Sustainability of the Water Footprint of Various Soil Types on Oil Palm Plantations

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Abstract. There are significant studies that have quantified oil palm water footprint as an indicator of environmental sustainability but an estimation of water footprint under varying soil types furthermore is still limited. The objectives of the study were to estimate whether annual variations of soil type and yields significantly affect the oil palm water footprint. The data from three types of soil (spodosol, inceptisol, ultisol) were collected from an oil palm plantation in Pundu village, Central Kalimantan, Indonesia. To perform the water footprint analysis we utilize water balance accounting equations via application Cropwat 8.0. From that, we determine the crop irrigation scheduling to compute the blue, green, and grey water footprint of oil palm fresh fruit bunch in the area. Our analysis found that the actual evapotranspiration of spodosol and inceptisol have the same value: 1242 mm/year whilst ultisol is 1239 mm/year. The total water footprint of oil palm varied considerably with the largest value being 1310.04 m³/ton for ultisol. The actual evapotranspiration of spodosol and inceptisol have the same value of 1242 mm/year whilst ultisol is 1239 mm/year. The higher production resulted in a lower water footprint and vice versa. Moreover, the total water footprint from ultisol soil type has the highest value due to the lowest yields. The difference in evapotranspiration value resulted in the insignificant value of total water footprint. The lower water availability, the lower water use, and the higher actual irrigation requirement in oil palm plantation yet showed the unnoticeable impact on water footprint in different soil types for the oil palm plantation.

Keywords: oil palm, soil type, sustainability, evapotranspiration, water footprint

1. Introduction
The oil palm industry is considered to be one of the primary economic developments in Indonesia’s agricultural sector. Indonesian palm oil exports, which are recognized globally, are predicted to contribute about 3.5% of the Gross Domestic Product (GDP) [1]. With that being said, solid, timely, and well-planned efforts are required by oil palm plantations to expand and increase productivity and profitability [2]. Our previous research has been focused on the application of agricultural precision for oil palm plantations by developing various information systems [1,3–6] as well as data-driven analysis via artificial intelligence for optimization purposes [2]. Recently, one of the major issues in oil palm plantations is how to manage water usage for environmental sustainability by computing water footprint.
A water footprint is a quantity to evaluate water utilization by plants to produce crops [7]. Some studies have shown quantification of the oil palm water footprint as one of the primary indicators for environmental sustainability [8,9]. Basically, the water footprint is estimated generally without considering the variation of soil type. A current study presented the prediction of water footprint for varying soil types yet in farm-scale under limited spatial and temporal [10]. The estimation of the water footprint in the life cycle assessment concept under varying soil types furthermore is still limited. A better understanding of water footprint variation under different soil types is beneficial to predict the distribution of effective water use of oil palm as an indicator of environmental sustainability. Furthermore, a broad insight of which main factors impacted on water footprint value such as water availability, water use, irrigation, production, etc. Referred to the problem statement, it is of interest to understand on 1) how does the annual evapotranspiration of oil palm vary under different soil type in the same area, 2) how do the annual water usage and production of oil palm vary on different soil type in the same climatic area, 2) how does the water footprint vary annually among the different soil type in the same climatic area and 3) furthermore to determine whether the variation of soil type and yields significantly effects to the oil palm water footprint.

A review by Lovarelli et al reported that parameters such as climatic conditions of plantation area, type of plantation land, and tree plant productivity significantly impact the values of the water footprint in agricultural areas for crops [8]. For example, data-driven analyses of weather patterns can be used to forecast local rainfall, which can be useful to predict green water availability in a given region [11–15]. Meanwhile, Suttayakul et al. used crop water scenario for the environmental sustainability within the oil palm plantation as suggested by Wackernagel et al. that the water footprint could contribute to determine the ecological footprint of oil palm trees [17].

2. Material and Methods

2.1. Data Collection

The data was collected from an oil palm plantation in Pundu village, Central Kalimantan, Indonesia, located at 11° 58’01’’ S and 113° 04’ 32’’ E at an altitude of 27 m above sea level. The area has an average annual rainfall of 3002 mm/year, the average annual temperatures range from 21.4 to 33.8 °C, and also the yearly average daily sunshine is about 5.9 hours. The total observation area is 3239.58 ha (Pantai Mas Estate).

Moreover, the data includes geographical location, climate data series for 2012-2015 with the rainfall data ranged from 11 to 254 mm/month from a local automatic weather station, crop characteristic, soil properties, oil palm yields, and chemical application rate (fertilization rate) during 2011-2014. The crop characteristics include the crop coefficient (Kc), rooting depth, critical depletion, and yield response fraction. The measured values of those quantities are given in Table 1. On the other hand, there are three types of soil in the area: inceptisol, ultisol, and spodosol. Table 2 shows the parameters used to describe the soil properties for different types of soil.
### Table 1. Crop characteristic of the oil palm

| Crop Characteristic | Value (1–20 years age crop) |
|--------------------|----------------------------|
| Kc                 | 0.82 – 1.00                |
| Rooting depth      | 0.50 – 8.00 m              |
| Critical depletion | 0.30 – 0.75                |
| Yield response fraction | 1.00 – 1.40           |

### Table 2. The soil properties of the observation area

| Soil properties                        | Inceptisol | Ultisol | Spodosol |
|----------------------------------------|------------|---------|----------|
| Total available soil moisture (mm/m)   | 96         | 129.9   | 88.7     |
| Maximum rain infiltration rate (mm/day)| 40         | 40      | 30       |
| Maximum rooting depth (cm)             | 200        | 100     | 80       |
| Initial soil moisture depletion (%)    | 0          | 0       | 0        |
| Initially available soil moisture (mm/m)| 96         | 129.9   | 88.7     |

#### 2.2 Computation

Our methodology is summarized as a workflow shown in Figure 1. First of all, we employ the essential information from the collected data: the location, the climate condition, crop characteristics, and soil properties as an input to compute the water balance. The water balance investigation to obtain the crop water use. We distinguish the term ‘green’ and ‘blue’ water. The former refers to rainwater stored in the soil and the latter is groundwater and water from surface resources (irrigation) [18]. The water balance accounting equation is given by Eq. 1 and implemented via application Copwat 8.0:

\[
D_{Rt} = D_{Rt-1} - (P - RO)_t - I_t - CR_t + ET_{Ct} + Dp_t \tag{1}
\]

\[
ET_{a} = D_{Rt-1} - DR_t. \tag{2}
\]
ETa is the actual crop evapotranspiration rate at day i, Dr, quantifies root zone depletion at the end of a day i while Dr_{i-1} is the amount of water content in the root zone at the end of the previous day, i-1. Further, P_i denotes precipitation on day i, RO refers to the runoff from the soil surface on day i, I, is total irrigation depth on day i that infiltrates the soil, Cr_i is a capillary rise from the groundwater table on a day i, ETc_i denotes the crop evapotranspiration on a day i, Dp_i is water loss out of the root zone by deep percolation on the day i, and Eta: actual water use by the plant. All quantities are measured in millimeter (mm). Furthermore, the reference evapotranspiration (ETo) and crop evapotranspiration (ETc) can be calculated using the Penman–Monteith equation [19]. The water balance accounting from the previous step can be used to estimate irrigation scheduling for crops. The crop water use is based on that scheduling for both the green and blue water use. Next, we compute the water footprint of oil palm fresh fruit bunch (FFB) according to Hoekstra et al [20] & ISO 14046 [21] using the following equations:

\[
WF_{green, blue} = \frac{10 \times \text{average } E Ta_{green, blue}}{\text{Yields}} (m^3 \text{ton}^{-1}) \quad (3)
\]

\[
WF_{grey} = \frac{\alpha \times AR (C_{max} - C_{nat})}{\text{Yields}} (m^3 \text{ton}^{-1}) \quad (4)
\]

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

where ETa green denotes the annual actual evapotranspiration during immature and mature stage for 2-20 years (mm/year), ETa blue is the annual actual evapotranspiration from irrigation during nursery stage age in the first year (mm/year). The annual average production of oil palm from Pundu Plantation (ton/year) is denoted by Yield. \(\alpha\) is a leaching fraction. Using the assumption of 10% nitrogen (concentration), we denote AR as a chemical application rate per hectare (ton/ha), \(C_{max}\) is the maximum allowable concentration (10 mg/L) and \(C_{nat}\) is a natural concentration (0 mg/L). The input AR, \(C_{max}\) and Yields are provided in the data. Moreover, the irrigation scheduling is needed to check irrigation requirements along with the quantity of rainwater contained in the root zone (effective rainfall) to measure the availability of different types of water (green, blue, gray, and total) for crops (see Figure 1). The grey water here refers to the amount of water polluted during the agricultural process.

3. Results and Discussion

3.1. Evapotranspiration analyses of oil palm plants from different types of soil

The analysis of annual crop water requirements using CropWat 8.0 presented the simulation result of oil palm ETa (mm/year) complete with the water contribution from precipitation rate (ETa green) as well as groundwater through irrigation (ETa blue). ETa, ETa green, and ET blue data are listed in Table 3. The result presented that the actual evapotranspiration of spodosol and inceptisol have the same value of 1242 mm/year whilst ultisol is 1239 mm/year. The corresponding annual ET of oil palm was 918 ± 46 and 1216 ± 34 mm/year, respectively [22]. The crop evapotranspiration of mature oil palm has a range from 1, 583 to 2, 003 mm/year case study in Peninsular Malaysia [23].

| Soil type | ETa (mm/year) | ETa green (mm/year) | ETa blue (mm/year) |
|-----------|---------------|---------------------|-------------------|
| Spodosol  | 1242          | 1171                | 71                |
| Inceptisol| 1242          | 1171                | 71                |
| Ultisol   | 1239          | 1168                | 71                |

3.2. Oil palm water footprint analysis

The palm oil water footprint consists of grey, green and blue water footprints. The grey water footprint represents the water required to leach the chemical fertilizer used at the farm to reach the natural concentration. It was estimated from the average fertilizer applied to the farm, the concentration of
nitrogen contained on fertilizer and the maximum concentration of nitrogen allow to the soil as well. The quantity of nitrogen that reaches free-flowing water bodies has been assumed to be 10% of the applied fertilization rate (in kg/ha/yr) [24]. The result of different grey water footprints based on Eq. (4) showed in Table 4. The effect of the use of other nutrients, pesticides, and herbicides on the environment furthermore has not been analyzed in this work.

### Table 4. The calculation of oil palm grey water footprint

| Soil type, Planting year | Average fertilizer applied (ton/y/ha) | Nitrogen leached to water bodies 10% (ton/year) | Max conc (mg/L) | Natural conc (mg/L) | Total EF proc grey oil palm (10⁶ m³/yr) | Yield (ton/ha) | WF grey (m³/tonne) | CWU grey (m³/ha) |
|--------------------------|-------------------------------------|-----------------------------------------------|---------------|-------------------|------------------------------------------|----------------|-------------------|------------------|
| Spodosol, 2008           | 1.44                                | 0.144                                         | 10            | 0                 | 0.0012                                   | 22             | 65.45             | 1440             |
| Inceptisol, 2008         | 1.39                                | 0.139                                         | 10            | 0                 | 0.0012                                   | 22             | 63.18             | 1390             |
| Ultisol, 2007            | 1.36                                | 0.136                                         | 10            | 0                 | 0.0012                                   | 10             | 136.00            | 1360             |

### Table 5. Oil palm water footprint

| Soil type, Planting year | CWU green (m³/ha) | CWU blue (m³/ha) | CWU grey (m³/ha) | Oil Palm Production (m³/ha) | WF green (m³/ton) | WF blue (m³/ton) | WF grey (m³/ton) | WF total (m³/ton) |
|--------------------------|------------------|------------------|------------------|----------------------------|-------------------|------------------|------------------|------------------|
| Spodosol, 2008           | 10960            | 440              | 14.3             | 22                         | 498.18            | 20.11            | 65.45            | 583.75           |
| Inceptisol, 2008         | 11791            | 432              | 1390             | 22                         | 516.32            | 19.64            | 63.18            | 599.14           |
| Ultisol, 2007            | 11400            | 340              | 1360             | 10                         | 1139.92           | 34.13            | 136.00           | 1310.04          |

Furthermore, using the grey water footprint from Table 4 and the green and blue water footprint from Table 3 and 5, the total water footprint of oil palm for three variations of soil type were estimated and presented in Table 5. The results showed that the total water footprint of oil palm varied considerably from 583 m³ ton⁻¹ for spodosol, 599 m³ ton⁻¹ for inceptisol, and 1310.04 m³ ton⁻¹ for ultisol. The obsolete factor of this significant variation was driven by the oil palm production (m³ ha⁻¹) (see Figure 2). The higher production resulted in a lower water footprint and vice versa. A recent study in the same area found that the water footprint is 1002.1 m³ ton⁻¹ in which the productivity was estimated at 13.41 ton ha⁻¹ and the plantation used 0.12 ton ha⁻¹ fertilizer. In addition, irrigation was only given to pre-nursery and nursery activities for simplicity [7]. The oil palm trees in the observation area were grown using water from precipitation, not from groundwater. The grey WF obtained was 8.9 % which is relatively lower than the average grey WF of oil crops worldwide. Another study of oil palm water footprint in Ogan Baturaja, South Sumatera presented an estimated 980.88 m³ ton⁻¹ for total water footprint and 821, 23, 137 m³ ton⁻¹ for green, blue, and gray water footprint respectively [25]. One other case study from oil palm plantation in Thailand 1063 m³ ton⁻¹ for total water footprint which comprised of 68, 18, and 14% green, the blue and grey water footprint of total WF, respectively.
Figure 2. The water footprint of oil palm in different soil types

3.3. Comparison of production factors and evapotranspiration as components of water footprint

Figure 3. Comparison of total water footprint, yields, and ET for different types of soil

Figure 3 represented the comparison of production factors and evapotranspiration as components of water footprint among the different soil types. The total water footprint from ultisol has the highest value due to the lowest yields. The water footprint of spodosol and inceptisol showed a slightly different value due to the close production value. The difference in evapotranspiration value resulted in the insignificant value of total water footprint. The unnoticeable effect from evapotranspiration to total water footprint has resulted from similar climate data from the research area. Another study in the same area resulted in a considerable variation of the water footprint on farm-scale in consequence of using a temporal and specific time approach in a certain period (monthly) [7]. Changes in consumptive water footprint are possible. Chukalla et al. compared the reduction in water footprint among the type of irrigation techniques and resulted that the blue water footprint was higher in a full irrigation system than rainfed agricultural system [26]. Nevertheless, their study also summarized that due to the increase of yields, the total water footprint tends to decrease implying the high efficiency of water usage.

3.4. Comparison of water balance as a component of water footprint

This study also undertook to figure out the comparison and relation between the water balance factor to the water footprint. Figure 4 indicated the commensurate portion of water availability and water use. Part of water use in oil palm was contributed from the insignificant amount of water from irrigation. The lower the water availability, the lower the water usage, and the higher the actual irrigation requirement. In line with the result, Arshad et al. presented that the water availability is varied among the soil type, and the higher the water availability the higher water use by crop and consequently reduce the amount of water for irrigation [23]. Muhammad-Muaz & Marlia indicated that the actual irrigation
requirement in the tropical area is low due to the high rainfall that impacts on higher water availability [27]. However, the water availability, water use, and actual irrigation requirement in this work showed the unnoticeable impact on water footprint in different soil types.

Figure 4. The comparison chart of water availability for different types of soil

4. Conclusion
Utilizing water footprint analysis in the oil palm plantation in Pundu village, Central Kalimantan, we found the actual evapotranspiration of spodosol and inceptisol have the same value of 1242 mm per year whilst ultisol 1239 mm per year. The insignificant value of evapotranspiration was due to the climate data from the same area. The total water footprint of oil palm varied considerably from 583 m³ ton⁻¹ for spodosol, 599 m³ ton⁻¹ for inceptisol, and 1310.04 m³ ton⁻¹ for ultisol. The obsolete factor of this significant variation was driven by oil palm production. The higher production resulted in a lower water footprint and vice versa. The total water footprint from ultisol soil type has the highest value due to the lowest yields. Further, we also demonstrated that the water footprint of spodosol and inceptisol showed slightly different values due to the close production value. The difference in evapotranspiration value resulted in the insignificant value of total water footprint. The lower water availability, the lower water usage, and the higher actual irrigation requirement in oil palm plantation yet showed the unnoticeable impact on water footprint in different soil types. Our analysis can be further improved by integrating data-driven analyses from our previous studies such as weather forecasting, AI-based computer vision to detect ripeness of oil palm, and more.

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