T_{avg}	average air temperature	ºC
T_b	base temperature for crop growth	ºC
T_f	temperature of canopy	ºC
$T_{a,i}$	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	ºC
T_{min}	minimum air temperature for the given hour	ºC
T_{set}	air temperature at sunset	ºC
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	$\mu mol\ m^{-2}$ leaf s^{-1}
$v_{d,total}$, $v_{d,canopy}$, $v_{d,soil}$	total, canopy, and soil velocity deposition for O_3, respectively	$m\ s^{-1}$
v_q	light-limited rate of CO_2 assimilation	$\mu mol\ m^{-2}$ leaf s^{-1}
v_s	sink-limited rate of CO_2 assimilation	$\mu mol\ m^{-2}$ leaf s^{-1}
$V_{c,max}$	Rubisco capacity rate (200)	$\mu mol\ m^{-2}$ 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*). Note: W_{trunk} is the total of upper ($W_{top,trunk}$) and lower ($W_{bottom,trunk}$) trunk weights.	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