Oil Palm Water Balance; a tool for Analysing Oil Palm Water Footprint and Root Water Uptake Distribution in Root Zone

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Abstract. The varying condition of climate, soil properties, crop stage, ground water existing in oil palm cultivation require the specific water balance model to perform the precision crop water use. The purposes for this research were to develop oil palm water balance model for calculating the hydrological parameter of oil palm and analysing oil palm water footprint and root water uptake distribution in root zone. The model of oil palm water balance was developed through the following step: oil palm root architecture study, instrument installation and data observation, model development and calibration. The oil palm water balance tool was developed by inputting the data base including climate, soil properties, crop stage, root density and root zone layer as well. The results in the case for 11th year oil palm tree on soil type ultisol in Central Kalimantan during the simulation climate data pointed out that the average root water is 3.46 mm/day and distributed 63% on 2st root zone. From the total water usage and the average production 14.19kg/month, it resulted the 1.053 m³/kg water footprint of FFB (76 % green water and 24% blue water).

1. Introduction

One of the common impact issue oil palm plantation expansion [1] is related to water problem [2][3]. Hence, an accurate crop water balance analysis which shows the precise crop water use analysis in each stage of oil palm is substantial for better understanding the most efficient and precise crop water requirement to reach the optimal productivity. The varying condition of climate, soil properties, crop stage, ground water existing in oil palm cultivation require the specific water balance analysis model to perform the precision condition of crop water use. Water balance parameter in oil palm could be predicted through unsaturated water flow approach by Richard equation [6] [7] which involve the complex hydrological parameter in root zone. The result of hydrological factors in root zone could determine the root water uptake and sum up the value of water footprint in oil palm plantation as one of environmental sustainability parameters [4] [5].

Previously, the oil palm water balance tool has been developed to predict the water content distribution in root zone and has been tested during the observation time (April to July 2017) [8].
order to accomplish the prior oil palm water balance tool and accustom to the water sustainability issues, this research was conducted to develop oil palm water balance model for calculating the hydrological parameter of oil palm and to analyse oil palm water footprint and root water uptake distribution in root zone, case study in Pundu, Kotawaringin Timur, Central Borneo, Indonesia.

2. Materials and Methods

2.1. Research procedure

2.1.1. Instrument Installation and Data Observation. Rainfall by rain gauge ECRN100, water content along the three root zone layer [9] by soil moisture sensor (type 10 HS decagon), automatic water level (Hobo U20L-04) and a set of AWS (automatic weather station) to cover the climate data.

2.1.2. Model Development and Calibration. The model was developed by building the numerical solution of unsaturated water flow [6] and the root water uptake and water footprint [4][5][13].

2.1.3. Water Content Change in Root Zone. Water content was calculated through the steps below:

Water retention calculated by van Genuchten model [10], [11]:

\[
\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^{m/2}\right)^{1/m}}
\]

\( m = 1 - 1/n \)  

Water capacity (Darcy law and Richards Equation) [6]:

\[
C(h) = \frac{d\theta}{dh} = \frac{\alpha^2 (\theta_r - \theta_s)(n-1)(|\alpha h|)^{-1}}{\left[1 + (\alpha h)^n\right]^{3/2}}
\]

Hydraulic conductivity calculated by Muallem model [12]

\[
K(S_e) = K_e \cdot \frac{1}{\left[1 - S_e\right]} \cdot \left[1 - \left(1 - S_e\right)^{n/m}\right]^{-2}
\]

S degree of saturation [10], [11]:

\[
S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r}
\]

Richard equation (positive downward) 1D vertical flow of Richard Equation[6]:

\[
C_w \frac{\partial h}{\partial t} = - \frac{\partial}{\partial z} \left( - \left( K \frac{\partial h}{\partial z} - K \right) \right) - S
\]

Where K is hydraulic conductivity (cm/hour), h is water pressure head (Pa), \( \theta_s \) is saturated water content (cm\(^3\)/cm\(^3\)), \( \theta_r \) is residual water content (cm\(^3\)/cm\(^3\)), \( \alpha \) is air entry value ((h\(_a\) = \( \alpha^{-1} \)), \( \lambda \) is pore-size distribution index, \( C(h) \) is water capacity, \( S_e \) is effective saturation / degree saturation, \( n \) is curve gradient, \( m \) = empirical parameters, \( C_w \) is total flux (cm/hour), \( S \) is sink factor, root water uptake (cm/hour).
2.1.4. Root Water Uptake and Water Footprint Analysis. The calculation of water footprint according to [4], [5], [13] consists of green, blue and total water footprint calculation in equation (6), (7), and (8).

\[
WF_{green} = \frac{10 \times ET_{green}}{Y} \ (m^2/ton) \tag{6}
\]

\[
WF_{blue} = \frac{10 \times ET_{blue}}{Y} \ (m^2/ton) \tag{7}
\]

\[
WF_{total} = WF_{green} + WF_{blue} + WF_{grey} \tag{8}
\]

Where ET Green and ET blue is root water uptake from rainfall (mm) and groundwater (mm) respectively, Y is average production of oil palm.

3. Results and Discussion

3.1. Structure of Oil Palm Water Balance Model

The oil palm water balance model was built through the structure illustrated in Figure 1 which describe the input data, calculation process and the output as the result of model. The script of model was built in R in finite different method.

![Figure 1. The structure of Oil palm water balance model](image)

The oil palm water balance model was built by previously by assuming the boundary condition [8] including the free drainage, no flux bottom and groundwater contribution.

3.1.1. Data Input of Model

The data input of this model generally consisted of 3 types of data:

1. Climate data; a series of hourly climate data (rainfall, temperature, relative humidity, wind speed, and solar radiation)
2. The soil properties data; consisting the soil texture, bulk density (gr/cm^3), porosity (%), permeability (Ks, cm/hour) and the generated Van-Genuchten parameters [10], [11] such as saturated water content (θs, cm^3/cm^3), residual water content (θr, cm^3/cm^3), air entry value (α) and soil gradient curve (n).

| Soil Type          | Ultisol |
|--------------------|---------|
| Sand (%)           | 33.3    |
| Silt (%)           | 30.32   |
| Loam (%)           | 36.39   |
| Bulk Density (g/cm^3) | 1.33   |
| Porosity (%)       | 49.91   |
Soil Type | Ultisol
---|---
Ks (Cm/hour) | 10.31
θs | 0.439
θr | 0.142
α | 0.011
n | 1.356

3. The crop properties; root density and root zone levelling from the oil palm root architecture study [9] and also the value of crop coefficient (Kc). The value of Kc as a determination factor of root water uptake was adjusted by calibrating the water content of model and observation.

Table 2. Root zone levelling and root density distribution for 11th year oil palm on ultisol soil type

| Root Zone* | Depth (cm)* | Root density (gr/cm3)** |
|---|---|---|
| Zone 1 | 15 | 0.0116 |
| Zone 2 | 45 | 0.0013 |
| Zone 3 | 90 | 0.0054 |

* [9], ** data analysis

For running the oil palm water balance in this study, it took the case of 11th year oil palm tree on ultisol soil type with ground water existing where the soil properties data performed on Table 1 and the root zone levelling [9] and root density on Table 2. The soil data properties of ultisol soil type used in running the model was performed in Table 1. Afterwards, the value of Kc for this 11th year oil palm was 0.8 according to the calibration model during observation.

3.2. Reference Evapotranspiration
The first output of the oil palm water balance model is the reference evapotranspiration (ETo (mm/hour) calculated using Penman Montheit equation [14], [15], [16]. Figure 2 shows that, ETo value during observation (10th July – 6th September 2018).

Figure 2. ETo Penman Montheit (mm/ hour) during observation (10th July – 6th September 2018)

3.3. Water Content Distribution
The next output calculated by the oil palm water balance model is the water content change along the soil depth through the calculation of eq (1) – (6). The water content change in influenced by the water flux both from rainfall, capillary in the case of ground water existing and also the root water uptake as the sink factor.
Figure 3 pointed out the water content on three root zone level in line with the root zone levelling determined in previous study. The water content in 3rd layer (blue line) performed the highest water content and followed by the 2nd layer (red) and the 1st layer (green). The 3st layer showed the highest water content probably due to the capillary flux of ground water. For the 1st layer of root zone that remains drier than other could be caused by the low rainfall during the observation climate data. Ones rainfall occurred, the water content in 1st layer reach the value more than the rest. However, the assumption of uniformity of soil properties along the soil depth is less fit to the real condition. Therefore, the variation of soil properties on root zone layer remains a challenge for this model.

3.4. Oil Palm Root water uptake and water footprint

Based on the root distribution on Table 2, the total root water uptake of oil palm was distributed along the root zone as shown on Figure 4. The daily average root water uptake is 3.46 mm/day which consisting of 2.19 mm/hour from root zone 1, 0.25 mm/day from root zone 2 and 1.02 from root zone 3. The root water uptake along the simulation in the case study show the highest contribution from 1st root zone and followed by the 3rd root zone and the 2nd root zone. This result performed that the root water uptake distribution depend on the root density distribution and the water availability both from rainfall and groundwater. As presented on Table 2, the highest root density of 11th year of oil palm tree on ultisol is on the 1st root zone followed by by the 3rd root zone and the 2nd root zone as the lowest. Since the root system of a tree spread to reach the water, then the availability of water on the upper (due to the rainfall) and the bottom (due to the groundwater) influence the root density of the crop.
The result of root water uptake distribution as the oil palm water usage furthermore was used to calculate water footprint of FFB (fresh fruit bunch) oil palm. Regarding the productivity of observed oil palm is 14.19 kg/month/tree and assumption tree area is 71.71 m$^2$/tree, the total water footprint of observed oil palm tree is 1.053 m$^3$/kg FFB. Thus total water footprint value was contributed from green water footprint (rainfall) for 0.786 m$^3$/kg and from blue water footprint (groundwater) for 0.268 m$^3$/kg.

The crop water usage is commonly predicted using the Cropwat model by FAO [17]. Some water footprint analysis in recent time use crop water usage analysis by this model [18], [19], [20]. But, the real time input data for predicting the real time condition seems to be lacking in Cropwat model. The more detail crop water usage can also analysed by Hydrus (1D, 2D, or 3D) through water content change and root water uptake [21], [22], [23]. However, the Hydrus model is not developed for a general crop and condition. Therefore, the development of oil palm water balance in this study has been addressed to those required issue.

The precise water use resulted from the oil palm water balance model could be the easy tool to assess the temporal water use of oil palm and furthermore to determine what strategy to applied if the water deficit happened. During the dry season the productivity are low and needs the implementation of irrigation system and fertilisation to maintain [24] [25]. The high productivity is obtained by the mature plantation that consume more water [2] [26]. Hence, the rapid calculation of water use of oil palm could avoid the decreasing in productivity. The variation of water usage on oil palm crop age showed that the better understanding of temporal water use is required [27]. In the fact, to meet the crop water requirement during the dry season through precision irrigation system still need the detail temporal water use both for maintaining the productivity and for environmental sustainability.

4. Conclusions
1. The oil palm water balance model have been developed for calculating the hydrological parameter in oil palm root zone including root water uptake along the root zone and the water footprint.
2. The highest contribution of root water uptake is from 1st root zone and followed by the 3rd root zone which depend on the root density distribution and the water availability (rainfall and groundwater).
3. The total water footprint of observed oil palm tree is 1.053 m$^3$/kg FFB which was contributed from green water footprint (rainfall) for 0.786 m$^3$/kg and from blue water footprint (groundwater) for 0.268 m$^3$/kg.

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