Agricultural Water Management 260 (2022) 107292

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Water requirements for oil palm grown on marginal lands: A simulation approach

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ARTICLE INFO

Handling Editor - Dr. B.E. Clothier

Keywords:
Oil palm expansion
Marginal lands
Water footprint
APSIM-Oil palm simulation

ABSTRACT

Oil palm is one of the most rapidly growing tree crops in the tropics. It is long-lasting and high yielding, serving as an input for a number of profitable industries. The rapid expansion of oil palm has triggered environmental change. Historically, the focus has been on the impact of biodiversity loss. However, the water requirements of oil palm plantations, which traditionally depended on rainfall only, are also changing, partly because environmental concerns are directing oil palm expansion and cultivation into marginal areas. According to some estimates, these lands with cultivable marginal soils— having an acid pyrite layer in the soil profile— comprise about 7.5 million ha in Indonesia. Here, we employed the Agricultural Production Systems sIMulator (APSIM) to simulate the growth of oil palm on marginal lands within Indonesia over an eight year period. APSIM-Oil palm was used to estimate the irrigation water requirement at different stages of plant growth for actual weather and soil conditions. Traditionally, water footprint accounting of oil palm plantations at the field level considers one uniform value of evapotranspiration. Our analysis shows that considering a single value for the entire period of oil palm growth underestimates the water requirement at the field scale. Annual irrigation needs were found to range from 2543 mm to 3865 mm for the plantation ages examined (0-8 years). We approximate that 8800 m^3 of blue water and 6200 m^3 of green water is required per ton of fresh fruit bunch produced from the study plantation occupying marginal lands, where water requirements were largely governed by maintenance of a high water table. Similarly high volumes are likely to be required where oil palm is cultivated on pyritic soils. Thus, the irrigation water requirement can no longer be neglected as oil palm plantations continue to expand onto marginal soils.

1. Introduction

Oil palm is one of the most valuable oil crops in the world (Gilbert, 2012). Oil palm is not only used for cooking but also as animal feed, input to a number of cosmetic products, and biofuel. Moreover, oil palm has a high yield per unit of fruit and the management of this crop is relatively easy. Therefore, it is not surprising that we are seeing the rapid development of oil palm plantations in different countries around the world. From 2009 to 2019, the area planted under this crop increased from 16 million ha to 28 million ha; at the same time, fresh fruit bunch yield has almost doubled from 217 million tonnes to 411 million tonnes. ("FAOSTAT," n.d.). This trend continues with the doubling of oil palm production in every decade (Khatun et al., 2017).

Oil palm (*Elaeis guineensis* Jacq.) originated in tropical areas of central and west Africa along the coastal belts between 5° N to 7° S (Corley and Tinker, 2015). Therefore, it is adapted to natural conditions of high rainfall throughout the year, so water requirements of oil palm are generally considered to be fulfilled by the rainfall in tropical areas (green water requirement). However, expansion of oil palm into other countries has increased its latitudinal range from 19° N to 16° S. Therefore, oil palm plantations in areas of less rainfall require additional water from irrigation (blue water requirement) to maintain yield levels (Carr, 2011). Moreover, the expansion of oil palm into areas of different soil characteristics can impose additional water demand for the plantations (Bloomfield and Zahari, 1982).

The expansion of oil palm outside Africa increased rapidly in

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https://doi.org/10.1016/j.agwat.2021.107292
Received 12 July 2021; Received in revised form 22 October 2021; Accepted 23 October 2021
Available online 6 November 2021

Southeast Asia during the 19th century. In fact, Malaysia and Indonesia, together, are responsible for 77% of the total production of fresh fruit bunches of the world and represent 70% of the total world area under oil palm plantations in 2019 ("FAOSTAT," n.d.). The recent exponential expansion in these nations has brought in substantial revenues to this region. For example, in 2014, oil palm production and processing contributed 17% of the total agricultural GDP of Indonesia and employed about 8 million people (Purnomo et al., 2020). However, the expansion of these plantations is imposing environmental stresses in-terms of biodiversity loss, land use change, and water stresses (Vijay et al., 2016). Some studies suggesting that global oil palm expansion (both small holder and large plantations) is responsible for a significant proportion of tropical forest replacement (Vijay et al., 2016), while other studies have pointed to a host of factors, such as illegal logging, commercial forestry, forest fires etc. contributing to the forest replacement (Gaveau et al., 2016). Regardless, 27% of global forest loss has been attributed to commodity production, including oil palm (Curtis et al., 2018).

Due to forest loss, there is a broad consensus to restrict the agricultural development in rainforests. For example, the Indonesian government with international help has imposed a moratorium in different forms from 2010 until now on the expansion of oil palm plantations in forested areas ("Palm Oil Industry in Indonesia - CPO Production & Export | Indonesia Investments," n.d.). On the other hand, to continue to reap the economic benefits of this crop, the government has made a policy for utilizing marginal lands which are not covered by forests or peatlands for plantations ("Degraded Land, Sustainable Palm Oil, and Indonesia's Future," 2010). This expansion of oil palm plantations into marginal lands thereby imposes different kinds of environmental and water management challenges, such as low pH levels of water and constant submergence of particular soil layers in water.

The marginal agricultural areas in Indonesia are the low potential coastal lands. These areas are swampy with poor drainage under natural conditions. Historically, these lands were submerged under the sea which caused the formation of acid sulfate (pyrite) soils, containing a pyritic layer, either in the shallow layer of the soil profile or in the deep layer. When this pyrite layer is exposed to the atmosphere, as a result of drainage, it is oxidized causing acidic conditions and other environmental impacts. According to some estimates, these marginal lands comprise about 18% of Indonesia's land area. In Sumatra alone (the highest producer of oil palm), there is 13 million ha of marginal lands, out of these 7.5 million ha can be brought under cultivation (Sulaiman et al., 2019). This makes Indonesia host to the largest area of pyritic soils as compared to other countries (Wignyosukarto, 2013).

Although these lands were historically reclaimed by local indigenous populations, the Indonesian government has started to utilize these lands on a large scale from 1970′s (Suryadi, 2020). The usual technique to drain these lands is to construct drainage canal networks, which will carry the water to the surrounding larger water bodies. However, this lowering of water exposes the pyritic soil layers to oxidation, resulting in the acidic conditions in the soil making them unsuitable for crop cultivation. Therefore, water management techniques for these plantations require the submergence of the pyritic layer, thereby adding to the total water requirement of the oil palm plantations.

The water requirement of oil palm plantations on marginal lands is twofold: the plant water requirement and maintenance of the groundwater level to submerge the acid pyrite layer and prevent oxidation. Therefore, calculations of the water footprint of oil palm plantations will increase considerably. Hashim et al. (2014) estimated the water footprint of oil palm plantations by considering a constant evapotranspiration need of the crop (Hashim et al., 2014). However, water footprint studies using a constant evapotranspiration value for the entire life of plantation can result in lower estimates of water needs. As plantations are affected by not only different climatic conditions where they are grown but also the different stages of growth, they require a different amount of water input. Moreover, Subramaniam et al. (2020) extended these calculations to assess the water footprint of the entire supply chain of the oil palm production. Their analysis showed that fresh fruit bunch production does not increase much pressure on the total blue water requirement as compared to the other processes in palm oil production. Apart from the variable water requirements because of the different climates and age of the plant, if pyritic marginal lands are utilized for the production of oil palm, it will further increase the water footprint of the crop at the field level. Therefore, it is important to include these important variables for the calculation of water needs for the production of fresh fruit bunch of oil palm grown on the marginal lands.

Crop modeling frameworks have been developed for better management of different inputs and improving yield by simulating the crop growth. Their gradual development over the past decades has resulted in the expansion of these modeling frameworks as agriculture production system models. These models incorporate information not only about the growth of the crops but link them to weather, soil, and management conditions. They are used for the guidance of farmers and policymakers for the optimum use of resources and planning purposes (Holzworth et al., 2015). Furthermore, these models can also help in the estimations of water footprint accounting of the crops.

Agricultural Production Systems sIMulator (APSIM) is one such modeling system (Keating et al., 2003, Holzworth et al., 2014). It contains different crop modules and management modules linked through a common framework for simulating the growth of different crops in different climatic and soil conditions. Huth et al. (2014) developed and tested the oil palm module of crop growth for this model. This module can simulate the growth of oil palm plantations for an extended period of time by accounting for the longer fruiting and growing periods and requires different inputs during different stages of plant growth (Huth et al., 2014). Different management interventions that can exert an effect on output of oil palm fruit are the input of water and fertilizers. Therefore, quantification of water input will be helpful for establishing water requirements of the crop at the field scale throughout the entire period of growth, which is the major component in the water footprint computation for oil palm.

APSIM-Oil palm has been used in a number of cases to study the growth of oil palm for extended periods of time to better understand its interplay with the environment. Okoro et al. (2017) studied the impact of climate change on the oil palm growth in the Nigerian delta region. They used global circulation models to predict the climate at the end of the century and resulting impacts on the oil palm growth (Okoro et al., 2017). Pardon et al. (2017) estimated the yield response of oil palm by varying the N application and resulting loss of N from the plantation by using APSIM. Culman et al. (2019) used APSIM-Oil palm to optimize the irrigation application by using vapor pressure deficit and soil moisture data in a Columbian plantation. This modeling platform can capture multiple complex processes over extended periods of time for better planting and environmental impact assessment.

Hence, in our study we use the APSIM modeling framework to quantify the water requirements of oil palm plantations occupying the marginal pyritic soils in Sumatra, Indonesia. This analysis is based on actual climate and soil conditions in the major oil palm growing area of the country, which also has the largest area of marginal lands in the nation. This is the first known study to quantify water requirements of oil palm grown on marginal soils at the field scale by taking into consideration both the local soil and climatic conditions for an extended eight-year period. The crop modeling framework used in this study can serve as a helpful tool for determining the crop water footprint at the field scale, where the usual practice is only to use one single value of crop evapotranspiration for oil palm regardless of growth period.

2. Material and methods

APSIM (Keating et al., 2003, Holzworth et al., 2014) was used for the simulation of oil palm growth from 2012 to 2019 (8 years). APSIM is able to model plant growth by taking consideration of actual soil conditions and weather conditions. Moreover, different management strategies can be applied according to the requirement of plant growth.

2.1. Study area

The study area was located in the Rawapitu district of Lampung Province of Sumatra Island at latitude 4°16′ S and longitude 105°36′E at 3 m (average) above sea level. The plantation is located near the coast of the Java Sea, and it is owned by the government company PT Perkebunan Nusantara. There are 135 trees planted per hectare. The plantation and the plot studied is shown in Figs. 1a and 1b. The river tributary Paidada also passes close to the plantation, which is the source of irrigation water for the plantation. The Paidada River joins the Tulangbawang River a little further downstream, which ultimately flows into the Java Sea. Water management infrastructure has been installed at the site to regulate water flows and levels. Specifically, a water gate was built to control inflow and outflow caused by tidal movement. Drain blocks also were installed within the canal to maintain subsurface water levels between 40 and 60 cm from the surface to enhance plant productivity.

2.2. Climate data

The Indonesian archipelago is located along the equator; this gives the country a hot and humid climate throughout the year. Indonesia, in general, has wet and a dry seasons, although the timing and intensity of precipitation varies with location and elevation. Seasonal differences are due to the monsoonal nature of the climate. The dry season starts in May and lasts until September, the wet season is from October to March. August is the driest month, averaging approximately 50 mm and December the wettest with a mean of 300 mm (a six-fold difference). The temperature range is rather constant between 22 and 33 °C with an average temperature of 28 °C; the annual average rainfall is in the range 2000–3000 mm.

The climate data (rainfall, air temperature, and solar radiation) for the present study were obtained from the NASA POWER (Prediction of Worldwide Energy Resources) project. The POWER project derives its data from the following NASA sources: World Climate Research Program (WCRP), Global Energy and Water Cycle Experiment (GEWEX), Surface Radiation Budget Project (NASA GEWEX SRB) and the Clouds and the Earth's Radiant Energy System (CERES) projects at NASA LaRC as well as the Global Modeling and Assimilation Office at the Goddard Space Flight Center (https://power.larc.nasa.gov).

2.3. APSIM model description

APSIM is an agriculture modeling framework that allows different components of the farming system to be plugged into the main engine; these include the modules for soil, weather, and different management practices. APSIM was developed by the Agriculture Production Systems Research Unit, a collaborating unit between the Commonwealth Scientific and Industrial Research Organization (CSIRO) and Queensland State Government Agencies, Australia. The main advantage of the model is that it allows the simulation of the growth of the crop by considering the different climatic and soil conditions; moreover, users can specify different management scenarios as well. Fig. 2 is the schematic diagram showing different components of the model. For a deeper description of the model, we refer readers to Keating et al. (2003) and Holzworth et al. (2014).

2.4. Oil palm simulation

For the biophysical development of the oil palm, the model developed by Huth et al. (2014) was used, which can be 'plugged in' to the APSIM modeling framework. APSIM-Oil palm was able to simulate the growth of the stem, fronds, roots, and bunches as well as water and elemental cycling. Moreover, it also incorporates the development of understory crop, which dies off as a plantation matures. The model was tested for multi-year data for three plantations in Papa New Guinea.

Fig. 1. (a) Google earth location of the plantation area on Sumatra Island (area is shown in white polygon). Credit: Google Earth. (b) Plantation area along with the irrigation system. The River Paidada passes close to the plantation site. The red area denotes the 40 ha plot where soil samples were acquired. Legend translation (from Indonesian to English) for Fig. 1(b) is as follows: Legenda = Legend; Blok = Block; Pintu air ulir = threaded sluice door/gate; Pintu air otomatis = automated

sluice door/gate; Jalan primer = primary road; Jalan produksi = production road; Saluran primer = primary channel; Saluran sekunder = secondary channel; Saluran border = border channel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

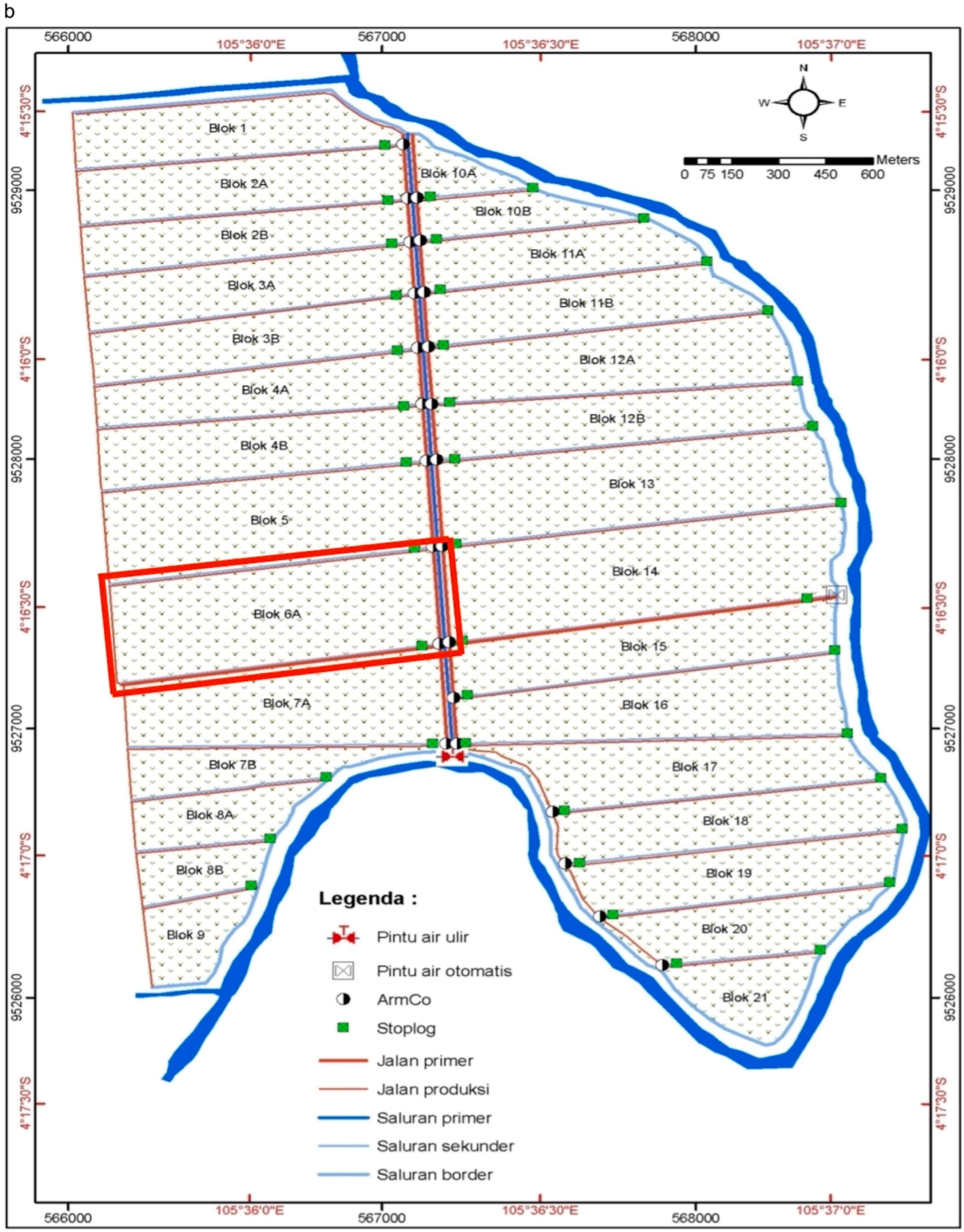

Fig. 1. (*continued*).

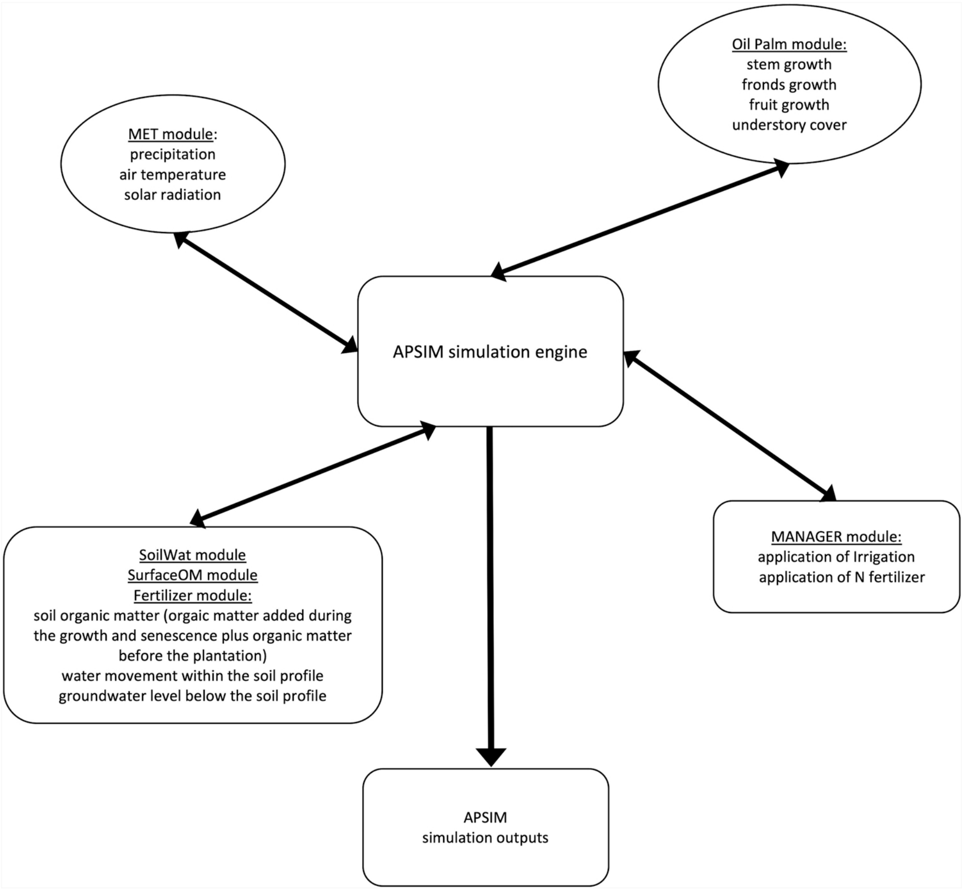

Fig. 2. Flow diagram showing the different modules of the APSIM model interacting through a central simulation engine as applied to an oil palm plantation growing on marginal lands.

They validated the model by comparing the modeled biomass growth to the actual growth observed for a 17-year period. For details about the development and model testing, the reader is referred to Huth et al. (2014).

For the validation of our simulation, we compared the modeled evapotranspiration (ET) values to the ET values computed by Röll et al. (2015) and Manoli et al. (2018). Röll et al. (2015) studied evapotranspiration values of different aged (2–25 years for 1 year) oil palms in Sumatra, Indonesia by measuring sap flux rate and employing the eddy covariance technique. Meanwhile, Manoli et al. (2018) modeled the ecohydrological impacts induced by tropical forest conversion to oil palm plantations.

2.5. Soil processes

APSIM has the capability to model soil processes in detail. Hence, the emphasis is not only on crop growth, but also the soil conditions, which are important. The water and Nitrogen (N) requirements are major considerations for any kind of crop. These are the principal inputs that require management intervention. Therefore, if we take optimum N application, we can estimate the amount of water that will be required for the entire growth period of the crop to achieve maximum growth. Moreover, the components related to soil organic matter were also kept the same as in Huth et al. (2014). This seems to be a reasonable assumption as our study area also lies along the same latitude as Huth et al. (2014).

2.6. Water movement

SoilWat is a cascading bucket water balance model. The plant water uptake lower limit is taken as the bottom of the bucket, while the maximum field capacity of the soil is taken as the top of the bucket. The algorithms used for the water distribution throughout soil profile are from the CERES family of models. However, minor modifications were implemented. For example, soil parameters (like unsaturated flow and saturated flow) were determined separately for each layer. Further, the decomposition of organic matter takes consideration of local climatic conditions (Probert et al., 1998).

Hydrologic processes in the soil were modeled by taking consideration of climatic conditions and plant needs. Plant uptake of water was specified for each layer in terms of the lower limit of − 15 bar potential (LL15, lowest potential below which plant cannot extract water), drained upper limit of −0.33 bar potential (DUL, akin to field capacity), and saturated volumetric water content. Before the start of the simulation, the initial water was kept at 50% of plant-available soil water throughout the soil profile. Runoff was calculated using the USDA curve number technique. Soil evaporation was calculated as a two-stage process: in the first stage, evaporation occurs at the potential evaporation rate (calculated from Priestly and Taylor (1972)); and in the second stage, after evaporation becomes limited, was defined by the fraction of square root of time after the end of first stage evaporation.

The movement of water from upper to lower soil layers happens in three ways. Firstly, water below the saturation and drained upper limit moves or infiltrates to the lower layer governed by the factor SWCON. Secondly, the water between the lower limit and drained upper or unsaturated water flow depends on the average amount of water in the two soil layers and value of diffusivity constant. Finally, the movement of water above saturation is controlled by MWCON; the value can be 0 or 1, a value of 1 indicates that all the water above saturation moves to the layer below. On the contrary, a value of 0 indicates an impermeable layer and water starts to back up. The soil layer where the value is set to zero will either become the groundwater below the layer or if it is the surface layer, water will back up as it ponds on the surface.

2.7. Groundwater level data

In our model setup, we have fixed the groundwater level at a depth of 60 cm (600 mm) below the surface of the soil. This level is set on the basis of actual field observations in which the water level fluctuates between 40 and 60 cm depth, thereby providing space for roots for proper development. Following Bloomfield and Zahri (1982), the required groundwater level for optimum growth of oil palm on pyritic soils is a constant high (40–45 cm) water table below the surface. If the water drops below this level, soils become more acidic, resulting in a significant drop of yield and wilting of crops. Therefore, the explicit purpose of irrigation in these soils at our particular site was to maintain a constant groundwater level of 40–50 cm rather than meeting the plant water requirements of the crop. Moreover, an irrigation efficiency of 80% was used because losses are only due to evaporation, and the rest of the water becomes part of the groundwater.

2.8. Soil data

For specifying the soil parameters for the crop growth, soil samples from different depths were taken from the plantation site. Three samples were taken at each depth, and the soil is classified according to the particle size distribution. Table 1 shows the soil characteristics taken from different depths of the plantation.

Pedotransfer functions (PTF) were used to calculate the hydraulic parameters of the soil for different soil characteristics. From Rosetta, developed by USDA, which uses the method of van Genuchten (1980), water retention parameters are calculated. The needed parameters are bulk density (g/cm^3), air dry, LL15, DUL (Drained upper limit) or field capacity, saturated content, and hydraulic conductivity (KS). Some KS values increase with soil depth. This is because of the specific texture of the soil profile in these marginal lands whereby some deeper soil layers either contain higher percentages of sand or have low bulk densities. For example, the middle two layers (from 20 to 82 cm) have lower bulk density, while the lower most layer (82–200 cm) has a higher sand fraction. The values are shown in Table 2.

2.9. Other data requirements

For fertilizer input, N fertilizer was simultaneously added at a rate of 0.14, 0.3, 0.6, 0.9, and 1.05 kg/palm for 1, 2, 3, 4 years and mature palms, respectively (after Indonesian Oil Palm Research Institute), using the Palm manager module. This resulted in no deficiency of N during the simulation period because plant growth is sensitive to N concentration.

Surface organic matter was simulated in two ways. First, APSIM simulated the effect of organic matter that is left from the previous plantation (or crop) on soil water; second, it degrades the organic matter and constantly adds to the soil organic pool, this includes not only previous organic matter that is present but also new matter added during harvest and natural aging of plants. These values were adopted after Huth et al. (2014) at 20,000 kg/ha of fronds and stem on the field before plantation with a carbon and nitrogen ratio of 75.

Table 1
Soil characteristics at different depths based on soil particle distribution.

Sr. No.	Depth of layer (cm)	Soil characteristic
1	0–20	Clay loam
2	20–60	Clay
3	60–82	Clay
4	82–200	Sandy loam

Table 2
Soil properties calculated for APSIM using a pedotransfer function.

Depth (cm)	Bulk density (g/cm^3)	Air dry (mm/mm)[a]	LL15 (mm/mm)[b]	DUL (mm/mm)[c]	SAT (mm/mm)[d]	KS (mm/day)[e]
0–20	1.370	0.084	0.125	0.276	0.429	135.3
20–60	1.220	0.091	0.251	0.311	0.451	321.9
60–82	1.220	0.091	0.251	0.311	0.451	315.7
82–200	1.430	0.049	0.123	0.192	0.386	299.3

[a] Air dry denotes volumetric water content for air dry soil in each layer.
[b] LL15 denotes volumetric water content for each layer corresponding to soil potential of − 15 bar.
[c] DUL denotes volumetric water content at drained upper limit for each soil layer.
[d] SAT denotes volumetric water content at saturation for each soil layer.
[e] KS denotes amount of water that is allowed to drain from the layer when soil water is above saturation.

2.10. Understory growth and model parameterization

The understory story growth in oil palm plantations under real conditions is either composed of legumes or grasses. The resulting interaction between the understory and overstory growth is a complex process, and the full complexity of growth of understory is not fully captured by any modeling platforms (Huth et al., 2014). In APSIM-Oil palm, the understory is modeled based on the simplified assumption that the understory cover decreases with age at first and then stabilizes with a fixed amount of understory present throughout the plantation's life after the initial decrease. The light use efficiency is assumed to be 1.3 g MJ^{-1} and the understory biomass enters the carbon pool of the soil profile with about 2% of it supplying N to the overstory biomass in case of legumes and 0.05% of N in case of grasses (Huth et al., 2014). The parameterization of the model is shown in the Table 3.

3. Results

3.1. Scenario #1: Control (without Irrigation)

Fig. 3 shows the plant water requirement of the oil palm per ha in the case of no maintenance of the groundwater level or irrigation. By eliminating these two factors, it is possible to see the evapotranspiration demand of the plantation under baseline conditions. Before the age of 4 years, the maximum plant water requirement reaches approximately 140 mm per month. There is considerable reduction of total evapotranspiration at the end of the third and seventh years due to reduced rainfall in these years. Therefore, at the plantation site there is water deficit that hampered the optimum growth of oil palm trees. Table 4 shows the total annual water use in-terms of evapotranspiration without irrigation. The annual evapotranspiration will reach the maximum level of about 1500 mm in the fifth year; on the other hand, the lowest value is about 800 mm during the first year. However, as the plantation matures, the rainfall is not sufficient to meet the water demand of the crop. Therefore, the annual evapotranspiration amount dropped from the fifth year onward—clearly indicating the need for irrigation to sustain yield

Table 3
Initial plantation parameters provided to the model.

Start date of simulation	1-Jan-2012
End date of simulation	31-Dec-2019
Cultivar	Dura x psifera (Dami)
Plants per ha	135
Irrigation water applied	Based on rainfall (if rainfall is less than 20 mm for three consecutive days apply 25 mm of water)
Irrigation efficiency	0.8

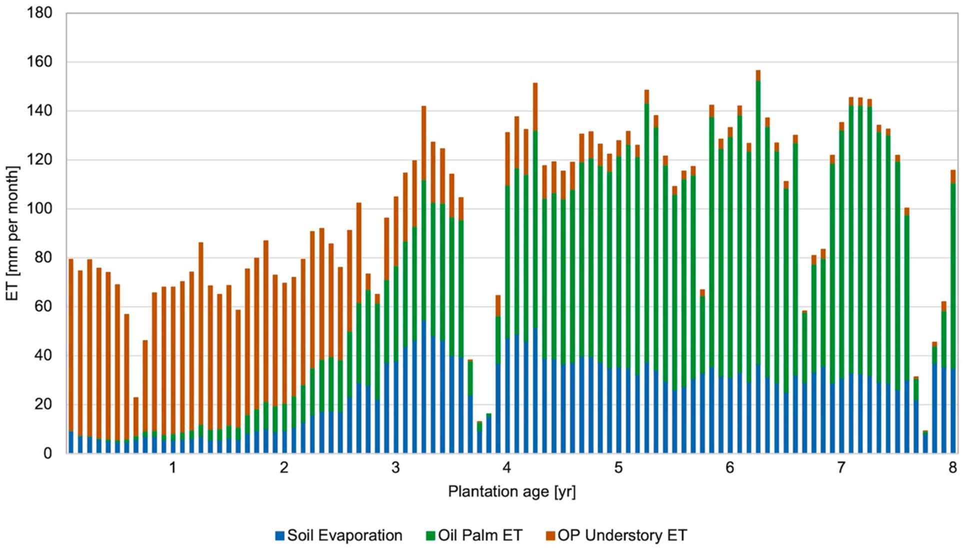

Fig. 3. Control scenario. Total evapotranspiration (ET) from the oil palm plantation (without any application of irrigation) during the first eight years of plantation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Total evapotranspiration from the plantation along with total annual rainfall for the control scenario without irrigation.

Year	Age of plantation (yrs)	Soil evaporation (mm)	Oil palm ET (mm)	Oil palm understory ET (mm)	Total ET (mm)	Annual rainfall (mm)
2012	1	76	15	689	780	2146
2013	2	89	80	707	876	2782
2014	3	269	323	437	1029	1950
2015	4	453	470	188	1111	1770
2016	5	486	896	150	1532	2528
2017	6	385	1047	47	1479	2262
2018	7	375	999	37	1411	1956
2019	8	350	809	29	1189	1920

from the plantations.

3.2. Scenario #2: Irrigation Application

In this second scenario, actual conditions at the plantation site are simulated in the model, which was the maintenance of a high water table through irrigation. The groundwater level was fixed at 600 mm below the soil surface of the plantations, and irrigation was applied to retain the maximum groundwater level of 500 mm (actual condition on the plantation). Fig. 4 shows the resulting increase in evapotranspiration from the plantation site. Notice the increased ET rates at the end of third and seventh years as compared to control scenario due to application of

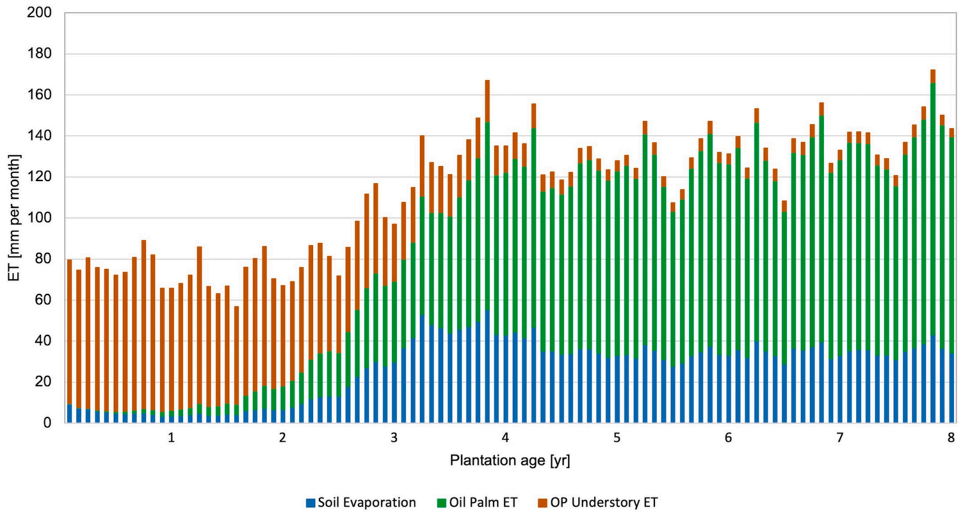

Fig. 4. Total evapotranspiration (ET) after the applied irrigation scenario from the oil palm plantation during the first eight years of plantation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

irrigation. ET rates mostly vary in the range of 120–170 mm per month from the 4th until the 8th year of plantation.

Table 5 shows the total annual rainfall, total annual irrigation applied, and corresponding evapotranspiration from the plantation site from 2012 to 2019. The total evapotranspiration steadily increased from about 900 mm per year to 1700 mm per year from the first to the 8th year of the plantation (Table 5). If we compare the difference of evapotranspiration from the plantation site with and without irrigation, the total increase in ET was about 150 mm in the first year and reached about 500 mm in the eighth year. However, the increase was not linearly distributed; in some years, such as fifth (2016) and seventh (2018), the increase was about 35 mm and 200 mm, respectively.

Fig. 5 shows the total amount of water applied and the average groundwater level during the eight years of plantation. The irrigated annual groundwater level generally remained at about 500 mm (albeit somewhat lower in the fifth and sixth years and higher in the fourth and eighth years), which aims to mitigate the impact of acidic soil conditions by covering the pyritic layer in the soil profile (Bloomfield and Zahari, 1982). The average water requirement for the plantation increases to about 5500 mm (double the amount of annual average rainfall at the plantation site) (Fig. 5). However, the distribution of the total amount of required water was different in different years. The total first-year irrigation water applied was the lowest, about 2500 mm, and in the fifth and sixth year it was the highest (about 3800 mm) (Table 5). The amount of irrigation applied was higher than the total amount of rainfall during any year.

4. Discussion

Oil palms grown on pyritic marginal soils provide a special challenge of maintaining a high water table level to mitigate the effects of acidic soils. Therefore, maintaining a high water table produces additional water demand on top of the plant water requirements, considerably increasing the total water requirement of the plantation. Our analysis of oil palm grown on a single plantation for eight years show that more than 95% of irrigation applied during 6 of 8 years was to fulfill the demand for maintaining a high groundwater level, and for the remaining two years, 80% of irrigation water applied was used for the same purpose. Irrigation applied to the plantation was more than the total annual rainfall in the region, thereby indicating that a large amount of water (i.e., on average 3300 mm of irrigation per year as compared to average rainfall of 2200 mm/year) is needed to maintain suitable groundwater levels to maintain oil palm yields. Therefore, the water footprint of oil palm grown on the marginal pyritic soils was 80–95% more than grown on normal soils.

Our simulated ET values were validated by comparing our ET values predicted by the model to the ET values reported in previous studies. Manoli et al. (2018) modeled evapotranspiration for young oil palm plants (age $<$ 5 years) in a range of 1000–1600 mm/year (on average), while for mature oil palms (age $>$ 8 years) from 1200 to 1800 mm/year. Similarly, our ET values for young oil palm varied between 900 and 1600 mm/year from the first to the fifth year. Likewise, our ET values ranged from 1600 to 1700 mm/year from sixth to eighth year – corresponding closely with their study. Using the eddy covariance methods, Röll et al. (2015) found an evapotranspiration rate of 2.8–4.7 mm/day on a sunny day for 2–12 years old stands for oil palms grown on Sumatra, Indonesia. By extending these values, they range from roughly 1022–1715 mm/year, which also lie close to our simulated values (900–1700 mm/year).

One major advantage of conducting the simulation study is that we can account for the water lost not only due to oil palm evapotranspiration but also evapotranspiration associated with oil palm understory and evaporation from the ground soil layer. The oil palm understory evapotranspiration was about 800 mm during the first year of plantation and dropped to approximately 60 mm at the end of the eighth year of simulation. Meanwhile, soil evaporation reached about 500 mm at the end of the fourth year and then stabilized at more or less 400 mm for the remaining four years (as the understory dies off and exposes more soil for direct evaporation) (Table 5 and Fig. 4). These processes account for about 90–80% of total evapotranspiration during the first two years of plantation. Hence, they cannot be ignored during the initial years of growth. Moreover, even during the seventh and eighth year, the combined evaporation from soil and understory ET account for 30% of total ET. Therefore, estimation of water footprint based on simulation shows diverse drivers of ET than merely using one constant value.

Our main goal of the simulation was to maintain the groundwater level at 500 mm below the soil surface of the plantation. This decision is based on the actual field practice of maintaining water level at this range. This is the standard practice that is followed after Bloomfield and Zahari (1982). Therefore, in order to maintain a constant water table level, we have used the criteria of applying irrigation if the rainfall in three consecutive days was less than 20 mm. This scenario produced the desired water level within the preferred range but with some year-to-year fluctuations (Fig. 5).

Furthermore, the effects of a high water table on the yield of oil palm are also not fully understood (Carr, 2011). Hardanto et al. (2017) compared the difference in sap flux densities of oil palm grown on low lying flooded lands and non-flooded lands, they found minor differences of sap flux densities between the two areas planted by the same species. However, the effects of change of yield were not observed in the study (Hardanto et al., 2017). There is also evidence of the change in root biomass in oil palm seedlings for waterlogged conditions, but no effect was observed on the above ground biomass of the seedlings (da Ponte et al., 2019). For flood tolerant trees, it is observed that about 96% recovery of photosynthesis within short period after flooding, however, long-term effects of flooding can have negative effects on the plant physiology (Pallardy, 2008). Therefore, it is required to establish a relationship between the different soil-types and different level of water tables below the soil surface to maintain the maximum yield from the oil palm plantations grown on different soil types (Carr, 2011). This will help to mitigate the yield gap for the plantations grown on the marginal lands.

The overall water movement in the soil profile of the plantation is captured by the SOILWAT model. It has couple of limitations that can

Table 5
Total evapotranspiration from the plantation along with total annual rainfall and irrigation.

Year	Age of plantation (yrs)	Soil evaporation (mm)	Oil palm ET (mm)	Oil palm understory ET (mm)	Total ET (mm)	Annual rainfall (mm)	Annual irrigation applied (mm)
2012	1	65	15	835	915	2146	2543
2013	2	62	80	718	859	2782	3738
2014	3	223	333	526	1082	1950	2760
2015	4	553	553	257	1364	1770	2976
2016	5	442	1031	93	1567	2528	3865
2017	6	399	1097	62	1558	2262	3865
2018	7	418	1135	68	1621	1956	3427
2019	8	428	1217	63	1708	1920	3240

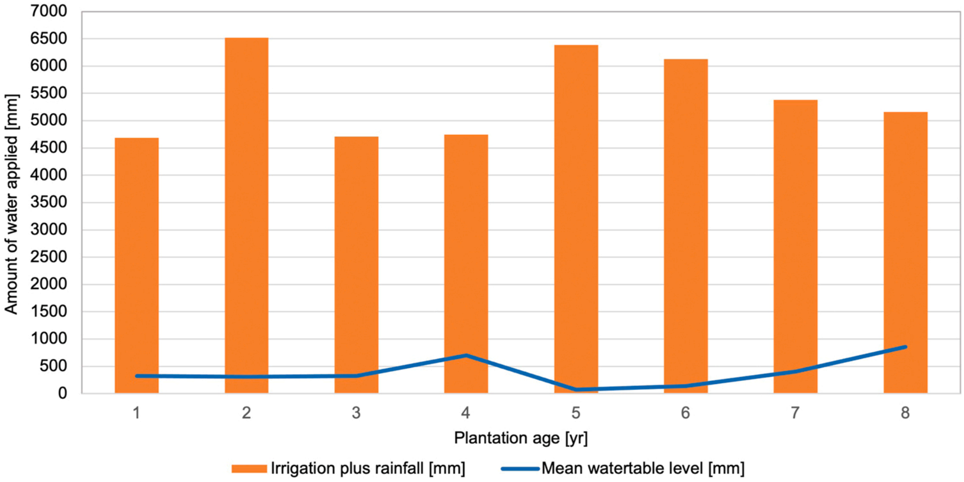

Fig. 5. Total amount of water applied to the plantation (rainfall plus irrigation) is shown by the brown bars. The mean annual water table levels are shown by the blue line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

impact the results. First, SOILWAT is developed for non-saturated soils and its application in saturated conditions can result in errors predicting soil water movement. Second, as this model is a cascading bucket model, it cannot predict accurately the effects of lateral movement of soil water. Tables 4 and 5 show that overall ET rates against the input of rainfall and irrigation. The excess water applied apart from ET for the plant requirements either becomes a component of runoff or part of the drainage component in the cascading bucket approach. Therefore, if we extend our results for plantations over a larger area, it can cause two outcomes: if plantations are on the upstream end of the ground water movement, drained water will become part of maintained groundwater for lower areas; second, if the plantations are located close to the sea then drained water will become part of the sea. Hence, for plantations located close to sea, our model results will not differ much but for upstream areas it would overpredict the water needs. However, further research can couple hydrodynamic models with plant growth to better capture the real water conditions.

One of the important considerations for the oil palm grown on marginal lands is the yield of fresh fruit bunches. The plantation site of our study area suffers from both high acidic content in soil layers and periodic low water table levels, which cause acidic conditions and likely compromise yields. Fig. 6 shows the actual yield from the plantation for an 8-year period and modeled yield. There was a considerable difference between the two yield levels. Maximum yield from the actual plantation reached levels of 10 tonnes/ha during the last two years. However, the maximum simulated yield reached the level of 30 tonnes/ha in the simulated scenario. Moreover, the yield gap starts to diverge from the second year onwards. There can be many factors that could have influenced the yield in our area. For instance, there is some evidence that the yield of oil palm is affected by the soil type of the plantations, therefore, subjecting plants to different types of stresses (Hoffmann et al., 2017). The FAO’s HWSD map indicates that the dominant soil in this area is a Dystric Histosols, which was consistent with our observations. The simulation of the oil palm module in APSIM was verified in the oil palm plantations of Papa New Guinea where the dominant soil groups are Molli Andisols subjecting soils to different stresses - such as seasonal moisture stresses – as compared to the soil of our current plantation – which suffers from poor drainage and sulfide layer in the soil profile (“Harmonized world soil database v1.2 | FAO SOILS PORTAL | Food and Agriculture Organization of the United Nations,” n.d.).

Although oil palm can better tolerate acidic conditions than most plantation crops, very low pH values can hinder growth and impact fruit yield. For instance, it is shown that oil palm can grow well even at a pH of 4.3 and less than ideal drainage conditions (Shamshuddin et al., 2014). However, the performance of oil palm is affected when pH drops below the above level. Moreover, water can become more acidic under

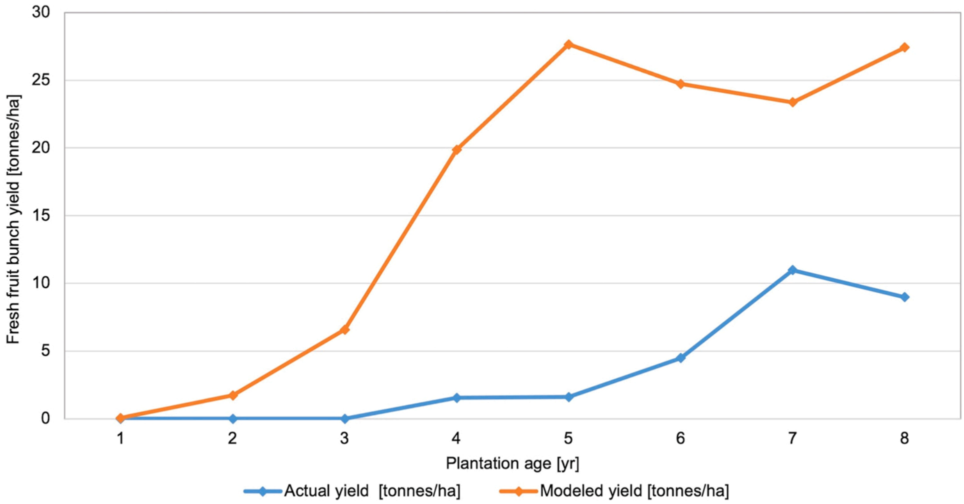

Fig. 6. Actual yield and modeled yield at the oil palm plantation study site on marginal land with a pyritic layer. As a point of reference, remotely sensed yields from Khiabani and Takeouchi (2020) across the region range from 8.5 to 15.4 tonnes/ha.

waterlogged conditions with consistent leaching of the pyritic layer (Shamshuddin et al., 2014). Hence, flushing is performed during the wet season by carefully operating the canal gates and replacing the old water from the dry season with the freshwater from rainfall and excess river flow. Although these mitigating measures can improve plantation conditions, they will produce less yield than plantations with better soils on prime land. Therefore, further research towards better cultivar types or soil treatments can improve the yield level of oil palm grown on marginal lands.

Apart from the wet soil conditions or water quality issues that impact the oil palm yield, yield calculations can be affected by the oil palm cultivar. The APSIM-Oil palm module is developed using the cultivar Dami developed by New Britain Palm Oil Limited (group) in Papua New Guinea. Although this cultivar is reported to be high yielding (Dumortier et al., n.d.), the cultivation of this variety on pyritic soils is not fully understood. However, the Indonesian Oil Palm Research Institute is also developing suitable cultivars that can better tolerate acidic conditions. Therefore, future model calibration should take into account the different cultivars of oil palm as well. In addition, there is a continued yield gap (difference between potential and actual yields) in some oil palm plantations of Indonesia between modeled values and remotely sensed estimations. Using remote sensing, Khiabani and Takeuchi (2020) showed that actual yield from the plantations of Sumatra, Indonesia ranged from 8.5 t/ha and 15.4 t/ha, while the yield from our plantation site varied from 5 t/ha to 10 t/ha from sixth year onward. We expected a lower bunch yield based on the marginal lands of our plantations. Our observed yields correspond better to remotely sensed yields than those output from APSIM (Fig. 6).

A total of 28 tonnes of fresh fruit bunches are harvested per ha during the eight year study period. However, the water applied to the site during the eight-year period was 17,000 mm of rainfall and 26,000 mm of irrigation. In other words, 170,000 m^3 of rainfall and 260,000 m^3 of irrigated water is used to produce 28 tonnes per ha of fresh fruit bunches from the study site. It is important to note that water footprint studies that are carried out in the literature generally ignore the blue water footprint (Subramaniam et al., 2014), although they acknowledge the large green water footprint of the oil palm plantations. Moreover, it is recognized in the literature that irrigation during the dry periods of the year can increase the overall yield from the plantation site (Carr, 2011). Our study shows that for oil palm grown on pyritic soils, there is a higher amount of blue water needed as compared to green water on the plantation site. Therefore, ignoring blue water footprint can cause severe underestimation of the total water footprint accounting for oil palm production.

5. Conclusions

The rapid expansion of oil palm, driven by its high profitability, has converted large tropical areas into plantations. This rapid expansion has resulted in regulations that have imposed moratoria on oil palm expansion and shifted development of plantations onto marginal lands. Plantations in these areas provide a different kind of environmental challenge. The yield of oil palm in low potential areas is considerably lower (because of acidic conditions) than yield in the high potential lands. Therefore, the most common measure in order to increase the yield of the oil palm from these lands is to maintain a high water table level.

We have run the simulations to account for the water requirement of the oil palm if they are planted on low-potential lands. Our analysis shows that the water requirement of the plants increases considerably with plantation age, especially 4-5 years after plantation establishment. Primarily due to the need of a sufficiently high water table, about 80–95% more irrigation water is required to make oil palm plantations possible on these lands. Previous studies conducted on water footprint accounting of oil palm ignore this consideration in their analysis. These studies also fail to address varying water needs during different stages of the plantation. We estimate that in our study area (Rawapitu Plantation in Indonesia), about 15,000 m^3 of water is required to cultivate 1 ton of fresh fruit bunches from the site. About 6200 m^3 is from green water use (rainfall), and 8800 m^3 is from blue water use (irrigation water applied to the site).

However, it is important to note that our modeling was not able to capture the effect of yield reduction on the marginal lands. It can either be due to a lack of understanding of soil chemical processes that affect the yield, cultivar, and/or the effect of high water level, none of which are well understood, on the oil palm growth on marginal lands. This shortcoming is an important area of future research. Nevertheless, using the APSIM modeling framework, along with the APSIM-Oil Palm and other modules, we are able to reasonably approximate field water requirements at our site over an eight year period, thereby highlighting the utility of APSIM for tracking oil palm water requirements in relation to plantation age on marginal soils.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was sponsored by the German Academic Exchange Service (DAAD) from 2014 to 2016 (Grant No.: A/13/90522). The authors also acknowledge the University of Delaware for providing funds to make our article open access. We kindly thank Saleem Ali for managing coordination and Neil I. Huth for providing valuable insights during the model development phase. We also acknowledge the APSIM initiative and its corresponding modeling software, which is provided free for research (see www.apsim.info for details). We also thank two anonymous reviewers for their valuable comments.

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