Estimating oil palm water usage in peat soils using sap flow technique

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Abstract. Massive issues on significant water used by oil palm trees suggest further estimation of water exploited by oil palm trees. This research employed sap flow technique using thermal dissipation probes (TDP), compared to Penman-Monteith equation as the benchmark. Water utilization by plants was studied through evapotranspiration, to investigate their water footprint and water productivity. Field study was carried out in a 17 year old oil palm plantation in Siak, Riau, Indonesia. Sap flow measurement was carried out on the 17th frond over sapric peat soil during 7th January – 18th March 2019. Water used from 19th oil palm was 40.97±6.63 L day-1 equals to 0.51±0.083 mm day-1 (mean ±SD). While, estimation based on Penman-Monteith equation was 286.3 ± 64.078 L day-1 equals to 3.58±0.80 mm day-1 (mean ±SD). Total accumulated water from Penman-Monteith equation (286.3 L day-1) was considerably higher than the one from sap flow measurement (41 L day-1). The result showed that water footprint from 17 year old oil palm tree based on sap flow and Penman-Monteith equation was 0.204 and 1.43 m3 kg-1 fresh fruit bunches respectively. While water productivity estimated from sap flow was 0.70 kg m-3 while Penman-Monteith equation achieved 4.89 kg m-3.

1. Introduction
Water used by plant is generally measured based on Penman-Monteith equation using microclimate data [1] or based on energy balance approach using flux data retrieved from flux tower [2]. The water relates to evaporation from soil and transpiration from plant. Methods to distinguish part of water evaporated from soil and transpired from plant remain a challenge. Water usage based on stand transpiration measurement from sap flux was developed based on thermal dissipation probes (TDP [3-5]). Calibrating TDP to oil palm tree was conducted in Jambi Province, Indonesia [6]. Nowadays, sap flow meter has been developed, although its application on oil palm is limited. With the dispute over significant water used by oil palm trees, further investigation on using sap flow technique based on TDP, compared to Penman-Monteith, is necessary.
2. Methodology

2.1. Site specification
Field study was carried out in a 17-year-old oil palm plantation (situated around 0°43’34.10” N 101°45’33.40” E), Siak Regency, Riau, Indonesia. Peat soils (sapric) bulk density ranged from 0.07 to 0.15 g/cm³ whilst water content varied from 275 to 474 % w/w [7]. Climatic condition is categorized as Equatorial where wet season occurs from February to March and September to November). Averaged annual air temperature is 25 to 37 °C with mean annual precipitation is 3045 mm.

2.2. Measurements and calculation
Methods of this study were consisted of measurements and calculation as presented below:
1. Sap flow measurement was carried out on 17th frond during 7th January – 18th March 2019. The placement of a sap flow meter is depicted in Figure 1, following Niu et al. [6]
2. Raw data exported from sap flow meter was sap velocity (cm hour⁻¹). It was converted to flux density (Js, kg cm⁻² day⁻¹) based on relationship among mass, velocity and water density.
3. Flux density was then converted to stand transpiration (liter per day or equals to mm per day) using equation 1 [3-5]. Additional data included average vessel density which was 12% among ten 1 cm² squares [6], total cross section area of petiole which was 36 cm², and total frond, i.e. 48.

\[ E_s = \frac{E_L \times N_L \times N_P}{A_g} = \frac{(J_s \times A_c) \times N_L \times N_P}{A_g} \]  

where: Es is stand transpiration (mm day⁻¹), EL (kg day⁻¹; equals mm m² day⁻¹) is average leaf water-use as a product of average integrated daily sap flux density (Js, kg cm⁻² day⁻¹) and average leaf water conductive area (Ac, cm²), NL is average number of leaves per palm, and Np is number of palms per ground area (Ag, m²).
4. Calculating evapotranspiration using microclimate data from local Automatic Weather Station (AWS) based on FAO’s Penman–Monteith equation [1] and a crop coefficient of 0.9 for mature oil palm plantations [8].
5. Estimating water footprint (m³ kg⁻¹) as total, monthly basis, water used per monthly fresh fruit bunches mass produced by oil palm tree; and water productivity (kg m⁻³) as total fresh fruit bunches mass per total water used. Averaged monthly oil palm yield during observation period was 15 kg.

![Figure 1](https://example.com/figure1.png)  
Figure 1. Cross-section of an oil palm petiole with the location of probe (a); and installation of TDP on oil palms (b) [6]
3. Results and discussion

3.1. Water usage

Measured water usage consumed by palm tree is presented in Figure 2.

Consumed water based on sap flow technique was 40.97 ± 6.63 L day−1 equals to 0.51 ± 0.083 mm day−1 (mean ± SD). Meanwhile, estimation by Penman-Monteith equation was 286.3 ± 64.078 L day−1 equivalent to 3.58 ± 0.80 mm day−1 (mean ± SD). Both techniques yielded similar pattern; however, the rates were significantly different. Total accumulated water based on evapotranspiration from Penman Monteith equation (286.3 L day−1) was considerably higher than the result of sap flow technique measurements (41 L day−1), as shown by Figure 3.

Figure 2. Daily water used of 17th year old oil palm tree in in sapric peat soils in Riau during 7th January – 18th March 2019

Mature palms reached crop evapotranspiration (ETc) rate of 4–5 mm day−1 in monsoon months (equivalent to 280–350 L palm−1 d−1) [8]. With this similarity, Penman-Monteith equation is often applied. Evapotranspiration represents water used by plant that consisted of water evaporated by soil and transpired through plant. However, water used based on sap flow measurement only represents transpiration from plants. This consequently resulted in lower rate of water used from sap flow measurement, compared to total evapotranspiration using Penman-Monteith equation. Sap flow meter provides a better understanding on the amount of water precisely utilized by trees.

Figure 3. Accumulated water used by oil palm tree
3.2. Water productivity

Water usage by perennial trees could represent sustainability parameter regarding water and environmental issues such as water footprint and water productivity. Water footprint is designed to evaluate the extent of water used by crops, compared to biomass yield. It basically consists of green, blue, and grey waters, each represents the source of water, i.e. rainfall, groundwater and water to leach fertilizer respectively [9]. Since irrigation was not applied on mature oil palm plantation and fertilization was not conducted during observation period, consequently, total water footprint from this study only relied on green water [10, 11]. Its footprint was calculated based on monthly accumulated water used from evapotranspiration in plant area (m$^3$) divided by the yield of oil palm fresh fruit bunches (kg).

In this study, we calculated water footprint rooted from either sap flow technique or Penman-Monteith equation (Figures 2 and 3) and averaged monthly yield of observed oil palm tree (15 kg fresh fruit bunches). The result showed that water footprint from 17 year old oil palm tree based on sap flow and Penman-Monteith was 0.204 and 1.43 m$^3$ kg$^{-1}$ fresh fruit bunches respectively. As the comparison, water footprint of oil palm in mineral soils based on Penman-Monteith equation ranged from 0.56 to 1.14 m$^3$ kg$^{-1}$ for various plant ages [10, 11]. Hence, water footprint of oil palm in peat soil in this case was lower than in mineral soils. Nevertheless, we would not be able to confirm the differences since variations in crop ages, productivity, and observation period exist. This research indicated that lower water footprint represents lesser amount of water used by plant to produce the same biomass. Despite the difference, water footprint from sap flow measurement more accurately deliver the information, suggesting more efficient water used by plants to produce biomass.

Sustainability of plant water consumption could be measured through water productivity (in kg m$^3$). It appears to be a reverse equation from water footprint, i.e. water productivity represents biomass produced by plant in comparison to water used [12, 13]. Water productivity of observed oil palm tree was estimated from average monthly yield of observed oil palm tree (15 kg fresh fruit bunches) compared to averaged monthly water used from sap flow and Penman-Monteith equation. The study pointed out that water productivity from observed oil palm tree based on sap flow and Penman-Monteith equation was 0.70 and 4.89 kg m$^{-3}$ respectively. As the reference, averaged water productivity of various crops (kg m$^{-3}$) was 2.47 for maize, 12.3 for watermelon, 1.39 for wheat and 0.65 for natural vegetation, based on a case study delivered in China [14]. From water productivity perspective, higher water productivity suggests a more efficient water used by plants.

Both parameters, water footprint and water productivity, are widely applied to quantify environmental sustainability regarding water resource challenge [15, 16]. Various methods were applied to predict consumed water as an essential element of water footprint and water productivity. Sap flow measurement could bring a new perspective of investigating water footprint and water productivity based on crop transpiration rate.

4. Conclusion

There were some essential subjects to summarize based on this study:
1. Water usage by oil palm trees in peat soils measured by sap flow was lower than the one from Penman-Monteith evapotranspiration. It represented stand transpiration; meanwhile the other indicated total water being evaporated by soil and transpired through plants.
2. With similar oil palm yields, water footprint based on sap flow measurement was lower than Penman-Monteith.
3. Consumed water from sap flow measurement brings a new perspective of investigating water footprint and water productivity based on crop transpiration rate.
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References
[1] Allen R G, Jensen M E, Wright J L and Burman R D 1989 Operational Estimates of Reference Evapotranspiration Agronomy Journal 81 650-62
[2] Beringer J, Hutyra L B, McHugh I, Arndt S K, Campbell D, Cleugh H A, Cleverly J, Resco de Dios V, Eamus D, Evans B, Ewenz C, Grace P, Griebel A, Haverd V, Hinko-Najera N, Huete A, Isaac P, Kanniah K, Leuning R, Liddell M J, Macarlane C, Meyer W, Moore C, Pendall E, Phillips A, Phillips R L, Prober S M, Restrepo-Coupe N, Rutledge S, Schroder I, Silberstein R, Southall P, Yee M S, Tapper N J, van Gorsel E, Vote C, Walker J and Wardlaw T 2016 An introduction to the Australian and New Zealand flux tower network – OzFlux Biogeosciences 13 5895-916
[3] Granier A 1985 A new method of sap flow measurement in tree stems Annales Des Sciences Forstieres 42 193-200
[4] Granier A 1987 Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements Tree Physiology 3 309-20
[5] Granier A, Biron P, Brêda N, Pontailler J Y and Saugier B 1996 Transpiration of trees and forest stands: short and long-term monitoring using sapflow methods Glob. Change Biol. 2 265-74
[6] Niu F, Röll A, Hardanto A, Meijide A, Köhler M, Hendrayanto and Hölscher D 2015 Oil palm water use: calibration of a sap flux method and a field measurement scheme Tree Physiology 35 563-73
[7] Adhi Y A, Anwar S, Tarigan S D and Sahari B 2020 Relationship between groundwater level and water content in oil palm plantation on drained peatland in Siak, Riau Province, Indonesia Pertanika Journal of Tropical Agricultural Science 43 415-27
[8] Carr M K V 2011 The water relations and irrigation requirements of oil palm (Elaeis guineensis): a review Experimental Agriculture 47 629-52
[9] Hoekstra A Y, Chapagain A K, Aldaya M M and Mekonnen M M 2012 The Water Footprint Assessment Manual (London (UK), Washinton DC (USA)
[10] Safitri L, Hermantoro H, Purboseno S, Kautsar V, Saptomo S K and Kurniawan A 2018 Water footprint and crop water usage of oil palm (Elaeis guineensis) in Central Kalimantan: Environmental sustainability indicators for different crop age and soil conditions Water 11 35
[11] Safitri L, Kautsar V, Purboseno S, Wulandari R K and Ardiyanto A 2018 Water footprint analysis of oil palm: (case study of the Pundu Region, Central Borneo) International Journal of Oil Palm 1 95-102
[12] Kijne J W, Barker R and Molden D J 2003 Water Productivity in Agriculture: Limits and Opportunities for Improvement, ed J W Kijne and J W Kijne (Wallingford (UK) pp xi-xix
[13] Descheemaeker K, Bunting S W, Bindraban P, Muthuri C, Molden D, Beveridge M B, Herrero M, Clement F, Boelee E and Jarvis D I 2013 Managing Water and Agroecosystems for Food Security, ed E Boelee and E Boele (Wallingford (UK) pp 104-17
[14] Ren D, Xu X, Engel B, Huang Q, Xiong Y, Huo Z and Huang G 2021 A comprehensive analysis of water productivity in natural vegetation and various crops coexistent agroecosystems Agricultural Water Management 243 106481
[15] Hossain I, Imteaz M A and Khastagir A 2021 Water footprint: applying the water footprint assessment method to Australian agriculture *Journal of the Science of Food and Agriculture* **101** 4090-8

[16] Molden D J, Murray-Rust H, Sakthivadivel R and Makin I 2003 *Water Productivity in Agriculture: Limits and Opportunities for Improvement*, ed J W Kijne, et al. (Wallingford (UK) pp 1-16